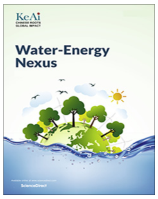
Water-Energy Nexus 3 (2020) 117–134

Contents lists available at ScienceDirect

Water-Energy Nexus

journal homepage: www.keaipublishing.com/en/journals/water-energy-nexus/



An optimization for water requirement in natural gas combined cycle power plants equipped with once-through and hybrid cooling systems and carbon capture unit

Saif W. Mohammed Ali [a,c], Nasser Vahedi [a], Carlos Romero [a], Alparslan Oztekin [b,*]

[a] Energy Research Center (ERC), Lehigh University, Bethlehem, PA, USA
[b] Department of Mechanical Engineering and Mechanics, Lehigh University, Bethlehem, PA, USA
[c] Mechanical Department, Collage of Engineering, Kufa University, Najaf, Iraq

ARTICLE INFO

Article history:
Received 9 February 2020
Revised 11 July 2020
Accepted 12 August 2020
Available online 25 August 2020

Keywords:
Optimization
Cooling system
Water withdrawal/consumption
NGCC power plant
Carbon capture unit
Water-energy nexus

ABSTRACT

A water-energy nexus analysis for a Natural Gas Combined Cycle power plant equipped with Post-Combustion Carbon Capture unit was studied. Once-through and hybrid indirect dry and wet cooling systems were considered. An optimization model was developed to minimize the water requirement in each of the cooling system. The model and numerical method were validated with previously reported experimental measurements. In once-through cooling system, the optimized mass flow rates were slightly less than the original operating condition. For hybrid cooling system, the effects of air to water ratio, humidity content, air wet bulb temperature, and the number of cycles of concentration on the water requirements were studied for a wide range of cooling load split factors. The difference in water requirement becomes insignificant when the cooling load exceeds 60%. It was shown that the increase in the number of cycles of concentrations reduces water losses within 5–6 cycles. It is recommended to consider dynamic control for the cooling system using the developed optimization algorithm to maintain optimum operating conditions. For the once-through cooling system, maintaining the least water withdrawal while protecting aquatic life is suggested. For hybrid cooling systems, keeping the split factor below 0.5 and optimizing water consumption and power penalty are recommended.

1. Introduction

Water-energy nexus, the relation between power generation and water consumption, has been gaining increasing attention recently by scientists and policymakers. Globally, 3% of freshwater is consumed, and 10% of it is withdrawn for electric power generation (IEA, 2016a). In the US, 45% of the facilitated water is used through power production processes (Maupin et al., 2014a), and 50% of the utilized water by power plants is used as a cooling heat transfer fluid (EEA, 2009). New technologies should be adopted to control water curtailments and their negative impact on the environment. Using a hybrid cooling system instead of a once-through system is an excellent approach to reduce the adverse effects of the once-through system on aquatic life. However, the hybrid cooling system deteriorates plant performance and consumes more freshwater, which affects global warming adversely. Results presented in the current study regarding controlling these aspects in the once-through and hybrid cooling systems provide original contributions in addressing water-energy nexus challenges. Minimizing water requirements can be exploited by optimizing the power plant cooling system. Furthermore, Integrating carbon capture unit to the power plant is necessary to mitigate the negative impact of CO_2 emissions on climate change, but it may nearly double the amount of water usage in the plant (Carter, 2010), where water is required massively in several stages of the capture and storage process. An optimization model has been developed to minimize water requirements in natural gas combined cycle (NGCC) power plants consisting of two distinct types of cooling systems: (1) a once-through cooling configuration, and (2) a hybrid of indirect dry and wet cooling configuration. Modeling the integration of post-combustion carbon capture (PCCC) to the NGCC power plant by employing a simple, new thermo-algorithm for optimization of water consumption in both once-through and hybrid cooling systems is a novel approach

---

[*] Corresponding author at: 19 Memorial Drive West, Packard Lab Room 563, Bethlehem, PA 18015, USA

https://doi.org/10.1016/j.wen.2020.08.001
2588-9125/

Abbreviations and Nomenclatures

NGCC	Natural Gas Combined Cycles
HRSG	Heat Recovery Steam Generator
HP, IP, and LP	High, Intermediate, and Low Pressure
IDACT	Indirect Air -Cooling Tower Hybrid System
IGCC	Integrated Gasification Combined Cycle
DCC	Direct Contact Cooler
PCCC	Post-Combustion Carbon Capture
Q. or q	Heat Duty
HR	Heat Rate
$\dot{m}$	Mass Flow Rate
h	Enthalpy
E_{net}	Electricity
C	Heat Capacity
T	Temperature
η	Efficiency
P	Power
S	*Solar Radiation Flux*
U	*River mean velocity*
d	*River depth*
DL	*dispersion coefficient*
t	*time*

Subscripts

in	*inlet*
out	*outlet*
ccs	*carbon capture system*
cool	*cooling*
cons	*condenser*
Cons – in or out	Condenser inlet or outlet
t	Thermal
Waste	Waste Heat
Cp	Specific Heat at Constant Pressure
evp	Evaporated Losses
rej	Rejected Heat
mu	Makeup Water
COC	Cycles of Concentration
bld	Blowdown Losses
LSC	Lean Solvent Compoun
FG	Fuel Gas
w	*Water*

Superscripts

TPP	Thermal Power Plant
Max	Maximum
Min	Minimum

Numerous studies were conducted on water consumption and withdrawal in thermal power plants. Ayoub et al. (2018), Salazar et al. (2013), Raphael et al. (2018) and Anozie and Odejobi (2011) developed and an optimization model to reduce water requirements and maximize the produced power in thermal power plants by involving weather and environmental factors and using a nonlinear algorithm. In the same context, Wiliam and Ashlynn (2019) studied water requirements of thermal power plants operating at various regions with different policy implications. Narjis et al. (2019) developed an optimization model to reduce water requirements of thermal power plants by implementing alternative energy resources and cooling technologies. Optimizing the hybrid system design of a waste-to-energy cogeneration plant by Barigozzi et al. (2011) was studied by involving the effect of environmental factors on the performance of the system. The impact of selecting the optimum cooling water mass flow rate on the condenser performance under variable power load was studied by Laskowski et al. (2016). The net produced power and entropy generation were the criteria to select this optimum value.

Optimizing water-cooling system network was developed by Zhang et al. (2018), Ma et al. (2017), Pawel et al. (2018), and Ponce-Ortega et al. (2010) to reduce water requirements and the cost of the system. A mixed-integer nonlinear optimization model was used by these investigators on a series, parallel, and combined system configurations. In the same context, Kim and Smith (2003) studied series and parallel reconfigurations of an optimized cooling system network to characterize the pressure drop constraints, the best efficient use, and the complexity of the cooling system network. Similarly, Sun et al. (2014) optimized the energy savings and the corresponding total annual cost of a cooling system by re-configuring the pumping system where an auxiliary pumping system was added to the main unit.

Modifying the performance of closed-loop cooling systems and the cooling tower units has a direct impact on water and energy management of the power plant. Lidia and Mariano (2020) studied the water footprint of power plants in different regions of Spain using techno-economic analysis. Liu et al. (2017) investigated the effect of air to water ratio on cooling tower performance and its related thermodynamic calculations with different meteorological parameters in July at Jinan, China. Smrekar et al. (2011) evaluated the performance of a natural draft cooling tower using the Cooling Tower Profiler (CTP) method, an empirical correlation, and the Poppe model. The model and method were validated with experimental data. Regucki et al. (2016) developed an analytical solution to calculate the SO_4^+ ions concentration in the recirculating water of a closed-loop cooling system and its associated water mass flow rate under different environmental conditions. They demonstrated that optimizing water mass flow rate not just reduces the consumed freshwater, but also reduces the cost of the wastewater treatment system. The performance of a counterflow cooling tower was investigated under different environmental conditions by Ataei et al. (2008). The mathematical model was developed by using an exergy analysis, and heat and mass transport equations for the cooling water and air through the tower.

The effect of carbon capture and sequestration on water requirements in the power plants has been investigated extensively as a negative impact on water stress. Harto et al. (2014) used a life cycle assessment approach to study the impact of different carbon capture technologies in fossil power plants on water consumption. It was demonstrated that IGCC (Integrated Gasification Combined Cycle) is the most efficient technology in terms of water-saving. Lim-Wavde et al. (2018) and Talati et al. (2014) investigated future and current policies and standards that evolve the tradeoff between electric power generation and water availability-CO_2 emission relationships. Wavde's results showed that as power plants are retrofitted with NGCC and renewable energy technologies as well as retiring the old fossil and coal-fired power plants, CO_2 emissions and water consumption levels would be decreased.

Minimizing water requirement in two potential types of cooling systems (once through and hybrid) for NGCC power plants with integrated PCCC is the main objective of this study. Due to more strict environmental regulations, NGCC plants are forced to integrate carbon capture system to reduce carbon footprint in the power generation process. In this study, the considered NGCC power plant is equipped with integrated PCCC, and the cooling system water requirement is optimized considering the effect of the carbon capture process. Cooling system water consumption optimization for a NGCC with integrated PCCC is the original contribution of this study. An optimization model is developed, and a novel simple-thermo algorithm was applied to solve the developed optimization model. Two potential cooling systems once-through and a hybrid of indirect dry and wet cooling systems were considered. The effect of PCCC integration in the objective function to optimize water requirements for both once-through and hybrid cooling systems was investigated. For the once-through cooling system, the amount of water used in the cooling system was optimized for different river velocities and surface temperatures obtained from field data. For the hybrid cooling system, the effect of wet bulb temperature, vapor content, air to water ratio, and the number of cycles of concentrations on water consumption and withdrawal were investigated for various values of the heat load split factor. The reference NGCC power plant with PCCC and integrated cooling systems were modeled using the COCO V3.3 code developed by Lawrence Livermore National Laboratory. The developed objective function and its algorithm were solved via using an in-house developed code using the VBA language (Visual Basic for Application). The present study addresses the water-energy nexus challenges and opportunities of a PCCC integrated NCGG power plant.

2. NGCC based power plant and integrated units

The NGCC power plant is considered in this study since CO_2 emission and water requirement of NGCC power plants is nearly less than half of other similar fossil power plants (Skone, 2016; McCall et al., 2016). However, extensive study in literature focused on reducing water requirements and CO_2 emission in Coal-Fired power plants compared to the NGCC. Therefore, this study focuses on optimizing water requirements in NGCC power plants, developing such a model which is a novel contribution to the field. A 630 MW_e NGCC including gas turbine cycle, Heat Recovery Steam Generator (HRSG) package with inlet flue gas temperature of 603 °C and steam turbine package with HP (High Pressure), IP (Intermediate Pressure) and LP (Low Pressure) turbines. The components of the reference NGCC plant are depicted in Fig. 1, and the main specifications of the plant are listed in Table 1.

2.1. Integrated cooling systems.

The present authors, Saif et al. (2019), studied the effect of cooling systems on water requirements and plant energy efficiency in a NGCC with and without integrating PCCC. The performance of the once-through, dry, wet, and hybrid cooling configurations was investigated and compared in that study. Here, the optimization of the once-through cooling system and the best hybrid of indirect dry and wet cooling systems configuration (IDACT) is considered to confront water-energy nexus concerns. The only disadvantage for the once-through cooling system is its negative impact on aquatic life. Thus, when this drawback is avoided by developing a suitable optimization model, once-through would be the most viable cooling system in the thermal power plant. The cold water is taken from its source directly and fed into a once-through condenser to remove the waste heat and then returns to its source with an elevated temperature, as shown in Fig. 2a. The heat gain of the source surface water temperature causes thermal pollution that affects aquatic life (Fleischli and Hayat, 2014). The considered hybrid cooling system in the present study is the Indirect Dry Air-Cooling Tower Hybrid System (IDACT). LP steam from the LP turbine is sep-

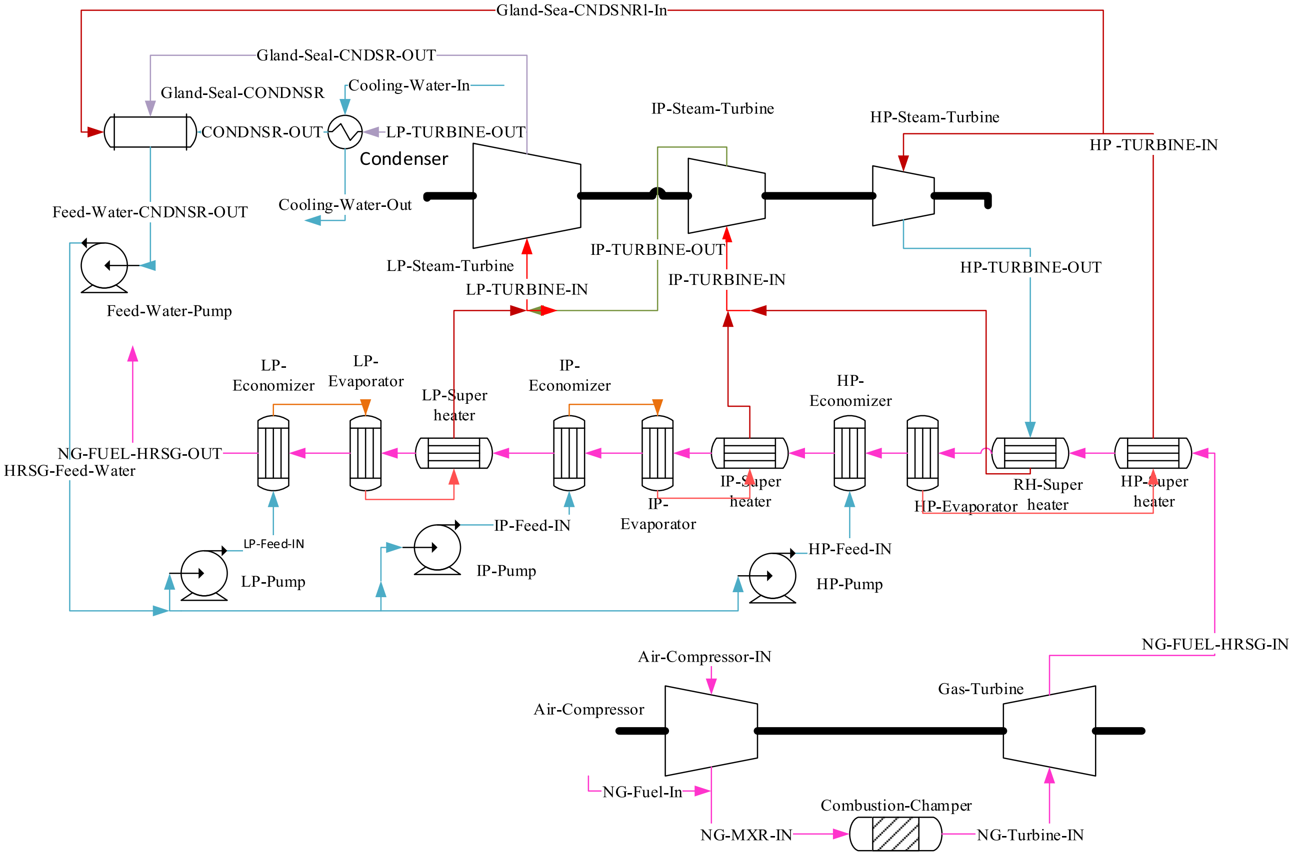


Fig. 1. Components of the NGCC.

