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Carbon Footprint Reduction by Reclaiming Condensed Water

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Abstract: Everyday activity incurs carbon footprints, which are classified as personal, production, organizational and national, and may be assessed by input–output analysis (IOA), life-cycle assessment (LCA), or the combination of LCA and IOA methods. Notwithstanding international standards, like ISO 14064 and Publicly Available Specification (PAS) released for standardization, carbon footprint results can vary and sometimes lack consistency that due to variations in data sources, crossover boundary definitions, and operational boundaries for indirect emissions. The novelty of this study is the direct utilization of condensed water in an existing cooling water system, without the need for prior wastewater treatment, as typically required for greywater. The lack of practical case studies exploring the water–energy nexus in the context of reclaiming condensed water for evaporative cooling tower systems makes this research particularly significant. This highlights that condensed water can be a straightforward and cost-effective solution for both water conservation and energy savings. This case study highlights the benefits of reclaiming condensed water as supplementary cooling water, which proved effective in water quality treatment and dilution augmentation, considering that a higher cycle of concentration (CoC) was achieved, leading to reduced bleed-off that resulted in a water saving of 44% for make-up and 80% for bleed-off water, and energy savings from 6.9% to 13.1% per degree Celsius of condensing refrigerant temperature (CRT). The analytical assessment revealed that reclaiming condensed water is a promising answer for green building and is a by-product of condensation without extra power demands, avoiding the generation of an increased carbon footprint and exacerbation of greenhouse gas (GHG) emissions from freshwater resource extraction, and for the production of energy-efficient devices or substitutions. By eliminating the need for wastewater treatment, this research enhances the practicality and feasibility of direct use of condensed water in various applications. This approach not only promotes sustainability by conserving water and energy but also renews interest among proponents of green building practices. It has the potential to accelerate the adoption of this method and integrate it into green building designs.

Keywords: carbon footprint; GHG emissions; water-energy nexus; condensed water; bleed-off

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1. Introduction

Almost every activity humans engage in has the potential to produce a carbon footprint (CF) that varies with each direct and indirect factor, like the type of energy resource, energy extraction technology, energy transformation efficiency, and supply chain. The reduction in emission of Green House Gas (GHG) is today's global paramount aim.

In the process of air-conditioning, moist air is condensed into water droplets via condensation that cools down the air temperature and lowers the humidity to achieve a comfort zone for human activities and/or the required working environment for industrial processes [1]. Instead of disposal of the condensed unused water, recycling it, in addition to utilizing it as top-up water for evaporative cooling towers, has several environmental benefits leading to carbon footprint abatement:

(a) Energy efficiency—Condensed water is intrinsically free from materials and is ideal water for diluting the mineral-laden cooling system water of the evaporative cooling tower. It improves water quality and alleviates water scale which is a kind of heat barrier deposits on the water and on the heat exchangers or condensers' surfaces. The use of condensed water optimizes the heat transfer efficiency between water and refrigerant while minimizing energy consumption, resulting in lower carbon emissions associated with energy production.

(b) Water conservation—Reclaiming condensed water reduces the demand for freshwater sources, helps conserve water resources, and lessens the energy-intensive processes involved in treating and distributing freshwater, thereby reducing associated carbon emissions.

(c) Reduced water treatment—The almost mineral-free condensed water augments the dilution effectiveness, which reduces the bleed-off water volume (BOV) and releases the use of chemical reagents for treating the system water against scaling and fouling. In addition, these effluents always contain chemicals that have environmental impacts. Minimizing wastewater generation can lower energy requirements, which are associated with carbon emissions, such as pumping, aeration, and chemical treatment.

Various sectors employ different strategies to reduce carbon footprints (CFs). In a study cited [2], the reduction of CF was demonstrated by reducing the consumption of animal-based foods, which were identified as primary contributors, and shifting towards a plant-rich diet. The results were obtained using an attributional life cycle assessment (LCA) database and compared to a top-down hybrid consequential LCA database. Another study [3] analyzed the water–energy–carbon nexus of water supply systems (WSSs) in relation to source extraction, water treatment, conveyance, and distribution. It was found that energy savings and CF reduction can be achieved through water management and treatment technologies, including proactive maintenance to extend the operational life of equipment and aging infrastructure. In [4], the environmental impact of a newly developed eco-friendly fertilizer was assessed, taking into account carbon and water footprints, through LCA. The study aimed to evaluate the implications of the fertilizer on the environment. Examining the electricity mix, ref. [5] utilized a hybrid LCA model to assess the transition from fossil fuels (such as oil, coal, and LNG) to non-fossil fuels (including nuclear and renewables). This transition was found to have the potential to reduce carbon emissions but could also intensify water consumption. The environmental impacts of two synthetic yarns in the textile industry were evaluated in [6] using a "cradle-to-customer plus waste" LCA assessment. The study concluded that polypropylene (PP) yarn had a lower carbon footprint compared to polyester (PES) yarn, making it a more environmentally friendly option.

The novelty of this case study lies in its exploration of the interconnected relationship between water and energy, specifically in addressing the gap in utilizing reclaimed condensed water. By reclaiming condensed water, not only is water conservation achieved, but energy savings are also enhanced. The assessment of energy savings in terms of CF reduction considered local organizational conversion factors of electricity [7] and water [8], respectively. This study seeks to promote the adoption of this approach in green building design and system development.

Previously, the use of condensed water for irrigation has been reported as a means of water recycling [9]. However, its adoption by cooling tower operators has been hindered by the variability in condensed water yield, which is dependent on unpredictable weather conditions [10]. Despite these challenges, the use of condensed water holds potential for corporate sustainability and the conservation of natural capital [11].

The first objective of this case study is to demonstrate the practicality of reclaiming condensed water by modifying the condensing drainpipe and improving the existing water capture system. Subsequent objectives involve assessing and implementing strategies for efficient water reclamation, supported by actual measurements, compared to analytical assessments. The final objective explores the intricate relationship between water and energy savings by utilizing reclaimed condensed unused water in the water-cooling facility and improving the performance of power-intensive equipment, and the associated carbon footprint in each stage is examined.

Through these objectives, the practicality and novelty of directly using condensed water in cooling water systems are realized. Additionally, this case study challenges the perception of condensed water as "greywater", which typically requires wastewater treatment before use [12,13]. Instead, it highlights the intrinsically good water quality of reclaimed condensed water, contributing to its expedited adoption without the need for extensive treatment processes.

1.1. Carbon Footprint Classification and Assessment Method

Carbon footprint has not yet reached a consensus definition [14–16] but it is usually recognized as the total amount of carbon dioxide emissions that are directly and indirectly associated with an entire product cycle.

There are five carbon footprint classifications:

(a) The first applies to the individual, the personal carbon footprint, in which CO_2 emissions are caused by the consumption of elements for each person's daily activities, regarding, e.g., clothing, food, housing and traffic.
(b) The second applies to the product, the product carbon footprint(PCF), which gauges GHG emissions throughout the whole life cycle (of, e.g., services, subsystems, systems or goods), starting from the harvesting of raw materials, to manufacture, fabrication, re-use, recycling, and final disposal.
(c) The third, organizational carbon footprint, applies to the measurement of GHG emissions of an organization, including energy consumption for operations, activities, and company vehicles.
(d) The fourth applies to a specific country, the country carbon footprint, which measures the direct and indirect CO_2 emissions of an entire country and its consumption of materials, energy, vegetation, carbon sequestrations, and import and export activities.
(e) The fifth one is planet Earth, whose natural phenomena, such as volcanic eruptions, wildfires, respiration and decay and soil erosion, also contribute to the carbon footprint.

The latter is usually out of the control of humans, but the human activities above are the primary cause of increasing carbon dioxide or greenhouse gases in the last century.

Boundary crossovers among the four types of carbon footprint are always encountered during carbon footprint assessment, as shown in Figure 1 [17].

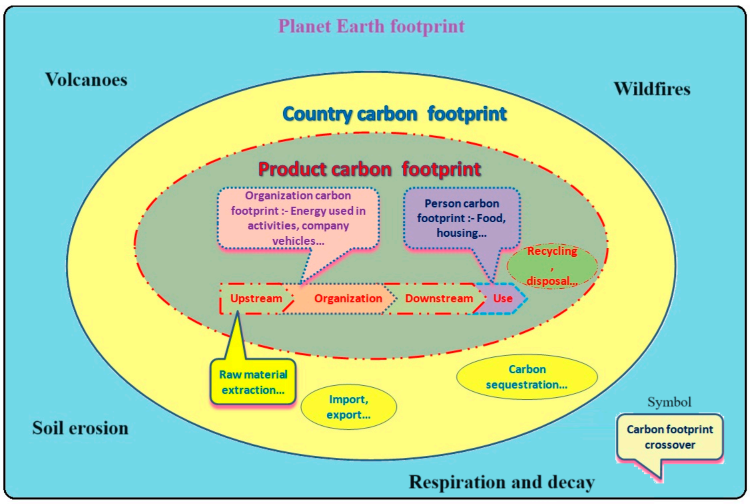


Figure 1. Different carbon footprint boundaries between person, product, organization, country and planet Earth.

The assessment of carbon footprint varies based on diverse working units, different dimensions, and methods employed for calculating carbon emissions. The input–output analysis (IOA), life-cycle assessment (LCA) and IO–LCA are the three carbon-emission calculation methods that satisfactorily meet the requirement of the carbon footprint definition. In the case of small scale products, the bottom-up LCA method is used, while the top-down IOA is adopted at the global scale. On the other hand, the hybrid method of combining LCA and IOA is increasingly used in most research cases, as shown in Figure 2.

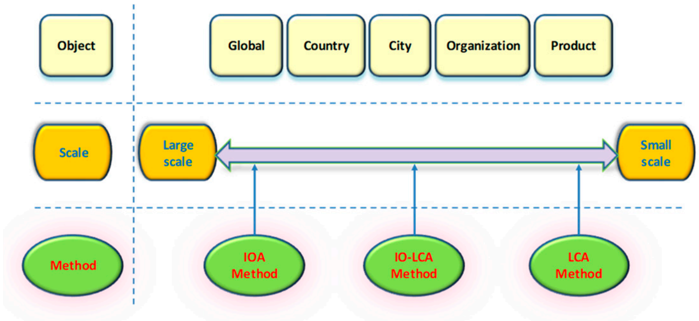


Figure 2. Assessment and calculation methods of carbon footprint.

Consensus assessment standards for carbon footprint would greatly promote global carbon emissions reduction, such as ISO 14064 [18], GHG Protocol [19], and PAS 2050 [20], but effectiveness is undermined by unscientific boundary definitions and ambiguous carbon factors, especially in the product field and the organization-related area.

