Advancing Water Conservation in Cooling Towers through Energy-Water Nexus

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Abstract

Life without water is not possible on the earth while modern humans need water not only for drinking, sanitization, and agriculture but also for industry, thermoelectric, and cooling plants. Hence, emphasis on water sustainability through different sectors including thermoelectric and cooling plants is an intelligent strategy while the tight connections of water and energy guide study towards energy-water nexus investigations. Cooling towers are equipment for dissipating the excess heat by water evaporation or they hidden gates for wasting water. The objective of the present study is to elaborate on the role of cooling towers, categorizing various methods for modifying water and energy consumptions through past studies, and mapping future studies regarding cooling towers. Presenting a history of energy-water modeling methods of cooling towers, the Markel, the Poppe, and the effectiveness–(NTU) models, has followed by assessing the environmental impact of cooling towers in the form of excess water consumption, plume, and energy usage. Summarizing and organizing the past efforts for upgrading water management in cooling towers have been in two directions either providing more water supply, or modifications of the cooling tower to use less water. Then the different methodologies for each direction are introduced for further elaborations. The practical outcome of this study is proposing the practical methods of improving water sustainability for any cooling towers from past studies to assist engineers in the industry for quick modifications of cooling towers. Showing the roadmap for the planning future investigations on the cooling towers based on the past efforts is another outcome of the present study to provide an insight for academia with research interest on cooling towers.

Keywords: Water conservation; water consumption; water sustainability; cooling tower; wet cooling tower; hybrid cooling tower.

Nomenclature

APD	Advanced Pinch Design
CFC	Chlorofluorocarbons
CHP	Combined Heat and Power
COP	Coefficient of Performance
ESCO	Energy Service Companies
FCC	Fan Cycling Control
FMC	Frequency-Modulating Control
GWDS	Gravity Water Distribution System
HCCCT	Hybrid Closed Circuit Cooling Tower
KSD	Kim and Smith
Mercaptobenzothiazole	MBT
MINLP	Mixed-Integer Nonlinear Programming
MSC	Stages of velocity
MW	MegaWatt
MWNT	Multi-Walled Carbon Nanotubes
NREL	National Renewable Energy Laboratory
NTU	Number of Transfer Unit
OC	Optimum Control
PI	Proportional Iterative
PPWD	Parallel Path Wet-Dry
PWDS	Pressure Water Distribution System
RO	Reverse Osmosis
VFD	Variable Frequency Drive
WESCO	Water Efficiency Service Companies
a_{fi}	the surface area of the fill per unit volume of fill
C_{pw}	the specific heat at constant pressure and at water temperature (J/kg K)
h_d	the mass transfer coefficient
f	the correction factor according to Berman
i_v	the enthalpy of the water vapor (J/kg)
$i_{masw,m}$	the enthalpy of saturated air at the mean water temperature (J/kg)
Me_M	the transfer coefficient or Merkel number according to the Merkel approach
Me_P	Merkel number according to the Poppe approach
Me_e	Merkel number according to the effectiveness–(NTU) approach
w_{sw}	the ratio of water saturation at the water temperature
w_{sa}	the humidity ratio of saturated air at temperature Ta
ε	the effectiveness ratio

1. Introduction

The cooling tower is one of the key components in industries such as power generation including renewable (geothermal [1] and solar thermal [2]) and non-renewable [3] power plants, chemical and petrochemical plants [4], refrigeration and air-conditioning plants [5]. Thermoelectric generation and its required cooling are responsible for approx. 10% of the total water demand in the world [6]. The role of the cooling tower is dissipating heat from the hot stream of the process into the air [7] in power plants, district cooling plants, and cooling systems. To address the water scarcity for a sustainable future (in smart cities) cooling towers have to receive special attention. Replacing the evaporation of water for dissipating the heat with another method, or capturing the vapor, or both are the ideas to support water conservation. Considering several cooling towers that are installed already highlights the importance of capturing the vapor and/or reducing evaporation studies.

The design of cooling towers focuses on the water distribution system, fill, and drift elimination [8]. The water distribution system introduces and spreads the process water as evenly over the fill through the use of water canals and nozzles [8]. The fill is a system of packing that delays the fall of water and improves heat transfer [8]. Drift eliminators at the air exit change the direction of airflow to reduce the volume of water transported out [8]. Within cooling towers, water is lost through three main modes. These modes are drift, blowdown, and evaporation [9]. Drift is the water losses associated with wind, evaporation loss occurs due to the heat transfer taking place, and blowdown is utilized to avoid the buildup of minerals and sediments within the cooling water that may damage other components within the system [9]. Blowdown is also a byproduct of the evaporation processes increasing the concentration of the minerals [9].

Oftentimes, cooling towers are oversized, and thus rarely operate at their design points [10]. One of the primary reasons for oversizing is to ensure proper cooling when ambient temperatures and humidity are high. At high ambient temperature and humidity, it is more difficult to reject heat from a cooling tower. The design parameters of the system dictate what the output temperature of the process water must be, and therefore the cooling tower must be able to reach that in any condition. Most of the time, however, ambient conditions are less extreme, and therefore the large size of the cooling tower is not required in these conditions [5].

National Renewable Energy Laboratory (NREL) has provided a protocol for cooling tower measurement and verification to ensure that water savings are properly recorded [11]. It has intended for energy service companies (ESCOs) and water efficiency service companies (WESCOs) to determine water savings resulting from cooling tower efficiency projects. When measuring both baseline and post-upgrade operations of a cooling tower, it is suggested that multiple seasons of data be used to establish averages. However, a minimum of one season of cooling data is required for analysis. If a flowmeter is being used, the flow of water should be normalized by multiplying the use of water over the cooling season by the sum of the wet-bulb temperature ratios. The sum of wet bulb temperature ratios is found by dividing the historical monthly wet-bulb temperatures for a location by the recorded wet-bulb temperatures during that same month. These ratios can then be added together for all the cooling seasons. The result scales the water-usage during the testing period to historical averages.

