NET ZERO WATER USE AT DATA CENTERS

By

LINDSAY MARIE VERMEIRE

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Approved by:

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Dr. Andrea Achilli
Department of Chemical and Environmental Engineering

Summary

According to the Department of Energy, as of 2014, there are over 3 million data centers in the United States. It is estimated that for the average 500-ton cooling tower approximately 14.8 million liters of water per year are wasted without being reclaimed. The NetZero system specializes in water recovery and wastewater minimization for existing industrial plants, specifically data centers. The scope of this report is to outline and assess the impact that the system has on carbon emissions and costs associated with the system. The NetZero system is specifically designed for a plant with a 500-ton cooling tower capacity, with an 80% wastewater recovery target. This is an estimated yearly reduction of about 11.8 million gallons of water and 34,000 metric tons a carbon dioxide emission. As said above, many data centers source high volumes of water for the purpose of cooling. A batch of water is used until a buildup of minerals and organic compounds from exposed cooling towers occurs, decreasing the efficiency of heat exchange and cooling potential. The NetZero system removes these contaminants by using sixty-eight membrane distillation units in parallel. The levelized cost of water to produce 1 m^3 is estimated to be $4.74.

Contributions of Team Members

Team Member	Contribution

Karina Palomares	• Design of System
	  ○ Configuration of System
	  ○ Stream Table Calculations
	• Block Flow Diagram
	• Process Flow Diagram
	• Alternative Analysis
	• Life Cycle Analysis Calculations
	• In Report
	  ○ Summary
	  ○ Current Market Information
	  ○ Premises and Assumptions
	  ○ Written Description of Process
	  ○ Process Safety Concerns and Engineering Controls (MD Unit)
	  ○ HAZOP Table (MD Unit)
	  ○ Life Cycle Analysis
	  ○ Conclusions and Recommendations

Sam Portillo	• Design of System
	  ○ Black Box Model
	  ○ Stream Table Calculations
	• PFD
	• Alternative Analysis
	• Utility Table
	• Equipment Sizing
	  ○ Cooler, Pumps, Vessels
	  ○ ASPEN Simulation
	• In Report
	  ○ Summary
	  ○ Premises & Assumptions
	  ○ Rationale for Process Choice
	  ○ Written Description of Process
	  ○ Equipment Description
	  ○ Hazops (Heat Exchangers)
	  ○ Equipment Table
	  ○ Utility Table
	  ○ Appendix

<table>
<tr><td>Theresa Ruffin</td><td>

Design of System
Parallel MD Design
Stream Table Calculations
Alternatives Analysis
Heat Exchanger Calculations
Utility Table
Concentration Limit Calculations
In report:
Summary
Equipment Description (Heat Exchanger, Vessel)
Process Safety Concerns and Engineering Controls (Heat Exchanger, Vessel)
Recommendations
Hazops Table (Heat Exchangers)
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<tr><td>Lindsay Vermeire</td><td>

Team Lead
Design of system:
Parallel MD configuration
Mass balance – stream table
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Introduction

Overall Goal

NetZero seeks to reduce the total annual water footprint on data center cooling operation by 80% using the 500-ton cooling tower as a basis of design. This design aims to investigate the application of membrane distillation to treat cooling tower blowdown water for re-use. Our solution will implement a parallel configuration of membrane distillation units that utilize low-grade heat from the data centers to replace the need of additional site utilities required for the system. Criteria for this design includes carbon emission reduction, cost-competitiveness against the current water treatment process, total utility usage required to power the units, and water purity.

Current Market Information

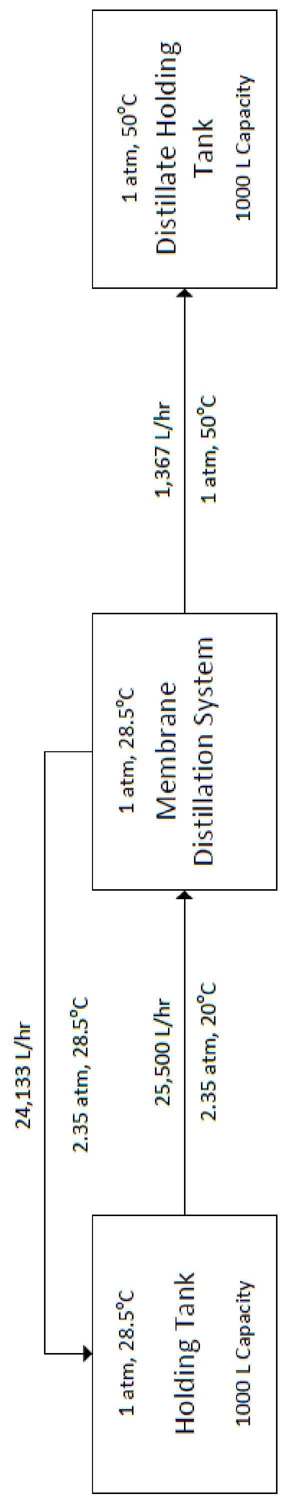
As of 2014, there are over 3 million data centers in the United States. The growing demand for cloud storage has resulted in major growth for the data center industry worldwide. The market information supporting NetZero's design is based on typical cooling tower data reported by Terlyn Industries Advanced Water Treatment Systems, as well as Aquastill membrane distillation product information. According to Terlyn Industries, a typical cooling tower flushes over 14.8 million liters of Cooling Tower Blow Down (CTBD) each year. This design was created to recover 80% of this reported CTBD discharge each year based on a membrane distillation study of industrial cooling tower blowdown water (Koeman-Stein Et al., 2016). Since CTBD is highly concentrated, it is necessary to reclaim this water for water conservation as well as pollution prevention. Industrial process water is used to refill the cooling tower when the concentration of contaminants becomes too high. Off-site water treatment is also recommended to remove the contaminants before water is returned to the environment. The cost of industrial process water used in this design is $0.80 per 1,000 gallons of water (Seider et al., 2017). In addition, the average cost of water treatment according to the Department of Energy is on average around $4.80 per kilogallon of water treated (U.S. Department of Energy, 2017). These reported costs are used in economic assessments performed for this design.

Project Premises and Assumptions

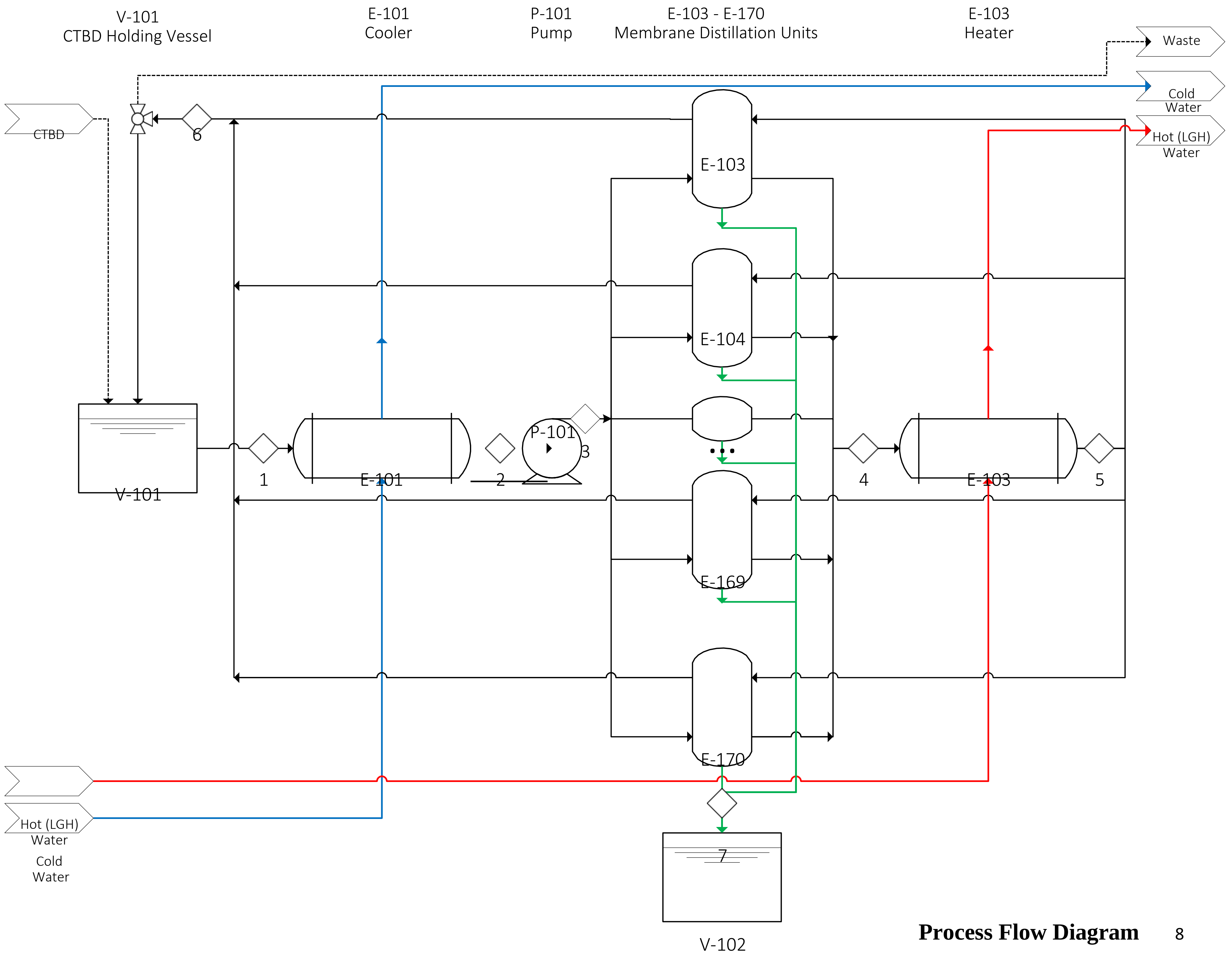
Since there was limited information available concerning the cooling water footprint from the stakeholder, Microsoft, an assumption is made that CTBD is readily available on-site, meaning concentrated CTBD can be transferred to the NetZero system at any given time for purification purposes. Based on data provided by Terlyn Industries, it was assumed that the average 500-ton cooling tower produces 3.9 million gallons of CTBD per year. This project is based on the assumption that 10,800 gal/day of CTBD (equivalent to 1366 L/h) is available to be treated on a daily basis to meet the target of 80% water reclamation by the years end. Additionally, it is assumed that the site of treatment is capable of running this system 24 hours; 7 days a week. Specific details regarding the membrane distillation unit, including temperatures, flow, rates, dimensions and purchase cost, were obtained from correspondence with its manufacturer, Aquastill. Assumptions concerning the water chemistry of the CTBD water are based on blowdown water concentration data available from Dow Benelux BV in New Zealand. This water contained a variety of chemicals including pH-regulating acids, corrosion inhibitors, total organic carbon (TOC), and bio-dispersants (Koeman-Stein et al., 2016). To make this analysis possible, composition data (available from the composition analysis done by Koeman-Stein et al.) was used to establish a total-dissolved solids (TDS) amount in the CTBD.