1.2. Organizational Aspect of Carbon Footprint

The results for organizational carbon footprint can be considered as a comprehensive carbon inventory testimony to the stakeholders by dominantly using IOA, which is assessed by the following steps, as shown in Figure 3.

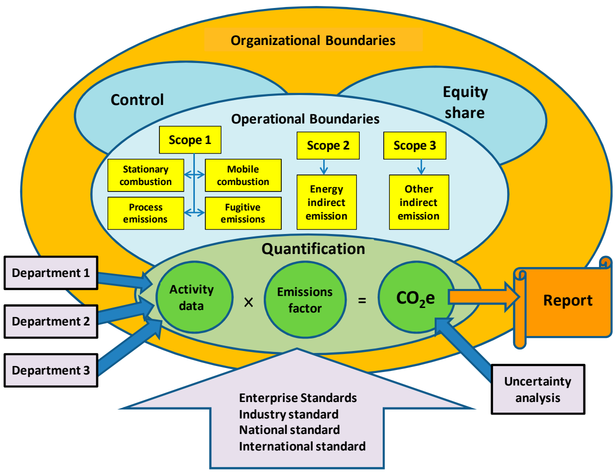


Figure 3. Evaluation methods for organizational carbon footprint.

This begins with defining an organizational boundary and sets guidelines for which parts of an organization should be considered as contributing to the organizational carbon footprint. Generally, the shareholding approach is used as a proposal for the facility-level GHG emissions and removals of a holding/controlling company.

The next step is to establish an operational boundary that defines which emission sources from which activities should be taken for an operational carbon footprint. Undoubtedly, Scope 1 (direct emissions) and Scope 2 (indirect emissions) fall into the list, whereas Scope 3 (other indirect emissions) is selective.

Once the established boundaries are set by stating all the assumptions and clarifying the discrepancies in the data, the carbon footprint (GHG) can be computed by multiplying the activity data by standard emissions factors.

Eventually, a carbon footprint report indicating a complete carbon emissions inventory of contributors and details of GHG emissions should be issued for public disclosure so that third-party verification becomes the pre-requisite for higher credibility.

The GHG Protocol was promulgated as an inclusive, consensus-based multi-stakeholder standard for corporate accounting and reporting in 2004 while, in 2006, the international ISO 14064 standard was released as a guiding, framework and for accounting certification, which reflects corporate social responsibility. Despite these two standards sharing identical organizational boundary settings, there are differences in the operational boundary for indirect emissions, and in quantization methods. The GHG Protocol considers indirect emissions from generation to be nothing but imported electricity, while ISO 14064 includes not only imported electricity but also imported heat and steam. Meanwhile, the quantization for ISO 14064 is recommended and adopted extensively. On the other hand, the GHG Protocol has published a series of complementary standards for improving the GHG activity data and emissions factors, which provide specific and working guidance for carbon footprint assessment, such as in the grid-connected electricity power industry.

1.3. Product Carbon Footprint

The carbon footprint for products (goods or services) in their entire life cycle is assessed by the LCA method with credibility and a simple method of evaluation. In 1996, ISO 14040/44 [21] standards based on the LCA method formulated frameworks and procedures for the evaluation of environmental management standards, which are analysed based on the following steps, as shown in Figure 4.

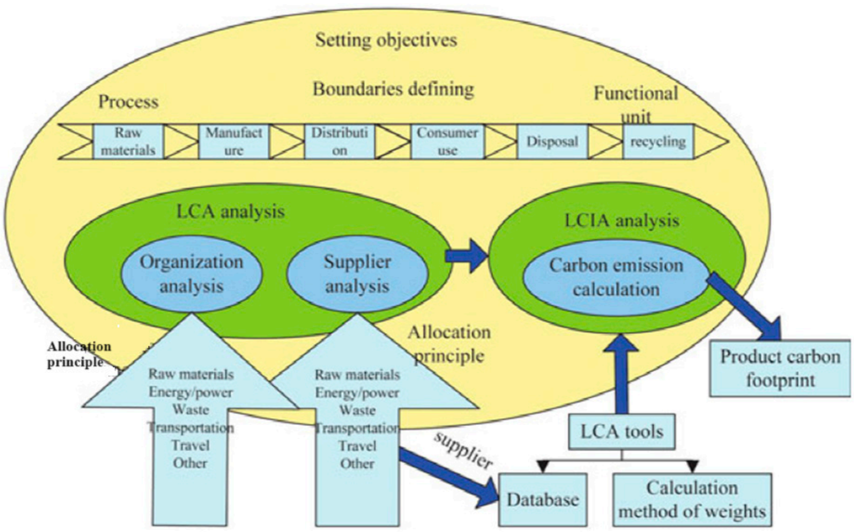


Figure 4. Assessment procedures for product carbon footprint.

This commences with a product life cycle analysis entailing all the components, actions, and procedures so that the selected product's function units are subdivided into constituent portions for the identification of the culprits regarding GHG emissions, respective impacts, manufacturing, and logistics.

The next step is to demarcate the system boundaries for the determination of which procedures have to be taken into consideration regarding PCF.

Once the system boundaries are set with well-collated consumption data, which include component amounts, actions and carbon emission factors throughout the entire life cycle's stages, the CF can be computed by multiplying the activity data with standard emissions factors without missing any of the inputs, outputs and waste.

Ultimately, a report is issued indicating the evaluation of the product's carbon footprint, which complies with relevant requirements and achieves its goal and scope. Meanwhile, organizations can effectively communicate with the public concerning the product's carbon footprint by a declaration or a performance tracking report.

The Publicly Available Specification (PAS) was published for measurement of the life cycle's GHG emissions, and its articles and provisions emerged in 2008 while, on top of this, ISO 14067 [22] was promulgated in 2013 as an international standard for internal management or external communication and collaboration. In between, the Technical Specification TS-Q0010 [23] and the Corporate Accounting and Reporting (CAR) standard [24] were released for the assessment of labeling, and the complementary standard for Scope 3 indirect emissions, respectively. The PAS 2050, TS-Q0010, and CAR are standards or protocols specifically designed for conducting carbon footprint assessments. They serve as frameworks with defined methodologies to measure and evaluate the greenhouse gas emissions associated with products, services, or entities, contributing to standardized and transparent approaches in carbon footprint analysis, while the ISO 14047 [25] is a combination of the existing assessment standards.

Although the carbon footprint approaches of these four standards are different in terms of treatment of distinct emissions and removals, land transformation, deferred emissions, and alternative energy resources, the practice of quantifying greenhouse gas (GHG) emissions or removals through the multiplication of GHG activity data with emission or removal factors is both recommended and substantially employed.

It makes sense that the carbon footprint becomes part of a comprehensive GHG accounting for any product or activity over its life cycle stages, especially for organizations and products, that is widely assessed by the GHG protocol and PAS is extended to the environment and ecosystem. Therefore, legal guidelines are indispensable for the relevant and unavoidable emission cuts and verifications and to monitor assessment standardization at the international level.

1.4. Carbon Footprint Equivalent

The carbon footprint measures CO_2 emissions associated with fossil use that are converted into biologically productive areas necessary for absorbing this CO_2. The carbon footprint is added to the ecological footprint because increasing CO_2 concentration in the atmosphere is a build-up of ecological debts and, sometimes, is expressed in tons released per year without translating this amount into the area needed to sequester them [26].

The GHG average warming capacity depends on the strength of radiative forcing and the gas molecule average time remaining in the atmosphere. The average warming caused by a GHG is known as global warming potential (GWP), which is calculated mathematically and is expressed relative to that of CO_2 using the unit of carbon dioxide equivalent (CO_2e) [27].

1.5. Greenhouse Gas Emissions

Carbon dioxide, CO_2 (76%), is one of several greenhouse gases (GHGs) such as methane, CH_4 (16%), nitrous oxide, N_2O (6%), ozone, O_3 (2%), and water vapor, H_2O (0%), that are anthropogenically emerging from human activities, like the combustion of fossil fuel for electricity. Considering that water vapor can only stay for a few days in the atmosphere, unlike CO_2 which takes 1000 years to be completely dissolved by nature, it is not attributed to human activities and is accounted as 0%. In 1997, the Kyoto Protocol pinpointed six important GHGs, of "Kyoto gases": carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFC), and hydrofluorocarbons (HFC) needed to be cut by 25% below the current 1997 level by 2050 in order to eliminate an annual 5% of global gross domestic product (GDP) loss caused by the impact of extreme weather events and climate change in the wake of the global temperature rise above 2 °C as compared to the pre-industrial level of 1750 [28].

Each type of GHG has its own global warming potential (GWP), which is the multiple warming effects from the same mass of CO_2, and the GWP of CO_2 is one (1). In 2015, the United Nations Framework Convention on Climate Change (UNFCCC) replaced the Kyoto Protocol with the Paris Climate Agreement to limit the earth's temperature to 2 °C, with an aspirational targeting of a 1.5 °C limit above that of pre-industrial levels. The Intergovernmental Panel on Climate Change (IPCC) gathers all GHGs into one place by creating a common measurement unit, the carbon dioxide equivalent, CO_2e, to express the GWP of different GHGs in terms of the equivalent amount of CO_2 as warming potential.

The carbon footprint is the quantity of GHGs expressed in terms of CO_2e, emitted into the atmosphere by an organization, process, activity, or product within specified boundaries, which is deliberately set and demarcated in accordance with the methodology (i.e., IOA, IO-LCA, and LCA), availability of data, and the objective of carbon footprint assessment (i.e., GHG Protocol and PAS), as well as the selection of GHGs for the type of activity or characteristics of the entity [27].

Nowadays, most of the power and water authorities [7,8,29–32] have converted from carbon emissions intensity (kg CO_2/kWh) to GHG emissions intensity (kg CO_2e /kWh) regarding their impacts and contributions to global warming. In this research, carbon footprints were assessed by taking the conversion factors of the Hong Kong Electric, HEC, as 0.71 kg CO_2e/kWh [7], and the Water Supplies Department, WSD, as 0.428 kg CO_2e/m^3 [8].

2. Methodology and Data

2.1. Set-Up

To optimize the collection of condensed water, the condensate pipes were rerouted and redirected to ensure the capture of all the possible condensed water from air conditioning equipment, such as fan coil units. It was necessary to conduct water analyses for the reclaimed condensed water, fresh make-up water, and bleed-off water to meet industrial standards. Additionally, accurate water metering for reclaimed water, bleed-off, make-up water, and evaporation was crucial to monitor water consumption precisely. These data enabled the investigation and analysis of the interconnected relationships and system responses, highlighting the benefits of reclaimed condensed water, including reduced bleed-off, improved descaling, and energy savings.