Table 1
Main parameters of the base NGCC.

Gas Turbine Produced Power (MW_e)	422.34
Steam Turbines Net Produced Power (MW)	219.9
Auxiliary Loads (MW)	11.2
Plant Net Produced Power (MW)	631
HP turbine inlet temperature (°C)/Pressure (bar)	565.565/166.5
IP turbine inlet temperature (°C)/Pressure (bar)	565.564/41.9
LP turbine inlet temperature (°C)/Pressure (bar)	272.326/5.101
Gas Cycle Pressure Ratio	31
Gas Cycle LHV Efficiency	38.3%
Steam Cycle LHV Efficiency	39.2%
Plant Net LHV Efficiency	57.1%

arated between both the dry and the wet systems where the cooling load split factor controls the ratio between them. In the indirect dry system, the flow enters first a sprayed condenser or direct contact cooler (DCC) to extract the vapor content, which equals to about 0.91 of the main streams (Saif et al., 2019). The extracted saturated steam then enters an air/water exchanger to complete the cooling process, as shown in Fig. 2b. On the other hand, the other portion of the LP-steam enters first a condenser to condense the vapor content, and the heated cooling water accesses the cooling tower to complete the process in the wet cooling system part.

2.2. Integrated carbon capture unit

Previous investigations have studied various aspects of the carbon capture unit. Triethanolamine (TEA) (Zoelle et al., 2015), Ammonia (NH3) (Chu et al., 2016), CaO (Yong and Alírio, 2001), and mono-ethanolamine (MEA) (Saif et al., 2019), the most conventional solvents, were used in these investigations to absorb CO_2 in the unit. Each one of these solvents has a different impact on the cooling system and plant performance and should be investigated in a separate work. Although it is expensive and has a power penalty, the MAE is more reactive, selective, and reversible with CO_2 compared to other sorbents (Ivaylo et al., 2016), making it the most conventional sorbent in the present study. The pre-combustion, post-combustion, and oxy-combustion are the conventional carbon capture systems in the industrial and energy sectors (Ivaylo et al., 2016). The post-combustion type of carbon capture unit integrated into the NGCC power plant is a new combination considered in the current study, as shown in Fig. 3. The integration simplicity with no required reconfiguration for the system, better suitability for gas plants, and maintenance flexibility are among the reasons for the selection of the post-combustion type carbon capture system (Ben-Mansour et al., 2016).

In the PCCC system, the fuel gas enters first a direct contact cooler (DCC) to reduce the temperature of the fuel gas from about 117 to 35°C before entering the absorber, as shown in Fig. 3. Decreasing the temperature of the fuel is necessary to avoid the degradation of the solvent in the absorber. In the absorber, a mono-ethanolamine (MEA)-solvent is used to extract the CO_2 from the fuel gas, where 70 to 90% percent of the CO_2 in the fuel gas is extracted to be removed in the final stage of the capture system. A vibrant and robust bond chemical compound of the CO_2 and solvent would be generated from the extraction process in the absorber. The CO_2 rich compound enters a heat exchanger where the rich solvent gains heat from the hot lean solvent, which exits from a stripper. The step before the final stage in the PCCC process is releasing the CO_2 gas in a stripper column where a high-value heat comes from an integrated reboiler to break the strong bond between the gas and the solvent and to evaporate the water content in the compound. The required heat for solvent regeneration in the reboilers can be extracted, whether from an external source likes solar thermal plant or from the LP turbine inlet. Extracting heat from an external thermal source reduces the penalty in the produced power, but it increases the cooling load in the condenser, causing a contradiction to addressing water-energy nexus concerns as the main objective of the present study. Required LP steam for PCCC system reboiler is withdrawn from the LP turbine inlet. Typically, LP steam has a temperature of about 270 °C and a pressure of 5.06 bar to be used to release the CO_2 gas and the water content in the stripper, resulting in an energy penalty in the produced power. Finally, the released CO_2 is compressed and sent for final storage. Waste heat is generated in the PCCC as a result of the cooling process at various stages in the PCCC by which the net cooling load of the plant is almost doubled, and the required water usage is increased consequently. Cooling the fuel gas exiting the HRSG unit, the lean solvent from the stripper, and the released CO_2-water vapor mixture from the stripper were considered to calculate water requirement and energy penalties.

3. Mathematical modeling and optimization method

For the optimization model, the objective function, which is for water requirement minimization, was derived from the first principle. The constraints that restrict this objective function should be specified, and the distributions of fuel heat rate inside the plant have to be configured, as illustrated in Fig. 4.

A major part of the heat that comes from the natural gas stream would be considered as waste heat, which should be removed by the cooling system. The rest of the gained heat in the HRSG system is exploited to generate electricity that could be used for processes like the flue gas desulfurization (FGD) process and PCCC.

The waste heat, $q_{cool-system}$, is calculated as (Rutberg 2012, Delgado and Herzog 2012):

$$q_{cool-system} = (HR - B) + C \tag{1}$$

where HR, the gained heat from the natural gas stream in the HRSG unit, is determined by:

$$HR = \dot{m}_{fuel} \times (h_{fuel-in} - h_{fuel-out}) \tag{2}$$

$\dot{m}_{fuel}$ is the mass flow rate of the natural flue gas (kg/s) that exits from the gas turbine and enters the HRSG unit. $h_{fuel-in}$ and $h_{fuel-out}$ are the inlet and exit enthalpy of the natural gas fuel, B is a combination of the electric power output and the heat used in other processes such as the heat used in the carbon capture unit. In this study, the heat that is used in other processes is only utilized in the PCCC. Thus,

$$B = E_{net} + q_{ccs} \tag{3}$$

C in Eq. (1) represents the extracted heat, q_{ccs}, from the PCCC. q_{ccs} is calculated using a mass and heat balance at each part of the PCCC (Brandl et al., 2017) as:

$$q_{ccs} = q_{DCC} + q_{LSC} + q_{Condenser} + q_{Compressor} \tag{4}$$

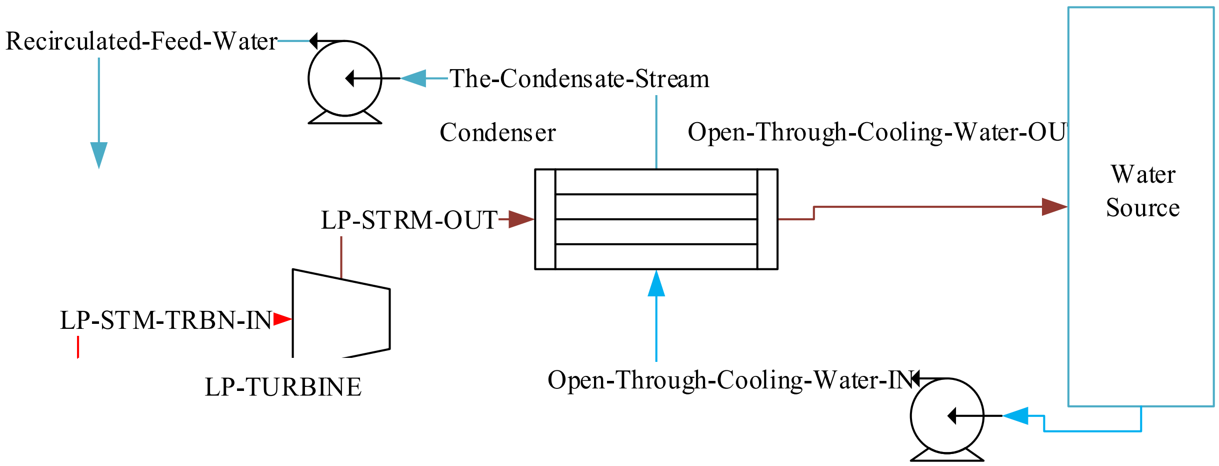
where q_{DCC} is the rejected heat from the DCC in the PCCC.

$$q_{DCC} = m_{\dot{F}G} \times C_{fg} \times (T_{DCC.in} - T_{DCC.out}) \tag{5}$$

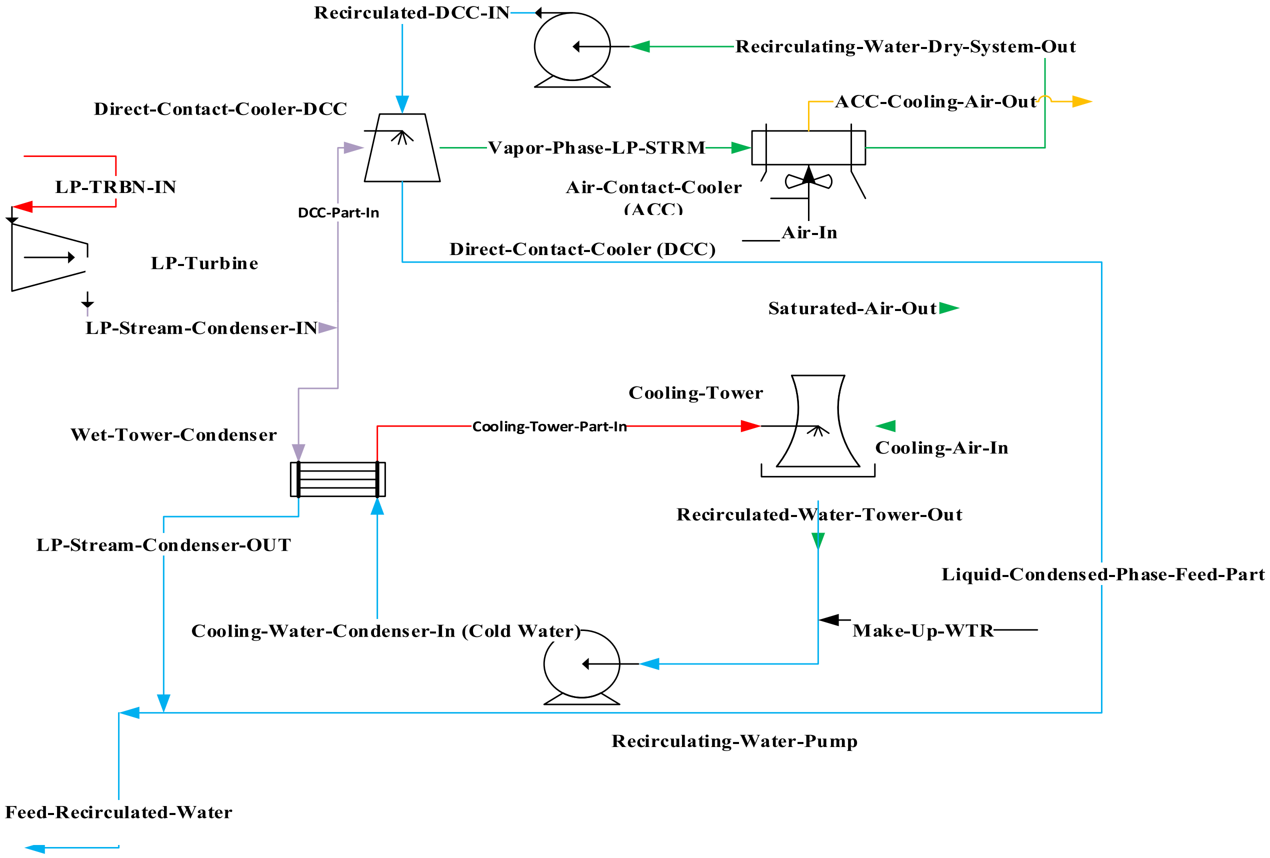
where $m_{\dot{F}G}$, C_{fg}, $T_{DCC.in}$, and $T_{DCC.out}$ are the flue gas mass flow rate, specific heat, and its temperatures at the inlet and the outlet of the DCC, respectively. q_{LSC} is the rejected heat from the lean solvent which comes from the stripper:

$$q_{LSC} = \dot{m}_{solvent} \times Cp_{solvent} \times (T_{LSC.in} - T_{LSC.out}) \tag{6}$$

where $\dot{m}_{solvent}, Cp_{solvent}, T_{LSC.in}$ and $T_{LSC.out}$ are the lean solvent mass flow rate, specific heat, and the inlet and outlet temperature of the lean solvent cooling system, respectively. $q_{Condenser}$ is the heat that is being rejected because of condensation inside the stripper. The heat rejection by condensation was set equal to 26% of the total



a) Once-through cooling system.



b) Indirect dry and wet hybrid cooling system (IDACT).