Cooling towers consume huge amounts of water and by considering water scarcity, improving water conservation is crucial. The goal of the present study is to map the previous studies by categorizing and explaining the objectives and related attempts for reducing energy and water consumption. As a foundation for elaborating former studies first different types and configurations of the cooling tower as well as the modeling history of cooling towers are explained. The past studies are concluded in the form of practical methods for improving the cooling tower energy and water conservations. Also, the direction for future studies is presented. The outcomes of this literature review study assist engineers with practical results and academia to show the future study roadmap, while support the environmental sustainability of cooling towers.

2. Cooling Towers Types

Cooling towers are classified based on different characteristics, although the following are the major ones:

- airflow
    - mechanical draft
    - natural draft types [12]
- water consumption
    - wet,
    - dry,
    - combination of wet-dry (hybrid) [13].

Choosing the proper cooling tower for a plant is a balance of different parameters like plant efficiency, capital and operation cost, water consumption, water withdrawal, and environmental impact which are illustrated in Table 1 [14].

Table 1: The summary of cooling towers tradeoffs [14]

Cooling system	**Water withdrawal**	**Water consumption**	**Capital cost**	**Ecological impact**
Wet cooling tower	Moderate	Intense	Moderate	Moderate
Dry cooling tower	None	None	High	Low

2.1. Wet Cooling Towers:

Wet cooling towers operation is through changing water from liquid to vapor to release the excess heat in the cooling cycle [15]. The thermal performance and stability of the wet cooling tower are better than the dry cooling tower because thermodynamic parameters rely less on ambient temperature [16]. The advantages of wet cooling towers are:

- saving energy and costs,
- reducing CFCs usage,
- improving life cycle cost-effectiveness [17].

Wet cooling towers are also categorizing by the movement of water and air inside of the cooling tower:

- the crossflow towers: air flows horizontally across the falling water,

- counterflow: the upward airflow that directly opposes the downward flow of the water providing [18].

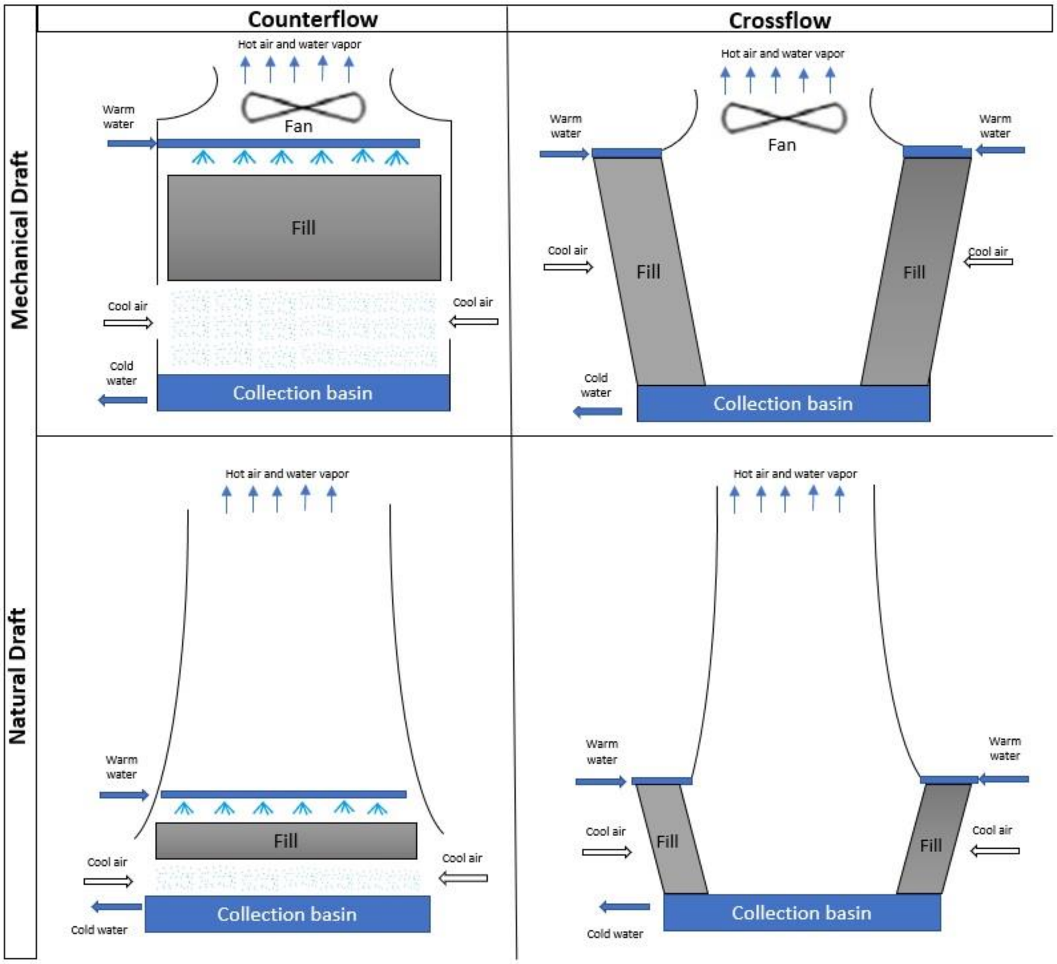

Figure 1: The schematic of different types of wet cooling towers

Since counterflow cooling towers are using more commonly there are more studies for them in comparison with crossflow [19]. The schematic of different types of wet cooling towers is shown in Figure 1.

In wet recirculating cooling tower systems, the warm water from a plant process condenser is pumped to a cooling tower where heat is dissipated to the ambient environment by evaporating water [20]. Surrounding ambient air is forced into the cooling tower by one or more fans [9] to accelerate heat dissipation the cooling tower which results in increasing the temperature of the incoming air. Once the water has been cooled, it can then be returned to the plant process for use.