To ensure that the benefits of condensed water were not compromised and to maintain the maximum tolerance of the CoC, the existing chemical dosage system remained unchanged. The dosage amount and frequency were not altered. Furthermore, the TDSs were monitored by a water quality controller, also known as an electrical conductivity controller, which continuously measured the electrical conductivity of the system water. The controller regulated the bleed-off valve, allowing the discharge of mineral-laden system water as necessary.

The energy savings were derived from the enhanced performance of the chillers. The effective descaling process improved the heat transfer efficiency of the heat exchangers, i.e., the cooling towers and condenser units. This, in turn, provided optimal operating temperatures for condensing refrigerant and improved the coefficient of performance (COP) of the chillers, resulting in an efficient operation. The outline of the system arrangement for reclaiming condensed water, water quality control, and the metering system are diagrammatically represented in Figure 5.

To maximize the collection of condensed water from air conditioning equipment, like fan coil units, the condensate pipes were redirected to condensed water storage tanks located before the cooling water towers. The quality of the recycled condensed water, new makeup water, and discharge bleed-off water was regularly analyzed to ensure compliance with industrial standards for setting the cycles of concentration (CoCs). Additionally, individual water consumption was measured using newly installed water meters, which tracked water usage for reclamation, bleed-off, make-up, and evaporation. The water quality controller oversaw the total dissolved solids (TDS) by continuously monitoring the real-time electrical conductivity (EC) of the facility water and controlling the valve for discharge mineral-laden water when necessary. These data allowed for investigating and analyzing the interconnected relationships and responses within the system, highlighting the advantages of using reclaimed condensed water, such as reduced bleed-off, improved descaling, and energy savings.

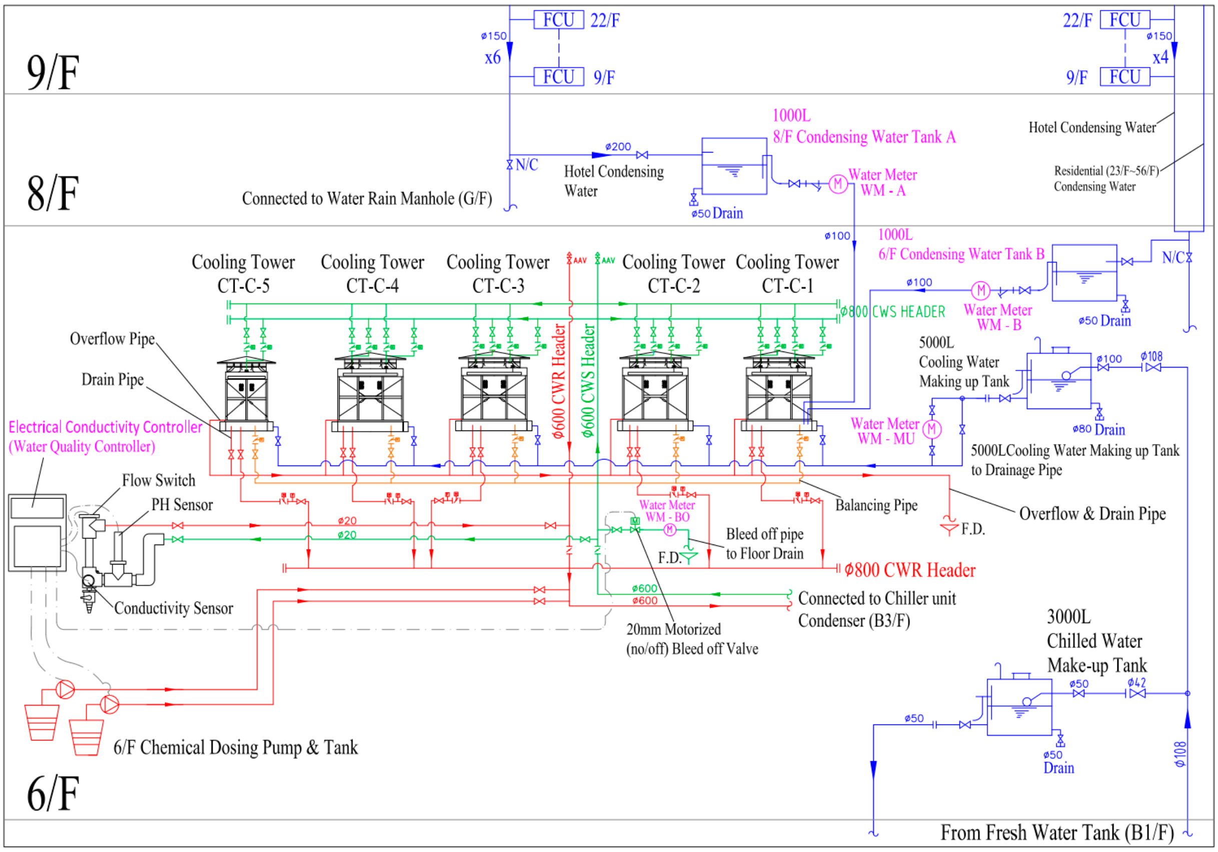


Figure 5. Schematic for reclaiming condensed water system.

On the other hand, energy savings were achieved through the enhancement of chiller performance. The effective descaling process improved the efficiency of the heat exchangers, the cooling towers and condenser units, resulting in optimal operating temperatures for condensing refrigerant. This, in turn, has significantly boosted the chiller's performance in terms of the coefficient of performance (COP), thereby improving energy efficiency. It also reduces premature replacement, which reduces the carbon footprint due to the manufacturing and installation of the new equipment. The coefficient of performance (COP) is a measure of the efficiency of a chiller, expressed as the ratio of useful cooling or heating provided to the work (energy) required. A higher COP indicates higher efficiency and lower power consumption.

To accurately assess and analyze water quality, as well as water and power consumption, several modifications were made. This included modifying the existing condensate drain downpipes and installing additional water meters and measuring equipment. These measures were crucial for recording, measuring, and monitoring the relevant data, which played a vital role in subsequent assessments, verifications, and analyses. Figures 6–9 provide a summary of the actual measurements obtained for the water sides.

The primary function of the water in the cooling system was to remove heat from the chiller unit's condenser, and it accomplished this by passing through the cooling towers where heat dissipation occurred through evaporation. After the water was cooled, it exited from the cooling towers and returned to the cooling loads to repeat the cooling process.

Throughout the monitoring period from January to December 2021, the temperatures of the water entering the cooling towers (ECT) and leaving the cooling towers (LCT) were recorded. It was observed that the highest LCT and ECT values were consistently recorded during the period from May to September 2021. On average, the LCT value was 31.9 °C, while the ECT value was 27.9 °C, as depicted in Figure 6.

The rate of evaporation varies depending on cooling loads, humidity, temperature, and weather conditions, particularly during the summer, when it tends to rise significantly. As a result of the high evaporation, there was a rise in the electrical conductivity of the system water. This, in turn, triggered the activation of the auto bleed-off system, which released the mineral-laden cooling water from the system.

In July, despite the high evaporation rate of 3195 m^3/month, a relatively low bleed-off value of 22 m^3/month was observed. This lower value can be attributed to the higher bleed-off volumes of 44 m^3/month in May and 52 m^3/month in June. These increased bleed-off volumes were a result of the routine cleaning maintenance performed on the cooling towers to ensure optimal cooling performance prior to the peak hot season.

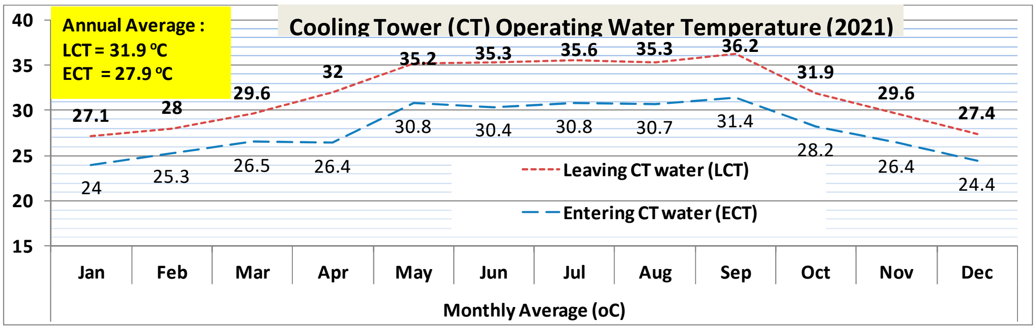


Figure 6. Cooling tower operating water temperature records.

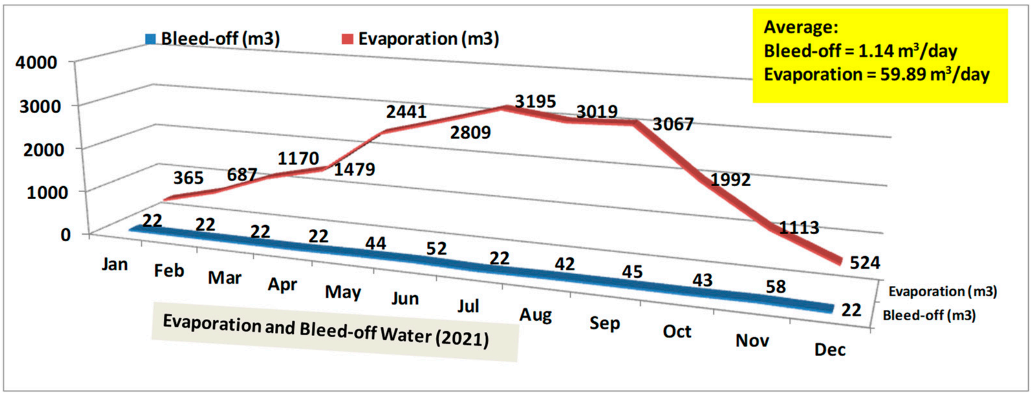


Figure 7. Evaporation and bleed-off water records.

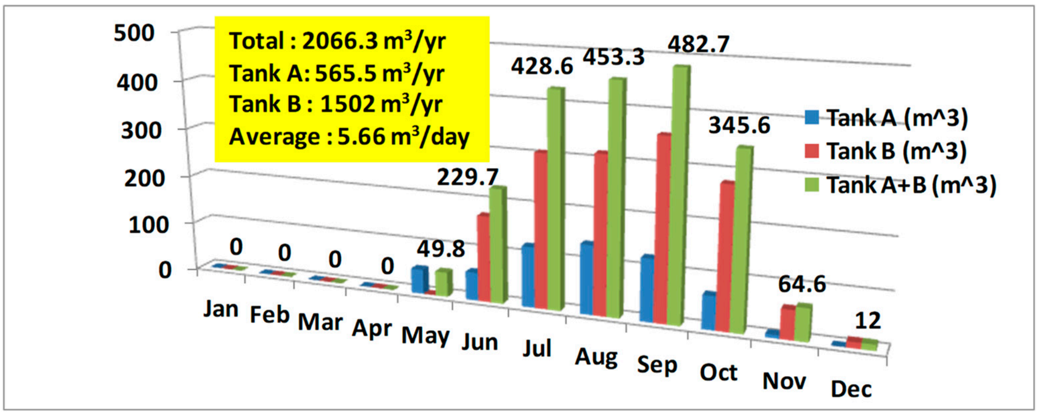


Figure 8. Reclaimed condensed water records.