Process Description, Rationale, and Optimization

Block Flow Diagram



*Total initial dissolved solids concentration in system (in exception to the distillate stream) is estimated to be 0.0028 kg/L.
*The solubility limit of 0.0099 kg/L is reached after 16 cycles in the span of 9 hours. The system is then flushed and re-filled with water at the concentration mentioned above.



Process Flow Diagram

V-102
Distillate Holding Vessel

Equipment Table

Heat Exchangers	**E-101 (Cooler Heat Exchanger)**	**E-102 (Heater Heat Exchanger)**	**E-103 to E-171 (Membrane Distillation)**
Type	Counter-current	Counter-current	Counter-current
Area (m^2)	28.96	28.96	7.2
Duty (MJ/h)	863	1104	76.62
Shell			
Temp (C)	28	69.7	N/A
Pressure (bar)	1.01	1.01	N/A
Phase	Liquid	Liquid	Liquid
MOC	Brass	Brass	PFTE
Tube			
Temp (C)	10	90	N/A
Pressure (bar)	1.01	1.01	N/A
Phase	Liquid	Liquid	Liquid
MOC	Brass	Brass	PFTE
Vessels/Towers	**V-101 (Holding tank CTBW)**	**V-102 (Holding tank Distillate)**	**-**
Temp (C)	28	68	-
Pressure (bar)	1.01	1.01	-
Orientation	Vertical	Horizontal	-
MOC	Polyethylene	Polyethylene	-
Size			
Height (in)	40.00	133.00	-
Length (in)	54.00	92.00	-
Width (in)	48.00	92.00	
Internals	N/A	N/A	-
Pumps	**P-101 (Pump)**	**-**	**-**
Flow (kg/h)	25571	-	-
Power (shaft) (kW)	3.7285	-	-
MOC	Cast Iron/brass	-	-

Table 1: Overall Equipment Table for NetZero Process

Stream Table

Stream Number	**1**	**2**	**3**	**4**	**5**	**7**	**8**
Temperature (℃)	28.50	20.00	20.00	69.70	80.00	28.50	50.00
Pressure (atm)	1.00	1.00	2.35	2.35	2.15	2.35	1.00
Volumetric Flow (L/h)	25,500	25,500	25,500	25,500	25,500	24,133	1,367
Mass Flow (kg/h)	25,571	25,571	25,571	25,571	25,571	24,204	1,367
Concentration (kg/L, H20)	0.0028	0.0028	0.0028	0.0028	0.0028	0.0029	0.0000
Component Molar Flow (kg/h):							
Water (kg/h)	25,500	25,500	25,500	25,500	25,500	24,133	1,366
TOC (kg/h)	1.35	1.35	1.35	1.35	1.35	1.35	0.00
Total dissolved solids: (kg/h)	69.47	69.47	69.47	69.47	69.47	69.47	0.00

Table 2: Stream Table

Utility Table

Equipment	**Electric Power (kWh)**	**Cooling Water (m^3/h)**	**Cost ($/h)**
E-101	-	15.00	7.94
E-102	-	21.60*	12.10*
E-103 to E-170	-	-	-
V-101	-	-	-
V-102	-	-	-
P-101	3.73	-	0.26
Total	3.73	15.00	8.20

Table 3: Utility Table for NetZero Process

*This is sourced from low grade heat and is therefore not included in the totals.

Written Description of Process

NetZero proposes to reduce 80% of the water wasted in the data center cooling process by implementing a water recovery system using membrane distillation. The proposed solution consists of 68 membrane distillation units in parallel as shown in Figures 1 and 2 above. At startup, the MD system is filled with CTBD until its full capacity of 5,000 L is reached. These 5,000 L are composed of 4,000 L of dead volume and a 1,000 L water storage tank that supplements the batch re-circulation process. The CTBD is continuously passed through the system at a flow rate of 25,500 L/h to pump P-101 where the pressure is increased to 2.35 atm. The stream is then pumped into heat exchanger E-101 to decrease the temperature from 28°C to 20.0°C. From the heat exchanger, the water is sent into the membrane distillation system, which consists of 68 modules (E-103 to E-170) in series. The incoming flowrate of each module is 375 L/h and the distillate flowrate is 20.1 L/h based on the manufacturer specifications. The outgoing concentrate streams are heated in the membrane distillation unit to 69.7°C and are recombined to be passed through a second heat exchanger. This combined stream is then sent to the E-102 heat exchanger where it is heated to 80°C and cycled back to the membrane distillation unit. This process of cycling the CTBD through the system continues for approximately 35 minutes until 80% of the V-101 is depleted. The system is refilled with CTBD to dilute the concentrated water from the previous run. The system is then started again. This cycle is repeated 16 times in the span of 9.4 hours until the water in the system is concentrated to 0.0099 kg/L. Once this concentration is reached, the remining volume of the system is discharged to a wastewater treatment facility and re-filled with CTBD at the initial concentration of 0.0027 kg/L.

Rationale for Process Choice

The existing process of water cycling and disposal was determined to be a poor design for sustainability. Every year, 14.8 million liters are disposed of and replenished in the data center's cooling tower due to contaminant fouling. In the existing system, the full cooling tower volume is cycled 2.5 times before fouling occurs and the water is sent to be cleaned. After considering several alternatives including an integrated continuous process, as well as evaluating potential for the current process, a batch process using membrane distillation was selected. NetZero's proposed solution is to implement a membrane distillation system to reclaim water by removing contaminants, which will allow for water to be cycled more times. Three different alternatives were considered and analyzed for this project. The first analyzed alternative was the existing design as mentioned above. The second alternative was a “continuous” flow design where the membrane filtration system is installed directly between the cooling tower and the data center. However, the filtration system cannot be placed in this manner because the cooling tower is open to the atmosphere. This configuration would lead to water becoming contaminated again after cleaning. Also, the cost of reconfiguring the entire system would be economical. Since the filtration system cannot be installed directly in line with the data center, NetZero proposes a third configuration that modifies the existing one. In this design, CTBD is pumped from a holding tank into the MD and heat exchanger system, and the permeate water is stored in an additional holding tank where it is later sent back to the cooling tower. This configuration separates the cleaning system from the data center and cooling tower in order to avoid additional contamination accrued from the cooling tower.

There are multiple methods for purifying water using membrane filtration. These include reverse osmosis (RO), membrane distillation (MD), pressure retarded osmosis (PRO), and ultrafiltration. The technology that was chosen for this process is membrane distillation (MD). Membrane distillation is a thermally driven separation process that is accomplished a temperature gradient between a ‘hot’ and ‘cold’ fluid side. As opposed to more classical membrane separation processes, the driving force for mass transfer across the membrane is not an applied pressure gradient, but rather a vapor pressure gradient caused by the aforementioned temperature gradient. Until more recently, the industrial application of membrane distillation was not widespread because of the lack of available new membranes and limitations on the understanding of heat and mass transfer in this application.

Membrane distillation consists of several different techniques including, but not limited to, direct contact, air-gap, sweeping gas, and vacuum (Alkhudhiri et al., 2012). Air-gap membrane distillation (AGMD) was chosen for this project because less heat is lost by heat conduction in the membrane compared to the other designs—this means that the majority of available energy is used to evaporate water (Camacho et al., 2013). This ‘conservation’ of heat makes AGMD one of the most energy efficient MD methods, especially for applications where available energy is scarce.

Similar to reverse osmosis filtration systems, membrane distillation units can be arranged in series or parallel. A parallel configuration of 68 AGMD units was chosen to reduce process volatility for key parameters like feed temperature and salinity, reduction of process equipment (pumps and heat exchangers) that would be needed to meet vendor suggested operating temperatures and flows needed for additional stages. This configuration is also the most optimal for membrane distillation because it results in higher distillate flux and volume compared to series configuration (Khalifa, 2017).