The open recirculating cooling towers withdraw water, then circulate that instead of discharging [21]. The significant amount of water consumes in the cooling towers, particularly freshwater in the power generation plants, depends on the type of fuel and generator technology [22]. Table 2 illustrates the water consumption of cooling towers in the different thermal cycles. It must be noted that wet cooling towers are not favorable in the region with water shortages due to the high water consumption of them [23]. Water availability has a key parameter in the decision-making process of choosing the cooling tower [24].

Table 2: The average water consumption of cooling towers in a different type of power plants

Fuel type	**Thermoelectric Technology**	**Cooling water consumption (m^3/MWh)**	**Reference**
Coal	Steam turbine	2.1/ 2.13	[25] [26]
Coal	Supercritical	1.5/1.3	[27] [28]
Coal	Integrated gasification combined cycle	1.44/1.14	[29][30]
Natural gas	Steam turbine	2.6/2.5-4.4/3.12	[25] [31] [32]
Natural gas	combined cycle	0.9/0.77	[25] [33]
Natural gas	Combined cycle with carbon capture and sequestration	1.48	[29]

2.2. Dry cooling towers:

A dry cooling tower depends on convective heat transfer that is governed by the dry-bulb air temperature [34]. In a dry cooling tower, heat exchangers are placed in the core of the tower which uses air as the cooling medium, and hot water becomes cold in a closed circulating loop [35]. Dry cooling is applicable by either mechanical draft or natural draft [36]. Figure 2 shows dry cooling towers in the form of a mechanical draft and a natural draft. The dry cooling towers in comparison with wet cooling towers:

- Dissipate less heat in the cooling process,
- Consume less water, therefore,
- Need less maintenance [80]

Therefore, it can be concluded dry cooling towers are a better candidate for regions with water scarcity, while they are less effective.

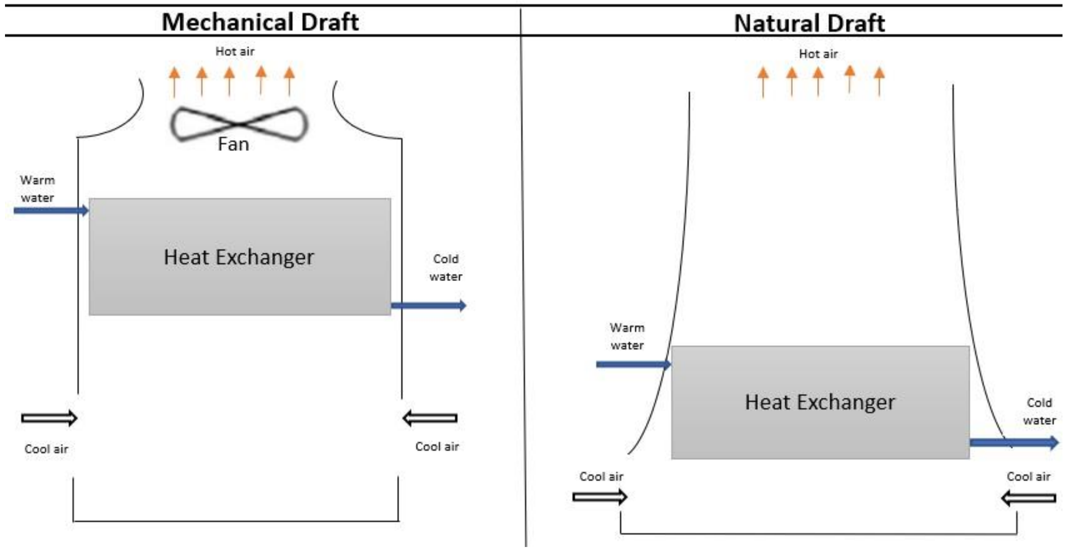

Figure 2: The schematic of natural and mechanical draft dry cooling towers

2.3. Hybrid Cooling Towers:

In the 1970s cooling towers both wet and dry combined as hybrid cooling towers [37]. Therefore, hybrid cooling towers components have advantages of both cooling towers [38]. They consume less water while still maintaining similar heat load rejection capacity. Hybrid cooling towers can be used separately or simultaneously either for water conservation [39] or plume abatement [40–42] purposes. A hybrid cooling tower benefits depends on the heat load, the airflow rate, and the ambient air conditions [43]. The performance of hybrid cooling towers was investigated by experimenting parallel to numerical simulations on various operation conditions [43]. The outcomes revealed the most important factor in designing the hybrid cooling tower was water to air ratio was related to the operation condition of the cooling towers. A computational procedure to predict hybrid cooling tower performance in a wide and variable range of working conditions was developed [43]. The parallel airflow was flowing through both dry and wet sections while the cooling tower load water runs in a series path from the dry cooling tower to the wet cooling tower [44]. It concluded the performance between dry cooling and wet cooling towers was dependent on the adjustable airflow to each section. Consequently, when a hybrid setup met the cooling demand, the required power was significantly reduced by lowering the airflow to the dry section. Furthermore, the higher fractions of airflow going to the wet cooling tower followed with a more favorable COP [43].

In a study, the hybrid cooling tower was designed by adding several dry cooling towers unites to the existence of a wet cooling tower at a power plant and a refinery station to reduce the water consumption and operational cost [6]. The results showed the total water consumption of the cooling tower in the various hybrid ratio was reduced to 38% which led to cost savings [6]. In a similar study, by three types of cooling system dry, wet, and hybrid in a power plant the thermodynamic models developed to study the effects of the dry bulb, wet bulb temperature, and humidity on the operation [16]. The case study was a 660 MW power plant in China, and results indicated that exploiting hybrid cooling towers led to reducing 46% of water consumption comparing with a wet cooling tower, reduction of 45.84% fan energy usage comparing with dry cooling [16]. The optimum hybrid cooling wet/dry parameters are defined for the 12.5 MW steam power plant in Iran based on the ambient data of the past 5-year [45]. It was shown exploiting from an optimum hybrid cooling tower led to a 63% water consumption reduction.