Water Quality Analysis Report (2021)						
Sample	Unit	Water Cooling Tower (System Water)	Make-up Water (Tap water)	Condensed Water Harvested (Tank A)	Condensed Water Harvested (Tank B)	Cooling Tower Water Industrial Standard Range
pH Value	--	8.1	7.3	6.5	6.5	7.0 ~ 8.5
Total Alkalinity as $CaCO_3$	mg/l	160	60	20	10	< 200
Turbidity	FTU	5	<1	<5	<5	< 50
Copper (Total) as Cu	mg/l	<0.1	0	0	0	< 0.2
Iron (Total) as Fe	mg/l	<0.1	0	0.1	0.1	< 0.1
Total Hardness as $CaCO_3$	mg/l	380	50	20	10	< 800
Total Dissolved Solid mg/l = ppm (ppm x 1.56 = µS/cm)	mg/l	1800ppm (2813µS/cm)	130ppm (202µS/cm)	120ppm (188µS/cm)	50ppm (78µS/cm)	< 2500ppm (3900µS/cm)
Bacterial Count (no. per ml)	no/ml	10^3	10^2	10^2	10^2	$< 10^5$

Figure 9. Water quality analysis reports.

Over the course of the year, the average bleed-off volume was approximately 1.14 m^3/day, while the evaporation rate was measured at 59.89 m^3/day, as indicated in Figure 7.

Because of limited space and existing congestion in the electrical and mechanical services, the condensed water pipe works were altered to collect the condensed water. This water was then stored in two separate tanks, Tank A and Tank B, located on different floors. These tanks not only stored the water but also acted as settlement tanks, removing any floating pipe rust and dust before the water flowed into the cooling tower water basin. During the hot and humid months, a significant amount of condensed water was reclaimed, as shown in Figure 8. In total, 2066.3 m^3 of condensed water was reclaimed annually, averaging approximately 5.66 m^3 per day.

In order to determine the CoC setting, samples of the operating system water, make-up water, and reclaimed water from Tank A and Tank B were collected and analyzed by a water treatment specialist, as mentioned in Figure 9. The analysis revealed that the reclaimed condensed water had a low TDS value of 50 ppm and 120 ppm, with an average of 69.2 ppm by volume proportion ratio, as stated in Section 2.5. This TDS value is even lower than the TDS value of tap water, which is 130 ppm and used as make-up water for normal water replenishment.

Considering the maximum allowable TDS of 2500 ppm based on industrial standards, the COC for this case study was set at 19.2. This value was determined by referring to the make-up water TDS of 130 ppm, as explained in Section 2.3.

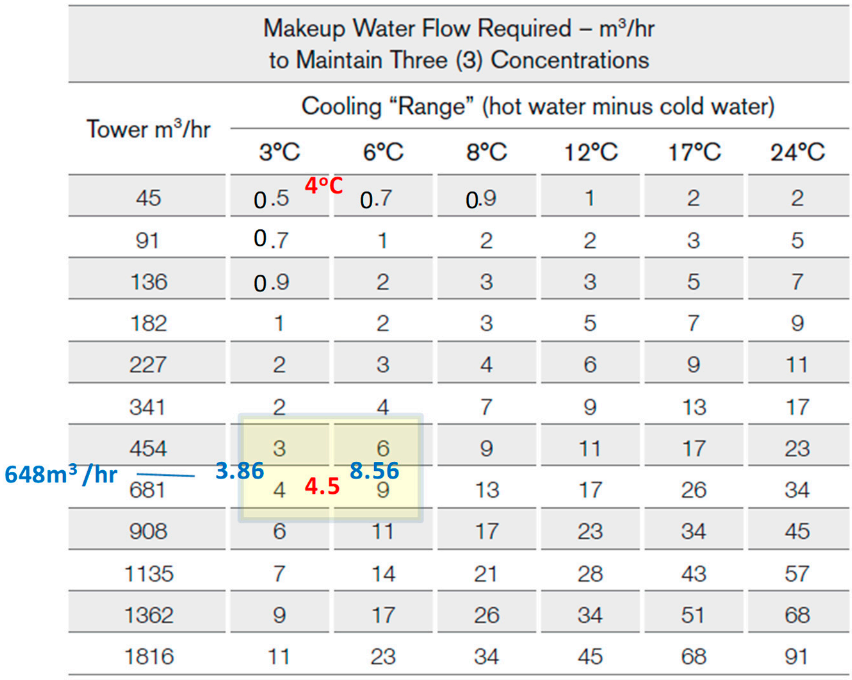
2.2. The Assessment of Annual Water Conservation

To calculate the water losses, the technical data from the cooling tower manufacturer [20] and the operating water temperature records in 2021, as shown in Figure 6, were consulted. The average range of temperature for the cooling tower, which represents the temperature difference between the water-in and water-out, was determined as follows:

Annual CT range = CT water-in temp – CT water-out temp

$$\text{Annual CT range temp} = 31.9\ ^\circ\text{C} - 27.9\ ^\circ\text{C} = 4\ ^\circ\text{C}$$

With this cooling tower temperature range and referring to the manufacturer's technical data [33] (Figure 10):



Tower m³/hr	Makeup Water Flow Required – m³/hr to Maintain Three (3) Concentrations					
	Cooling "Range" (hot water minus cold water)					
	3°C	6°C	8°C	12°C	17°C	24°C
45	0.5	0.7	0.9	1	2	2
91	0.7	1	2	2	3	5
136	0.9	2	3	3	5	7
182	1	2	3	5	7	9
227	2	3	4	6	9	11
341	2	4	7	9	13	17
454	3	6	9	11	17	23
681	4	9	13	17	26	34
908	6	11	17	23	34	45
1135	7	14	21	28	43	57
1362	9	17	26	34	51	68
1816	11	23	34	45	68	91

Figure 10. Interpolation chart for make-up water flow demands [20].

A cooling tower water flow rate of 648 m^3/h, which was the cooling water pump flow rate circulating the system's cooling water, and based on interpolation, a range temperature of 4°C in the cooling tower required a new make-up water flow rate of 4.5 m^3/h to compensate for the heat loads lost through evaporation. The bleed-off Equation (1) indicates that the higher the CoC, the less the bleed-off. This means that, at higher CoC settings, the water losses become equivalent to the water loss through evaporation, which must be replenished by the make-up water. In other words, the bleed-off decreases to its minimum value at higher CoC settings, resulting in an evaporation rate that is nearly equal to the make-up water rate [34]. Therefore, the manufacturer' table for a CoC of 3 can be used to determine the make-up water demand for a CoC of 19.2. This calculation takes into account that 94.8% of the water loss is due to evaporation, while the remaining 5.2% is attributed to bleed-off, as explained in Section 2.3.

The analyzed new make-up (condensation) water consumption is calculated as:

$$W_{AnalyseddMakeupCoC19} = 4.5\ m^3/hr \text{ or } 1.25\ L/s \text{ or } 3283\ m^3/mth$$

2.3. The Maximum Tolerance for CoC

To maintain normal system operation during the cooling process by evaporation, it is necessary to compensate for the water losses due to evaporation, including bleed-off and drift losses, by adding new make-up water. The cycles of concentration (CoCs) were determined using bleed-off Equation (1) and CoC Equation (2) as described in [35].

$$B = \frac{E - (CoC - 1) \times D}{CoC - 1} \quad (1)$$

The CoC for the system water is:

$$CoC = \frac{TDS_{BO}}{TDS_{mu}} \quad (2)$$

$$CoC = \frac{2500\ ppm}{130\ ppm} = 19.2$$

where

$TDS_{BO,}$ is the Bleed-off TDS = 2500 ppm (refer to Figure 9).
$TDS_{mu,}$ is the Make-up TDS = 130 ppm (refer to Figure 9).
E is the Evaporation = $W_{ActualEvapCoC19}$ = 59.89 m^3/day or 0.693 L/s (refer to Figure 8).
The water losses of drift, D = 0.005% (refer to the product data) [20].
Since losses of drift loss are insignificant and can be ignored, then

$$B = \frac{E}{CoC - 1} \quad (3)$$

$$B_{AnalysedHardBleedoffCoC19} = \frac{0.693}{19.2 - 1} = 0.038 \text{ L/s or } 3.28 \text{ m}^3/\text{day}$$

The ratio of the hard bleed-off to the total water consumption, which is the sum of make-up water and hard BOV at CoC 19.2, can be expressed as a percentage:

$$W\%_{AnalysedHardBleedoffCoC19} = \frac{W_{AnalysedlHardBleedoffCoC19} \times 100\%}{W_{ActualEvapCoC19} + W_{AnalysedHardBleedoffCoC19}} = \frac{0.038}{0.693+0.038} = \frac{0.038}{0.731} \times 100\% = 5.2\%$$

Using bleed-off Equation (3), the bleed-off rate was calculated as 5.2% of the make-up water flow rate at a CoC of 19.2. Therefore, the cooling tower operating with analytical make-up water at a 4.5 m^3/h (equivalent to 1.25 L/s) flow rate at a CoC of 19.2 would require a bleed-off rate of 5.2%, resulting in:

$$W_{AnalysedHardBleedoffCoC19} = W_{AnalysedMakeupCoC19} \times W\%_{AnalysedHardBleedoffCoC19} = 1.25 \text{ L/s} \times 5.2\% = 0.065 \text{ L/s or } 5.616 \text{ m}^3/\text{day}$$

The analytical evaporation is the difference between make-up water and bleed-off volume:

$$W_{AnalysedEvapCoC19} = W_{AnalysedMakeupCoC19} - W_{AnalysedHardBleedoffCoC19} = (1.25 - 0.065) \text{ L/s} = 1.19 \text{ L/s}$$

Thus, the analytical evaporation, $W_{AnalysedEvapCoC19}$ =1.19 L/s was 94.8% of the new top-up water to make up the difference at above average CoC 19.2 set points.

2.4. Measuring Water Consumption and Conservation

The condensed water collected and stored in Water Tank A and Tank B, as shown in Figure 7, was reclaimed and used as supplemental water for make-up. In 2021, a total of 2066.3 m^3 of make-up water was metered.

