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RESEARCH ARTICLE

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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

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Summary

Electric power generation from thermoelectric power plants is associated with a negative impact on water availability, referenced as the water-energy nexus, which is aggravated by climate change. In the present study, the effect of four different hybrid cooling system configurations on water usage and power penalty of a natural gas combined cycle has been investigated. The hybrid cooling system with a parallel connected indirect dry cooling system and wet cooling system is the most conventional studied hybrid cooling system in the literature, while the other studied hybrid configurations in the present study are novel regarding their effect on water requirement and power penalty. Simulations were conducted using the COCO 3.3 software and have been validated using data sets from a reference natural gas combined cycle plant, both with and without carbon capture unit, which is available in the literature. Four hybrid cooling system configurations were explored to evaluate their water requirements and power penalty. Other conventional cooling systems such as closed cooling, once-through, and direct and indirect dry cooling methods were simulated with and without postcombustion carbon capture (PCCC) integration for comparison. It was found that the hybrid configuration, including indirect air-cooled condenser and natural draft wet cooling tower, has the best performance as compared to the other conventional and hybrid cooling systems,

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Abbreviations: NGCC, natural gas combined cycle; FD, forced draft; ACC, air contact cooler; CT, cooling tower; ACTD, ACC-CT hybrid cooling system; ACTS, ACC-CT in series hybrid cooling system; DACW, direct ACC-wet cooling hybrid system; IDACT, indirect air-CT hybrid cooling system; DOE, Department of Energy; NETL, National Energy Technologies Laboratory; LHV, low heating value; HHV, high heating value; PV, photovoltaic; CSP, concentrated solar power; GCAM, Global Change Assessment Model; CWI, consumption water intensity; BAU, business as usual; LEAP, Long-range Energy Alternative Planning System; EGR, exhaust gas recirculation; HRSG, heat recovery steam generator; LP, IP, HP, low pressure, intermediate pressure, high pressure; PCCC, postcombustion carbon capture; DCC, direct contact cooler; MEA, methyl ethanol amine; CCS, carbon capture system

Nomenclatures: Q, amount of heat (J/s); $\dot{m}_{\mathrm{HW}}$, mass flow rate of hot water (kg/s); H_{HWout}, enthalpy of hot water out (kJ/kg); H_{HWin}, enthalpy of hot water In (kJ/kg); $\dot{m}_{\mathrm{C.air}}$, cooling air mass flow rate (kg/s); $H_{\mathrm{C.\ airout}}$, enthalpy of air out (KJ/Kg); $H_{\mathrm{C.\ airin}}$, enthalpy of air in (KJ/Kg); $\mathrm{Eff}_{i,j}^{m}$, Murphree efficiency; $y_{i,j}$, vapor phase for component i at stage j; Pr, air pressure (Pa); T, air temperature (K); Vol, volume (m^3); R, universal gas constant (J/mol. K).; $\dot{m}_{\mathrm{evp.los}}$, evaporated losses rate (kg/s); $\dot{m}_{\mathrm{cwcdsr}}$, cooling water mass flow rate (kg/s); $\Delta T_{\mathrm{tower}}$, temperature difference through the cooling tower (K); COC, cycles of concentrations; $\dot{m}_{\mathrm{feed.Suh.Stm}}$, superheated steam mass flow rate; $\dot{m}_{\mathrm{fuel.mass.Inlet}}$, fuel mass flow rate entering the plant; $\dot{m}_{\mathrm{gas.fuel.HRSG.in}}$, gas fuel mass flow rate into HRSG unit; η_{steam}, steam thermal efficiency; η_{gas}, gas thermal efficiency; $h_{\mathrm{g.\ fuel.\ HRSG.\ out}}$, enthalpy of the combusted gas at the outlet of the HRSG unit; $Q_{\mathrm{HRSG.\ in}}$,Q_{ccs}, heat imported to the HRSG and PCCC, respectively

amounting to 2.038 (gal/min)/MW_{net}, 1.573 (gal/min)/MW_{net}, and 12.29 MW for water withdrawal, consumption, and energy penalty, respectively, for the case of a unit without PCCC unit and 3.9 (gal/min)/MW_{net}, 2.928 (gal/min)/MW_{net}, and 15.177 MW for water withdrawal, consumption, and energy penalty, respectively, for a unit with carbon capture unit. It was confirmed that the PCCC integration approximately doubles the water withdrawal and consumption for all cooling systems. In addition, the indirect air-cooled condenser and wet cooling tower is still the best performing cooling system with PCCC integration.