The flow resistance of the natural draft of a hybrid cooling tower with parallel airside cooling sections of wet and dry cooling was investigated to determine the annual thermal and economic performance in different ambient conditions [46]. The study was on wet, dry, and hybrid cooling towers coupled with a 660 MW steam power plant. Results indicated the operation costs of hybrid cooling tower was lower than dry and wet cooling towers while the net benefits of $200/h in 2010 and $100/h in 2018 could be attained, respectively.

Through an experimental study, the impacts of bare-type copper tubes and fin tubes on the cooling capacity in a hybrid closed circuit cooling tower showed a 22% and 26% increase in the cooling capacity of wet and dry modes, respectively. However, the operation cost increased due to the pressure drop increase [47]. The use of finned tubes in a Hybrid Closed Circuit Cooling Tower (HCCCT) was studied by switching from wet to dry modes depending upon the cooling load. [47]. It was shown experimentally that using finned tubes made an increase in the cooling capacity of the wet and dry modes by 22% and 26% respectively, in the trade-off with a large pressure drop. Additionally, the use of finned tubes required only 80% of the airflow that regular tubes required.

A method of retrofitting existing wet cooling towers to reduce water consumption was introduced by employing air-cooled heat exchangers and installing them in an existing wet cooling tower [37]. The existing wet fill was lowered to make room for the dry section above. An airflow control system has been introduced that controls the airflow to minimize water loss. The system was known as a Parallel Path Wet-Dry (PPWD) system. In this system, the water flows first into the dry section and then into the wet section. The air streams were in parallel and only mix in the plenum above the dry section. It was concluded that an annual water consumption reduction between 4.3% to 6.7%, depending upon the dry section heat exchanger design by the hybrid PPWD cooling tower in comparison to a wet type.

3. Colling Towers Modeling

Modeling of the cooling towers started with Lewis who analyzed the cooling tower thermodynamically in the 19th century [48]. Then, equations for the cooling tower was developed by Robinson based on Lewis' work [49]. Merkel proposed a model in which enthalpy was potential as the driving force for air-water exchange, heat, and mass convection transfer employing Lewis number [50]. Some underestimation of cooling towers sizing existed in Merkel's model [51]. Bourillot modified the Merkel model about insufficiency to define water consumption over excess simplification of the model [52]. Poppe and Roger added the heat and mass transfer coefficients for supersaturated and unsaturated air in their model to the Bourillot model and defined a new Merkel number formulation [53]. Braun et al. and Jaber et al. developed the effectiveness– Number of Transfer Unit (NTU) model and found a method for calculation of the cooling tower performance by improving the Merkel's model [54–56]. Both the Merkel and effectiveness-NTU models could accurately predict the outlet water temperature, both were inadequate in the evaluation of the evaporated water flow rate and properties of outlet air while the Poppe model was able to predict the states of the outlet air accurately [57]. Finally, Klopper proposed a model based on the Poppe model to calculated the water evaporation rate based on the actual value of the Lewis factor [58].

Before further explanations, it must be noted that the wet cooling tower models are defined based on the ambient properties. The thermal performance of wet cooling towers strongly depends on the humidity and temperature of the ambient [59].

The Merkel, Poppe, and e-NTU models have been implemented in many cooling towers studies with different objectives. To map the applications of each cooling tower modeling method concerning the goal of the studies since 2003, papers are summarized in Table 3, based on the modeling type and objectives.

Several studies were conducted to compare the Merkel, Poppe, and e-NTU models through experimental observation in test conditions. The summary of those studies are as following categories:

- **Air outlet temperature**: When the outlet air from the cooling tower was saturated, Merkel and e-NTU models were capable of predicting the temperature of that, while the Poppe model did not need any assumption for estimation of the outlet air temperature from the cooling tower [60].
- **Water outlet temperature:** When the draft in the cooling tower was the same, the outlet water temperature from the cooling tower in three models were the same. A small difference in the outlet water temperature from the cooling tower was observed in Merkel and Poppe models over the outlet air from the cooling tower since outlet air assumed saturated in the Merkel model [61].
- **Heat rejected:** The loss of water due to evaporation in the cooling tower reduced the water outlet mass flow rate which was ignored in the energy equation in the Merkel and e-NTU models while it was seen in the Poppe model. The estimated heat rejection rate by the cooling tower was larger by the Poppe model in comparison with Merkel and e-NTU models [61].
- **Evaporation rate:** The water evaporation rate in the cooling tower was underestimated by the Merkel model in comparison with the Poppe model [62]. Since the evaporation was an important factor in designing the hybrid cooling towers, using the Poppe model was preferred [61,63].

- **Lewis factor:** The Poppe model proposed a reliable equation to determine the Lewis factor value [60]. While in the Merkel model the Lewis factor was a constant number of 1. Most researchers believed that Merkel's assumption was not accurate since the Lewis factor was between 0.6 to 1.3 [64].