Fig. 2. The integrated cooling system considered for the NGCC: a) Once-through cooling system and b) Hybrid cooling system.

required heat energy (Brandl et al., 2017). $q_{Compressor}$ and the corresponding required water was not implemented in the final calculation since the CO_2 compression process is not a part of the integrated PCCC in the present study.

Thus, the final estimation of the total required cooling water in the cooling system can be calculated as:

$$\dot{m}_{cool-water} = \frac{q_{cool-system}}{C_p \nabla T_w} = \frac{HR - (E_{net} + q_{ccs})}{C_p \nabla T_w} + \frac{q_{ccs}}{C_p \nabla T_w} \quad (9)$$

Finally, the objective function would be expressed as:

$$MIN\left(\dot{m}_{cool-water} = \frac{q_{cool-system}}{C_p \nabla T_w} = \frac{HR - (E_{net} + q_{ccs})}{C_p \nabla T_w} + \frac{q_{ccs}}{C_p \nabla T_w}\right) \quad (10)$$

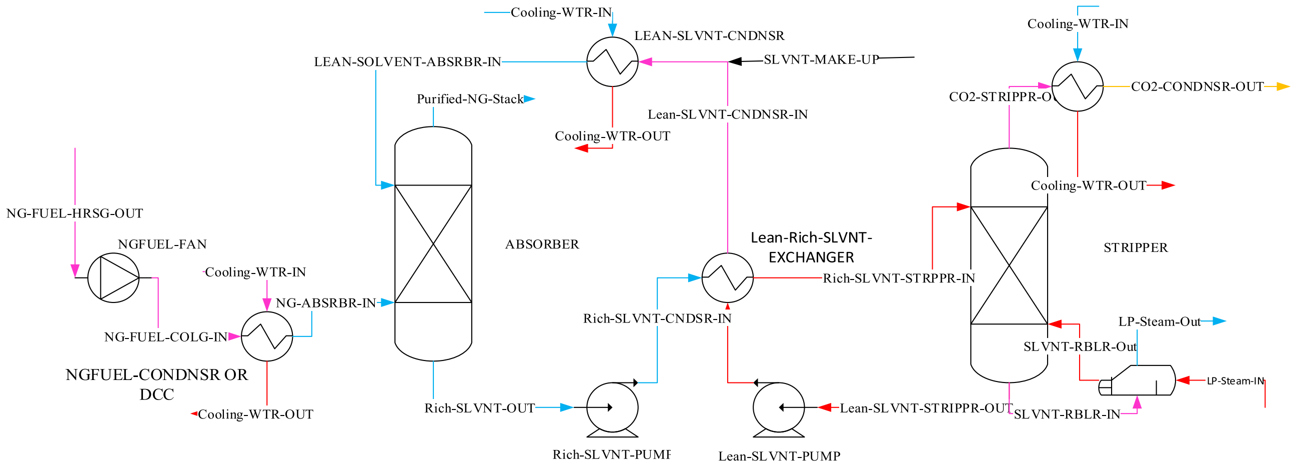


Fig. 3. Post-combustion carbon capture unit.

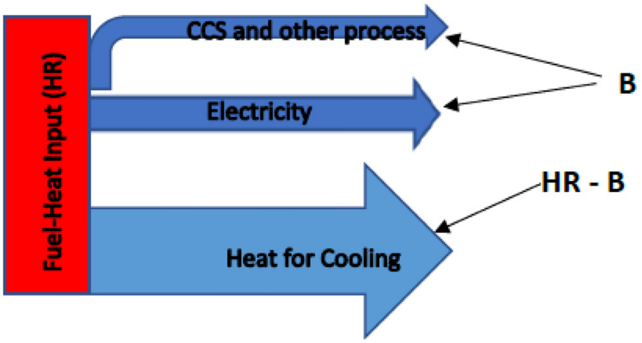


Fig. 4. Distribution of heat rate of fuel.

The total calculated cooling water flows in this approach is consistent with what was reported by Zhai et al. (2011).

The final derived objective function was restricted by several constraints that govern the minimum water mass flow rate value. The different constraints need to be used for the once-through cooling system and the hybrid cooling system.To consider the constraints that govern the objective function, the NGCC power plant was assumed to operate at full load. The constraint that restricts the objective function in the once-through cooling is the water source temperature that impacts aquatic life. Specific limitations and policies have been set by regulatory organizations. For the present study, the European Fish Directive (EU, 1978) policy for Salmonid water was taken as constraints for the objective function where:

$$\nabla T_{river} \leq 1.5\,^{\circ}C \quad \text{and} \quad T_{river}^{max} \leq 21.5\,^{\circ}C \tag{12}$$

ΔT_{river} and T_{river}^{max} should be estimated in terms of plant waste heat energy. With the waste heat, $Q_{waste,}$ in the condenser (Gjorgiev, and Sansavini, 2018) expressed by:

$$Q_{condsr} = \frac{P_{net}^{Tpp} \times \left(1 - \eta_t^{Tpp}\right)}{\eta^{Tpp}} \leq Q_{waste} \tag{13}$$

P_{net}^{Tpp} represents the net produced power of the steam cycle, while η_t^{Tpp} represents the thermal efficiency of the cycle. The relationship between Q_{Waste}, ΔT_{river} and T_{river}^{max} can be determined by:

$$Q_{Waste} = \dot{m}_{cool-water} \times C_p(T_{Cons-out} - T_{Cons-in}) \tag{14}$$

$$\nabla T_{river} = T_{river}^{max} - T_{Cons-in} \tag{15}$$

T_{river}^{max} can be calculated from an energy and mass balance for the river

$$T_{river}^{max} = \frac{\left(T_{out}^{Conddenser} \times \dot{m}_{cool-water}\right) + \left(T_{in}^{river} \times \dot{m}_{river}\right)}{(\dot{m}_{river-net} + \dot{m}_{cool-water})} \tag{16}$$

$$\dot{m}_{river-net} = (\dot{m}_{river} - \dot{m}_{Cons-out}) \tag{17}$$

where:

$$T_{in}^{river} = T_{Cons-in}$$

In the indirect hybrid cooling concept, the dry cooling system and the wet tower cooling system are combined in a parallel connection in the hybrid cooling system of the present study. No water consumption and withdrawal are required in the dry cooling system because air is the primary cooling medium. Therefore, the next mathematical formulations are described for the wet part of the hybrid cooling system, where raw water withdrawal and consumption should be made up to the system as a result of evaporation, drift, and blowdown losses. The evaporation losses in the cooling tower are calculated by performing an energy and mass balance in the cooling tower. The NGCC power plant was simulated using the COCO.3.3 software, where a RADFRAC column was used as a cooling tower, according to Queiroz et al. (2012). According to the report of U.S. Department of the Interior and U.S. Geological Survey (2013), the expected evaporation losses would be equal to:

$$\dot{m}_{evp} = \frac{Q_{rej}}{\left(\frac{h_{air.out} - h_{air.in}}{W_{out} - W_{in}}\right) - h_{mu}} \tag{18}$$

Q_{rej} is the amount of the rejected heat in the tower (W), $h_{air.out}$,W_{out} and $h_{air.in}$,W_{in} are the specific enthalpy of air and the specific vapor content at the outlet and inlet of the tower, respectively; while h_{mu} is the specific enthalpy of the makeup water. In the present study, Eq. (18) has been corrected by using an experimental correlation which was developed by (Perry and Green, 1997) to estimate the final amount of the evaporation losses rate as:

$$\dot{m}_{evp} = 0.00085 \times \nabla T \times \dot{m}_{cool-water} \times 1.8 \tag{19}$$

$\dot{m}_{evp}$ and ∇T represent the evaporative losses and temperature difference through the cooling tower, respectively, and $\dot{m}_{cool-water}$ is the circulated cooling water mass flow rate. Drift losses were assumed to be 0.001 of the total amount of cooling water that enters the tower. According to Martín et al. (2011), blowdown losses are equal to:

$$\dot{m}_{bld} = \frac{\dot{m}_{evp}}{COC - 1} \tag{20}$$

And,

$$COC = \frac{C_B\ (Solid\ Concentartion\ in\ the\ Blowdown\ Water)}{C_m\ (Solid\ Concentartion\ in\ the\ Makeup\ Water)} \tag{21}$$

where COC is the number of cycles of concentrations.Finally,

$$Raw\ Water\ Withdrawal = makeup\ water = \dot{m}_{evp} + \dot{m}_{bld} + \dot{m}_{drift} \tag{22}$$

where

$$\dot{m}_{evp} + \dot{m}_{drift} = Raw\ Water\ Consumption \tag{23}$$

3.1. Method of optimization

The first step of optimization is to simulate the integrated NGCC power plant (the cooling system and the PCCC). This step is very important to simplify the optimization algorithm. Instead of calculating the objective function's variables from first principle and basic equations, these variables would be determined from plant simulations and imported to the code by which the algorithm is being converted to a more simplified form. The in-house code was written and developed by using Visual Basic for Application language (VBA) and has been interfaced with a plant model's workbook sheet. As the hot stream from the condenser ($\dot{m}_{Cons-out}$) would be mixed with the river's temperature (T_{in}^{river}) to get the final temperature after mixing (T_{river}^{max}) from Eq.(16), the conservation of energy for the river water stream should be implemented in the final calculation (Caissie et al., 2007, Sinokrot, and Stefan 1993, and Gjorgiev and Sansavini, 2017) as:

$$\frac{\partial T}{\partial t} = -U\frac{\partial T}{\partial x} + DL\frac{\partial^2 T}{\partial x^2} + \frac{S}{\rho C_p d} \tag{24}$$

where T is the temperature (°C) of the river water stream, t is time (s), U is the river mean velocity, x is the streamwise distance (m), s is the net solar radiation on the water surface (W/m^2), d is the river depth (m), ρ is water density (kg/m^3), and C_p is water specific heat (W/kg. °C). DL represents a dispersion coefficient in the direction of the flow. Solar radiation, $S = S_s + S_l + S_e + S_c$, consists of the following components: S_s, the short-wave solar radiation, S_l, the longwave solar radiation, S_e, the evaporative heat flux, and S_c, the convective heat transfer (Caissie et al., 2007; Sinokrot and Stefan, 1993).

For simplicity, the components of solar flux were assumed as constant since the main purpose of this work was to study the effect of thermal properties of the surface water of the river on the cooling system. Furthermore, since meteorological river data have not been hard-implemented in the solution, the current study can be generalized for any river or water source that would be used as a water source for the cooling system of any plant.

In the present study, it was assumed that the stream temperature reaches a quasi-uniform longitudinal profile, and thus Eq. (24) yields:

$$\frac{\partial T}{\partial t} = \frac{S}{\rho C_p d} \tag{25}$$

An explicit finite difference method was used to solve Eq. (25) where T_{river}^{max} is considered as the initial condition for the solution with iteration error equals 0.001. To solve the simple linear thermo-algorithm, the NGCC plant simulation with its integrated parts was commenced using an initial estimated water surface temperature and water mass flow rate to the condenser. The resulted thermal data from simulations were implemented in Eqs. (14)–(17) and (25) for the once-through cooling system, where these equations work within loop iterations to find the minimum values of water mass flow rate by applying the corresponding constraints as the primary objective. Eqs. (19)–(23) are utilized to find the minimum water mass flow rate for the hybrid cooling system. The flow chart of the optimization process is depicted in Fig. 5.

3.2. Algorithm development and discretization method.

From Eqs. (14)–(17), it can be concluded that:

$$Mass_{\min(n+1)} = \frac{((C_p \times T_{rivern}^{max} \times \dot{m}_{river}) - (C_p \times T_{in} \times \dot{m}_{river-net}) - Q_{Waste})}{C_p \times T_{in}} \tag{26}$$

$T_{Cons-out}$ at each cooling loop can be determined from T_{rivern}^{max} and $Mass_{\min(n+1)}$ as:

$$T_{Cons-out(n+1)} = T_{in} + \frac{Q_{Waste}}{C_p \times Mass_{\min(n)}} \tag{27}$$

To find the river average surface temperature at each cooling loop, $Mass_{\min(n+1)}$ and $T_{Cons-out(n+1)}$ from the above equations would be implemented in the equation below:

$$T_{river(n+1)} = \frac{(T_{Cons-out(n)} \times Mass_{\min(n)}) + (T_{in} \times \dot{m}_{river-net})}{\dot{m}_{river}} \tag{28}$$

Now, $T_{river(n+1)}^{max}$, which represents the temperature of the river after mixing $T_{Cons-out(n)}$ with $T_{river(n+1)}$, can be estimated by applying the finite difference method, including the forward differencing scheme on Eq. (25) to get finally:

$\frac{{T_{river}^{\max(m+1)}}_{(n+1)} - T_{river(n+1)}^{(m)}}{\Delta t} = \frac{S}{C_p \times d}$ (forward discretization). Thus,

$${T_{river}^{\max(m+1)}}_{(n+1)} = \Delta t \times \frac{S}{C_p \times d} + T_{river(n+1)}^{(m)} \tag{29}$$

The results gained from the abovementioned equations should be restricted by the below constraints as has been mentioned in the previous sections:

$\nabla T_{river} \leq 1.5^{\circ}C\ \ and\ \ T_{river}^{max} \leq 21.5^{\circ}C$ according to the European Fish Directive policy for Salmonid water (EU., 1978).