Equipment Description, Rationale, and Optimization

The two heat exchangers were selected based on calculated flow rates and the duties. The duty was estimated using the following simplified energy balance model:

$$Q_{heater/cooler} = m_{CTBW}Cp_{CTBW(T)}(T_{Hot\ out} - T_{Hot\ in})$$

In this model, only the energy entering and leaving the MD unit system was considered. Temperatures for the process water side of the heat exchangers were based on manufacturer specifications, with an exception being the inlet process water for the cooler. This water was estimated to have a temperature of approximately 28 °C because during operation, the concentrate out stream exits at a temperature of 28 °C. The low-grade heat temperature was set based on a temperature range for water utilized in DC cooling processes (Wahlroos, Mikko, et al, 2017). The two heat duties amounted to 1,045,000BTU/h (or 1,104,000 KJ/h) for the heater and 818,000 BTU/h (or 863,255 kJ/h) for the cooler. The flow rate of the CTBD water for both the cooler and the heater was calculated to be 25,500 kg/h. The most cost-effective solution from Grainger was chosen based upon the sizing above; more specific specifications can be found in Table 10.

The pump for this system was sized and selected based on the circulating flow needed for the entirety of the membrane distillation system to produce a combined hourly distillate flowrate of 1348 L/h or approximately 113 GPM. The circulating flow rates for each module to produce the desired amount of distillate was specified by the vendor Aquastill at 375 L/h. Because the system was sized to have 68 Membrane Distillation units, the total flow rate needed was calculated to be

25,500 L/h. The vendor Grainger was utilized for selecting an appropriate pump with the designed operating characteristics. A careful examination of the available pumps led to the selection of a Gould Water Technology, Model 3656/3756 S-Group, Centrifugal pump (see equipment tables in appendix E for technical specifications).

Gould Water Technology's pump catalog for the 3656/3756 S-Group Centrifugal pump included a variety of pump curves which were used to appropriately size these pumps to 25,500 L/h. It was determined that the 3500 RPM model, with a diameter of 5-15/16'', $NPSH_a$ of 8ft, and running at a power setting of 5hp yielded a favorable efficiency rate of approximately 72%. The pump was sized to overcome the head in the system (primarily from the CTBD vessel) was approximated off the 1 m vessel height or 3.28 ft.

Since this process is run in batch, vessel volume for the feed of CTBD to the process was minimized to reduce capital costs. A 1000 L (1 m^3) polyethylene IBC tote was selected for the feed tank to the process. The size of the holding tank for the collected distillate was also selected to also be a 1000 L (1 m^3) polyethylene tank. The reasoning behind the same volume for both tanks was that, the time that it would take to pump in new CTBD for the feed to the MD units, is the same amount of time it would take to pump the distillate back to the cooling tower. The rationale behind selecting a polyethylene tank was to minimize any adverse effects to the structural integrity of the tanks. Because the feed vessel would contain CTBD, which contains corrosive additives and materials, polyethylene was selected as a suitable thermoplastic because of its ability to be corrosion / chemical attack resistant.

Air gap membrane distillation (AGMD) was selected as the purification technology for this project. AGMD is favorable to other types of membrane distillation because of its lower heat conduction (as compared to direct contact membranes), resulting in lower heat losses and thus lower energy consumption per volume of distillate produced (Meindersma, G.w., et al., 2006). Because each membrane distillate unit is rated at a ~5.4 % recovery per pass (or 20.1 L/h) the system required 68 membrane distillation units to reach the target distillate flow rate. Aquastill, a major manufacturer of membrane distillation units, was selected as the primary vendor for these units.

Process Safety Concerns and Engineering Controls

Scope of Indicators

A Hazard & Operability Study (HAZOP) was conducted on each major process equipment. The study included examining nodes for each piece of equipment and classifying deviations (referred to as Hazards) from regular process conditions. For each deviation, a corresponding consequence of the deviation is listed with a corresponding control systems or methods to prevent the deviation. The scope of the safety concerns is in relation to the following major pieces of equipment: process vessels, pumps, membrane distillation units, and heat exchangers. A more extensive list of the safety considerations for each piece of process equipment can be found in HAZOP in Appendix G (tables 5-8).

Identify Hazards

Heat Exchangers

Relevant nodes for the heat exchanger include both the shell and tube sides of the exchanger. These different sides carry the process fluid & enable heat transfer via indirect contact through heat exchanger internal piping. The identified hazards are as follows: process water flow rate, water temperatures, and concentration for both the shell & tube side for both the E-101 and E-102 Heat exchanger units.

Pumps

The pump is found between vessel V-101 and heat exchanger E-101. The relevant nodes analyzed for the pump were process water and the pump motor. The process parameters evaluated include water pressure, water flow rate, motor speed and motor rotation. The water flow rate can deviate from normal system operation by being too high, too low, or not present. Similarly, water pressure can deviate from normal conditions in the same ways. Motor speed can diverge from normal operation by slowing down, and motor rotation can diverge by rotating in the reverse direction.

Vessels

The two vessels in the system are used at the beginning and end of the system. The first tank (V-101) holds the incoming contaminated water while the end distillate tank (V-102) holds pure water. Both tanks have a small volume of 1 m^3 which limits some potential safety hazards. The identified hazards for the tanks are as follows: water flow rate, water corrosivity, and operator errors.

Membrane Distillation Units

There are 68 membrane distillation modules used for water recovery that are central to this system. In order to evaluate hazards associated with these units, water and the membrane are important nodes to consider. The hazards associated with these nodes could result in failure to meet the desired water recovery levels for the system and could result in unexpected financial burdens. Table 7 displays possible parameter deviations and consequences to the nodes described.

Identify Immediate Causes

Heat Exchangers

For the aforementioned hazards, the possible immediate causes were determined and will be discussed below. For process water flow rate, if no flow were to be observed, the potential causes were determined to be: either clogging in piping upstream from the distillation units, broken or non-operational pump, or a controller malfunction that prevented flow from getting to the distillation units. If flow were too low, the potential causes were determined to be a leak in piping upstream, clogging in piping upstream due to potential scaling in the system, or pump malfunction. For flow that is too high, the potential causes were determined to be: a controller or pump malfunction.

For process water temperature, if observed temperature was too high, it was determined to be the cause of: either the temperature of the incoming cooling water is either deviating from the vendor specifications (too hot or too cold)--this mainly would be caused by either a lack or excess of the cooling or heating fluids for the cooler or heat exchanger unit. If the process water temperature was observed to be too low, a similar analysis as the temperature being too high could be made.

For process water concentration, if the observed concentration was too high, it was determined to be caused by either the increased concentration of the incoming cooling tower blowdown water to be treated. Additionally, a controller malfunction could have caused an inappropriate amount of cycles to be run; this would concentrate the volume occupying the membrane distillation units past the critical scaling concentration.

Pumps

There are multiple causes for the nodes relating to pump hazards. Regarding water flow, less flow will be supplied to the system if there is a leak in the piping or pump material. Similarly, lack of flow can be caused by closed valves restricting water movement in the pipes, a severe leak in the system, or no available water in the feed tank. If there is an overflow of feed water or a change in flow setpoint, then water flow through the pump will be increased.

Changes in water pressure are fairly dependent on water flow. A low flow rate or no flow rate will result in pump pressure that is too low. Conversely, water flow that is too high will result in higher water pressure. Low water pressure is also caused by non-water related issues such as electrical failure, motor failure, or gauge and sensor failure. Causes for motor deviations are also related to electrical issues. Motor speed may deviate because of power failure or overheating. Motor speed can deviate because of faulty wiring or shorts.

Vessels

As mentioned previously, the possible hazards—water flow rate, water corrosivity, and operator errors—may have some underlying causes. If the water flow rate abruptly stopped there could be a clog or broken pipe, a valve incorrectly turned to a close or near close position, or a pump malfunctioning. If the flow was to increase and cause an overflow in the tank the cause could be either from a clog outside of the vessel (misplacing the dead space of the system), a clog in the pipe for the flow out of the vessel, or incorrect control of a valve.

The water corrosivity could also pose as a risk to the vessel. This could be caused by natural variation in the water's dissolved solids or from a change in source of process water. An increase in the corrosivity can make the tank brittle over the lifetime of the tank—this brittleness can lead to potential failure and create a leak.

The operator errors pose different risks to the vessel. Being made of polyethylene, mishandling of the tank could cause breakage and leaks. Machinery, like forklifts, could pose the risk of puncturing the tanks because of its material.

Membrane Distillation Units

Hazards regarding the water node for the membrane distillation unit have several identified causes. Hazards attributed to water pressure, such as having too low or too high of pressures could be attributed to pump malfunctions. Extremely low pressures can also be cause by a blocked pipe or pipe fouling over time. In turn, any variation in pressure can be the leading cause for changes in flow – high pressures can induce flow rates that are too high while low pressures can cause too low of flows or no flow. The causes for deviations in water temperature in the system can be attributed to heat exchanger malfunctions resulting in temperatures that are either too high or too low for desired operation. Deviations in concentration can be due to the CTBD feed concentrations being too high at startup. Additionally, concentration conductivity probe malfunction can also be the cause for high concentrations in the system.

Hazards regarding the membrane node for the membrane distillation unit such as membrane wetting or fouling can be linked to a few causes. Membrane wetting can be a consequence of high pressures, which lead to high flow rates through the membrane. Fouling on the membrane can also be a cause for membrane wetting. This membrane fouling can be caused by scalant buildup on the membrane over time. This buildup of scalants results from high concentrations of salts and total dissolved solids flowing through the membrane over time.

Risk Control Systems

Heat Exchangers

Risk-aversion in this process could be implemented in the form of temperature sensors placed on both the heating and cooling process fluids. The appropriate deviation variables would be the exiting temperature of the process water from exchanger unit. For example, if one considers the cooler, the exiting temperature of the CTBD to be purified would be the deviation variable. If the CTBD water's temperature was high low, then the flow rate of the cooling water should increase based on the control system selected (P, PI, or PID).