Table 3: Modeling approaches and objectives of wet cooling towers studies

Study	**Objective**	**Model**
(Irok et al. 2003) [65]	Performance analysis	Merkel
(Khan, Qureshi, and Zubair 2004) [66]	Performance analysis	effectiveness–(NTU)
(Söylemez 2004) [67]	Performance optimization	effectiveness–(NTU)
(Papaefthimiou, Zannis, and Rogdakis 2006) [68]	Performance analysis	Merkel
(Kranc 2006) [69]	Performance analysis	Merkel
(C. Ren 2006) [70]	Model improvement	Merkel
(Jin et al. 2006) [71]	Model improvement	Merkel/effectiveness–(NTU)
(Qi and Liu 2007) [72]	Performance analysis	Poppe
(Williamson, Behnia, and Armfield 2008) [73]	Performance analysis	Merkel
(C. Q. Ren 2008) [74]	Performance analysis	effectiveness–(NTU)
(Tyagi et al. 2008) [75]	Cost optimization	effectiveness–(NTU)
(Klimanek and Białecki 2009) [76]	Model analysis comparison	Poppe
(Marmouch, Orfi, and Nasrallah 2009) [77]	Performance analysis	effectiveness–(NTU)
(M. Lucas et al. 2009)[78]	Performance analysis	Merkel
(Rubio-Castro et al. 2011) [79]	Cost optimization	Poppe /Merkel
(T.-H. Pan et al. 2011) [80]	Performance optimization	Merkel
(Picón-Núnez et al. 2011) [59]	Design optimal Cooling tower	effectiveness–(NTU)
(Smrekar, Kuštrin, and Oman 2011) [81]	Performance analysis	Poppe
(Rao and Patel 2011) [82]	Performance optimization	Merkel
(Gololo and Majozi 2012) [83]	Water consumption optimization	Poppe
(Picardo and Variyar 2012) [84]	Model improvement	Merkel
(T. Pan et al. 2013) [85]	Performance optimization	Merkel
(Grobbelaar, Reuter, and Bertrand 2013) [86]	Performance analysis	Merkel
(Khamis Mansour and Hassab 2014) [87]	Performance analysis	effectiveness–(NTU)
(Hernández-Calderón, Rubio-Castro, and Rios-Iribe 2014) [88]	Model improvement	Poppe
(Nasrabadi and Finn 2014 [89]	Performance analysis	effectiveness–(NTU)
(Nasrabadi and Finn 2014 [90]	Performance analysis	Merkel
(Uzgoren and Timur 2015) [91]	Performance optimization	Poppe
(Y. Wang et al. 2015) [92]	Performance analysis	Poppe
(Xu et al. 2015) [93]	Performance analysis	Merkel
(Keshtkar and Mehdi Keshtkar 2016) [94]	Performance optimization	Poppe
(Singh and Das 2016) [95]	Performance optimization	Merkel
(Singla, Singh, and Das 2016) [96]	Performance optimization	Merkel
(Llano-Restrepo and Monsalve-Reyes 2016) [97]	Model improvement	Merkel
(Qi et al. 2016) [98]	Performance analysis	Poppe
(Singh and Das 2017) [99]	Performance optimization	Merkel
(Sharqawy et al. 2017) [100]	Performance analysis	effectiveness–(NTU)
(Gilani and Parpanji 2017) [101]	Performance analysis	Poppe
(Huang et al. 2017) [102]	Performance analysis	Poppe
(Y. Li et al. 2017) [103]	Performance optimization	Poppe
(Zhou, Zhu, and Ding 2017) [104]	Performance analysis	Poppe
(Ayoub, Gjorgiev, and Sansavini 2018) [61]	Model improvement	Merkel/ Poppe/ effectiveness–(NTU)
(Mishra, Srivastava, and Yadav 2019) [105]	Performance analysis	Merkel
(González Pedraza et al. 2018) [106]	Model improvement	Merkel
(Liao et al. 2019) [107]	Performance optimization	Poppe

(Jes´ et al. 2019) [108]	Model improvement	Poppe
(Ke, Huang, and Ling 2019) [57]	Performance analysis	Merkel
(Gilani, Doustani Hendijani, and Shirmohammadi 2019) [109]	Performance optimization	Poppe

4. Environmental Impact

Using wet cooling towers has some negative impacts on the environment while using them to reduce CFC in the atmosphere which is strongly harmful to the Ozon layer. The major categories that wet cooling towers cause impact the environments water, plume, and energy.

4.1. Water

The wet cooling towers are widely used and considering the high water consumption in this type of cooling towers, they are not desired in zones with water resources limitation [110]. Many ideas have been proposed and investigated as mitigations for resolving issues. All approaches are in two categories:

- Improving the design parameters, operations, structure of the cooling towers to reduce water consumption. Many of these studies are explained under improving water conservation in the present study.
- Focusing on the circulating water in the cooling tower for lesser evaporation through different approached.

Some of these methods are detailed in improving water conservation.

4.2. Plume

The ambient conditions influence the cooling towers environmental impacts such as making visible plume [111] and releasing hazardous materials [112]. When the moisture is released by a wet cooling tower, it mixes with cooler atmospheric air while the amount of vapor closely approaches the saturation point, the plume moisture gets condense quickly and generates a visible plume [113]. Visible plume is not considered as an air pollutant but sometimes contains the mineral and chemical which can be hazardous [114]. For safety purposes, some countries have mandated the visible plume by cooling towers [115]. Using solar collectors particularly for commercial buildings, using hybrid towers instead of evaporative, and abating the plume by enhancing the performance of cooling towers [40]. The plume control performance is accessible by using an alternative arrangement of the evaporative side of heat pumps which provides hot water for the plume abatement system and enhances the energy efficiency of the chiller plant [116].

The fog harvesting and Atmospheric Water Harvesting (AWH) for capturing the vapor to produce water are new approaches for plume abatement [117,118]. Experimental data from outlet fog harvester systems demonstrate that the rate of water collection in cooling tower fog harvester was 3 to 5 times more than atmospheric air fog harvester due to a high level of relative humidity (RH) in cooling towers. Moreover, the source of fog in cooling towers was more permanent than atmospheric air in providing sufficient fog for harvester during the year [119]. Zapping the fog with the beam charged particles (ions) of electrically improved capturing water droplets from fog harvester by directing droplets to the storage in a low-cost and low-energy method for collecting of 20% to 30% of wastewater in cooling towers [120,121].

4.3. Energy

The energy savings provided by using a Variable Frequency Drive (VFD) fan in cooling towers were studied as a Proportional Iterative (PI) feedback controller with a temperature zone setting to manage the outlet temperature of the water from the cooling tower [20]. The goal was to reduce energy consumption and reduce or eliminate frequent on/off fan switch that was typical in cooling towers. The control strategy reduced energy consumption by 38% within the simulations and was also validated using experimental data. The study of seasonal climate change impact on the cooling tower performance for reducing its power consumption by using VFD in Brazil yields a significant power consumption reduction, especially in colder days [122]. VFD could reduce up to 60% of annual power consumption in different weather conditions [122]. A novel counterflow cooling tower that utilizes a VFD fan and a by-pass loop equipped with microfilters and UV lights to keep the water at cleaner levels and reduced required blowdown [11]. The results of the experiment indicated that at 50% capacity, the upgraded cooling tower had an energy savings of 76% and an overall water savings of 23% in comparison to the original design with a single-stage fan and no water filtration system [7].