Caissie et al. (2007) calculated components of solar flux daily at each water surface temperature for the Catamaran Brook and Little Southwest Miramichi Rivers, Canada, from 1992-1999. In the present study, these models were utilized.

3.3. Cooling load split fraction for the hybrid cooling system.

The effect of the cooling load split factor, a parameter that shows the heat rejection portion by each part of the hybrid cooling system, has been studied by several investigators (Zhai and Rubin, 2016; William and Rasul, 2008; Lee et al., 2018). The saturated mixture leaving the LP-turbine should be condensed to release the latent heat by using indirect dry and wet hybrid cooling systems. The dry system consumes more energy while the wet system consumes more fresh water, having an environmental impact. Thus, a new factor, wet system cooling load split factor, is considered in this study to control the mass flow rate of the saturated mixture streams and separate them between the dry system and the wet system in the hybrid cooling system to manage these penalties.

$$Wet\ Cooling\ Load\ Split\ Factor = 1 - \frac{Mass\ Flow\ Rate\ of\ the\ stream\ in\ drycooling\ System}{Total\ mass\ flowrate\ of\ the\ stream\ from\ the\ LP - turbine} \tag{30}$$

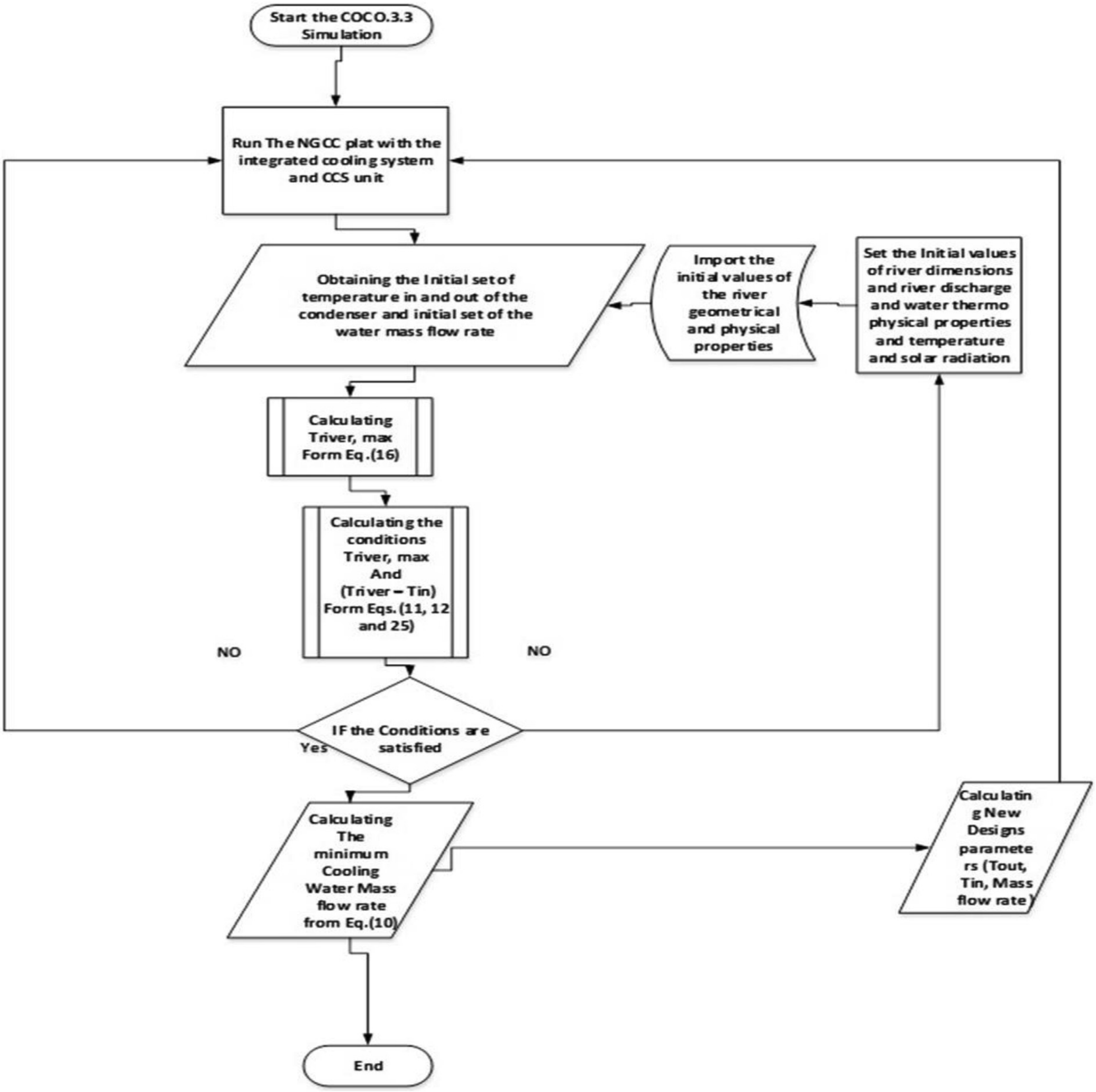


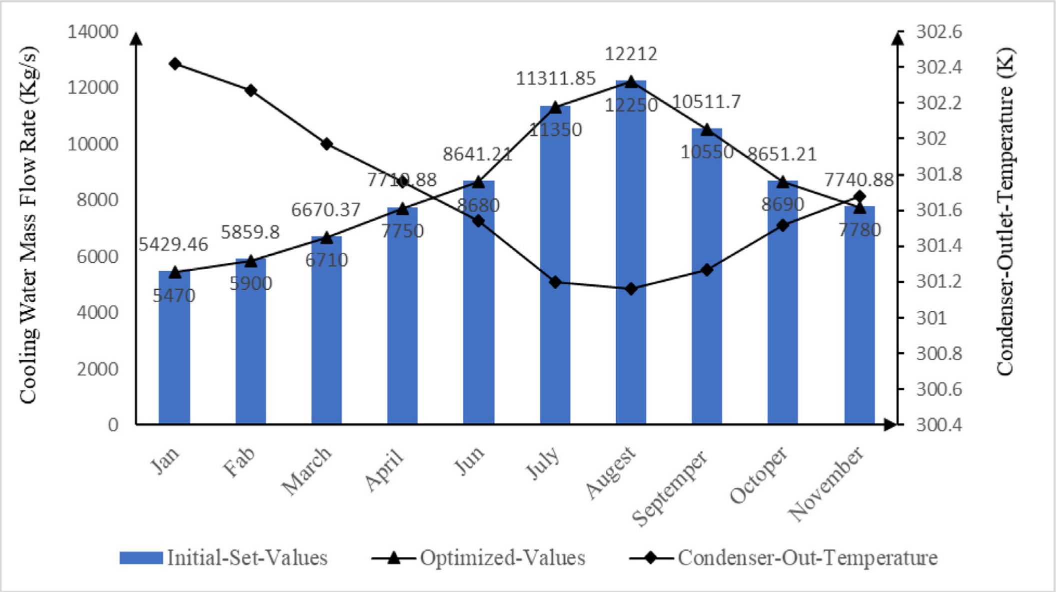
Fig. 5. Flow chart of the optimization process.

Table 2
Simulation results of the base NGCC unit with the integrated cooling system and PCCC compared against NETL results reported by (Zoelle et al. 2015).

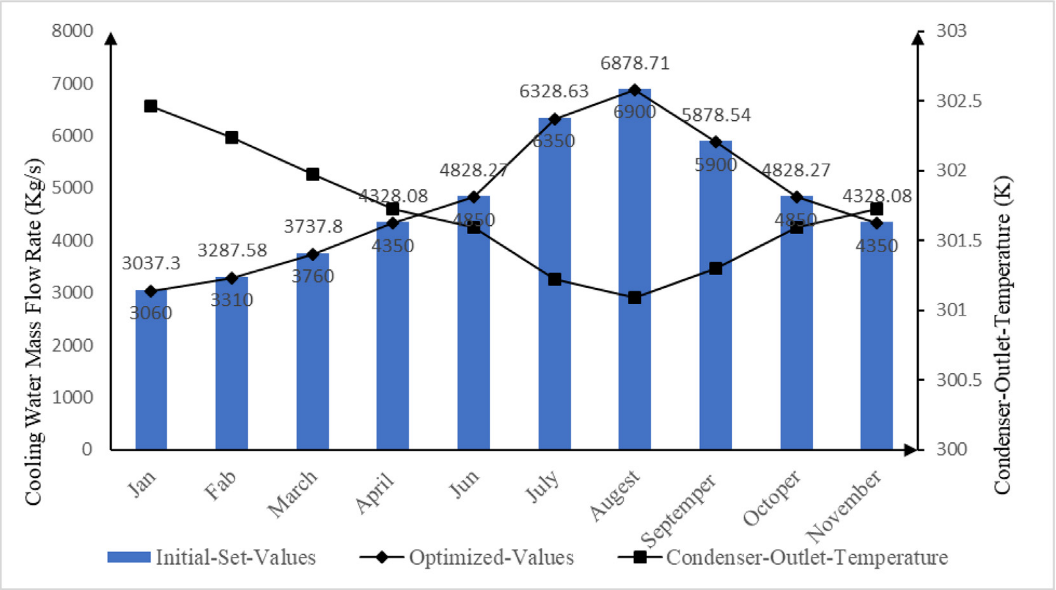
Parameters of Validation	NETL Report Results	Simulation Results
Plant Gross Power without PCCC (MWe)	641	642
Plant Gross Power with PCCC (MWe)	601	601
Plant Net Power without PCCC (MWe)	630	629.5
Plant Net Power with PCCC (MWe)	559	559.45
Steam LHV efficiency without PCCC	39.1	39.1
Steam LHV efficiency with PCCC	33.5	33.5
Net LHV Efficiency without PCCC	57.0	57.1
Net LHV Efficiency with PCCC	50.6	50.7
Condenser Duty with PCCC (MW_{th})	246.66	260.98
Condenser Duty Without PCCC (MW_{th})	355.83	373.90
Raw Water Withdrawal without PCCC (gal/min)/MWe_{net}	4.20	4.26
Raw Water Withdrawal with PCCC (gal/min)/MWe_{net}	7.20	7.34
Raw Water Consumption without PCCC (gal/min)/MWe_{net}	3.30	3.32
Raw Water Consumption with PCCC (gal/min)/MWe_{net}	5.40	5.72

Table 3
Monthly water discharge and related data for Catamaran Brook River, Canada, 1992 (Chadwick, 1995).

Surface Temperature (°C)	Month	Discharge (m^3/s)	Velocity (m/s)
0	January	0.253	0.144
2	February	0.144	0.082
5	March	0.213	0.121
8	April	1.13	0.643
10	June	1.43	0.814
14	July	0.384	0.218
15	August	0.479	0.273
13	September	0.5	0.285
10	October	0.139	0.079
8	November	0.45	0.256



a) Initial mass flow rate and optimized (reduced) mass flow rate with integrated PCCC.



b) Initial and optimized mass flow rate without PCCC integration.

Fig. 6. Monthly initial and optimized cooling water mass flow rate (kg/s) corresponding to data from Catamaran Brook River, Canada, in 1992 (Caissie et al., 2007; Chadwick, 1995).