The average daily volume of reclaimed condensed water can be calculated as:
$W_{ActualReclaimed}$ = 5.66 m^3/day or 0.066 L/s

Make-up water includes evaporation and bleed-off, which were separately metered and recorded in Figure 8:
Bleed-off rate: $W_{ActualAutoBleedoffCoC19}$ = 1.14 m^3/day or 0.013 L/s
Evaporation rate: $W_{ActualEvapCoC19}$ = 59.89 m^3/day or 0.693 L/s

Therefore, the actual flow rate of new make-up water, as measured, can be calculated as:
$W_{ActualMakeupCoC19}$ = (0.693 + 0.013) × 30.4 days/month × 24 hrs/day × 3600 s/h = 1855 m^3/month.

The ratio of real top-up water for make-up to analytical top-up water in 2021 can be expressed as:

$$W\%_{ActualMakeupCoC19} = \frac{W_{ActualMakeupCoC19}}{W_{AnalysedMakeupCoC19}} \times 100\%$$

$$W\%_{ActualMakeupCoC19} = \frac{1855 \text{ m}^3/\text{mth}}{3283 \text{ m}^3/\text{mth}} \times 100\% = 56.5\%$$

The saving of make-up water including the reclaimed condensed water is:

$$W\%_{ActualMakeupCoC19Saving} = 100\% - 56.5\% = 43.4\%$$

2.5. The Analysis of Water Quality

The quality of the system water, new make-up water, and reclaimed condensed water was evaluated and compared to the industrial standards for cooling water in cooling towers, as shown in Figure 9.

The TDS (Total Dissolved Solids) levels for each type of water was as follows:

Bleed-off water TDS: 1800 ppm.

Make-up water TDS: 130 ppm

Condensed water stored in Tank A TDS: 120 ppm.

Condensed water stored in Tank B TDS: 50 ppm.

The condensed water was collected from distinct sources and through different pipe routes, resulting in variations in volume (Figure 8) and TDS levels (Figure 9) for the water samples from Tank A and Tank B.

The metered volume of reclaimed condensed water from Tank A was 565.5 m^3 with a TDS of 120 ppm, while the metered volume from Tank B was 1502 m^3 with a TDS of 50 ppm.

To determine the mean TDS, $TDS_{CondTankAB}$, the TDS levels from Tank A and Tank B were averaged:

$$\begin{aligned} TDS_{CondTankAB} &= \frac{TDS_{CondTankA} \times V_A + TDS_{CondTankB} \times V_B}{V_{TankA} + V_{TankB}} \\ &= \frac{120 \text{ ppm} \times 565.5 + 50 \text{ ppm} \times 1502}{565.5 + 1502} = 69.2 \text{ ppm} \end{aligned}$$

where,

V_{TankA} = Condensed water reclaimed in volume by Tank A

V_{TankB} = Condensed water reclaimed in volume by Tank B

$TDS_{CondTankA}$ = TDS of condensed water stored in Tank A

$TDS_{CondTankB}$ = TDS of condensed water stored in Tank B

Due to the low TDS feature of the condensed water, it could effectively dilute the mineral-rich system water.

The amplification of the freshwater TDS to the reclaimed condensed water TDS was named the augmented dilution of condensed water, A_{aug}

$$A_{aug} = \frac{\text{TDS of fresh make} - \text{up water}}{\text{TDS of reclaimed condensed water}} = \frac{130}{69.2} = 1.88$$

The reclaimed volume of TDS 69.2 ppm was amplified 1.88 times in condensed water and the dilution was equivalent to the same amount of freshwater of TDS 130 ppm.

The equivalent physical size of new make-up water, $W_{DiluteEqv}$ is:

$$W_{DiluteEqv} = A_{aug} \times W_{ActualReclaimed} = 1.88 \times 5.66 \text{ m}^3/\text{day} = 10.64 \text{ m}^3/\text{day}$$

where $W_{ActualReclaimed}$ = 5.66 m^3/day (refer to Figure 8).

The bleed-off is controlled by the electrical conductivity (EC) controller and the volume is recorded as shown in Figure 8.

The flow rate for auto bleed-off is $W_{ActualAutoBleedoffCoC19}$ = 1.14 m^3/day (refer to Figure 7).

The reduction of volume flow rate for bleed-off is:

$$\begin{aligned} W_{ReduBleedoffCoC19} &= W_{AnalysedHardBleedoffCoC19} - W_{ActualAutoBleedoffCoC19} \\ &= (5.616 - 1.14) \text{ m}^3/\text{day} = 4.476 \text{ m}^3/\text{day} \end{aligned}$$

The ratio of the actual auto to analytical hard bleed-off size can be expressed as a percentage:

$$\begin{aligned} W\%_{ActualBleedoffCoC19} &= \frac{W_{ActualAutoBleedoffCoC19}}{W_{AnalysedHardBleedoffCoC19}} \times 100\% \\ &= \frac{1.14}{5.616} \times 100\% = 20\% \end{aligned}$$

The bleed-off saving is:

$$W\%_{ActualBleedoffCoC19Saving} = (100 - 20)\% = 80\%$$

2.6. The Assessment for Mitigation of GHG Emissions from Water Sides

The analytical make-up water, $W_{AnalysedMakeupCoC19}$, is 3283 m^3/month. Therefore, the total volume of make-up water in the year 2021 can be calculated as:

$$W_{AnalysedMakeupCoC19Annual} = 3283\ m^3/mth \times 12 = 39,400\ m^3/year$$

The saving of make-up water is 43.4%, represented as:
$W\%_{ActualMakeupCoC19Saving} = 43.4\%$ (refer to Section 2.4)
The total volume saving of make-up water can be calculated as:

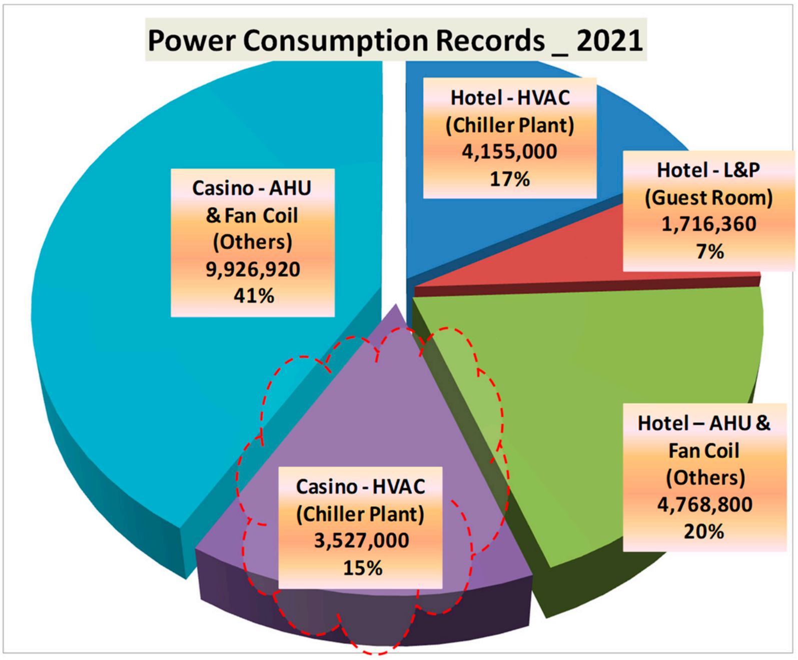
$$W_{MakeupCoC19SavingAnnual} = 39,400\ m^3/year \times 43.4\% = 17,100\ m^3/y$$

The annual saving of water consumption results in a reduction in carbon dioxide equivalent (CO_2e) emissions. The emission factor for water, which represents the equivalent GHG emissions, is 0.428 kg CO_2e/m^3 [8]. Therefore, the carbon footprint reduction from water saving can be calculated as:

Carbon footprint reduction from water saving = $W_{MakeupCoC19SavingAnnual} \times 0.428\ kg\ CO_2e/m^3 = 17,100\ m^3/y \times 0.428 kg\ CO_2e/m^3 = 7318\ kg\ CO_2e \approx 7.5\ Ton\ CO_2e$.

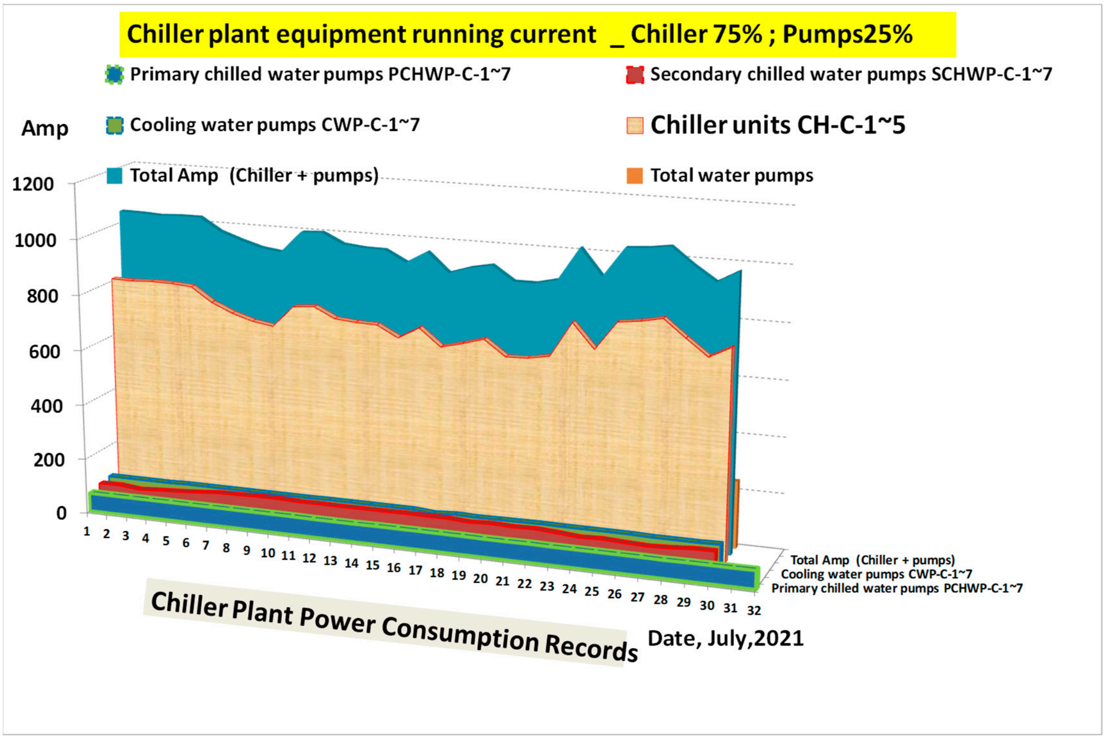
2.7. The Assessment for Energy Saving

The chiller plant was the main consumer of power, accounting for 3,527,000 kWh, which represented approximately 15% of the overall building electrical load, as depicted in Figure 11A.