5. Water Conservation

To advancing the technology of the cooling towers to reduce water consumption there are many studies with different approaches. Many of the focusing advancing the structure, some aiming at operation parameters, and some centering the water. The methodologies for the investigations are in a wide range including experiment, modeling, simulation, and optimization, and other methods for modifications.

In the following paragraphs, the major studies are classified and elaborated. Finally, the methods of water consumption reduction in wet cooling towers are summarized.

5.1. Water Focus

Filtration of water is a known and widespread practice in the industry to soften the water for reducing the make-up water as well as protecting equipment and pipes from fouling and corrosion. Excess water and maintenance of equipment are costly for any energy/cooling plant. Also, governmental incentives are always an effective means for enticing customers to adopt water-saving methods [123]. Generally, various options available for reducing make-up water within wet cooling towers are [14]:

- *Soft water make-up:* removing calcium and magnesium, which are the two largest formers of scale. This reduces blowdown requirements while increasing pipe corrosion and cost of creating the make-up water,
- *Acid Feed:* increasing solubility of calcium and magnesium for allowing more cycles of concentration. Although, the acid may present a safety concern,
- *Reverse Osmosis (RO) Concentrate:* blending with potable water for make-up,
- *Rainwater:* collecting and using as make-up water, some anti-bacterial process may be required,
- *Air Handling Condensate:* replacing other equipment in large quantities of condensate,

- *Fixing Leaks:* repairing leaks always reduce water usage. They are wasteful and oftentimes can be overlooked if small, but their waste adds up over time [123].

A relatively new type of cooling tower known as a water-jet cooling tower was used for the experiment and numerical simulations study [124]. It was designed with a significant advantage over traditional wet cooling towers for contaminated water such as seawater or oil-water mixtures. Replacing the fill or packing material and substituting that with fine water droplets were made form special high-pressure nozzles [124]. Another advantage was removing the fan. The results of the thermodynamically study heat rejection load, wet-bulb temperature, water to air ratio, tower spray zone height, droplet diameter, discharge droplet velocity, and air velocity in water-jet cooling tower showed as drop diameter increased, exergy efficiency decreased. By increase of the water to air ratio, exergy efficiency for a smaller droplet size increased while the heat transfer decreased. The feasibility of using seawater instead of freshwater in circulating wet cooling tower in an experimental showed the impact of saltwater concentrations on the cooling tower decrease 9.86% of its performance and presented a valuable theoretical basis for developing seawater cycling instead of freshwater usage [98]. In another study, the effect of the thermophysical properties of seawater on the thermal performance of the cooling tower was concluded that the efficiency of the cooling tower was reduced by 5-20% [125].

Water harvesting from cooling towers fog is by mounting woven metal meshes at the outlet plane of the cooling tower cell. The fog droplet capture efficiency is analyzed using different mesh configurations by changing the spacing between adjacent wires in the woven mesh and varying the geometry of the fog net frame that led to the total water reduction by 40% in a 500 MW power plant in the optimal case [126].

The influence of the wettability of a mildly hydrophilic metal mesh for fog harvesting purposes in cooling towers was experimentally investigated on small scale. The outcome indicated that from 8% to 23% of water content in the fog flow stream was collected [127].

Multi-walled carbon nanotubes (MWNTs) and nanoporous graphene nanoparticles within a cooling tower were used to understand the effects on the energy and water conservation performance of a mechanical wet cooling tower experimentally [128]. For inlet water temperatures of 40 ˚C, the use of MWNTs and nano-porous graphene nanoparticles with a 0.1% mass concentration reduced the water consumption rate by 10% to 19%. The water savings was due to the increase of sensible heat effect and reduction in the latent heat effect. Reduction in the latent heat effect was thought to be a result of the surface tension change of the water as nanoparticles created resistance against evaporation [128]. Another experimental study on the performance of cooling towers in six different beds by using nanofluid showed the metal reticular bed as the most suitable bed when using nanofluids because using ZnO/water nanofluid instead of pure water in the cooling tower improved the thermal efficiency of the tower up to 9.45% [129]. However, the economic analysis of this idea, particularly for large scale cooling towers, hazardous impacts of using nanofluids in the water, and the feasibility of performing in the real plant are not considered by the authors.

The effects of increasing the cycles of concentration within a power plant cooling system to reduce water consumption investigated by increasing the cycles of concentration in blowdown which led to overall water consumption reduction [130]. (Cycles of concentration refers to the concentration of dissolved solids in the cooling tower water.) The used water went through the pretreatment, pH adjustments, chlorination control, and inhibitors to improve the quality of water for use. It was concluded that despite all the treatment, phosphate deposits were observed at higher cycles of concentration. Corrosion and scale control using MBT and $ZnSO_4$ was found effective at reducing corrosion in the carbon steel and brass pipes of the heat exchangers. Increasing the cycles of concentration from 6.5 to 9 yielded a water savings of 1.1×10^6 m^3 of water per year while cooling requirements were satisfied.

A lab-scale experimental study was conducted to recover evaporated water in the cooling tower by implementing an independent cold-water circulating loop through an array of copper tubes on both sides of the tower which led to the capture of 11% of vapor. Also, a combination of copper tubes assisted with metal foams could improve the result [131].