It was calculated that the indirect cooling system consumes about 1.5% of the net produced power when split factor cooling load is equal to 0.5 (Saif et al., 2019). Previously, it has been shown that 30% of the wet cooling load factor is the most feasible factor economically in the hybrid cooling system (Zhai and Rubin, 2016, Ashwood and Bharathan, 2011; Loscutoff, 1976). The cooling load is given by

$$Q_{Co.Lo.} = \dot{m}_{cooling-water} \times C_p\left(T_{Outlet-cooling-water} - T_{in}\right) = \text{constants} \tag{31}$$

The parameters in Eq. (31) are involved in the cooling side of the condenser where $\dot{m}_{cooling-water}$, and T_{in} are constants while $T_{Outlet-cooling-water}$ is restricted by

$$T_{Outlet-cooling-water} \leq 27 - 29\,^{\circ}C \tag{32}$$

In addition, the heating load is calculated from

$$Q_{He.Lo.} = \dot{m}_{LP-Steam} \times (h_{out} - h_{in}) \tag{33}$$

$h_{out},\ h_{in},\ and\ \dot{m}_{LP-Steam}$ are the inlet enthalpy, outlet enthalpy, and mass flow rate of the LP-stream that exits from the LP-turbine and has 91% of a vapor content as a heating load. The only factor that controls the heating load ($Q_{He.Lo.}$), which should be removed in the condenser, is $\dot{m}_{LP-Steam}$. There is a constraint on $Q_{He.Lo.}$

$$Q_{He.Lo.} \leq Q_{Co.Lo.} \tag{34}$$

The inequality (34) is essential to make a complete or ideal cooling process; otherwise, a residual heating load would be represented as vapor residual in the cooling system pipes causing corrosion. The cooling load, $Q_{Co.Lo.}$, is controlled by the design outlet temperature in the cooling side of the condenser ($T_{Outlet-cooling-water}$). Because the mass flow rate ($\dot{m}_{cooling-water}$) and inlet temperature (T_{in})of the cooling water are design parameters and set as constants in the system, the rise in the $Q_{Co.Lo.}$ would be accompanied by an increase in the design outlet temperature ($T_{Outlet-cooling-water}$). There would be no increase in the $Q_{Co.Lo.}$ since all the parameters in Eq. (31) become nearly constant when the outlet temperature approaches to the limit. When the mass flow rate of the LP-stream ($\dot{m}_{LP-Steam}$) be larger than the amount required to make $Q_{He.Lo.}$ less than or equal to $Q_{He.Lo.}$ according to Eq. (34), a residual heating load remains in system pipes as a vapor content leading to corrosion in these pipes. As a result, water losses from this stream in the cooling tower will not be changed when $T_{Outlet-cooling-water}$ is near 27–29 °C. Since the wet cooling load split factor is the only factor that controls the mass flow rate of the LP-stream ($\dot{m}_{LP-Steam}$) and its corresponding heating load, the maximum heating load that should be removed in a condenser is obtained for the split factor of 0.55–0.6. Thus, any increase in the split factor after threshold causes incomplete cooling process and vapor residual in the system pipes, and therefore, no more water losses in the tower. The studies from literature are focusing on split factors ranged from 0.1 to 0.5 for the wet cooling system load portion to reduce the economic penalties caused by the dry cooling system. The present work goes beyond these values ignoring the financial penalty of the dry cooling system to calculate the optimum amount of the wet system cooling load portion as a part of the novel optimization model in the current study. The split factors of 0.4, 0.6, and 0.8 are selected as a basis in the present work.

4. Results and discussion

4.1. Results validation

Results were validated for a base NGCC plant with its integrated cooling system and PCCC. The base cooling system for the base plant is a wet tower cooling system. The validation was carried out by comparing the results obtained in this study with data from a (Zoelle et al., 2015), as shown in Table 2.

As it is shown in Table 2, the selected unit parameters predicted by the model developed in this study are in the range of the corresponding values in the (Zoelle et al., 2015). However, condenser duties are slightly higher than those reported in (Zoelle et al., 2015). This is likely due to the difference in the method used to calculate the thermophysical properties in the NETL report (Zoelle et al., 2015)and the present study. Consequently, the amount of raw water withdrawal and consumption predicted here is slightly higher than the corresponding values in the NETL report (Zoelle et al., 2015).

4.2. Optimization results for the once-through cooling system.

In the once-through cooling system, the temperature of the source, a river, should not exceed a specified limit after the returned stream mixes with the river discharge. An objective function was developed in this study with the constraint of decreasing

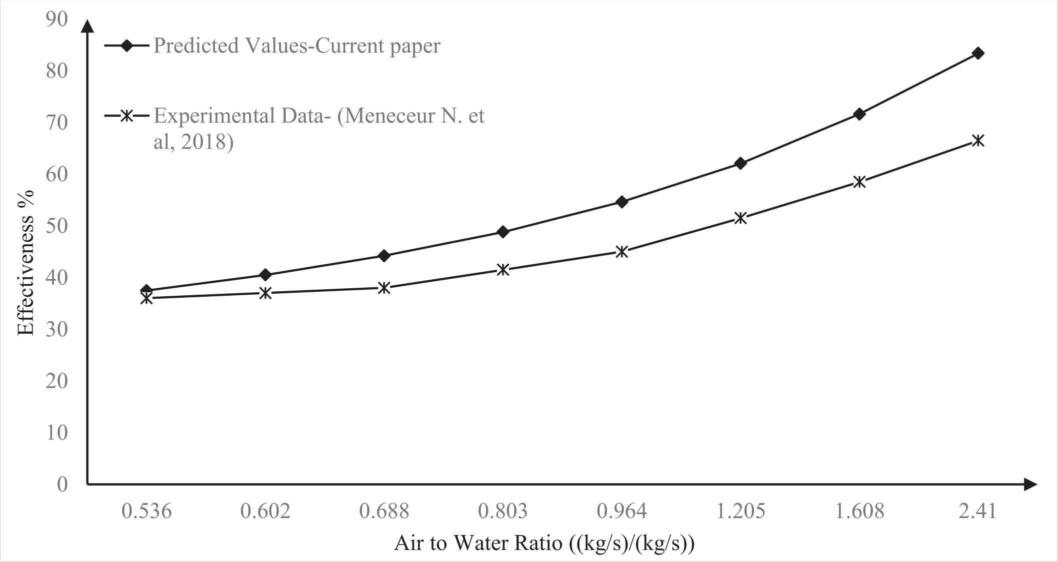


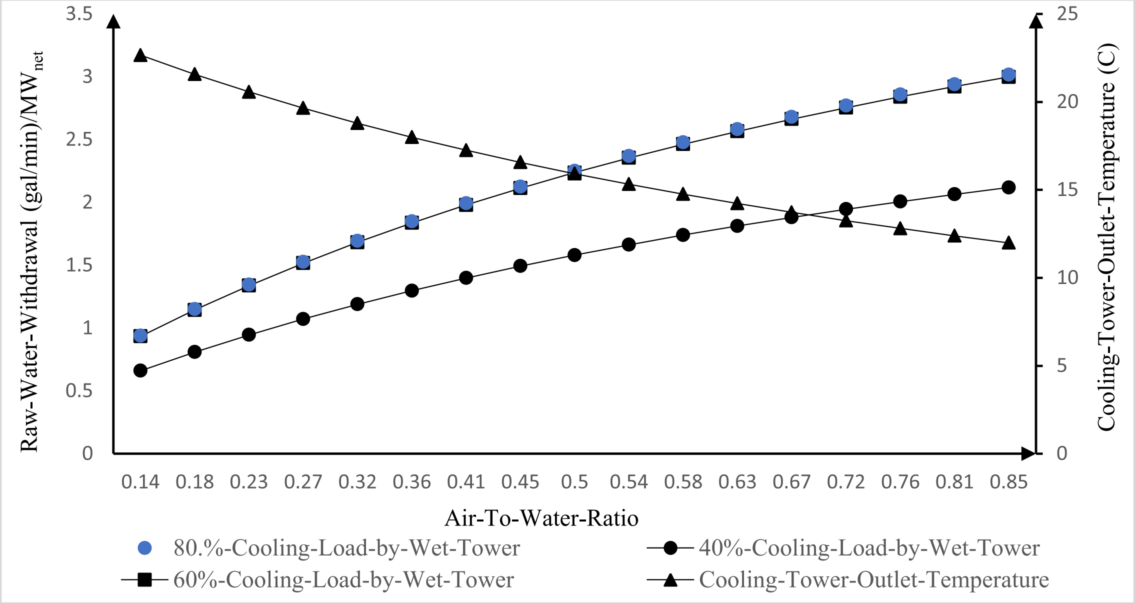
Fig. 7. Predicted and measured effectiveness as a function of the air to water mass ratio.

cooling water mass flow rate to meet regulatory demands on water and the corresponding reduction in energy addressing water-energy nexus concerns. To make these results more applicable, data from the Catamaran Brook River, Canada, were utilized in a similar fashion that was discussed by Caissie et al. (2007).

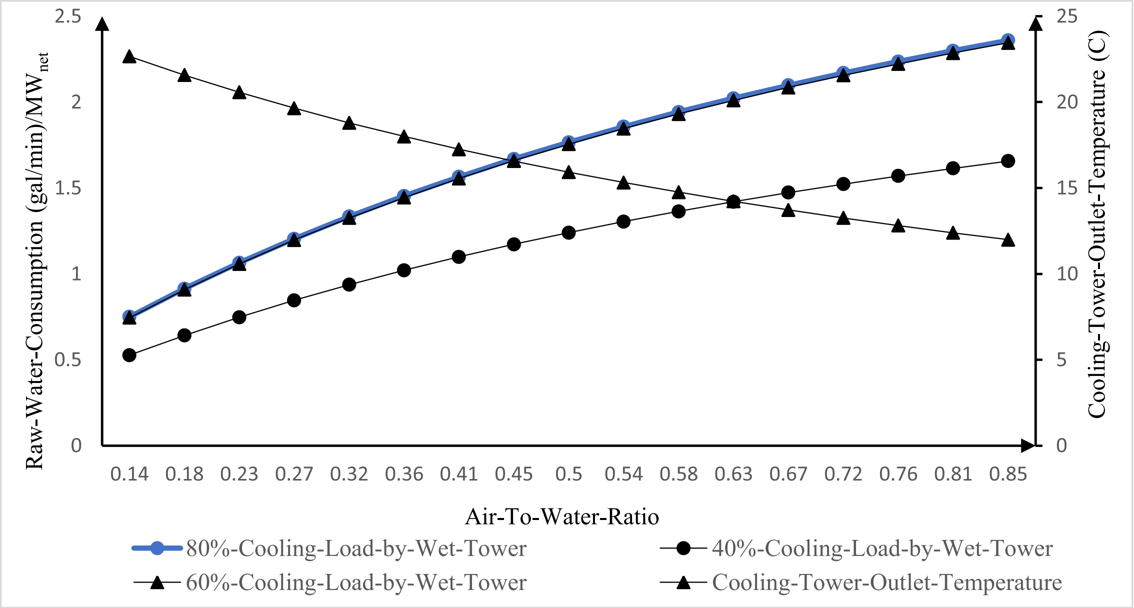
The water source surface temperature has a direct relation to the amount of water used for cooling in the cooling system. Because it has been assumed in the model that the net produced power is constant in time (no ramp up or down), the condenser duty is constant. This means that any increase or decrease in the water inlet temperature to the condenser would lead to a change in the cooling water rate level. This has also been mentioned by (Caissie et al., 2007; Chadwick, 1995). Table 3 shows the monthly variation of the discharge flow rate and temperature of the discharge for the Catamaran Brook River, Canada, in 1992 (Chadwick, 1995). The width and the depth of the river are 0.308 m and 5.7 m, respectively. This is in direct relation to the solar radiance flux and air temperature, which affects the temperature of the river water surface, according to Eqs. (24), and (25).

In Table 3, listed data were used in the objective function, constraints, and governing equations. Discharge and water surface temperature change monthly, leading to a change in the optimized design parameter of the cooling system. Data in Table 3 are real meteorological data of the Catamaran Brook river in Canada in 1992.

Fig. 6 (a, b) shows monthly expected cooling water mass flow rate and condenser outlet temperature for the NGCC power plant with and without PCCC. It is shown that the optimization model provides cooling water mass flow rates at a reduced rate than the initial levels during the entire seasonal variations throughout



a) Raw water withdrawal versus air to water ratio.



b) Raw water consumption versus air to water ratio

Fig. 8. Effect of air to water ratio on water usage (gal/min)/MWnet; a) raw water withdrawal, b) raw water consumption.

the year and for the plant with and without PCCC where the initial mass flow rate can be calculated as: -

$$\dot{m}_{int.river} = Velocity \times Density \times Crosssectionalarea \tag{35}$$

The seasonal velocity, listed in Table 3, is the same as the velocity used in Eq. (35). The water density is 1000 kg/m^3, and the cross-sectional area is equal to:

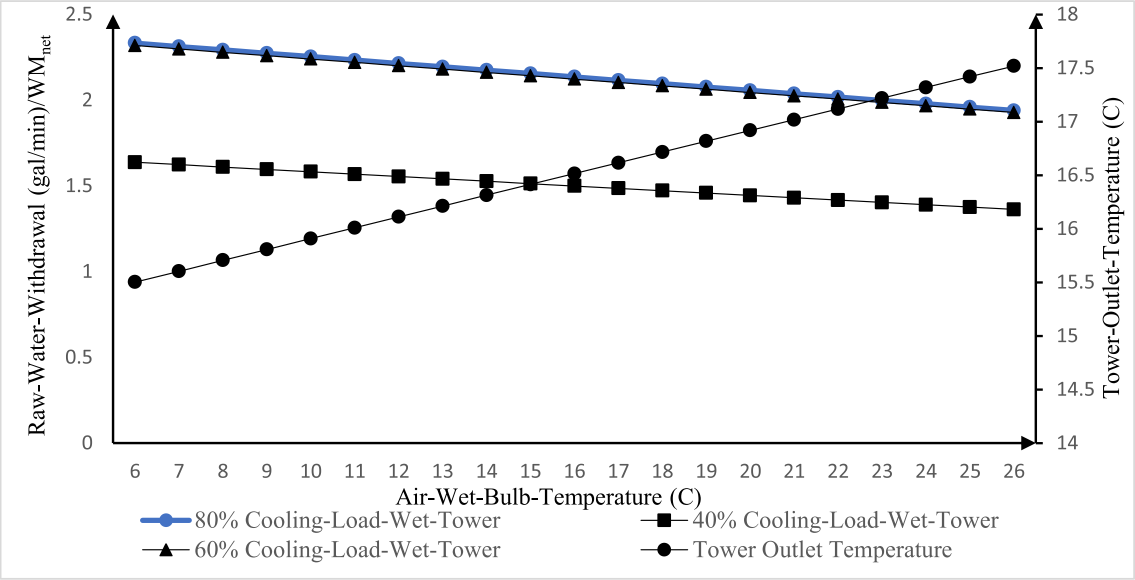
$$A_{cross} = riverdepth \times width \tag{36}$$

Additionally, condenser outlet temperature varies inversely with the cooling water mass flow rate since constant values were assumed for produced power, capacity factor, and condenser duty in the model. Consequently, any changes in the cooling water mass flow rate lead to the opposite response in condenser outlet temperature, according to Eq.14. The optimized mass flow rate and temperature gradients are consistent with the monthly water surface temperature variations, which was listed in Table 3. Furthermore, the condenser outlet temperature has been bounded to avoid undesirable changes in the river temperature, even if these changes are negligible.