(**A**)

Figure 11. *Cont.*



(**B**)

Figure 11. (**A**) The distribution of electrical loadings; (**B**) the operating current for chiller plant main equipment.

Within the chiller plant, the chiller units (compressors) were the most power-intensive equipment. They accounted for 75% of the total chiller plant power consumption, while the remaining 25% was attributed to the water pump sets, as shown in Figure 11B.

Based on the actual power consumption record for the chiller plant in 2021, which was 3,527,000 kWh, the power consumption specifically attributable to the chiller units (compressors) can be calculated as:

$$P_{chillerunit} = 3{,}527{,}000\ \text{kWh} \times 75\% = 2{,}645{,}000\ \text{kWh}$$

The casino chiller plant, which consists of chiller units and water pump sets, accounted for 15% of the overall electrical load of the building. This load included the hotel and other equipment, such as the kitchen facilities, restaurants, lighting and power, fan coil units (FCU), and air handling units (AHUs), as depicted in Figure 11A. In terms of power consumption in the chiller plant, the chiller units were the most energy-intensive, responsible for 75% of the total power consumption. The remaining 25% of the load was shared by the chilled water and cooling water pump sets, as illustrated in Figure 11B based on the power consumption data from July 2021.

2.8. Energy Consumption against Fouling

Considering the susceptibility of an open-loop circulating water system for an evaporative cooling tower to contamination from foreign particles, a higher fouling factor is permitted for the water-cooled refrigerant condensers (0.00025 hr•ft^2/Btu). On the other hand, a lower fouling factor is adopted for the evaporator closed-loop chilled water route, which is protected against the intrusion of external contaminants. The AHRI [36] has demonstrated that a fouling factor of 0.00025 hr•ft2/Btu leads to a decrease in system/chiller efficiency flow rate to 0.65 W/kg from the previous 0.6 W/kg.

Other studies have indicated that a fouling factor of 0.0001 hr•ft^2/Btu, equivalent to a water scale thickness of 0.3mm formed on the condenser tube surfaces, results in 11%

higher energy consumption [37] and a corresponding increase in condensing refrigerant temperature (CRT) by 2.5 °C [38]. Consequently, it can be inferred that every degree Celsius rise in CRT leads to a 4.4% increase in energy consumption.

By averaging the standard fouling factors ranging from 0.001 to 0.003 hr•ft^2/Btu, it was determined that there is a 4.1% incremental energy consumption per degree Celsius increase in CRT, as depicted in Figure 12.

Power consumption vs. fouling factors					
Fouling	Scale thickness	↑ in Energy	Cond Temp Rise		
		Ev or Cd	Cd	Energy increased /°C	
hr.ft^2.°F/Btu (hr.m^2.°C/W)	Inches (mm)	%	°C	%	% Ave
0.001 (1.76×10^{-4})	0.012 (0.3048)	11%	2.5	4.40%	4.10%
0.002 (3.52×10^{-4})	0.024 (0.6096)	22%	5.5	4%	
0.003 (5.28×10^{-4})	0.036 (0.9144)	33%	8.5	3.90%	

Figure 12. Power consumption vs fouling factor [37,38].

2.9. The Actual Change in CRT Measurement

The measurements for the change in condenser approach temperature (CAT) were conducted both before and after the annual cleansing of the condenser tubes. This cleansing process effectively removed the water scale, resulting in improved heat transfer between the refrigerant and the cooling water flowing through the condenser tubes. Additionally, measurements were taken to evaluate the change in condensing refrigerant temperature (CRT). This assessment aimed to gauge the energy performance and reduction in losses achieved by removing water scales and increasing the cooling fan speed to lower or improve the CRT.

The evaporative cooling towers were equipped with two-speed axial fans that drew in outdoor air through baffles, facilitating the cooling of the system water through evaporation. By elevating the fan rotational speed, the circulation and heat exchange between the forced draw-in air and water was enhanced, accelerating the removal of latent heat through vaporization. The cooled water then flowed out of the cooling tower and entered the condenser unit to regulate the CRT, which represents the actual working conditions of the refrigerant. The operations and power consumption of the chiller were logged for assessment purposes.

2.10. The Actual Effect of CRT

Having boosted the heat exchange by increasing the cooling fan speed, the CRT was enhanced from 36.4 °C to 35.7 °C and the temperature was improved:

$$(36.4 - 35.7)\ ^{\circ}\mathrm{C} = 0.7\ ^{\circ}\mathrm{C}$$

Less power was consumed by the compressor, kW:

$$(255 - 243.3)\ \mathrm{kW} = 12.3\ \mathrm{kW}$$

The improvement of power utilization:

$$\frac{12.3}{0.7\ ^{\circ}\text{C} \times 255} = \frac{17.57}{255} = 6.87\%\ \text{per}\ ^{\circ}\text{C}$$

The energy savings resulting from these factors are presented in Figure 13.

Condenser Temperature Change vs Power consumption measurement (2022-yr)									
	Before Annual Condenser Tube Cleansing (2022-04-21)				After Annual Condenser Tube Cleansing (2022-04-30)				Energy Saving by Removing Water Scale in Annual Tube
	Before Low Speed Fan	After High Speed Fan	ΔChange = (After - Before)	Change %	Before Low Speed Fan	After High Speed Fan	ΔChange = (After - Before)	Change %	
Chiller (CH-C-5)									
Running Current (Amps)	**418**	**397.67**	**-20.33**		**449.67**	**368.67**	**-81**		
Motor Power (kW)	**255.6**	**243.3**	**-12.3**	**-4.81%**	**280**	**228.6**	**-51.4**	**-18.36%**	
Entering Condenser Water Temp **(ECWT) = Cooling Tower Leaving** Water Temp (°C)	**27.5**	**27**	**-0.5**		**27.1**	**26.6**	**-0.5**		
Leaving Condenser Water Temp (LCWT) = Cooling Tower Water Entering Temp (°C)	**32.2**	**31.6**	**-0.6**		**32.1**	**31**	**-1.1**		
Condenser Refrigerant Temp (CRT) (°C)	**36.4**	**35.7**	**-0.7**		**34.2**	**32.8**	**-1.4**		
Condenser Approach Temp (CAT) (°C)	**4.2**	**4.1**	**-0.1**		**2.1**	**1.8**	**-0.3**		
Energy Saving per °C of CRT				**6.87%**				**13.11%**	**6.24%**

Figure 13. Summary of actual CRT change by condenser tube washing.

The entering condenser water temperature (ECWT) was lowered by increasing the ventilating fan in the cooling tower. This allowed the cooling water to absorb more heat released by the refrigerant in the condenser. As a result of this heat transfer, two parameters were affected. The first parameter, known as the condenser refrigerant temperature (CRT), directly influenced the power demands of the chiller unit's compressor. The second parameter, referred to as the condenser approach temperature (CAT), indicated the extent of water scale deposits on the heat exchanger surfaces.

Based on measurements, it was observed that the CRT showed an improvement of 0.7 °C by increasing the speed of the cooling tower's ventilating fan before the annual condenser tube cleansing. After the condensed tube cleansing was performed, the improvement in CRT increased to 1.4 °C, as depicted in Figure 13.

The actual measurement indicated that 1 °C of CRT reduces energy consumption by 6.87% before tube washing, while the energy saving was enhanced to 13.11% per °C of CRT after tube cleansing. The depositions of water scale were aggravated before annual tube cleansing, and the improvement in descaling was averaged to half of the energy saving accordingly:

$$P\%_{\text{CRTAnnualSaving}} = P\%_{\text{CRTSavingAfterCleansing}} - P\%_{\text{CRTSavingBeforeCleansing}}$$

$$P\%_{\Delta\text{CRTAnnualSaving}} = 13.11\% - 6.87\% = 6.24\%$$

$$P\%_{\text{CRTAnnualSavingAve}} = \frac{6.24\%}{2} = 3.12\%$$

2.11. Reduction in Greenhouse Emissions from Electrical Power

The improvement in Condenser Refrigeration Temperature (CRT) achieved through the use of condensed water has resulted in reduced power consumption and greenhouse gas (GHG) emissions. The reduction in GHG emissions can be quantified as the equivalent emission of carbon dioxide (CO_2e) per degree Celsius (°C) of CRT improvement in a year.

The power supply for the organization requires electricity generation, and the equivalent GHG emissions associated with electricity are represented by the emission factor for electricity.

The power consumption of the chiller units in 2021, denoted as $P_{chillerunit}$, is 2,645,000 kWh (as referenced in Section 2.7).

The emission factor of electricity in terms of GHG emissions is 0.71 kg CO_2e/kWh [7].

To calculate the carbon footprint reduction from electricity saving, the following formula can be used:

Carbon footprint (CF) reduction from electricity saving = $P_{chillerunit} \times P\%_{CRTAnnualSavingAve}$ × Electricity emission factor

Note: The value of $P\%_{\_CRTAnnualSavingAve}$ represents the average percentage improvement in CRT achieved annually.

$$\begin{aligned} \text{CF reduction} &= 2{,}645{,}000 \text{ kWh} \times 3.12\% \times 0.71 \text{ kg} \frac{CO_2e}{\text{kWh}} \\ &= 58{,}592 \text{ kg } CO_2e \approx 59 \text{ Ton } CO_2e \end{aligned}$$

3. Results

In accordance with Section 2.4, the cooling towers were supplemented with condensed water and operated with an average range temperature of 4 °C. This resulted in a water saving of 44%, equivalent to 1429 m^3/month.

To determine the make-up flow rate requirement for the cooling tower, the manufacturer's technical data [33] was consulted. According to the data, the cooling tower has a flow rate capacity of 648 m^3/h and operates at a cooling range of 4 °C. This indicates that a make-up water flow rate of 4.5 m^3/h is required, equivalent to 3283 m^3/month.

Next, the bleed-off rate at a CoC of 19.2 was assessed to be approximately 5.2% (rounded down to 5%) of the make-up water, as explained in Sections 2.2 and 2.3. Additionally, the evaporation rate was estimated to be 95%, equivalent to 3112 m^3 per month.

Actual measurements were taken, and the evaporation rate was found to be 1820 m^3/month, while the auto bleed-off rate was 35 m^3/month. These values were summed up to determine the overall make-up water consumption, which amounted to 1854 m^3/month.