Pumps

Risk control systems should be implemented to avoid dangers to equipment and system operation. For both water pressure and water flow, high and low alarms can be set to alert operators when these parameters approach potentially hazardous levels. In the case of low pressure or flow, controls or a process to increase flowrate should be included. If there is no flow, broken piping and open valves should be checked for. The flowrate should then be decreased to a safe level. For flowrates that are too low, leaks should be checked for and pump suction head issues should be troubleshot. Suction head issues should also be monitored if there is no water pressure in the pump. In the case of pressures or flows that are too high, a relief or runoff valve should be included in the design.

For the pump motor, a thermocouple can be installed to monitor spikes in temperature that are characteristic of overheating. Motors should also be routinely cleaned to prevent damage that will affect motor performance. For motor rotation, a process should be implemented to check for faulty wiring.

Vessels

Engineering controls are to be implemented in this design to ensure maximum dissolved solids concentration is not exceeded. If the system is operated over the maximum desired concentration, there is high risk for fouling in the membrane. If fouling occurs, membrane efficiency decreases. Additionally, controls are put in place to alert operators if the tank levels are outside of the desired range. This will allow for corrective action to be taken before harm is done to the system by overflowing or running dry. To minimize the risks of physical damage to the vessel's bumpers are put in place around the corners of the vessels in addition to the cage (put in place by the manufacturer) that surrounds the vessels.

Membrane Distillation Units

Several risk control systems have been determined as preventative measures for the hazards analyzed in the membrane distillation unit. Pressure and temperatures must be monitored prior to water entering the membrane distillation unit. Having a control system to keep temperatures and pressures at the desired setpoint values will prevent the potential hazards associated with temperature and pressure deviations. In addition to monitoring and controlling temperature and pressures, it is necessary to monitor water flow rates and concentrations. In order to prevent hazards such as scalant buildup and wetting, flow rates and concentrations must be kept within the desired setpoint and ranges, respectively. Flow rates must be monitored and controlled to remain at 375 L/h through each membrane in order for the system to function optimally. Concentrations must be continuously monitored to ensure that the solubility limit is not exceeded. Exceeding this limit will result in scaling and fouling. Performing preventative maintenance in the form of chemical cleaning will reduce the risk of scaling in the membrane. Lastly, to reduce hazards associated with the membrane performance, it is necessary to replace each membrane after its lifetime of 10 years.

Life Cycle Assessment

Goal and Scope

The goal of this life cycle assessment is to determine the environmental life cycle impact associated with addition of the membrane distillation schematic. More specifically, this assessment compares the CO_2 emissions from a data center before and after the addition of this water filtration process. The scope of this fence to fence analysis includes the small CO_2 emissions due to powering the system—i.e., the single pump P-101—, but the main source of the emissions is resulting from the wastewater treatment of the disposed water.

This study will use data from existing wastewater treatment plants to estimate carbon emissions. Additionally, the quantity of power needed to run the pumps was used to calculate its CO_2 emissions from a "pounds of CO_2 : MWh" ratio provided by the U.S Environmental Protection Agency.

The NetZero water recovery system recovers 80% of CTBD and disposes of the remaining 20% of concentrated water to be treated. NetZero will be recovering 80% of the 14.7 million liters bled from a typical cooling tower each year. The CO_2 emissions associated with the process for this recovery as well as the associated emissions from wastewater treatment of the water waste are assessed.

Life Cycle Inventory

This section outlines the NetZero design's water and energy inputs and its resulting water waste and carbon dioxide emission outputs. To further evaluate the benefits of waste reduction from current data center cooling processes, the amount of CO_2 emissions associated with successive waste water treatment is also assessed. The process's energy requirements were estimated using an EPA CO_2 emission equivalency ratio. The amount of emissions associated with waste water treatment was extrapolated using a carbon footprint analyses of mainstream wastewater treatment.

Life Cycle Impact Assessment

With the NetZero water recovery system in place, the system itself emits 0.06 metric tons of carbon dioxide per day based on a 24-hour process and the wastewater treatment of the CTBD emits around 18.83 metric tons of carbon dioxide per day based on a 24-hour process. The implementation of the recovery system would be a significant reduction from the current emission quantity of 94.13 metric tons per day.

Interpretation

The NetZero water recovery process is significantly less carbon intensive than other carbon emitting activities. The proposed system produces 0.57 kg of CO_2 emitted per kg of water recovered. The water reduction from shifting to the current process previously discussed to NetZero's design also contributes to a significant reduction in CO_2 emissions associated with wastewater treatment. Figure 3 below shows a visual representation of the amount of CO_2 emitted for this proposed CTBD treatment versus other carbon dioxide emitting activities. By and large, the proposed treatment process of CTBD has significant environmental benefits such general water conservation and pollution prevention unlike the current data center cooling process.

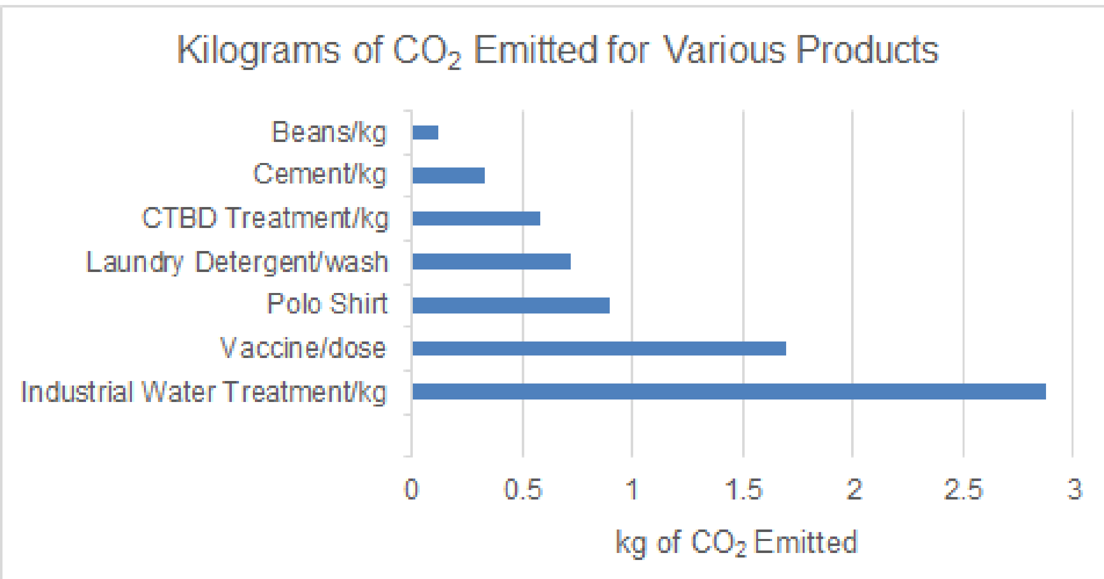


Figure 3: A visual comparison of kg of CO_2 emitted by the production of various products

Economics Analysis and Hazards

The total bare module cost of equipment was calculated using information from Chapter 16 of (Seider et al.) and vendor pricing. As seen in Table 4, the total bare module cost of purchasing equipment is $702,000. The membrane distillation units contributed most to the total price of equipment. Membrane distillation is a relatively new technology and is expected to decrease in price as it becomes more commercially available.

Equipment Description	**F_m**	**F_t**	**F_l**	**F_p**	**C_p**	**F_{bm}**	**C_{bm}**
E-101	-	-	1.25	1.05	$ 6,060	3.17	$ 19,200
E-102	2.14	-	1.25	1.05	$ 6,060	3.17	$ 19,200
E-103 to E-170	-	-	-	-	$ 204,000	3.20	$ 652,000
V-101	1.00	-	-	-	$ 236	-	$ 236
V-102	1.00	-	-	-	$ 236	-	$ 236
P-101	1.00	1.00	-	-	$ 3,410	3.30	$ 11,000
Total Equipment Cost							**$ 702,000**

Table 4: Bare module cost of equipment

The total capital investment was also calculated using the method in Chapters 16 and 17 of (Seider et al.) as seen in Table 5. The total depreciable capital was first found by adding the total bare module cost of equipment and cost of spares for the heat exchangers and pump. The value of total depreciable capital is $884,000, and the value of total capital investment is $1,520,000.

Components of Total Capital Investment (C_{TCI})		
Bare module equipment cost	C_{equip}	$842,000
Bare module cost of spares	C_{spare}	$42,000
Cost of storage	$C_{storage}$	$0
Cost of catalysts	$C_{catalyst}$	$0
Cost of computer setup	C_{comp}	$0
Total bare module investment, TBM	C_{TBM}	$884,000
Cost of site preparation	C_{site}	$0
Cost of service facilities	C_{serv}	$0
Allocated cost for utility plants and related facilities	C_{alloc}	$0
Total direct permanent investment, DPI	C_{DPI}	$884,000
Cost of contingencies and contractors' fees	C_{cont}	$0
Total depreciable capital, TDC	C_{TDC}	$884,000
Fraction of TDC over three years	fC_{TDC}	$295,000
Cost of land	C_{land}	$0
Cost of royalties	C_{royal}	$0
Cost of system/plant startup	$C_{startup}$	$0
Total permanent investment, TPI	C_{TPI}	$1,330,000
Working capital	C_{wc}	$199,000
Total capital investment, TCI	$\mathbf{C_{TCI}}$	**$1,520,000**

Table 5: Components of Total Capital Investment

As shown in Table 6, a cash flow analysis was completed using the template provided in Chapter 17 of (Seider et al.). The cash flow was analyzed for a period of 20 years because that is the lifetime of membrane distillation units. At year 10 and year 20, the replacement cost of MD membranes was included in $C_{excl\ dep}$ because the membranes fully foul after 10 years and need replacing. Instead of sales revenue, the saved cost per year of process water, water treatment and water pretreatment were used for the analysis. This amount was found to be $22,000 per year. Depreciation was modeled using a straight-line approach. As seen in Table 6, the system does not break even over the 20-year lifetime using the traditional cash flow approach. For the system to break even, an additional cost of $532,000 must be provided each year. This would most likely be provided by the customer in the form of fees.