KEYWORDS

CCS integration, hybrid cooling system, NGCC power plant, power penalty, water consumption, water energy nexus, water withdrawal

1 | INTRODUCTION

The water-energy-nexus term describes the strong relationship between electric power generation and water supply shortage,[1] where water withdrawal represents about 41% of the US total water usage, while the consumed water is equal to about 3% of the total US available fresh water.[2] Designing an efficient power plant cooling system network affects water requirements because 86% of the processed water in the plant is exhausted by the cooling system.[3] Wet cooling system is the main integrated unit in the plant where the major percent of water is consumed. Evaporated losses, drift losses, and blowdown losses in the cooling tower (CT) represent the water losses where the total discharge water in a system should be made up. To decrease water losses in the wet cooling system, CT could be combined with a dry cooling system, using air instead of water, as the cooling medium, although, dry cooling systems result in power penalties in the plant. Integrating wet and dry hybrid systems efficiently leads to a decrease in water requirements and power penalty simultaneously. Hybrid cooling systems are the best option by which the performance of power plant cooling process can be modified in terms of decreasing both water and power penalty requirements. Hybrid systems can be configurated in different arrangements corresponding to the plant's needs and its environmental conditions as will be discussed in this paper. Another factor affecting water and auxiliary power requirements in fossil power plant is adding carbon capture (CC unit), where adding this unit to the plant has been reported to double the amount of water requirement.[4] The only considered hybrid cooling system configuration in previous studies in terms of water requirement and power penalty is the parallel integrated configuration between wet and dry cooling systems where low-pressure (LP) stream from LP turbine is distributed between direct dry and wet cooling systems, and then, the condensed LP streams are combined and turned back again to the steam cycle, while the other hybrid configurations have not been investigated yet. Therefore, the novelty in this study is investigating the effect of three new configurations of hybrid cooling systems on water requirements and power penalty in addition to the conventional one. Two of the new considered hybrid designs are parallel connected and series connected direct dry and wet hybrid cooling systems, respectively, where the heated cooling water from the condenser is distributed between both the connected cooling systems. The third one is a parallel connected indirect dry and wet hybrid cooling systems where the LP stream from the LP turbine is distributed between both the connected cooling systems. Carbon dioxide emissions and water requirements for natural gas combined cycle (NGCC) power plants are about half these of those for coal-fired power plants.[5] Therefore, studying the effect of both PCCC and different hybrid cooling system configurations on water losses and power penalties in NGCC is considered in this study.

The relationship between water requirements and power generation has been studied extensively. Dehaghani and Ahmadikia[6] studied computationally retrofitting a 12-cell wet tower and a dry hybrid cooling system configuration with a high accuracy air flow regulation to decrease fan power and water requirement. It was found that increasing accuracy of air flow control leads to decrease in consumed power by the fan by about 64.6%; while retrofitting with the dry/wet hybrid system decreases water consumption by about 9.4%. Zhai and Rubin[3] investigated water usage and the added cost of pulverized coal power plant equipped with wet and dry cooling systems, with and with integrating PCCC by using the IECM software. It was found despite adding a dry cooling system to the hybrid configuration decreases the amount of water usage, the capital cost would be increased. Adding a PCCC doubles the amount of water usage and increases the capital cost. Research by Zhai and Rubin[7] investigated the effect of a hybrid cooling system on the total annual cost and water usage of a coal-fired and NGCC power plants with and without the integration an amine-based CC unit. The hybrid cooling system was designed by combining an ACC (air cooled condenser) and a wet tower in a parallel configuration. It was found that the hybrid system reduces the amount of water by about 80% without PCCC and 52% with the CC unit. To decrease the cost of the system in the summer season, only 30% of the system cooling load was removed by the wet cooling system. Tidwell et al[8] performed an analysis using the POWERSIM Studio 9 Expert software to characterize withdrawn fresh water by retrofitting a cooling system or using nonpotable water such as brackish groundwater and wastewater as an alternative resource in US power plants. It was shown that the use of brackish water is the least expensive approach despite having a higher operating and maintenance cost. Tidwell et al[8] recommended that retiring old power plants is more economic than retrofitting their cooling systems. Zhang et al[1] assessed water consumption in coal-fired power plants in China by retrofitting new cooling system technologies. They studied the water scarcity for various water resources and reported that increasing water consumption leads to increasing stress in northern China. El-Khozondar and Koksal[9] investigated water consumption in Turkish power plants by minimizing water requirements and upgrading cooling systems. Their simulations were conducted using the LEAP software (Long-Range Energy Alternative Planning System). Results showed that a BAU (business as usual) scenario has the highest water consumption throughout the estimated period. It was recommended replacing wet cooling systems by hybrid ones, to decrease the forecasted water consumption. The water-energy nexus for an Illinois's power plant was evaluated by Denooyer et al.[10] Two scenarios were studied: (a) switching coal fuel to natural gas and (b) changing once-through cooling to a closed-loop cooling system. An economic analysis was performed to evaluate retrofitting the fuel type and cooling system by utilizing a bottom-up engineering accounting approach. It was shown that retrofitting coal to natural gas and once-through cooling system to a wet cooling system decreases the total amount of water consumption, despite that this operation is less economically favorable. Loew et al[11] studied the feasibility of switching coal to natural gas and dry cooling to wet and once-through cooling by using the Integrated Environmental Control Model tool. It was founded that water withdrawal is reduced in a coal-fired power plant more than in the NGCC power plant when the dry cooling system is retrofitted. The cost of retrofitting a once-through cooling by a wet cooling system is lower for water withdrawal and higher for water consumption. Denooyer et al[10] and Loew et al[11] have suggested that retiring the old and the low-efficiency plant will be more cost-effective than retrofitting its cooling system.