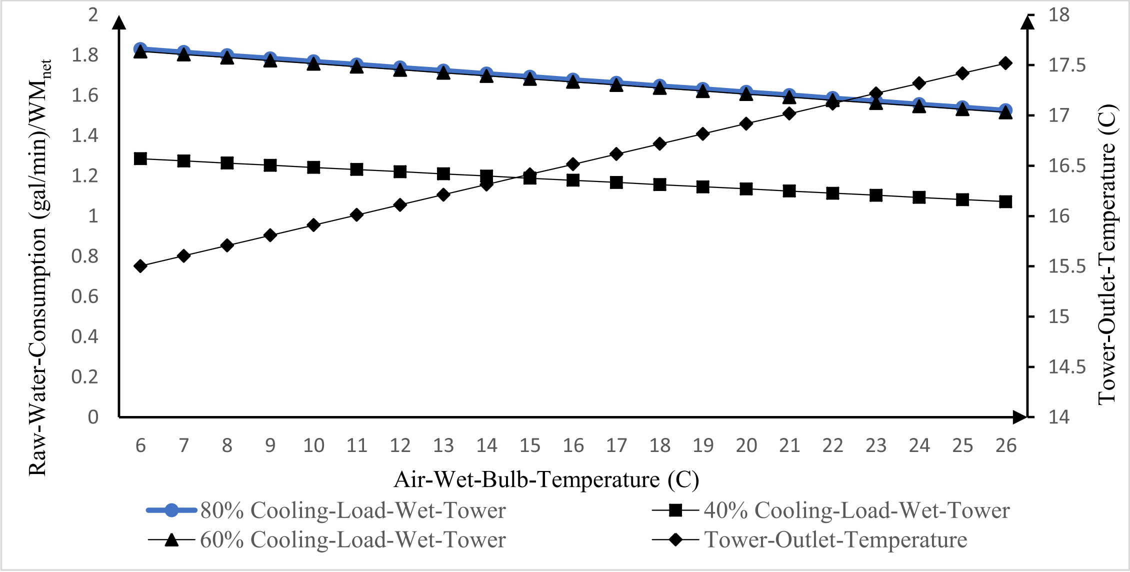
4.3. Model results for the indirect dry and wet hybrid cooling system (IDACT)

4.3.1. Model validation

To validate the developed model for the hybrid cooling system, experimental measurements reported by Meneceur et al. (2018) were considered. The predicted and measured values of the cooling



a) Raw water withdrawal versus air wet-bulb temperature.



b) Raw water consumption versus air wet-bulb temperature.

Fig. 9. Effect of air wet-bulb temperature on water usage (gal/min)/MW$_{net}$. a) Raw water withdrawal and b) Raw water consumption.

tower effectiveness were compared for a wide range of air to water mass ratio. The effectiveness was defined following Meneceur et al. (2018)

$$Effectiveness = \frac{T_{water-Cooling-Tower-In} - T_{water-Cooling-Tower-Out}}{T_{water-Cooling-Tower-In} - T_{air-Wet-Bulb-Tower-In}} \quad (37)$$

The predicted and measured values of effectiveness versus the air to water flow rate ratio are depicted in Fig. 7. It illustrates that the deviation between predicted and measured data decreases from 24% to 4% as air to water ratio decreases from 2.41 to 0.54. A significant deviation between the prediction and experiments at higher air to water ratio can be attributed to the reverse relation of cooling water rate and cooling water temperature, which results in a similar trend in measurement error. The uncertainties in the measured temperatures decrease as more cooling water flows to the cooling tower. Another potential reason for the deviation is that the experiments were performed at different environmental conditions causing different inlet wet-bulb temperatures at different water flow rates. However, for the range of air to water ratio considered in the present study ($\leq$0.85), the agreement between the predictions and measurements is reasonably good.

4.3.2. Model results for the indirect dry and wet hybrid cooling system (IDACT)

In the hybrid indirect dry and wet cooling system (IDACT), the wet and indirect dry cooling systems are connected in parallel, in such a way that the LP stream leaving the LP turbine is split between both cooling systems according to the set split fraction. Results of the parametric study and sensitivity analysis are presented and discussed next. The effect of the air to water ratio, ambient conditions (ambient temperature and humidity), and cycles of concentrations (COC) on raw water withdrawal and consumption of the wet tower part of the evaporative cooling system of the plant with and without PCCC was examined for various values of the cooling load split factor.

Fig. 8 (a, b) shows the effect of air to water ratio at the cooling tower, in the wet system part of the hybrid cooling system, on water withdrawal and consumption at cooling load split fractions of 0.4, 0.6, and 0.8. The effect on cooling tower outlet temperature, resulting from changing the amount of water withdrawal and consumption, is also shown in Fig. 8. It can be seen that the increase in the air to water ratio leads to an increase in the amount of both water withdrawal and consumption. Increasing water consumption as a result of increasing air to water ratio comes from the fact that more water absorption is required to saturate the increased amount of air. In the same context, because the heat duty of the tower and the inlet temperature to the tower are constant, the increase in consumed water leads to a reduction in tower outlet temperature, as shown in Fig. 8. The relationship between tower water losses and air to water ratio is consistent with findings reported by Ataei et al. (2008). It is expected that increasing the contribution of the wet cooling system in the cooling process leads to an increase in water losses as the wet cooling load split factor increases up to 0.6. The water losses become nearly constant for the split factor greater than 0.6 because of the design outlet temperature of the condenser($T_{Outlet-cooling-water}$) becomes constant when the wet cooling load split factor approaches 0.55–0.6, according to Eqs. (31–34) Further investigation regarding the balance between water consumption and cooling system efficiency would be needed.

Fig. 9 (a, b) shows the impact of changing ambient air bulb temperature on water losses of the wet system part of the hybrid cooling system. The water withdrawal and consumption decrease almost linearly with increasing ambient air wet-bulb temperature. This behavior is expected because the increasing temperature would lead to a reduction in the air temperature difference through the cooling tower by which the removed latent heat via air entering the tower is reduced. Since the tower heat duty is constant, the water losses associated with this latent heat are reduced. The tower outlet temperature would also increase as a result of the change in air tower inlet temperature. Fig. 9 (a, b) shows an almost linear gradient of the tower outlet temperature as a result of increasing ambient wet bulb temperature and, consequently, decreasing tower water losses. As shown in Fig. 9 (a, b), an increase of the cooling loading split fraction leads to an increase in the amount of water usage until the value of the wet cooling load split factor reaches 0.6, which is also consistent with the results shown in Fig. 8.

Figs. 8 and 9 depict the fact that water withdrawal and consumption per unit of generated power are hardly changed when the cooling load split fraction exceeds 0.6 as the condenser outlet temperature of the wet system is constant. In conclusion, the increase in the contribution of the dry cooling system decreases

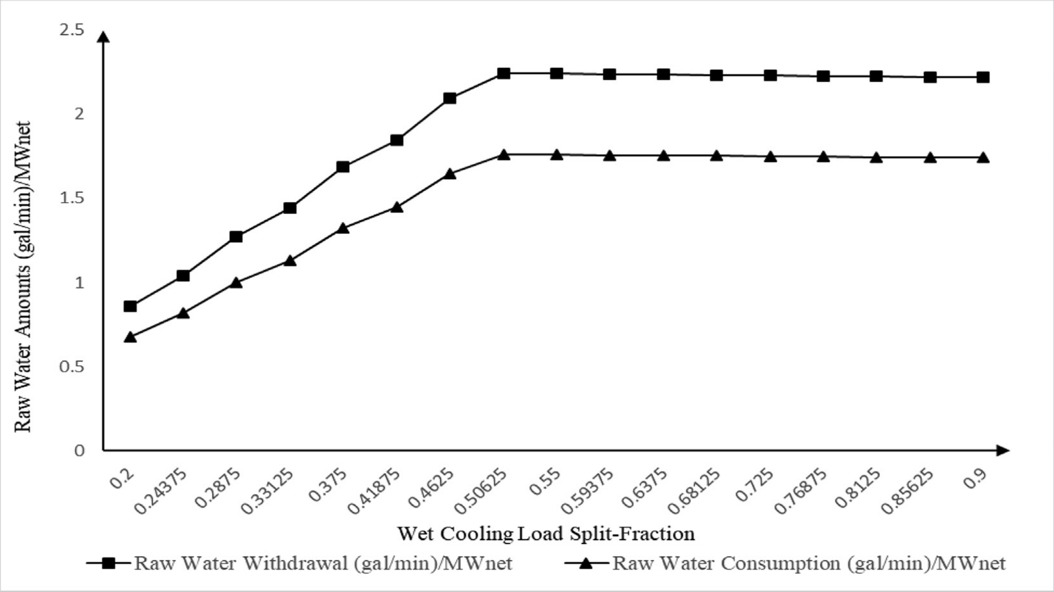
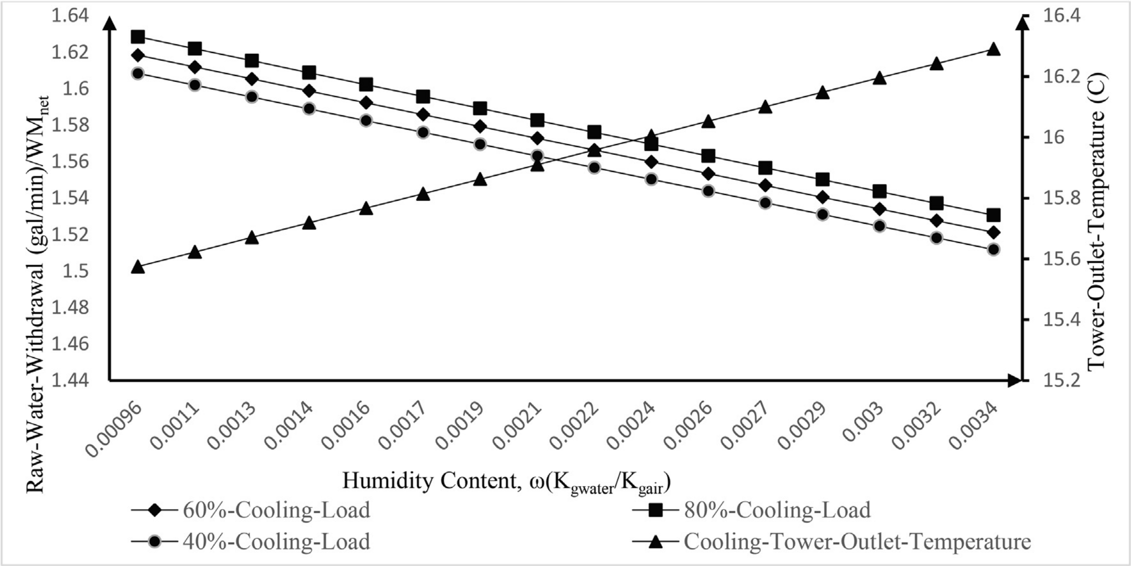


Fig. 10. The relationship between cooling load split factor and the required water amounts.

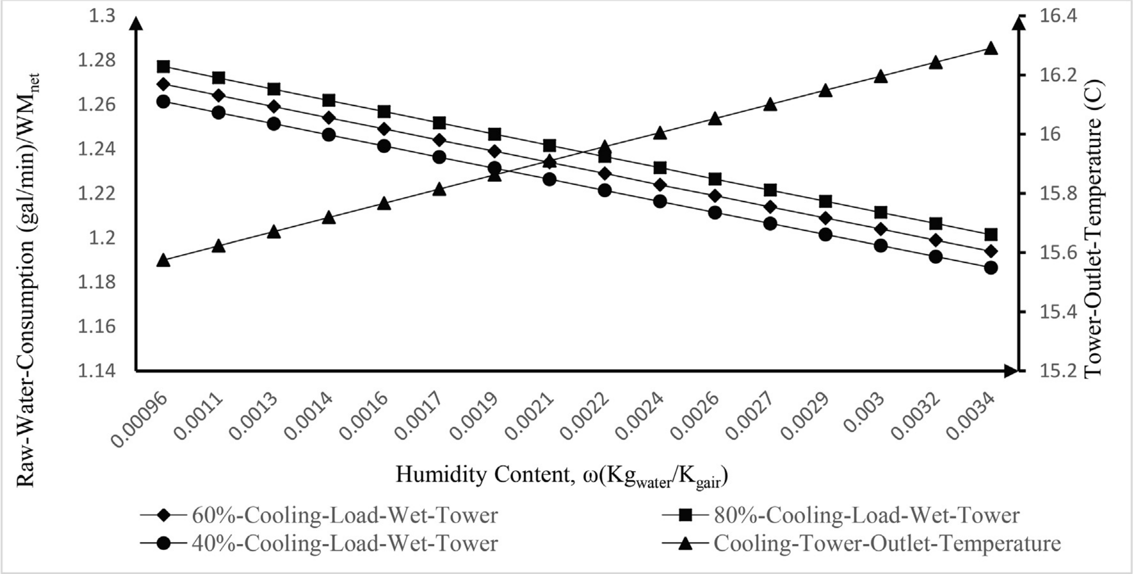
the water withdrawal and consumption but increases the power penalty of the plant significantly where dry cooling consumes more power as the compression ratio of the cooling working fluid, air, is much larger than the compression ratio of water.