Year	fC_{TDC}	C_{wc}	D (straight line)	$C_{excl\ dep}$	S (Saved cost)	Net earn	C (Cash flow)	Cum PV (20%)
0	($295,000)			$0	$21,600	$0	($295,000)	($295,000)
1	($295,000)			$0	$21,600	$0	($295,000)	($540,000)
2	($295,000)	($199,000)		$0	$21,600	$0	($493,000)	($883,000)
3			$14,800	$109,000	$21,600	($64,300)	($49,500)	($911,000)
4			$14,800	$109,000	$21,600	($64,300)	($49,500)	($935,000)
5			$14,800	$109,000	$21,600	($64,300)	($49,500)	($955,000)
6			$14,800	$109,000	$21,600	($64,300)	($49,500)	($972,000)
7			$14,800	$109,000	$21,600	($64,300)	($49,500)	($986,000)
8			$14,800	$109,000	$21,600	($64,300)	($49,500)	($997,000)
9			$14,800	$109,000	$21,600	($64,300)	($49,500)	($1,010,000)
10			$14,800	$761,000	$21,600	($475,000)	($460,000)	($1,080,000)
11			$14,800	$109,000	$21,600	($64,300)	($49,500)	($1,090,000)
12			$14,800	$109,000	$21,600	($64,300)	($49,500)	($1,090,000)
13			$14,800	$109,000	$21,600	($64,300)	($49,500)	($1,100,000)
14			$14,800	$109,000	$21,600	($64,300)	($49,500)	($1,100,000)
15			$14,800	$109,000	$21,600	($64,300)	($49,500)	($1,100,000)
16			$14,800	$109,000	$21,600	($64,300)	($49,500)	($1,110,000)
17			$14,800	$109,000	$21,600	($64,300)	($49,500)	($1,110,000)
18			$14,800	$109,000	$21,600	($64,300)	($49,500)	($1,110,000)
19			$14,800	$109,000	$21,600	($64,300)	($49,500)	($1,110,000)
20		$199,000	$14,800	$761,000	$21,600	($475,000)	($261,000)	($1,120,000)

Table 6: Cumulative present value cash flow analysis

A more appropriate method to assess the system's profitability is by analyzing the levelized cost of water (LCOW). This is defined as the total lifetime cost divided by the total lifetime clean water generation, or the cost per cubic meter of clean water produced. The target LCOW for this system is $1.50/m^3 of permeate water ("Solar Desalination", 2017). The calculated LCOW for the design was $4.74/m^3, which is three times higher than the target. Therefore, the system is not economically sustainable with current prices.

A sensitivity analysis was also completed for LCOW. As water becomes scarcer, the price of clean water and water treatment are expected to increase in the future. Figure 4 shows LCOW for percent increases in the price of process water, water treatment, and water pretreatment. Analysis of these trends shows that LCOW is the most sensitive to the price of water treatment. However, the lowest value of LCOW calculated was still significantly higher than the target.

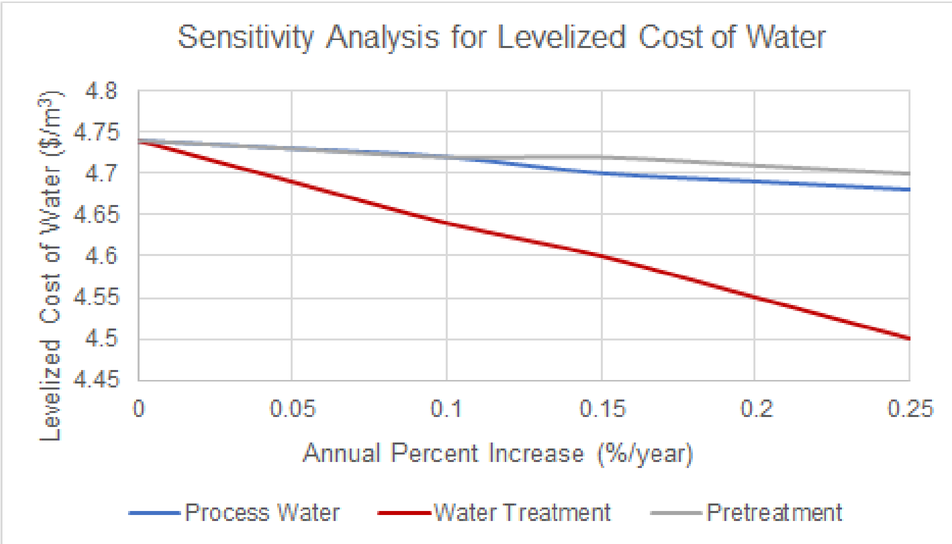


Figure 4: Comparison of changes in LCOW for process water, water treatment, and water pretreatment

There are multiple economic hazards associated with this system design. The most prevalent hazard is the need to provide an additional amount of money from the customer for the system to break even after 20 years. The monetary savings from purchasing less water and chemical treatment alone do not offset the cost of the system. As seen in Table 6, the net present value remains negative after 20 years without an additional sum of money to offset operational costs. This was also the case for net present value. If this monetary sum could not be provided, the system would begin to lose money each year.

The above sensitivity analysis shows that an increase in the cost to purchase industrial water, wastewater treatment and pretreatment would decrease the LCOW. However, this analysis was only conducted up to an increase of 25%. If these costs were to increase more than 25%, the total cost of the system would decrease and become more economical. Similarly, changes in equipment price can influence the profitability of the system. As stated above, the price of membrane distillation technology is expected to decrease in the next 20 years. The cash flow analysis for this design used current market prices for the MD units as an overestimate. If this were to decrease, the expected cost at years 10 and 20 would also decrease.

Another major economic hazard is the availability of LGH. The current cost of industrial electricity is 4.67 ¢/kWh ("Electric Power Monthly," 2019). For this design, the saved cost of electricity is $125,000 per year when using LGH for the heater. If no free LGH is available near the data center, the cost of operating the system would increase dramatically.

Conclusions and Recommendations

The purpose of this design is to demonstrate a solution for net-zero energy water use in data centers. In order to achieve this, the potential of membrane distillation coupled with the use of low-grade heat from data centers was evaluated for the treatment of CTBD. This CTBD reclamation design is comprised of a modular system of 68 membrane distillation units in parallel. This system treats CTBD for make-up and re-use reducing demands on local freshwater resources. The implementation of this system will reclaim 80% of the typical amount of CTBD that would be flushed each year. The basis for this design is for a 500-ton cooling tower that would flush 17.8 million liters of water each year. The cost of implementing this design is $842,000 with a yearly operating cost of $125,000. With the rapidly increasing demand in the data center industry worldwide, the implementation of this design will diminish environmental burdens that result from current data center cooling methods using cooling towers.

In order to further improve the proposed system, a renewable energy source could be implemented to reduce costs required for utilities. Depending on the site location, river water could be utilized in replacement for the cooling process water in heat exchanger E-101 in order to further reduce costs. For the system to result in net-zero water use, a crystallizer could be utilized to save the remaining water from the currently discarded concentrated stream.

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Nomenclature

Common Acronyms Used in Report		
#	**Acronym**	**Description**
1	MD	Membrane Distillation
2	AGMD	Air-gap Membrane Distillation
3	PRO	Pressure Retarded Osmosis
4	CTBD	Cooling Tower (Water) Blowdown
5	LCA	Life Cycle Analysis
6	ROI	Return on Investment
7	GPM	Gallons/min
8	GPD	Gallons/day
9	TDS	Total Dissolved Solids
10	PBP	Payback Period
11	P	Proportional Control
12	PI	Proportional Integral Control
13	PID	Proportional Integral Derivative Control
14	MWh	Megawatt hour
15	NPSHa	Net Positive Suction Head Absolute
16	LCOW	Levelized Cost of Water
17	DC	Data Center

Table 1: Common Acronyms Used in the Report

Calculations Nomenclature & Variables		
#	**Variable**	**Description**
1	Cp	Heat Capacity of a given fluid or solid
2	Vt	Volume of the V-101 holding tank
3	C1	Starting concentration of a new batch of pure CTBD
4	C2	Concentration after 80% of a 1000L batch is depleted
5	C_{new}	New starting concentration after diluting the remaining 20% of 1000L from a previous batch
6	Amd	Cross sectional area of the membrane distillation unit
7	Lmd	Length of the membrane distillation unit
8	Rmd	Radius of the membrane distillation unit
9	F	Mass flow rate
10	Q_{CTBD}	Daily target amount of CTBD needed to meet 80% annual recovery
11	Q_{md}	Flux of a single MD unit at 5.35% recovery per pass (20.1L/h) this data was available from the vendor Aquastill