Hette and Andy[12] have discussed the impact of a full-scale PCCC for a coal-fired power plant in Rotterdam (Netherlands) by utilizing ROAD (Rotterdam Opslag en Afvang Demonstrattieproject). Seawater was used as the cooling medium in the unit, which was integrated with flue gas desulfurization unit. It was shown that using ROAD leads to reduce freshwater because of the highly integrated design of the plant. Herraiz et al[13] investigated the effect of adding EGR (exhaust gas recirculation) to a CCGT (combined cycle gas turbine) power plant by using a rotary regenerative gas/gas heat exchanger to manage the water balance around the CC unit. It was found that using the hybrid cooling system with an upstream regenerative heat exchanger in the PCCC as dry direct contact cooler (DCC) reduces cooling water demand by 67% and process water demand by 35%, compare to using a wet cooling system Li et at[14] studied the effect of EGR (exhaust gas ratio) on a CCGT plant by investigating various recirculation ratios. It was found that a recirculation ratio greater than 50% increases the plant's efficiency by 0.4% and thus reduces the total energy and water consumption by increasing the CO_2 concentration in the reboiler. Ou et al[15] studied the effect of CO_2 capture level on water usage and process life cycle for both a coal-fired and a natural gas-fired power plant. Also, a sensitivity and uncertainty analysis of the life cycle was implemented. Yang Ou has shown that adding a PCCC increases the water life cycle remarkably as compared to the plant without CC unit. The amount of water usage differs with the type of coal-fired and the cooling technology installed. Magneschi et at[16] has also studied the impact of PCCC on the total water usage for several power plants, cooling systems, and PCCC technologies. Magneschi and his colleagues challenged and dispelled the quoted statement "adding PCCC doubles the total water usage in power plants." They concluded that the amount of plant's water usage is highly dependent on plant types, cooling technologies, and PCCC technologies. Gjorgiev and Sansavini[17,18] conducted an optimization study to reduce power curtailments and maximize electric power with reduced water requirements. Four parameters were included in this optimization study: hydrogenation, thermal generation, water river temperature, and river flow discharge. It was shown that electric generation is independent of water temperature and water discharge. Additionally, it was found that the once-through cooling system is more influenced than a wet tower system by water constraint policies.

Ackerman and Fisher[19] studied the effect of the water-energy nexus on long-term electricity planning by using carbon and water prices and by calculating the most and least water intensity with imposed limits on carbon emission and water usage. Frank and Fisher have found that the scenario without imposing limits on water usage and carbon emission is the most cost-effective. Vliet et al[20] studied the effect of water availability and climate change on thermal and hydropower plants, economically and technically. It has been concluded that the climate and temperature change, and water availability influence the power generation capacity for both thermal and hydropower plants. They also noticed that technology development will not reduce the concerns that involve increasing water scarcity. A number of steps should be taken to decrease these concerns whether by using renewable energy technologies or by adopting new strategies. Peck and Smith[21] have developed a new model and method to quantify water usage in power plants by calculating water consumption and withdrawal factors for various operating conditions and spatial scales. It was found that water usage is dropping in regions where renewable energy technologies have more contribution to electricity generation than other energy production technologies. Lin and Chen[22] evaluated the future water demand for power generation in China under three scenarios: upgrading the cooling system technology, increasing the number of nonthermal power plants, and reallocation of thermal power plants to the West of China. Lin and Chen reported that water withdrawal and consumption are projected to be 63.75 and 8.3 billion m^3 in 2030, respectively. It has been documented that upgrading the cooling system technology and power plant reallocation influence the total amount of water usage, while increasing the number of nonthermal power plants decreases the stress on water. Liu et al[23] has developed a Global Change Assessment Model (GCAM) by implementing a model for electricity and water demand in the United States at the state level. Seven scenarios were studied by including fuel portfolios, the type of cooling system, the intensity of water usage, and the tradeoff between water usage and water saving. With significant variation between states, water requirements are decreasing for all cases.