5.2. Cooling Towers Modifications

To capture the vapor out of the cooling tower, a design utilized cooling sprays of water drawn by pumps from the bottom of the cooling tower to condense water vapor that flows under vacuum conditions through the vertical channel [2]. A laboratory testing on a wet cooling tower using air to an air heat exchanger to cool the humid hot exiting air was performed [20]. The warm-wet air out of the tower was cooled by relatively drier and cooler ambient air, while the warm-wet air from the tower was cooled by an auxiliary fan, and the water was built up was collected. A water savings of 35.4% total evaporation was achieved when the temperature difference between the warm humid air and the cooler ambient air was 15 ˚C. At a temperature difference of 3 ˚C, the water savings was 15.1%.

TRNSYS was used to model, simulate, and evaluate cooling tower performance and water loss from experimental data that used 4 control strategies and 6 different drift eliminators with 2 different water distribution systems [8]. The control strategies were Fan Cycling Control (FCC), Multiple-speed fan motor control in 3 stages of velocity (MSC), via VFD Frequency-modulating control (FMC), and Optimum Control (OC) [8]. The two different distribution systems were the Pressure Water Distribution System (PWDS) and Gravity Water Distribution System (GWDS) [8]. Three of the drift eliminators were composed of a zig-zag structure and fiberglass plates separated at distances of 55, 37, and 30 mm, respectively. The remaining drift eliminators utilized a plastic honeycomb structure, a 45◦ tilted rhomboid mesh, a 45◦ tilted lower half, and a 135◦ tilted upper half. The results concluded that the best FCC control strategy operation for reducing water loss was FMC, OC, and MSC following close behind. There were no substantial benefits between the controls due to most of the water loss occurring in blowdown (70%) while only 0.3% accounted to drift.

Theoretically and experimentally the heat transfer characteristics and pressure drop of a cooling tower were studied [132]. The experiment was testing the changes in the inlet/outlet air flow rate and inlet temperature and flow rate of water. It was found that increasing airflow rate into the cooling tower resulted in decreased exiting temperature and decreased outlet water temperature [132]. However, the outlet air temperature approached a minimum amount as the airflow increased and the pressure drop across the cooling tower rapidly increased as the airflow was increased in the tower [132].

A study of hybrid cooling towers concerning water conservation conducted by numerical simulation and experiment on parallel and series configurations of a hybrid system in Tabriz Refinery (Tabriz, Iran) [39]. Based on the heat exchanger area of the refinery, the water consumption reduction was between 37% to 23% during the summer months for the series and parallel configuration, respectively. Additionally, the payback period for recovering the costs of the upgrades was around 7 years for series, while the parallel was found to never return the initial investment. The method of retrofitting an existing wet cooling tower into a hybrid cooling tower with PPWD configuration to reduce make-up water within was developed in unit 5 of the Isfahan (Isfahan, Iran) thermal power plant [37]. The goal was to modify the system with minimal effort from the plant personnel labor and cost. The first hybrid used the existing wet towers packing in the same place, while the second one lowered the packing by 1.4 m to increase the dry section cooling area. Under identical scenarios, the first hybrid set up lowered water consumption by 7.0 % while the second setup, with the larger fraction of total cooling, was delivered from dry cooling and lowered water consumption by 9.4% [37].

5.3. Optimization Approach

Optimization as a tool for finding the optimum parameters for the ideal performance has been applied in some cooling tower studies. It needs to be clear that the optimization of cooling towers and related systems by using air volumetric flow and cooling water flowrate as parameters have three main shortcomings:

- optimization models often assume that process parameters can be modified at any time. Adjustments in process parameters of existing cooling towers require input from operators and equipment manufacturers.
- fluctuations in environmental conditions are disregarded.
- there is a lack of systematic identification and assessment of efficiency measures [9].

The dynamic correlations for temperature and humidity ratio of the air for an existing cooling tower in a power plant were developed by using weather temperature and humidity data as well as the cooling tower data including its geometry, water inlet temperature, and its mass flow rate while dynamic simulation for 24-hour was running [133]. Three objective functions were defined as minimizing operating cost, minimizing the accumulation of water in the tank, and minimizing makeup water flowrate. The results indicated that the makeup water flow rate could be reduced up to 57% while costs and energy usage were minimum possible [133]. Optimization of a cooling tower under load for minimal economic impact by considering fan speed, water removal flow rate, and valve positions at the heat exchanger branches of the load were conducted [10]. It was observed that the outlet temperature of the cooling tower had to keep as high as the heat load to economically optimize the system [10]. The most economically minimizing action was to increase the flow rate of the cooling tower water when the load demand was increased and then increase the fan speed by an increase of cooling demand [10]. The worst scenario was to introduce additional makeup water to cool the cooling tower water which let to an increase in water usage [10].

The mathematical model for designing a sustainable natural draft wet cooling tower developed to estimate water consumption as a function of the power plant location in Spain for two different types of power plant, Rankine and combined cycle [134]. The objective functions were defined to find the optimum water consumption, tower size, and cost as a function of humidity, temperature, and atmospheric pressure for different power plant sizes ranged from 40 to 450 MW. Their outcomes showed a reasonable agreement between the calculated results and the practical ones for the combined cycle, plus the higher level of temperature and humidity led to higher water consumption in wet cooling towers. A combined-cycle plant in the southeast region of Spain with higher temperature and humidity range consumed around 2 L/kWh water, while a similar plant in the northwest of Spain with lower temperature and humidity used about 1.5 L/kWh water at the same time [134].

The optimization of a cooling water system using mixed-integer nonlinear programming (MINLP) model was performed to reduce water consumption, improve system operation, and reduce the capital cost of a cooling network using series, parallel, as well as combined series and parallel configurations [135]. When their MINLP optimization algorithm was employed, the combined series and parallel configuration has minimized the cost, with parallel only being last.

A cooling tower using Advanced Pinch Design (APD) to allow for maximum amounts of heat transfer to occur within a system optimized. The APD algorithm let interaction between the cooling tower performance and heat-exchanger network configuration to be considered simultaneously. In comparing APD to another optimization algorithm known as the Kim and Smith (KSD) method costs were decreased from $72,000 per year and $59,000 per year for the conventional and KSD systems respectively, to $52,000 for the APD system. The APD algorithm was then modified to optimize for minimal makeup water, which resulted in costs of $39,000 per year while 46% of make-up water was saved [136].