Table 2: Nomenclature for Variables Used in Calculations

Appendices

Appendix A: Final Calculations

#	Equation	Description
1	C2 = C1*(Vt+Vd)/((Vt+Vd) - 0.8*Vt)	This equation calculates the concentration after 80% recovery of a $1m^3$ batch of CTBD
2	C_new = C2*((Vd+0.2*Vt)+0.8*C1*V2)/(Vt+Vd)	This calculates the new concentration after diluting the remaining 20% ($0.2m^3$) from a previous batch to ($1m^3$)
3	Vd = (3.14*Lmd*(1/3)*Amd)	This calculates the dead volume of a membrane distillation units. The (1/3) factor represents the actual volume of water in this system. (2/3) of the volume of a membrane distillation unit is occupied by spacers, lining, and the membrane itself.
4	$Amd = PI*(Rmd)^2$	This calculates the area of the membrane distillation unit.
5	F2 = F1	Mass balance for CTBW around E-101 Exchanger
6	F3 = F2	Mass balance for CTBD around P-101
7	F9+F14+F18+…+F344 = F3	Mass balance for the cold-water split (or feed to the membrane distillation units)
8	F4 = F10+F15+F20+…F345	Mass balance for the combining of the concentrate streams from the membrane distillation units
9	F5 = F4	Mass balance around the E-102 Heat Exchanger
10	F11+F16+F20+…+F346 = F5	Mass balance for the hot-water split (for feed to the membrane distillation units)
11	F6 = F12+F7+F22+…+F347	Mass balance for the combining of the hot-side concentrate
12	F7 = F13+F18+F23+…+348	Mass balance for the combining of the distillate screams from the membrane distillation units
13	Q_CTBD [L/day] = 0.8*V_CTBD/365	Target recovery of CTBD water required to meet 80% of annual waste this served as the basis of our design
14	N_md = Q_CTBD/Q_md	This calculates the number of membrane distillation units

Table 3: Relevant Calculations Used in System Sizing and Optimization

Appendix B: Other Spreadsheets

Batch Run Number	Starting Concentration of DS (kg/L)	New Concentration (kg/L)
0	0.00278	0.00330
1	0.00322	0.00383
2	0.00366	0.00435
3	0.00410	0.00488
4	0.00454	0.00540
5	0.00498	0.00593
6	0.00543	0.00645
7	0.00587	0.00698
8	0.00631	0.00750
9	0.00675	0.00803
10	0.00719	0.00855
11	0.00763	0.00908
12	0.00808	0.00960
13	0.00852	0.01013
14	0.00896	0.01065
15	0.00940	0.01118
16	**0.00984**	**0.01170**
17	0.01028	0.01223
18	0.01072	0.01275
19	0.01117	0.01328
20	0.01161	0.01380

Table 4: Critical Concentration Table for Successive Batches

Appendix C: Overall Mass and Energy Balances

Stream Number	1	2	3	4	5	7	8
Temperature (℃)	28	20.00	20.00	69.70	80.00	28.50	50.00
Pressure (atm)	1.00	1.00	2.35	2.35	2.15	2.35	1.00
Volumetric Flow (L/h)	25500.00	25500.00	25500.00	25500.00	25500.00	24133.20	1366.80
Mass Flow (kg/h)	25570.82	25570.82	25570.82	25570.82	25570.82	24204.02	1366.80
Concentration (kg/L, H20)	0.0028	0.0028	0.0028	0.0028	0.0028	0.0029	0.0000
Component Molar Flow (kg/h):							
Water (kg/h)	25500.00	25500.00	25500.00	25500.00	25500.00	24133.20	1366.80
TOC (kg/h)	1.35	1.35	1.35	1.35	1.35	1.35	0.00
Total dissolved solids: (kg/h)	69.47	69.47	69.47	69.47	69.47	69.47	0.00
Cl- (mg/L)	549.00	549.00	549.00	549.00	549.00	549.00	549.00
NO3- (mg/L)	88.00	88.00	88.00	88.00	88.00	88.00	88.00
HCO3- (mg/L)	65.00	65.00	65.00	65.00	65.00	65.00	65.00
SO24F- (mg/L)	1109.00	1109.00	1109.00	1109.00	1109.00	1109.00	1109.00
Na+ (mg/L)	332.00	332.00	332.00	332.00	332.00	332.00	332.00
Ca2+ (mg/L)	437.00	437.00	437.00	437.00	437.00	437.00	437.00
Mg2+ (mg/L)	61.00	61.00	61.00	61.00	61.00	61.00	61.00
K+ (mg/L)	81.00	81.00	81.00	81.00	81.00	81.00	81.00
Dissolved Fe (mg/L)	0.20	0.20	0.20	0.20	0.20	0.20	0.20
P (mg/L)	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Chrolophyll A (mg/L)	0.20	0.20	0.20	0.20	0.20	0.20	0.20

Table 9: Overall Mass & Energy Balances Table

Appendix D: Aspen Output

#											
1	Size 13.25 X 66.625	in	Type BEM	Hor			Connected in		1 parallel	2 series	
2	Surf/Unit (gross/eff/finned)		311.8	/ 297.7	/	ft^2	Shells/unit	2			
3	Surf/Shell (gross/eff/finned)		155.9	/ 148.9	/	ft^2					
4	Design (Sizing)			PERFORMANCE OF ONE UNIT							
5			Shell Side		Tube Side		Heat Transfer Parameters				
6	Process Data		In	Out	In	Out	Total heat load	BTU/h		1067448	
7	Total flow	kg/h	25571		21575		Eff. MTD/ 1 pass MTD	°F	16.55	/	16.55
8	Vapor	kg/h	0	0	0	0	Actual/Reqd area ratio - fouled/clean		1.01	/	1.01
9	Liquid	kg/h	25571	25571	21575	21575					
10	Noncondensable	kg/h	0		0		Coef./Resist.	BTU/(h-ft^2-F)	ft^2-h-F/BTU		%
11	Cond./Evap.	kg/h	0		0		Overall fouled	218.9	0.0046		
12	Temperature	°C	69.7	79.63	90	77.8	Overall clean	218.9	0.0046		
13	Dew / Bubble point	°F					Tube side film	317.7	0.0031		68.9
14	Quality		0	0	0	0	Tube side fouling		0		0
15	Pressure (abs)	psi	14.7	14.04	14.7	14.38	Tube wall	3750.22	0.0003		5.84
16	DeltaP allow/cal	psi	3	0.66	1.6	0.32	Outside fouling		0		0
17	Velocity	ft/s	1.02	1.03	0.82	0.82	Outside film	866.6	0.0012		25.26
18	Liquid Properties						Shell Side Pressure Drop		psi		%
19	Density	lb/ft^3	61.03	60.657	60.234	60.728	Inlet nozzle		0.13		19.19
20	Viscosity	cp	0.4021	0.3527	0.3113	0.3609	InletspaceXflow		0.07		9.99
21	Specific heat	BTU/(lb-F)	1.037	1.0405	1.045	1.0398	Baffle Xflow		0.07		11.18
22	Therm. cond.	BTU/(ft-h-F)	0.383	0.387	0.391	0.387	Baffle window		0.05		8.16
23	Surface tension	lbf/ft					OutletspaceXflow		0.07		9.92
24	Molecular weight		18.02	18.02	18.02	18.02	Outlet nozzle		0.06		8.85
25	Vapor Properties						Intermediate nozzles		0.22		32.71
26	Density	lb/ft^3					Tube Side Pressure Drop		psi		%
27	Viscosity	cp					Inlet nozzle		0.04		12.74
28	Specific heat	BTU/(lb-F)					Entering tubes		0		1.35
29	Therm. cond.	BTU/(ft-h-F)					Inside tubes		0.03		9.86
30	Molecular weight						Exiting tubes		0.01		2.09
31	Two-Phase Properties						Outlet nozzle		0.06		17.61
32	Latent heat	BTU/lb					Intermediate nozzles		0.18		56.35

#									
33	Heat Transfer Parameters					Velocity / Rho*V2	ft/s		lb/(ft-s^2)
34	Reynolds No. vapor					Shell nozzle inlet	3.74		852
35	Reynolds No. liquid	14385.02	16400.26	11555.13	9966.5	Shell bundle Xflow	1.02	1.03	
36	Prandtl No. vapor					Shell baffle window	1.36	1.37	
37	Prandtl No. liquid	2.63	2.29	2.01	2.35	Shell nozzle outlet	2.92		517
38	Heat Load	BTU/h		BTU/h		Shell nozzle interm	3.75		855
39	Vapor only	0		0			ft/s		lb/(ft-s^2)
40	2-Phase vapor	0		0		Tube nozzle inlet	2.48		371
41	Latent heat	0		0		Tubes	0.82	0.82	
42	2-Phase liquid	0		0		Tube nozzle outlet	4.24		1091
43	Liquid only	1045971		-1088924		Tube nozzle interm	4.25		1095

#											
44	Tubes				Baffles			Nozzles: (No./OD)			
45	Type			Plain	Type	Single segmental				Shell Side	Tube Side
46	ID/OD	in	0.584	/ 0.75	Number		4	Inlet	in	1 / 4	1 / 4.5
47	Length act/eff	ft	5.5521	/ 5.3021	Cut(%d)	37.74		Outlet		1 / 4.5	1 / 3.5
48	Tube passes		1		Cut orientation		H	Intermediate		1 / 4	1 / 3.5
49	Tube No.		143		Spacing: c/c	in	13.25	Impingement protection		None	
50	Tube pattern		30		Spacing at inlet	in	11.9375				
51	Tube pitch	in	0.9375		Spacing at outlet	in	11.9375				
52	Insert			None							
53	Vibration problem		No	/ No				RhoV2 violation			No