To evaluate water savings, a comparison was made between the analytical and actual evaporation, auto bleed-off, and overall make-up water consumption. The analysis revealed that there was a 42% reduction in evaporation, an 80% reduction in auto bleed-off, and a 44% reduction in overall make-up water consumption, as presented in Figure 14.

In 2021, despite the fluctuation in cooling loads, humidity, and temperature, an average of 5.66 m^3/day of condensed water with a total dissolved solids (TDS) concentration of 69 ppm was reclaimed. This reclaimed condensed water effectively augmented dilution and provided the same level of dilution as 10.64 m^3/day of new make-up water with a TDS concentration of 130 ppm. By adhering to the industrial standards of TDS 2500 ppm (or 3900 μS/cm) for the system and of TDS 130 ppm for freshwater, a cycle of concentration (CoC) of 19.2 was determined.

The electrical conductivity (EC) controller monitored the TDS level within the acceptable range of 2500 ppm, which was achieved by bleeding off mineral-rich system water. As a result, the bleed-off was reduced to 1.14 m^3/day, representing an 80% saving (equivalent to 4.476 m^3/day) compared to the analytical hard bleed-off of 5.616 m^3/day, as stated in Section 2.5. The hard bleed-off was reported to be approximately 5% of the analytical make-up water flow rate of 4.5 m^3/h (or 1.25 L/s) at CoC 19.2, as stated in Section 2.3.

Water Consumption_Annual_2021yr					
Analytical	L/s	m^3/day	m^3/mth	m^3/yr	Makeup%
Evaporation	1.185	102	3112	37,370	95
Hard hleed-off	0.065	5.616	171	2050	5
Make-up	1.25	108	3283	39,420	100
Actual	L/s	m^3/day	m^3/mth	m^3/yr	Makeup%
Evaporation *	0.693	59.86	1820	21,848	98
Auto Bleed-off	0.0132	1.14	35	416	2
Overall make-up**	0.706	61	1854	22,264	100
* - Water evporated = Evaporation + Reclaimed condensed water					
**- Overall make-up = Fresh make-up + Reclaimed condensed water					
Saving	Individual%		m^3/mth		Overall make-up%
Evaporation	42%		1293		90%
Auto bleed-off	80%		136		10%
Overall Make-up	44%		1429		100%

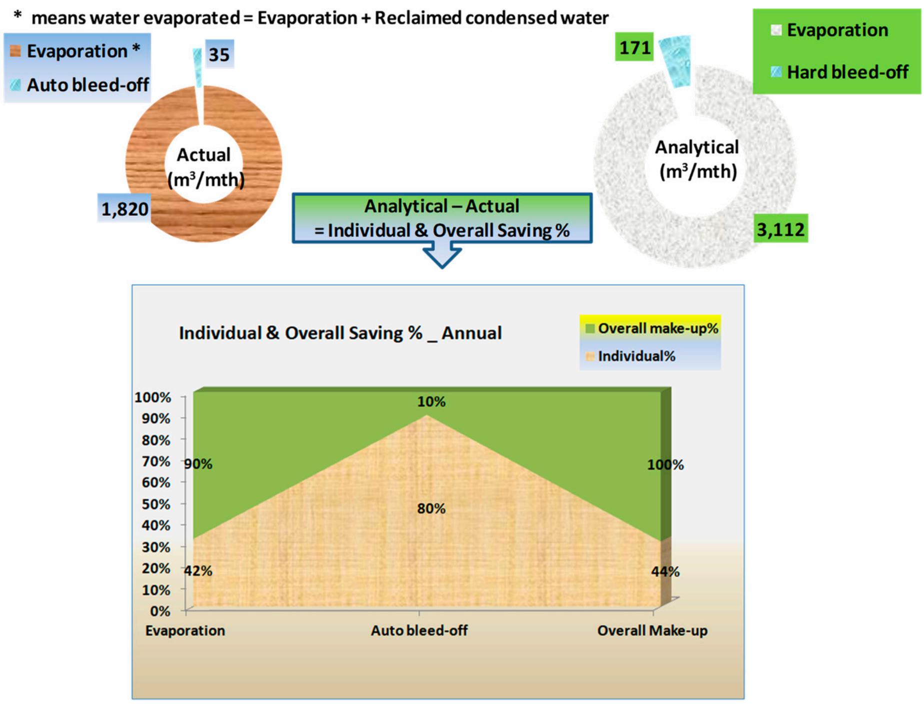


Figure 14. Outline of cooling water consumption.

The reduction in water demand also led to power energy savings in water supply delivery, resulting in a reduction of approximately 7500 kg CO_2e/y in greenhouse gas emissions.

Using the GHG emissions factor for water, which is 0.428 kg CO_2e/m^3, the water savings achieved for evaporation, bleed-off, and make-up water were converted into greenhouse gas (GHG) emission reductions. The calculated GHG emission reductions were

6640 kg CO_2e/y for evaporation, 699 kg CO_2e/y for bleed-off, and 7339 kg CO_2e/y for make-up water, as presented in Figure 15.

GHG Emissions Reduction _ Annual_2021yr						
Analytical GHG emissions	L/s	m^3/day	m^3/mth	m^3/yr	kg CO_2e/yr	Makeup%
Evaporation	1.185	102	3112	37,370	15,994	95
Hard hleed-off	0.065	5.616	171	2050	877	5
Make-up	1.25	108	3283	39,420	16,872	100
Actual GHG emissions	L/s	m^3/day	m^3/mth	m^3/yr	kg CO_2e/yr	Makeup%
Evaporation *	0.693	59.86	1820	21,848	9351	98
Auto Bleed-off	0.0132	1.14	35	416	178	2
Overall make-up**	0.706	61	1854	22,264	9529	100
* - Water evporated = Evaporation + Reclaimed condensed water						
**- Overall make-up = fresh make-up + reclaimed condensed water						
GHG emission Reduction	Individual%		m^3/mth		Reduced kg CO_2e/yr	Overall make-up%
Evaporation	42%		1293		6640	90%
Auto bleed-off	80%		136		699	10%
Overall Make-up	44%		1429		7339	100%
Taking GHG emissions factorof water = 0.428 kg CO_2e/m^3						

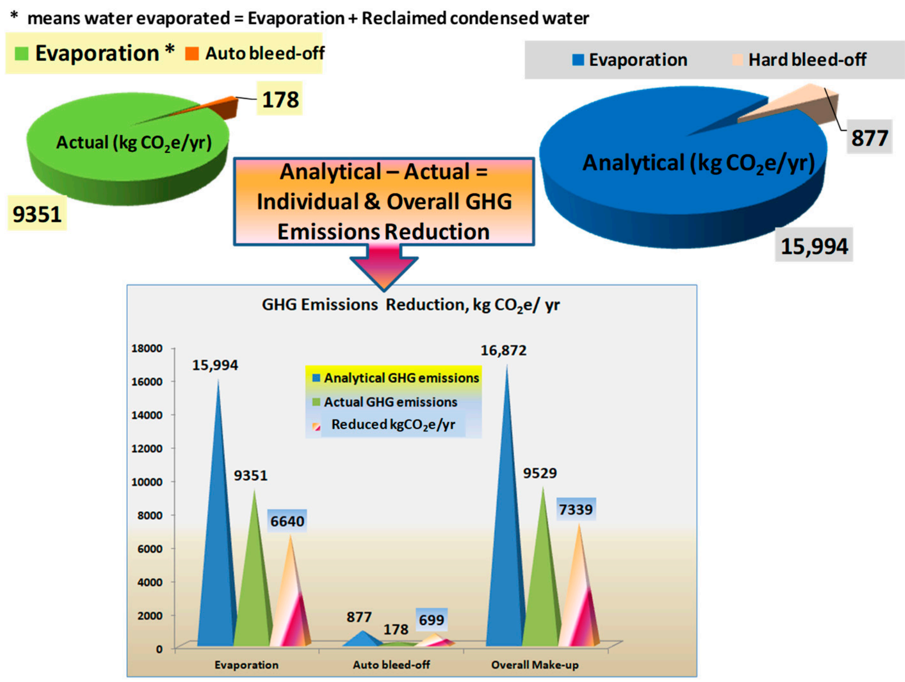


Figure 15. Outline of GHG emissions reduction for water saving.

4. Discussion

Although reducing the CoC is a straightforward way to maintain good water quality, the literature [35] specifies a minimum CoC of 6 to minimize bleed-off. In an effort to achieve water savings, the CoC was increased to 19.2, which complies with the industrial standard of 2500 ppm TDS. This change was evaluated based on the condensed water with a TDS of 69 ppm and the fresh make-up water with a TDS of 130 ppm, resulting in a dilution factor of 1.88 times.

To reduce the bleed-off rate, 5.66 m^3/day of reclaimed condensed water was used as a supplement to the cooling water. This not only improved water treatment but also saved 80% of the bleed-off water and minimized chemical discharges. Ultimately, this improvement in the cooling water system, including heat exchanger performance, resulted in a 44% reduction in fresh make-up water. In terms of greenhouse gas (GHG) emissions, approximately 7500 kg CO_2e/y were correspondingly reduced.

Although the condensed water is naturally mineral-free, its purity can be affected during the water harvesting process, particularly in the collection pipework [39]. The quality of the condensed water was tested and found to have very low levels of TDS and a slightly acidic nature. Thanks to the hydrophilic nature of condensed water, the solubility of calcite was improved, inhibiting the formation of water scale in the system water.

The evaporative cooling tower dissipates heat through evaporation to the open air, but this process also allows foreign particulates from the outdoor air to enter the circulating system water, leading to contamination. The cooling tower's baffles or fills can easily accumulate dust and organic materials, promoting the formation of water scales and fouling. The design of smooth water flow and distribution across the tower fills is compromised, resulting in uneven and blocked water and air flows. This impairs the heat exchange rate and reduces the cooling effect through evaporation. Consequently, the cooling tower is unable to effectively cool down the system water and condenser tube surfaces, and heat transfer between the water and refrigerant is greatly diminished, leading to a higher condensing refrigerant temperature (CRT). As a result, the condenser refrigerant operates under unfavorable heat transfer conditions and higher cooling water temperature, requiring more energy to compensate for the decrease in the chiller unit's coefficient of performance (COP).

The system water is treated with chemical reagents commonly used for water quality control. Chemical water treatment not only provides comprehensive coverage for inaccessible portions and areas of the water circuitry, but also offers cost-effectiveness and a range of combinations for specific purposes.