Fig. 10 shows the relationship between the cooling load split factor of the wet cooling system and raw water withdrawal and consumption in the tower. It can be shown that any increase in the split factor leads to an increase in the required water amounts, for the split factor is less than 0.55. For SF $\geq$ 0.55, the water requirement becomes nearly constant because the design outlet temperature of the cooling water in the condenser section of the wet cooling system becomes constant, as mentioned above. In contrast, an increase in the split factor beyond 0.6 would be harmful and leads to a vapor content residual in the LP-stream, which should condensate, as a consequence of the incomplete cooling process.

Fig. 11 (a, b) shows the effect of the humidity content of the air accessing the cooling tower on water withdrawal and consumption and resulting tower outlet temperature. These results show that increasing humidity content leads to a decrease in water losses in the wet tower. This comes from the fact that increasing humidity leads to reducing the amount of water that could be taken by air to reach saturation conditions. As a result, the removed latent heat from the hot water and the corresponding water losses are reduced. The tower outlet temperature also increases as the humidity content increases. As humidity content increases, the increase in the wet system cooling load split factor leads to increased water requirements in the system.



a) Raw water withdrawal versus humidity content.



b) Raw water consumption versus humidity content.

Fig. 11. Effect of humidity content on water usage (gal/min)/MW$_{net}$; a) Raw water withdrawal, b) Raw water consumption.

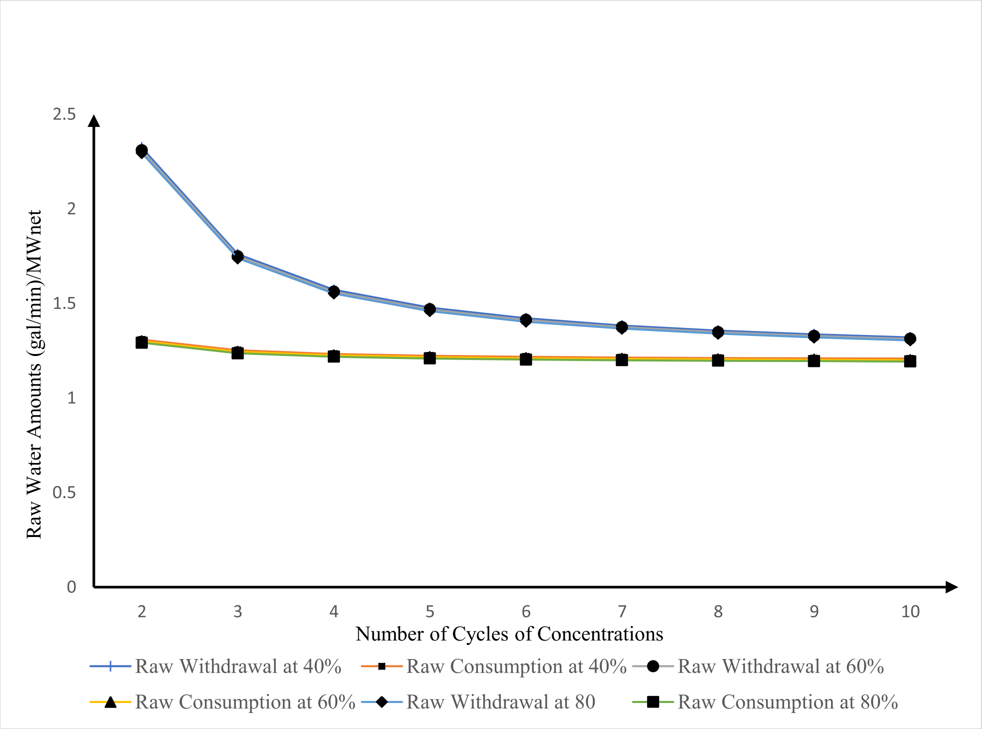


Fig. 12. Effect of the number of cycles of concentration on raw water withdrawal and consumption.

Fig. 12 shows the effect of the number of cycles of concentration on raw water withdrawal and consumption. Water withdrawal is impacted mostly by increasing the number of cycles of concentration than water consumption because water withdrawal is a combination of blowdown and evaporated losses where the blowdown losses are strongly dependent on the number of cycles of concentrations while the evaporated losses are weakly dependent on it, according to Eqs. (20), (22) and (23). Additionally, Fig. 12 shows that after 5–6 cycles of concentration, the change in water losses would be insignificant. Even though there would be no significant water losses after 5–6 cycles, the increase in the cycles leads to a rise in the solids concentration in the blowdown leading to expand water treatment processes and increase the power penalty in the plant. Therefore, 5–6 cycles of concentration are the preferred number of cycles in the system.

4.4. Effect of PCCC's reboiler duty and carbon capture on water requirements and power penalty

The impact of PCCC's reboiler duty and carbon capture rate on condenser duty, power penalty, and water withdrawal and consumption are discussed for the IDACT hybrid cooling configuration as the main affecting parameters for water-energy nexus studies.

Fig. 13 shows the impact of reboiler duty and the increase in plant net cooling duty as a function of carbon capture rate. It was found that reboiler heat duty increases almost linearly with increasing capture rate, and this behavior is consistent with the work by Szuhanszki et al. (2015). This is because the heat that is being used in the reboiler is required for increasing the temperature of the solvent to the required temperature, breaking the bonds between the carbon dioxide and the solvent, and evaporating the carbon dioxide and water to be separated in the PCCC stripper (Zhang et al., 2017). Thus, increasing the carbon capture rate requires more heat in the stripper to separate the carbon dioxide from the solvent and evaporate it with water from the stripper reboiler. Fig. 13 also shows that increasing the plant net cooling duty with an increase in carbon capture rate would lead to an increase in waste heat that should be removed by the cooling system.

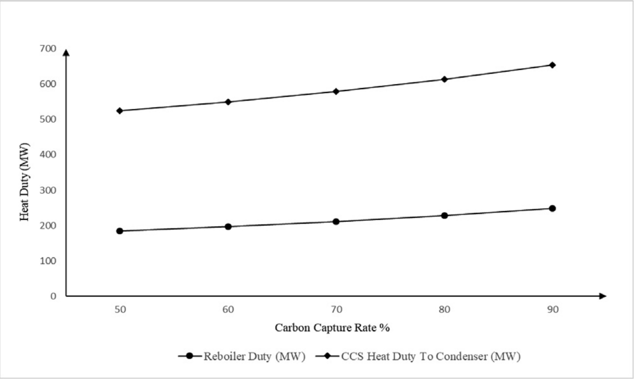


Fig. 13. Plant net cooling duty, including PCCC heat duty and reboiler heat duty at different carbon capture rates at split factor 0.5.

Fig. 14 shows the power penalty and water withdrawal and consumption as a function of the carbon capture rate at split fraction equals to 0.5. It was explained that the trend in water withdrawal and consumption is directly related to the reboiler and net cooling duty, as shown in Fig. 14. Because the power penalty of the closed cooling system is much lower than the penalty of the dry cooling system, where the consumed power in the air fan of the dry system is much higher than the consumed power in the water pump of the closed cooling system, the increase in reboiler duty and carbon capture rate would slightly impact the power penalty by using the dry cooling system. Most of the PCCC waste heat is removed by using a closed cooling system in the present study.

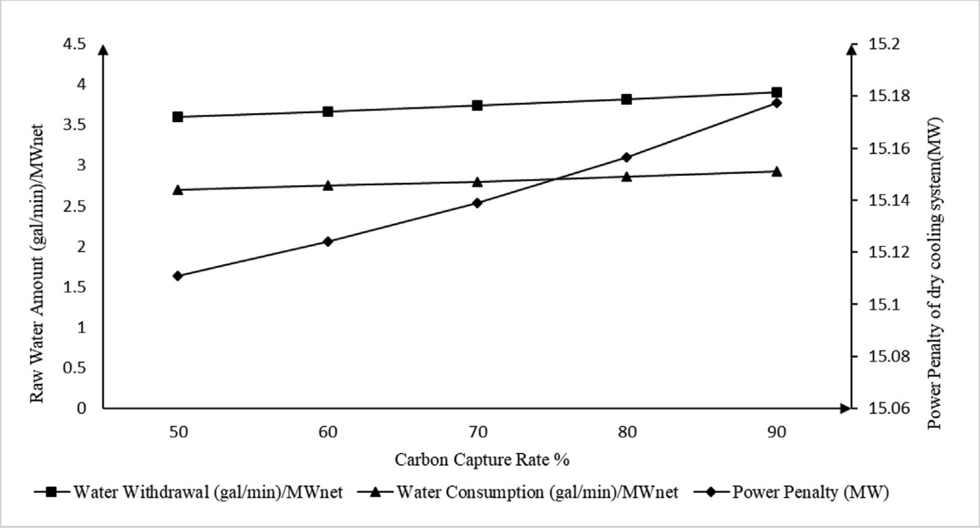


Fig. 14. Power penalty and raw water withdrawal and consumption at different carbon capture rates at split factor 0.5.

5. Conclusions and future recommendations.

A Natural Gas Combined Cycle (NGCC) with Post-Combustion carbon capture (PCCC) unit was considered as a reference case for optimization in water requirements minimization for two types of cooling systems. Once-through and hybrid cooling systems (Indirect Dry and Wet Cooling system (IDACT)) are cooling systems considered for optimization to mitigate challenges of water-energy nexus. One of the significant contributions of the present study is the development of a unique simple thermo-algorithm to solve the optimization function and its implemented constraints. COC.3.3 flow sheet software was used to simulate the NGCC power plant integrated with the PCCC and cooling systems. Also, a suitable code has been developed by using Visual Basic for Application (VBA) to solve the optimization algorithm. Both once-through and hybrid cooling systems were investigated in the optimization model for minimizing the water requirements. Meteorological data of the Catamaran Brook river in Canada in 1992 were selected as a feed to the objective function for the once-through system. The required cooling water rate was optimized, considering the constraint for return cooling water temperature. For the hybrid cooling system, a parametric study was conducted as a base for the optimization model. Air to water ratio accessing the cooling tower, ambient air wet bulb temperature, humidity content, and the number of cycle of concentrations at three different cooling load split fractions (40%, 60%, and 80%) are the factors which their effects were studied on water requirement.

Results show that the optimization model works well for the once-through cooling system where the initial monthly setting of the cooling water mass flow rate decreases slightly for the plant with and without PCCC, implying that the initial setting is close to the optimum level. For the hybrid cooling system, it was found that increasing the air to water ratio leads to an increase in water losses in the system where more air needs to be saturated by absorbing additional water. In contrast, increasing ambient air wet bulb temperature and humidity content leads to a reduction in water withdrawal and consumption in the system because of reducing the latent heat removal as a result of decreasing the driving temperature difference. Increasing wet system cooling load fractions leads to increasing water losses in the system. The maximum water losses in the wet cooling system occur when the load split factor approaches 0.55–0.6. The consumed water becomes nearly constant as the design outlet temperature ($T_{Outlet-cooling-water}$) of the cooling water form condenser reaches its limit. Regarding the number of the cycles of concentration, it was found that increasing this value leads to a reduction in the water requirement up to 5 to 6 cycles, and it becomes nearly constant as the number of cycles is increased further. Thus, 5–6 cycles represent the optimum since additional cycles increase wastewater treatment and increase the power penalty as a result. Further investigation regarding the balance between water consumption and cooling system efficiency would be needed. The validation study demonstrated that the results predicted in the present work are in good agreement with the experimental data, implying that the results predicted by the developed model are valid. Due to the direct impact of the ambient condition on cooling system performance and its variable nature, it is recommended to apply a dynamic controller for the cooling system to maintain its operation at an optimum level. Developed algorithms can be used for such controllers to optimize cooling system performance dynamically. In hybrid cooling systems, maintaining the split factor below 0.5 is a recommended practice for water consumption optimization. This paper recommends using a once-through cooling system in regions with easy access to water resources while using a hybrid cooling system in regions suffering from water scarcity. It was shown that the ambient. In addition, the integration of the PCCC system results in a further increase in cooling load demand and consequent water withdrawal and consumption. Using absorbent with reduced water requirements such as Ammonia is recommended to be considered in PCCC systems.

Examining the impact of partial load operating conditions of the plant on the cooling system and related optimization process is a good candidate for future study. The application of other potential absorbents in the PCCC system could also be considered for future research. Further studies are needed to examine challenges and opportunities regarding water-energy nexus of PCCC integrated NCGG power plants.

CRediT authorship contribution statement

Saif W. Mohammed Ali: Conceptualization, Methodology, Formal analysis, Software, Investigation, Data curation, Writing - original draft. **Nasser Vahedi:** . **Carlos Romero:** Supervision, Project administration, Methodology, Conceptualization, Writing - review & editing. **Alparslan Oztekin:** Supervision, Project administration, Methodology, Conceptualization, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study was made possible by the provided financial support for Mr. Saif W. Mohammed Ali by the Higher Committee for Education Development (HCED) of Iraq and Kufa University.

References

Anozie, A., Odejobi, O., 2011. The search for optimum condenser cooling water flow rate in a thermal power plant. Appl. Therm. Eng. 31 (17–18), 4083–4090. https://doi.org/10.1016/j.applthermaleng.2011.08.014.