Figure 1: Heater Simulations Results

#											
1	Size	13.25 X 66.625	in	Type	BEM	Hor	Connected in	1 parallel	2 series		
2	Surf/Unit (gross/eff/finned)		296.5	/ 283.2	/	ft²	Shells/unit	2			
3	Surf/Shell (gross/eff/finned)		148.3	/ 141.6	/	ft²					
4	Design (Sizing)			PERFORMANCE OF ONE UNIT							
5			Shell Side		Tube Side		Heat Transfer Parameters				
6	**Process Data**		In	Out	In	Out	Total heat load	BTU/h		831188	
7	Total flow	kg/h	15000		25571		Eff. MTD/ 1 pass MTD	°F	11.46	/	12.69
8	Vapor	kg/h	0	0	0	0	Actual/Reqd area ratio - fouled/clean		1.01	/	1.01
9	Liquid	kg/h	15000	15000	25571	25571					
10	Noncondensable	kg/h	0		0		**Coef./Resist.**	BTU/(h-ft²-F)	ft²-h-F/BTU	%	
11	Cond./Evap.	kg/h	0		0		Overall fouled	258.4	0.0039		
12	Temperature	°C	10	23.25	28	20	Overall clean	258.4	0.0039		
13	Dew / Bubble point	°F					Tube side film	487.03	0.0021	53.06	
14	Quality		0	0	0	0	Tube side fouling		0	0	
15	Pressure (abs)	psi	14.7	13.35	14.7	13.98	Tube wall	3835.13	0.0003	6.74	
16	DeltaP allow/cal	psi	3	1.35	1.6	0.72	Outside fouling		0	0	
17	Velocity	ft/s	2.11	2.13	1.97	1.96	Outside film	642.7	0.0016	40.21	
18	**Liquid Properties**						**Shell Side Pressure Drop**		psi	%	
19	Density	lb/ft³	63.225	62.738	62.696	63.013	Inlet nozzle		0.11	8.26	
20	Viscosity	cp	0.9009	0.7532	0.6711	0.7415	InletspaceXflow		0.07	5.39	
21	Specific heat	BTU/(lb-F)	1.018	1.0222	1.0196	1.0163	Baffle Xflow		0.62	45.76	
22	Therm. cond.	BTU/(ft-h-F)	0.354	0.361	0.366	0.363	Baffle window		0.21	15.3	
23	Surface tension	lbf/ft					OutletspaceXflow		0.07	5.35	
24	Molecular weight		18.02	18.02	18.02	18.02	Outlet nozzle		0.08	5.83	
25	**Vapor Properties**						Intermediate nozzles		0.19	14.11	
26	Density	lb/ft³					**Tube Side Pressure Drop**		psi	%	
27	Viscosity	cp					Inlet nozzle		0.05	7.21	
28	Specific heat	BTU/(lb-F)					Entering tubes		0.05	7.29	
29	Therm. cond.	BTU/(ft-h-F)					Inside tubes		0.36	49.82	
30	Molecular weight						Exiting tubes		0.08	11.28	
31	**Two-Phase Properties**						Outlet nozzle		0.04	6.08	
32	Latent heat	BTU/lb					Intermediate nozzles		0.13	18.32	

#									
33	**Heat Transfer Parameters**					**Velocity / Rho*V2**	ft/s		lb/(ft-s²)
34	Reynolds No. vapor					Shell nozzle inlet	2.83		506
35	Reynolds No. liquid	13801.56	16508.55	13359.28	12092	Shell bundle Xflow	2.11	2.13	
36	Prandtl No. vapor					Shell baffle window	1.17	1.18	
37	Prandtl No. liquid	6.26	5.16	4.52	5.03	Shell nozzle outlet	2.85		510
38	**Heat Load**	BTU/h		BTU/h		Shell nozzle interm	2.84		509
39	Vapor only	0		0			ft/s		lb/(ft-s²)
40	2-Phase vapor	0		0		Tube nozzle inlet	2.83		500
41	Latent heat	0		0		Tubes	1.97	1.96	
42	2-Phase liquid	0		0		Tube nozzle outlet	3.62		826
43	Liquid only	818208		-844168		Tube nozzle interm	3.63		828

#	**Tubes**			**Baffles**			**Nozzles: (No./OD)**			
45	Type		Plain	Type		Single segmental			**Shell Side**	**Tube Side**
46	ID/OD	in	0.584 / 0.75	Number		14	Inlet	in	1 / 3.5	1 / 4.5
47	Length act/eff	ft	5.5521 / 5.3021	Cut(%d)		26.43	Outlet		1 / 3.5	1 / 4
48	Tube passes		2	Cut orientation		H	Intermediate		1 / 3.5	1 / 4
49	Tube No.		136	Spacing: c/c	in	3.75	Impingement protection		None	
50	Tube pattern		30	Spacing at inlet	in	7.4375				
51	Tube pitch	in	0.9375	Spacing at outlet	in	7.4375				
52	Insert		None							
53	Vibration problem		No / No				RhoV2 violation			No

Figure 2: Cooler Simulation Results

Appendix E: Information from Vendor Sites

Item	Heat Exchanger
Type	Shell & Tube
Max. BtuH (Water to Water Application)	3,450,000
Max. BtuH (Oil to Water Application)	631,000
Pressure	Shell 300 psig, Tube 150 psig
Temp. (F,C)	300, ~149
Construction Material	Brass
Connection	Shell 3’’ NPT, Tube 2’’ NPT
Capacity (GPM,L/h)	Shell 140, 32,000; Tube 105, 24,000
Height (in)	11
Length (in)	66.625
Width (in)	10.5
Weight (lbs)	255

Table 10: Heat Exchanger Technical Specifications

Item	Centrifugal Pump
Item - Straight Centrifugal Pumps	Straight Centrifugal High Flow Pump
HP - Pumps	3
Voltage - Pumps	120/208 to 240VAC
Phase - Pumps	1
Housing Material - Pumps	Cast Iron
Inlet Size - Pumps	3’’ NPT
Outlet Size - Pumps	2-½” NPT
Max. Pressure - Pumps	27 psi
Max. Head	61 ft
Best Efficiency Range: GPM @ Head	110 to 170 gpm @ 60 to 50ft.
Amps	29/15-14.5
Impeller Type	Closed
Impeller Material	Bronze
Seal Material	Buna-N Elastomers, Carbon/Ceramic Face, 316 Stainless Steel Metal Parts
Length	20-¾”
Width	12-13/16”
Height	10-½”
Motor RPM	3500
Hz	60
Motor Type	JM
Wetted Materials	Cast Iron, Bronze, Carbon, Ceramic, Stainless Steel
Max. Liquid Temp.	212 F with Standard Seal, 250 F with High Temperature Seal
GPM @ 50 Ft. of Head	170
GPM @ 60 Ft. of Head	98

Max. Specific Gravity	1.0
Max. Case Pressure	175 psi
Inlet Pressure	100 psi
Max. Dia. Solids	7/16''
Duty	Continuous
Fram	182JM
Port Rotation	90 Increments
Max. GPM @ Head	180 @ 45 ft.
Best Efficiency - GPM @ Head	130 @ 55 ft.
Min. GPM @ Head	77 @ 55 ft.

Table 11: Pump Specifications

Pump Property	Value
Target Flow (L/h - GPM)	25,500 - 113
Target Flow (L/h - GPM) + 20%	30,600 - 134.7
Target Flow (L/h - GPM) - 20%	20,400 - 89.8
Impeller Size Required	5-15/16"
Hp Required	5
Efficiency	72.2%
$NPSH_R$ (ft)	8

Table 12: Optimized Pump Sizing Table

Vessel Sizing

Item	Chemical IBD Tote ($1m^3$)
Part Number	IBC-BTL003
Specific Gravity Rating	1.5 (Tank Holds 12.5 Lbs. Per Gallon)
Capacity	330 Gallons
Size	40"L x 48"W x 54''H
Weight	195 lbs.

Table 13: Vessel Sizing Information for V-101 and V-102

Appendix F: Meeting Minute Logs

See D2L Dropbox.