To ensure the effectiveness of the chemical water treatment and its compatibility with the use of reclaimed condensed water as supplementary make-up cooling water, the dosage amount and frequency of the chemical treatment remain unchanged. This approach benefits water quality control, including improved dilution effectiveness and facilitation of descaling. Based on measurements of chiller performance before and after annual condenser tube cleansing, the energy-saving benefits derived from reclaimed condensed water were quantified as an annual energy saving of 3.12% per degree Celsius of CRT (equivalent to 80,090 kWh), which is close to a reduction of 57,000 kg CO_2e/yr. per degree Celsius of CRT improvement.

Even in modern society, freshwater shortages and water scarcity continue to be a recurring problem in various parts of the world [34,39,40] despite our perceived distance from these issues. Today, population growth, soaring living standards, global warming, and the uncertainties of climatic variability have already affected water availability, demands, and uneven water distribution, causing more than two billion people to live in water-deficient areas or during water crises [41,42]. Different strategies and dedicated materials were researched for water extraction from atmospheric air devoted to the enhancement of water productivity and versatility in applications [30–34,43–47] particularly in arid regions for the alleviation of water scarcity [42]. While storing water is important, there are limits to how much we can store. However, atmospheric vapor can be collected through condensation [48], providing a source of reclaimed condensed water that can be used for cooling water systems. Surprisingly, the advantages of using condensed water have not been adequately explored or evaluated [49], especially in the context of water-cooling towers, commonly found at the highest levels of air-conditioning systems or on rooftops. This topographical challenge leads to additional energy consumption and costs associated with lifting the reclaimed condensed water to these high locations. Moreover, the fluctuating quantity of condensed water due to humidity levels does not appeal to cooling tower operators [50–52]. Additionally, the term "grey water" has deterred direct application of condensed water [53,54].

This research presents a practical example of direct use of condensed water for evaporative cooling towers without the need for a wastewater treatment plant [55]. This approach overcomes spatial limitations and reduces power consumption. The mineral-free nature of condensed water improves water quality, conserves water, and reduces water scale buildup, resulting in enhanced heat transfer performance and energy savings.

To promote the reclamation of condensed water, several potential approaches can be considered:

Apparatus integration: Incorporate condensation capture systems as standard features in new apparatus, similar to air conditioners.

Meliorated harvesting system: Design and implement more efficient and effective systems for capturing condensation, which can increase the amount of water reclaimed. This may involve optimizing collection surface design and placement, using specialized materials, or employing innovative technologies.

System combination: Integrate the condensed water reclamation system with other water management systems in buildings to optimize water use and distribution. This may involve retrofitting existing systems or considering water reuse during the design phase of new buildings.

Thermal Conservation: Improve the insulation of the collection and storage system to conserve thermal energy and minimize heat losses to the surroundings. Proper insulation reduces the need for excessive cooling or heating, resulting in energy savings.

Nurture and Incentives: cultivate users by communicating the benefits of reclaimed condensed water and provide financial incentives or rebates, such as concessions or reductions in water discharge levies. Consider promoting a "Water Buyback" program, similar to power companies purchasing electricity generated by photovoltaic (PV) panels.

It is important to note that the feasibility and effectiveness of these approaches may vary depending on local regulations, climate conditions, and building characteristics. However, by implementing a combination of strategies and technologies, it is possible to improve the utilization of condensed water and promote sustainable water management in high-rise buildings.

5. Conclusions

In simple terms, condensed water can be directly reclaimed as a supplement to fresh water in the cooling water system without the need for extensive water treatment. The primary benefit of using condensed water is water conservation, but there are additional layers of benefits that contribute to energy savings.

One of these benefits is the improvement in heat transfer efficiency of condensers and cooling towers, which results from the conducive properties of condensed water for descaling and water quality control. By effectively preventing scale formation, the use of anti-scaling chemicals can be optimized before bleed-off, reducing the amount of chemicals used and discharged. This hindrance of scale formations and fouling promotes efficient heat dissipation from water to air in the evaporative cooling tower, as well as heat transfer from the refrigerant to water in the condenser units.

The severity of fouling and scale formations, which act as heat-resistant barriers, is reflected in the increase in the condensing approach temperature (CAT). Additionally, the rise in condensing refrigerant temperature (CRT) directly corresponds to an increased power requirement by the compressor. Therefore, by effectively controlling scale formations and fouling through the use of condensed water, energy consumption can be reduced.

As a result, significant improvements were achieved with a water saving of 44% for make-up water and 80% for bleed-off water. Additionally, the use of the condensed water led to improved water descaling and enhanced condenser heat transfer in the chiller system. These favorable conditions resulted in an increase in energy saving from 6.9% to 13.1% per degree Celsius of condensing refrigerant temperature (CRT), both before and after the annual condenser tube cleansing.

Reclaiming the condensed water, which is a by-product of condensation and does not require additional power demands, as supplementary make-up cooling water for the evaporative cooling tower resulted in direct water conservation equivalent to the amount of reclaimed condensed water. Additionally, indirect reduction in carbon footprint was revealed through the improved performance of the cooling water system and the increased efficiency of power-intensive processes.

The potential of condensed water to significantly reduce carbon footprints can be realized by fostering collaboration among industry partners, government organizations, and standards bodies. Incorporating these practices into green building designs at the early stages can effectively harness the interdisciplinary relationships between water and energy for sustainable outcomes.

Future developments in utilizing the inherent thermal energy of condensed water will focus on pre-cooling water for temperature-controlled areas or specific components, such as chilled beam systems. These systems typically consist of a finned tube system that circulates the condensed water at lower or after-coil temperatures. They are often installed on ceilings or walls in areas like battery storage rooms or integrated into heat sink designs to remove heat and improve the thermal management of electronic components. By harnessing the thermal energy of condensed water, pre-cooled water can supplement mechanical cooling systems, reducing overall energy consumption.

However, the limited availability of condensed water poses a challenge that must be addressed. Implementing a central condensed water system can ensure feasibility, water stability, and thermal conservation integrity.

In this case study, condensed water was collected by gravity and directed to lower water usage points. However, it is more common for water usage points, such as water cooling towers, to be located at the highest point of a building's roof. In such cases, water transfer pumps are necessary to lift the condensed water from the storage tank at the lowest level. Additionally, the existing water-capturing system in the high-rise building was not well insulated, resulting in significant heat losses. To optimize the thermal energy contributions of condensed water, it is recommended to implement an all-insulated system for capturing, pumping, and storing condensed water.

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Abbreviations

BOV	Bleed-off volume
CT	Cooling tower
CAT	Condensing approach temperature
CoC	Cycles of concentration
COP	Coefficient of performance
CRT	Condensing refrigerant temperature
EC	Electric conductivity
IOA	Input-output analysis
GHG	Greenhouse gas
GWP	Global warming potential
IPCC	The Intergovernmental Panel on Climate Change
LCA	Life-cycle assessment

PAS	Publicly available specification
PV	Photovoltaic
TDS	Total dissolved solids
UNFCCC	United Nations framework convention on climate change
Notations	
A_{aug}	The dilution factor augmented by reclaimed condensed water
B	Bleed-off rate
$B_{AnalysedHardBleedoffCoC19}$	The analytical bleed-off water flow rate without automatic bleed-off control system (i.e., hard bleed-off) at CoC19 setting in litre/second
D	Drift losses in litre/second
E	Evaporation rate in litre second
$P_{Chillerunit}$	The power consumption for the chiller unit in kWh
$P\%_{AnnualCRTSaving}$	The change in condensing refrigerant temperature (CRT) improvement after and before condenser tube cleansing as a percentage
$P\%_{AftercleansingSavingCRT}$	The improvement in condensing refrigerant temperature (CRT) after condenser tube cleansing in percentage
$P\%_{BeforecleansingSavingCRT}$	The improvement in condensing refrigerant temperature (CRT) before condenser tube cleansing in percentage
$P\%_{CRTSavingAfterCleansing}$	The power consumption per °C of CRT after condenser tube cleansing in percentage (%)
$P\%_{CRTSavingBeforeCleansing}$	The power consumption per °C of CRT before condenser tube cleansing in percentage (%)
$P\%_{CRTAnnualSaving}$	The annual energy saving per °C of CRT by improving CRT in percentage (%)
$P\%_{CRTAnnualSavingAve}$	The annual average energy saving per °C of CRT by improving CRT in percentage (%)
$TDS_{CondTankA}$	The total dissolved solid of condensed water stored at Tank A in ppm
$TDS_{CondTamkB}$	The total dissolved solid of condensed water stored at Tank B in ppm
$TDS_{CondTankAB}$	The total dissolved solid of condensed water stored at Tank A and Tank B in ppm
V_A	The volume of condensed water reclaimed by Tank A in m^3
V_B	The volume of condensed water reclaimed by Tank B in m^3
V_{TankA}	The volume of condensed water stored at Tank A in m^3
V_{TankB}	The volume of condensed water stored at Tank B in m^3
$W_{ActualAutoBleedoffCoC19}$	The actual measurement for bleed-off water flow rate with automatic bleed-off control system at CoC19 setting in litre/second
$W_{ActualEvapCoC19}$	The actual measurement for evaporation water flow rate in litre/second
$W_{Actual\ MakeupCoC19}$	The actual make-up water flow rate at CoC19 setting in litre/second
$W_{ActualReclaime}$	The actual measurement for reclaimed condensed water flow rate in litre/second
$W\%_{ActualBleedoffCoC19}$	The actual bleed-off water flow rate at CoC19 setting in percentage (%)
$W\%_{ActualBleedoffCoC19Saving}$	The actual bleed-off water flow rate saving at CoC 19 setting in percentage (%)
$W\%_{Actual\ MakeupCoC19}$	The actual make-up water flow rate at CoC19 setting in percentage (%)
$W\%_{Actual\ MakeupCoC19Saving}$	The actual make-up water saving at CoC19 setting in percentage (%)
$W\%_{AnalysedHardBleedoffCoC19}$	The ratio of the analytical bleed-off water flow rate without automatic bleed-off control system (i.e., hard bleed-off) at CoC 19 setting to the total water consumptions in percentage (%)
$W_{AnalysedHardBleedoffCoC19}$	The analytical bleed-off water flow rate without automatic bleed-off control system (i.e., hard bleed-off) at CoC19 setting in litre/second
$W_{AnalysedEvapCoC19}$	The analytical evaporation rate at CoC19 setting in litre/second
$W_{AnalysedMakeupCoC19}$	The analytical make-up water flow rate at CoC19 setting in litre/second
$W_{AnalysedMakeupCoC19Annual}$	The annual analytical make-up water flow rate at CoC19 setting in litre/second
$W_{DiluteEqv}$	The equivalent water volume after dilution augmentation in litre/second
$W_{MakeupCoC19SavingAnnual}$	The annual analytical make-up water saving at CoC19 setting in litre/second
$W_{ReduBleedoffCoC19}$	The analytical reduction in bleed-off rate at CoC19 setting in litre/second

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