Ashwood A, Bharathan D. (2011). Hybrid cooling systems for low temperature geothermal power production. Technical Report submitted to NREL.

Ataei, A., Panjeshahi, M.H., Gharaie, M., 2008. Performance evaluation of counter-flow wet cooling towers using exergitic analysis. Trans. Canad. Soc. Mech. Eng. 32 (3–4), 499–512. https://doi.org/10.1139/tcsme-2008-0033.

Ayoub, A., Gjorgiev, B., & Sansavini, G. (2018). Cooling Towers Performance in a Changing Climate: Techno-Economic Modeling and Design Optimization. Energy, 160, 1133-1143. doi: 10.1016/j.energy.2018.07.080.

Barigozzi, G., Perdichizzi, A., Ravelli, S., 2011. Wet and dry cooling systems optimization applied to a modern waste-to-energy cogeneration heat and power plant. Appl. Energy 88 (4), 1366–1376. https://doi.org/10.1016/j.apenergy.2010.09.023.

Ben-Mansour, R., Habib, M.A., Bamidele, O.E., Basha, M., Qasem, N.A.A., Peedikakkal, A., Laoui, T., Ali, M., 2016. Carbon capture by physical adsorption: Materials, experimental investigations and numerical modeling and simulations – a review. Appl. Energy 161, 225–255. https://doi.org/10.1016/j.apenergy.2015.10.011.

Brandl, P., Soltani, S.M., Fennell, P.S., Dowell, N.M., 2017. Evaluation of cooling requirements of post-combustion CO_2 capture applied to coal-fired power plants. Chem. Eng. Res. Des. 122, 1–10. https://doi.org/10.1016/j.cherd.2017.04.001.

Caissie, D., Satish, M.G., El-Jabi, N., 2007. Predicting water temperatures using a deterministic model: application on miramichi river catchments (New Brunswick, Canada). J. Hydrol. 336 (3–4), 303–315. https://doi.org/10.1016/j.jhydrol.2007.01.008.

Carter, N.T., 2010. Energy's Water Demand: Trends, Vulnerabilities, and Management. Congressional Research Service, Washington, DC.

Chadwick M., (1995). Water, Science, and Public: The Miramichi Ecosystem. Canadian Special Publication of Fisheries and Aquatic Sciences, New Brunswick, Canada, No. 123.

Chu, F., Jon, C., Yang, L., Du, X., Yang, Y., 2016. CO_2 absorption Characteristics in ammonia solution inside the structured packed column. Ind. Eng. Chem. Res 55, 3696–3709.

Delgado A., and Herzog H., (2012), A simple Model to Help Understand Water Use at Power Plant., A working Paper Submitted to Massachusetts Institute of Technology.

EEA, 2009. Water Resources across Europe: Confronting Water Scarcity and Drought. European Environment Agency, Copenhagen.

EU. (1978), Council Directive 78/659/EEC of 18 July 1978 on the quality of fresh waters needing protection or improvement in order to support fish life. In: Union E, editor. Brussels: Official Journal of the European Union.

Fleischli S., and Hayat B., (2014), Power Plant Cooling and Associated Impacts: The Need to Modernize U.S. Power Plants and Protect Our Water Resources and Aquatic Ecosystem. NRDC Issue Brief Report, IB: 14-04-C.

Gjorgiev, B., Sansavini, G., 2018. Electrical power generation under policy constrained water-energy nexus. Appl. Energy 210, 568–579. https://doi.org/10.1016/j.apenergy.2017.09.011.

Gjorgiev, B., Sansavini, G., 2017. Water-energy nexus: impact on electrical energy conversion and mitigation by smart water resources management. Energy Convers. Manage. 148, 1114–1126. https://doi.org/10.1016/j.enconman.2017.06.053.

Harto, C., White, E., Horner, R., & Schroeder, J. (2014). Technology Choice and Water Consumption for Coal Electricity Production with Carbon Capture and Storage. Volume 2: Simple and Combined Cycles; Advanced Energy Systems and Renewables (Wind, Solar and Geothermal); Energy Water Nexus; Thermal Hydraulics and CFD; Nuclear Plant Design, Licensing and Construction; Performance Testing and Performance Test Codes; Student Paper Competition. doi:10.1115/power2014-32178.

IEA, (2016 a), Water Energy Nexus, Excerpt from the World Energy Outlook, OECD/IEA (International Energy Agency), France P. 13.

Ivaylo, H., Farida, D.L., Patrick, L., Moussa, D., Chavdar, C., Ivan, P., 2016. Carbon dioxide capture by adsorption (review). J. Chem. Technol. Metal. 51 (6), 609–629.

Kim, J., Smith, R., 2003. Automated retrofit design of cooling-water systems. AIChE J. 49 (7), 1712–1730. https://doi.org/10.1002/aic.690490711.

Laskowski, R., Smyk, A., Lewandowski, J., Rusowicz, A., Grzebielec, A., 2016. Selecting the cooling water mass flow rate for a power plant under variable load with entropy generation rate minimization. Energy 107, 725–733. https://doi.org/10.1016/j.energy.2016.04.074.

Lee, G., Ra, H., Lee, B., Lee, Y., Roh, C., Baik, Y., Cho, J., Shin, H., 2018. Preliminary study on the effect of dry/wet cooling combinations for the sustainable management of water of cooling tower. Int. J. Low-Carbon Technol. 13, 61–66. https://doi.org/10.1093/ijlct/ctx020.

Lidia, S.G., Mariano, M., 2020. On the water footprint in the power production: sustainable design of wet cooling towers. Appl. Energy 263,. https://doi.org/10.1016/j.apenergy.2020.114620 114620.

Lim-Wavde, K., Zhai, H., Kauffman, R.J., Rubin, E.S., 2018. Assessing carbon pollution standards: electric power generation pathways and their water impacts. Energy Policy 120, 714–733. https://doi.org/10.1016/j.enpol.2018.05.067.

Liu, N., Zhang, L., Jia, X., 2017. The effect of the air water ratio on counter flow cooling tower. Procedia Eng. 205, 3550–3556. https://doi.org/10.1016/j.proeng.2017.09.925.

Loscutoff, W.F., 1976. Preliminary Evaluation of Wet/Dry Cooling Concepts for Power Plants. Battelle; Pacific Northwest Laboratories, Richland, Washington.

Ma, J., Wang, Y., Feng, X., 2017. Simultaneous optimization of pump and cooler networks in a cooling water system. Appl. Therm. Eng. 125, 377–385. https://doi.org/10.1016/j.applthermaleng.2017.07.026.

Martín, M., Ahmetović, E., & Grossmann, I. E. (2011). Optimization of Water Consumption in Second Generation Bioethanol Plants. Industrial & Engineering Chemistry Research, 50 (7), 3705-3721. doi:10.1021/ie101175p.

Maupin M. A., Kenny J. F., Hutson S. S., Lovelace J. K., Barber N. L., Linsey K. S., (2014 a), Estimated Use of Water in the United States in 2010. Geological Survey Circular, U.S., p. 52.

McCall, J., Macknick, J., & Macknick, J. (2016). Water-Related Power Plant Curtailments: An Overview of Incidents and Contributing Factors. doi:10.2172/1338176.

Meneceur N., Boulahrouz S., Khounfais K., and Boukhari A. (2018). Theoretical and Experimental Study of Thermal Performance Within a Counterflow Wet Cooling Tower, Journal of Engineering Science and Technology, (13) 11, 3961-3709. ISSN: 1823-4690.

Narjis, N., Farhad, B., Adel, N., Hamid, S., Wilkistar, O., 2019. Water withdrawal and consumption reduction for electricity energy generation systems. Appl. Energy 248, 196–206. https://doi.org/10.1016/j.apenergy.2019.04.023.

Pawel, R., Marek, L., Renata, K., Hussam, J., 2018. Numerical study of water flow rates in power plant cooling systems. Therm. Sci. Eng. Process 7, 27–32. https://doi.org/10.1016/j.tsep.2018.04.015.

Perry, R.H., Green, D.W., 1997. Perry's Chemical Engineer's Handbook. McGraw-Hill, New York.

Ponce-Ortega, J.M., Serna-González, M., Jiménez-Gutiérrez, A., 2010. Optimization model for re-circulating cooling water systems. Comput. Chem. Eng. 34 (2), 177–195. https://doi.org/10.1016/j.compchemeng.2009.07.006.

Queiroz, J.A., Rodrigues, V.M., Matos, H.A., Martins, F., 2012. Modeling of existing cooling towers in ASPEN PLUS using an equilibrium stage method. Energy Convers. Manage. 64, 473–481. https://doi.org/10.1016/j.enconman.2012.03.030.

Raphael, P.B., Federica, B., Claus, D., Peter, B.G., 2018. Optimization of regional water – power systems under cooling constraints and climate change. Energy 155, 484–494. https://doi.org/10.1016/j.energy.2018.05.043.

Regucki, P., Engler, B., Szeliga, Z., 2016. Analysis of water management at a closed cooling system of a power plant. J. Phys. Conf. Ser. 760,. https://doi.org/10.1088/1742-6596/760/1/012026 012026.

Rutberg M., (2012), Modeling Water Used at Thermo-electric Power Plant., Thesis Submitted to Massachusetts Institute of Technology.

Saif, W.M., Vahedi, N., Romero, E.C., Oztekin, A., 2019. Water usage and energy penalty of different hybrid cooling system configurations for a natural gas combined cycle power plant—effect of carbon capture unit integration. Int J Energy Res. 2019, 1–18. https://doi.org/10.1002/er.4694.

Salazar, J.M., Diwekar, U., Constantinescu, E., Zavala, V.M., 2013. Stochastic optimization approach to water management in cooling-constrained power plants. Appl. Energy 112, 12–22. https://doi.org/10.1016/j.apenergy.2013.05.077.

Sinokrot, B.A., Stefan, H.G., 1993. Stream temperature dynamics: measurements and modeling. Water Resour. Res. 29 (7), 2299–2312. https://doi.org/10.1029/93wr00540.

Skone, J.T., 2016. Life Cycle Greenhouse Emissions: Natural Gas and Power Production. NETL Report in EPRI Winter Meeting, Natural Gas Interest Group.

Smrekar, J., Kuštrin, I., Oman, J., 2011. Methodology for evaluation of cooling tower performance – Part 1: description of the methodology. Energy Convers. Manage. 52 (11), 3257–3264. https://doi.org/10.1016/j.enconman.2011.05.005.

Sun, J., Feng, X., Wang, Y., Deng, C., Chu, K.H., 2014. Pump network optimization for a cooling water system. Energy 67, 506–512. https://doi.org/10.1016/j.energy.2014.01.028.

Szuhanszki, J., Akram, M., Palma, C. F., Hughes, K. J., Ingham, D. B., Ma, L., & Pourkashanian, M. (2015). Sensitivity Analysis of Post-Combustion CO2 Capture at Pilot Scale Level. In 3rd Post Combustion Capture Conference (PCCC3) in Canada.

Talati, S., Zhai, H., Morgan, M.G., 2014. Water impacts of CO2 emission performance standards for fossil fuel-fired power plants. Environ. Sci. Technol. 48 (20), 11769–11776. https://doi.org/10.1021/es502896z.

U.S. Department of the Interior and U.S. Geological Survey, (2013), Methods for Estimating Water Consumption for Thermoelectric Power Plants in the United States, Scientific Investigations Report, 2013-5188.

William C. R. and Rasul M.G., 2008, Feasibility of a Hybrid Cooling System in a Thermal Power Plant, Int. Conf. on Energy & Environment, University of Cambridge, UK, February 23-25, ISBN: 978-960-6766-43-5.

Wiliam, N.L., Ashlynn, S.S., 2019. Analyzing the economic value of thermal power plant cooling water consumption. Water Resour. Econ. 27,. https://doi.org/10.1016/j.wre.2019.01.003 100137.

Yong, Z., Alírio, E.R., 2001. Adsorbent materials for carbon dioxide. Adsorpt. Sci. Technol. 19 (3), 255–266.

Zhai, H., Rubin, E.S., Versteeg, P.L., 2011. Water use at pulverized coal power plants with postcombustion carbon capture and storage. Environ. Sci. Technol. 45 (6), 2479–2485. https://doi.org/10.1021/es1034443.

Zhai, H., Rubin, E.S., 2016. A techno-economic assessment of hybrid cooling systems for coal- and natural-gas-fired power plants with and without carbon capture and storage. Environ. Sci. Technol. 50 (7), 4127–4134. https://doi.org/10.1021/acs. est.6b00008.

Zhang, H., Feng, X., Wang, Y., Zhang, Z., 2018. Optimization of cooler networks with different cooling types in series and parallel configuration. Ind. Eng. Chem. Res. 58 (15), 6017–6025. https://doi.org/10.1021/acs.iecr.8b04059.

Zhang, W., Sun, C., Snape, C.E., Irons, R., Stebbing, S., Alderson, T., Liu, H., 2017. Process simulations of post-combustion CO 2 capture for coal and natural gas-fired power plants using a polyethyleneimine/silica adsorbent. Int. J. Greenhouse Gas Control 58, 276–289. https://doi.org/10.1016/j.ijggc.2016.12.003.

Zoelle, A., Keairns, D., Pinkerton, L. L., Turner, M. J., Woods, M., Kuehn, N., Chou, V. (2015). Cost and Performance Baseline for Fossil Energy Plants Volume 1a: Bituminous Coal (PC) and Natural Gas to Electricity Revision 3. NETL Report submitted to DOE, doi:10.2172/1480987.