Appendix G: Figures and Diagrams

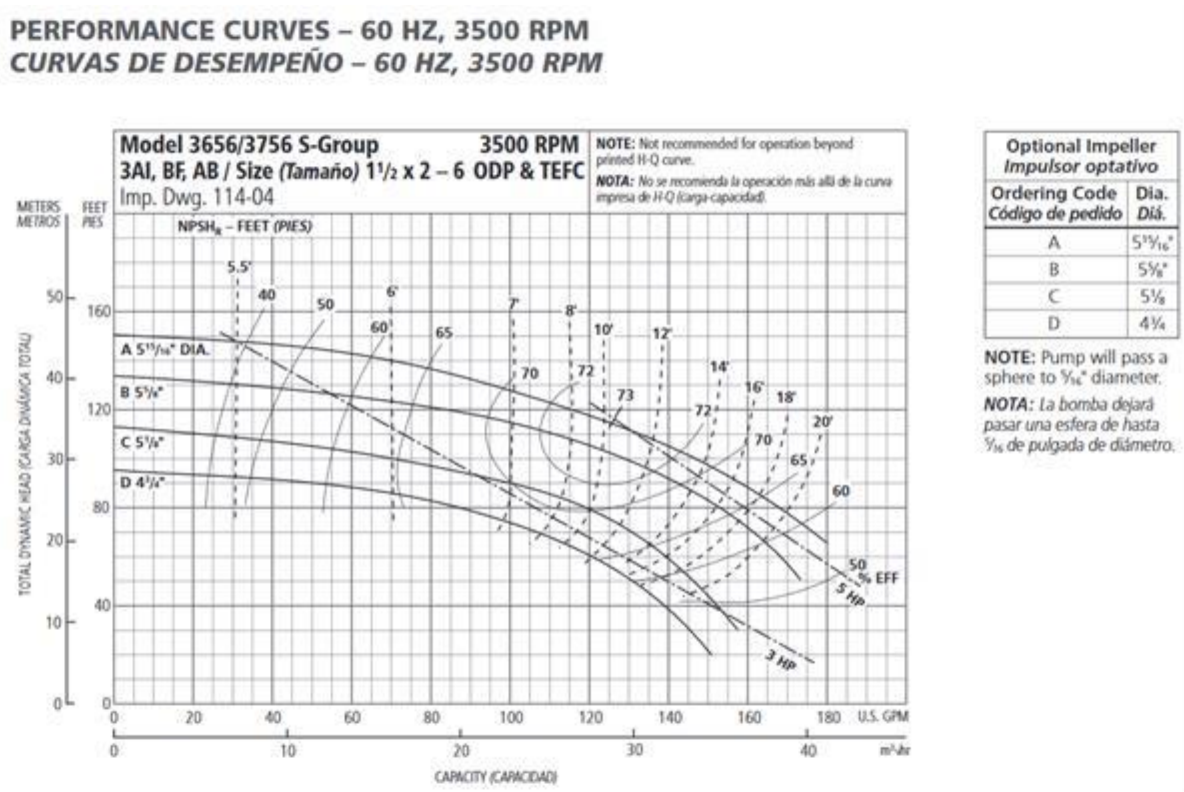

Figure 3: Pump Curve for 3500 RPM Model 3656/3756 S-Group

Study Node	Process Parameters	Deviations (Guide Words)	Possible Causes	Possible Consequences Include info on process immediately downstream	Action Required
Process Water Node	Flow	None	Upstream Clog in Pipe Broken Pump Controller Malfunction	Having no process water would mean the filtering system was no longer functioning and would thus mean that the target filtered goal would not be reached.	Monitor flow rates of distillate for fluctuation. Clean / replace pipe or reprogram controller.
		Too Low	Pump Malfunction Controller Malfunction Pipe Leak	Low flow would deviate from the optimal conditions of the MD units and thus less distillate flow.	Monitor flow rates of distillate for fluctuation. Fix leak, increase pump power, or reprogram controller.
		Too High	Pump Malfunction Controller Malfunction	High flow rates would increase the pressure on the MD units, possibly causing wetting and a decrease in distillate flux.	Monitor flow rates of distillate for fluctuation. Decrease pump power or reprogram controller.
	Temperature	Too High	Cooling Tower Blowdown is unusually hot Upstream Cooling Heat	Water going into MD units would not be set to correct temperature, could disturb membranes	Add thermocouple or thermometer to process water inlet feed

			Exchanger Malfunction		Monitor flow rates of distillate for fluctuation. Decrease temperature of cooling water in upstream heat exchanger
		Too Low	MD Units Malfunction Upstream Cooling Heat Exchanger Malfunction	Water going into MD units would not be set to correct temperature, could disturb membranes	Add thermocouple or thermometer to process water inlet feed Monitor flow rates of distillate for fluctuation. Decrease cooling done in heat exchanger by increasing utility cooling water temperature
	Concentration	Too High	Blowdown water has unusually high concentrations of dissolved solids Controller malfunction causes too many batches	Scaling of the tubes may occur which would decrease the efficacy of the heat exchanger and thus reduce the distillate flow rate in MD units.	Flush heat exchanger with chemicals to descale and clean heat exchange surfaces.

			to be run before system flush		
Low Grade Heat Water Node	Flow	Too High	Pump Malfunction Controller Malfunction	Wasting “utilities” and could then run dry of low grade heat water which would cause MD system to cease production.	Monitor flow rates into the heat exchanger. Reprogram controller
		Too Low	Pump Malfunction Pipe Leak Low Availability at Data Center Controller Malfunction	Not having enough of the hot water would fail to get the process water to the correct high temperature, thus decreasing the flux of the distillate.	Monitor flow rates into heat exchanger for fluctuation. Fix leak, increase pump power, or reprogram controller.
		None	Pump Broken Pipe Broken Controller Malfunction	Process water would not be heated and MD units would not work properly, thus creating no distillate.	Monitor flow rates of inlet streams to heat exchanger for fluctuation. Clean / replace pipe or reprogram controller.
	Temperature	Too Low	Data center releases lower heat duty	The process water would not heat to a high enough temperature for the system to run at its full potential.	Additional utilities would need to be added to increase temperature.
		Too High	Data center releases	The process water would	Decrease the fluids flow

			higher heat duty	be too hot which could increase the pressure in the MD units and cause wetting or a decrease in distillate flux.	rate to decrease the heat transfer.
	Concentration	Too High	Controller malfunction causing delay in blow down water release, thus creating increase in concentration Disturbance in source water for data center higher in dissolved solids	Scaling of the tubes may occur which would decrease the efficacy of the heat exchanger and thus reduce the distillate flow rate in MD units.	Flush heat exchanger with chemicals to descale and clean heat exchange surfaces.

Table 5: HAZOP Study for the E-102 Heat Exchanger

Study Node	**Process Parameters**	**Deviations (Guide Words)**	**Possible Causes**	**Possible Consequences Include info on process immediately downstream**	**Action Required**
Shell Side (Process)	Process Water Flow Rate	Too Low	Pump not providing necessary flow Foulants or scaling causing pressure drop	Not enough circulating flow through MD Units Lowered % recovery from not meeting operating specifications	Investigate pump power, operating settings, pressure head in system
		Too High	Pump run-settings improperly configured		

	Water Temperature	Too High	Not effective heat transfer within membrane distillation unit (from concentrate) Not effective cooling of process water from cooler to MD Unit	Reduced cold side approach; less driving force for mass transfer	Investigate fouling within membrane systems
	Concentration	Too High	Concentrating of system from running in batch mode Controller malfunction	Fouling in membrane; reduction of mass transfer	Tune controller
Tube Side (Cooling utility water with minimal scalants)	Cooling Water Flow Rate	Too low	High utility demand upstream Pump not appropriately sized	Increased temperature for entry (cold-side) water into Membrane Unit; reduced driving for mass transfer	Tune controller for flow rate to ensure proper heat transfer between fluids
					Page 2 of 2
	Water Temperature	Too low	Non-effective insulation Upstream temperature issues	Entry temperature drops low; may alter MD purification efficiency.	Ensure upstream temperature controls are working Tune controller for water temperature upstream
		Too High	Upstream temperature issues	Increased temperature for cold side entry.	

				Mass transfer reduced due to lower temperature difference on cold-side approach	

Table 6: HAZOP Study for the E-101 Heat Exchanger

Study Node	**Process Parameters**	**Deviations (Guide Words)**	**Possible Causes**	**Possible Consequences Include info on process immediately downstream**	**Action Required**
Water	Pressure	Too Low	Pump Malfunction Blocked Pipe Fouling	Having too low of pressure would deviate from desired conditions and would thus produce less distillate than desired	Monitor and control pressure Set controls for pressure at inlets of MD unit to ensure proper pressure is maintained.
		Too High	Pump Malfunction	Too high of pressures could result in wetting of the membranes in the unit which would result in the inability to filter water and would lead to membrane replacement.	Monitor and control pressure Set controls for pressure at inlets of MD unit to ensure proper pressure is maintained.
	Temperature	Too Low	Heat Exchanger Malfunction	Having flow too low in temperature in the hot stream of the MD unit	Monitor and control temperature by incorporating

				could inhibit the heat transfer necessary to produce distillate in the MD unit	thermocouples at the water inlet streams
		Too High	Heat Exchanger Malfunction	Having flow too high in temperature in the cold stream would eliminate the temperature gradient needed to drive the MD unit to produce the desired distillate	Monitor and control temperature by incorporating thermocouples at the water inlet streams
	Concentration	Too High	Concentration Conductivity Probe Malfunction CTWB Feed Concentration is Above Desired Setpoint	Having a flow of highly concentrated water would result in fouling that would lead to decreased efficiency of the MD system	Monitor and control starting inlet concentration to modify number of batches needed to reach the solubility limit
	Flow	Too Low	Low Pressure Fouling	Having flow rates that are too low would deviate from optimal conditions and would lead to less distillate flow.	Monitor and control flow rates and pressure into the MD units.
		Too High	High Pressure	Flow rates that are too high could result in wetting of the membranes in	Monitor and control flow rates and pressure into the MD units.

				the unit which would result in the inability to filter water. Membrane replacement would be needed.	
		No Flow	Low Pressure Blocked Pipe	Having no flow would cease the filtration process.	Monitor and control flow rates. Replace broken valves/pumps. Re-adjust control system.
Membrane	Pores	Wetting	High Pressure/ High Flow Rate Fouling	Wetting of pores in the MD unit will result in decreased flux through the distillation unit and would produce less distillate than desired	Monitor and control flow rates and pressures into the MD units. Chemical cleaning of membranes to prevent wetting from fouling.
		Fouling	Scalant Buildup	Fouling in the MD unit can result in wetting. Fouling would result in decreased flux through the membrane and would reduce the unit's efficiency. Fouling also has the potential to inhibit heat transfer	Chemical Cleaning Preventative Maintenance Replacement of Membrane After Lifetime (10 years)

				through the membrane.	

Table 7: HAZOP Study for Membrane Distillation Units V-103 – V-170

Study Node	**Process Parameters**	**Deviations (Guide Words)**	Possible Causes	Possible Consequences Include info on process immediately downstream	Action Required
Water	Pressure	Too low	Low flow rate Electrical failure Motor failure Gauge/sensor failure	Pump cavitation Inability to provide enough flow to run MD system	Increase flowrate Set low alarm for pressure
		Too high	High flow rate	Damage to pump Pump vibration	Include or install a relief valve Set high alarm for pressure
		None	No flow	Inability to run system (no purification of water)	Check for pump suction head issues
	Flow	Too low	Water leakage	Inability to run MD system (Same as low pressure)	Check for leaks Increase flowrate Troubleshoot pump for suction head issues
		Too high	Overflow of feed water Change in flow setpoint	Overflow of distillate tank Flooding of MD units	Set high alarm Include relief or runoff valve Decrease flowrate
		None	Severe leakage Valve failure	Inability to run system	Check for broken piping Check that

					valves are open Troubleshoot or replace controls
Motor	Speed	Too low	Power failure Overheating	Not enough flow or head	Install thermocouple to monitor spikes in temperature Routinely clean motors
	Rotation	Opposite direction	Faulty wiring	Pump failure	Check wiring and rewire if necessary

Table 8: HAZOP Study for Pump P-101