The optimizing heat transfer in a cooling tower by studying the water distribution system was conducted through measured the velocity and temperature fields of the water inlet by using a mobile robot equipped with high-quality sensors [19]. The ambient air velocity, the air temperature in the vicinity of the cooling tower, and the air density in the vicinity of the cooling tower were measured as well. It was concluded that the optimal water/air mass flow ratio should be small and uniform across the entire plane area of the cooling tower. By keeping the water/air mass flow ratio constant, entropy generation, and thus exergy destruction, was minimized [137]. Multi-objective optimization and experimental evaluation of a forced draft cooling tower using different fill options conducted [138]. The fills were wooden splash, wire mesh, and honeycomb. Objective functions for tower range (temperature difference between inlet water and outlet water), Merkel number, effectiveness, and evaporation rate were formulated using experimental data and then simultaneously optimized using genetic algorithm and different flow rates of water and air.

6. Research Trend

Going through comprehensive literature reviewing on cooling towers with the focus on water sustainability in the present study presents the opportunity of mapping the completed studies. The authors present the conclusion of their study in the form of the research trends to facilitate the future study plan for advancing water conservations in cooling towers. Figure 5 illustrates the map of the research trend in advancing sustainability in wet cooling towers.

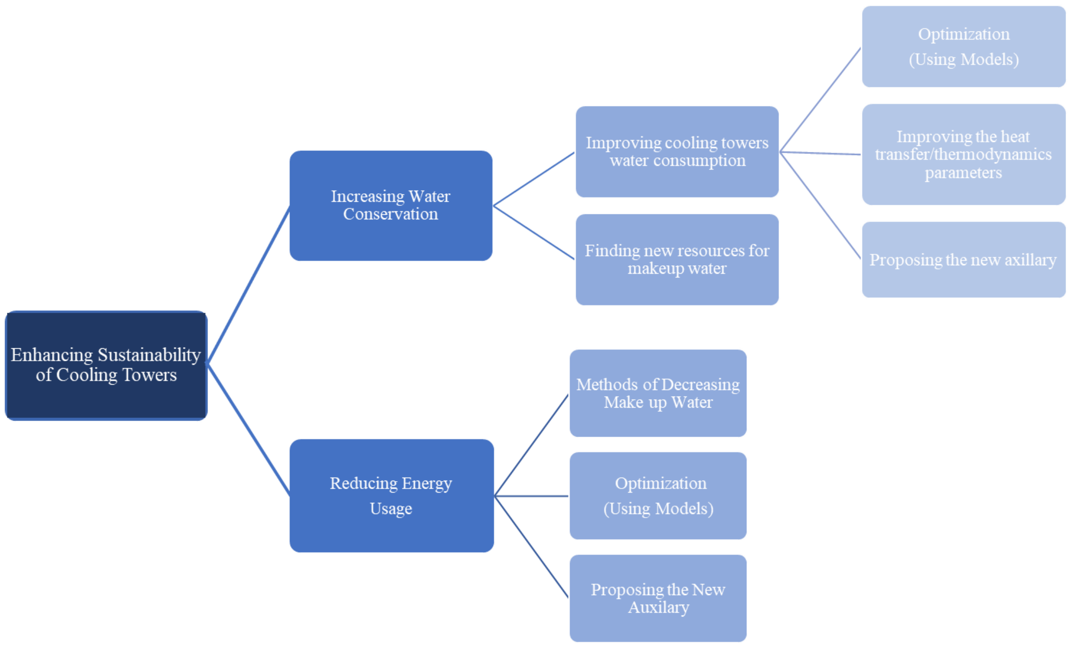

Figure 5: Research Map for Enhancing Sustainability of Cooling Towers

Finally, the proven effort for decreasing water usage in cooling towers from the past studies can be concluded as:

- Deploying cooling loops by reuse or recycle water [107],
- Changing wet cooling tower to hybrid or dry cooling tower [2],
- Adding the dry cooling section to current wet cooling towers [107],
- Using air to air heat exchanger on the cooling tower [20],
- Applying the airflow control method by taking advantage of fan VFD to reduce the water and energy consumption of cooling towers [21],
- Installing a RO water filtration system, or other water filtering systems to reduce required blowdown [3],

- Reduction in blowdown with increasing of concentration cycles [2],
- Decreasing pump power demand by installing a new pump motor for improved efficiency [3],
- Reduction of the number of backwashing cycles [3],
- Changing of the fan control mode to variable speed with parallel fan combination [3].

7. Conclusions

Considering the dependency of life to water and its scarcity reveals the urgency of studying on reducing water consumption in the cooling towers since cooling towers are the gate for the invisible dissipation of water. The present study elaborated on the roles of cooling towers in cooling cycles while narrated the history of energy-water modeling methods of cooling towers through the Markel, the Poppe, and the Effectiveness–(NTU) Models since water and energy are deeply connected in cooling towers. The major classifications and configurations of cooling towers showed the wet cooling towers consume the highest water while dry cooling towers use the minimum water in a trade-off with performance. The hybrid cooling towers have the advantages of both while they are more costly. The past challenges for boosting water conservation in cooling towers were allocated in focusing on water supply sources or modifications of the cooling tower. There are some practical approaches to reduce the environmental impact of cooling towers in the form of excess water consumption like water filtration and adding a dry section while using VFD reduces energy consumption. Finally, the trend of future studies presents the potential investigations for water and energy reduction opportunities in the light of water-energy nexus. Proposing the new auxiliary equipment, finding methods of decreasing make-up water, and optimization of the energy models are the major path for future investigation to reduce energy consumption in cooling towers. Similarly, improving cooling towers water consumption is through optimization, improving the heat transfer and thermodynamics parameters in cooling towers, and proposing the new auxiliary equipment, while findings new resources for makeup water are future paths for boosting water conservations in cooling towers.

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