Water resources managing in a perfect way is necessary for reducing water requirements in cooling system. Walker et al,[24] Feeley et al,[25] and Hill et al[26] have investigated in their study using alternative water resources and management systems to reduce water withdrawal and consumption in the evaporative cooling systems. They used wastewater as a makeup water instead of using the fresh water by which the total demand on fresh would be reduced. Their results show that using wastewater as an alternative option for the fresh could be viable technically and economically in terms of water and energy cost saving if the concentrations of the salt and solids can be controlled in such a way that wastewater treatment cost would not be passed a certain limit.

In this study, an assessment of water withdrawal, water consumption, and power penalty for a NGCC power plant equipped with PCCC and a wet-cooling system has been investigated. Four proposed designs of hybrid cooling systems were analyzed for raw water withdrawal, water consumption, and power penalty. The effect of retrofitting the cooling system to once-through, direct and indirect air-cooling systems on water withdrawal and consumption, and power penalty has been investigated too. The hybrid configurations are a ACC-CT in parallel hybrid cooling system (ACTD), a ACC-CT in series hybrid cooling system (ACTS), direct ACC-wet cooling in parallel hybrid system (DACW), and an indirect air-CT parallel hybrid cooling system (IDACT). The only conventional investigated hybrid cooling system in literature works regarding the impact on water usage and power penalty is the DACW configuration. Thus, the novelty of the present work is investigating the effect of the other three configurations and compares the results with the conventional one (DACW). The study has conducted for hybrid cooling systems with and without PCCC effect. The COCO.3.3 software was employed to perform simulations, and an EXCEL workbook interface was enabled in the software to develop all the required calculations for water requirements and power penalty estimates.

2 | THE HYBRID COOLING SYSTEM DESIGN CONFIGURATION

In power plants, the major portion of withdrawn water is used for the cooling system to dissipate the waste heat of the power cycle in the condenser section. Conventional cooling systems can be classified into water-cooled (wet type) and air-cooled (dry type), based on the cooling medium. In wet cooling systems, water consumption is a major concern, while in dry cooling system, the consumed power for running the cooling system, power penalty, is the main drawback. In order to benefit from the advantages of both systems and mitigate their drawbacks, hybrid cooling systems are proposed in which both wet and dry cooling systems are combined. With hybrid cooling systems, the cost and energy penalties of the dry cooling system and the vulnerability of water scarcity of wet cooling systems would be reduced. Four different hybrid system configurations are proposed and studied. In the first two designs, the condensation process is handled in the main condenser and required cooling water is supplied through parallel or series configuration of wet and dry cooling systems. For the other two designs, the main condenser is eliminated, and the condensation process is handled in downstream wet and dry cooling systems that are arranged in a parallel configuration. For a better comparison of system performance, the loading condition for wet and dry cooling systems is considered equal. This equal loading is not necessarily the optimum operating condition, but it is considered for an unbiased comparison of system performance among the configurations studied.

2.1 | ACC-CT hybrid cooling system (ACTD)

In this configuration, an ACC (dry cooling system) and a natural draft CT (wet cooling system) are arranged in a parallel arrangement. The hot cooling water leaving the main condenser (stream 6) is divided equally between the ACC (stream 7) and CT (stream 9) units. After cooling in the parallel systems, the cooling water streams merge and return to the condenser unit as cooling water supply (streams 10, 11, 12, and 5; see Figure 1A). The total cooling load of the system depends on the cooling water flow rate and enthalpy changes in the cooling system.

$$Q_{\text{main-condenser}} = \dot{m}_{\text{HW}} \times (H_{\text{HCWout}} - H_{\text{CCWin}}). \quad (1)$$

As the enthalpy change remains constant, the controlling parameter for cooling load adjustment is the water mass flow rate, $\dot{m}_{\text{HW}}$; H_{HCWout} is the enthalpy of the hot cooling water exiting from the condenser; H_{CCWin} is the enthalpy of the cold cooling water entering to the condenser. It is assumed that the cooling water mass flow is divided equally between both parallel dry and wet systems. Equal distribution of cooling water flow rate (fraction factor) is controlled in the flow splitter that is located after the main condenser. Maintaining equal water flow rate for parallel cooling systems, ACC and CT, results in an equal cooling load distribution. The split

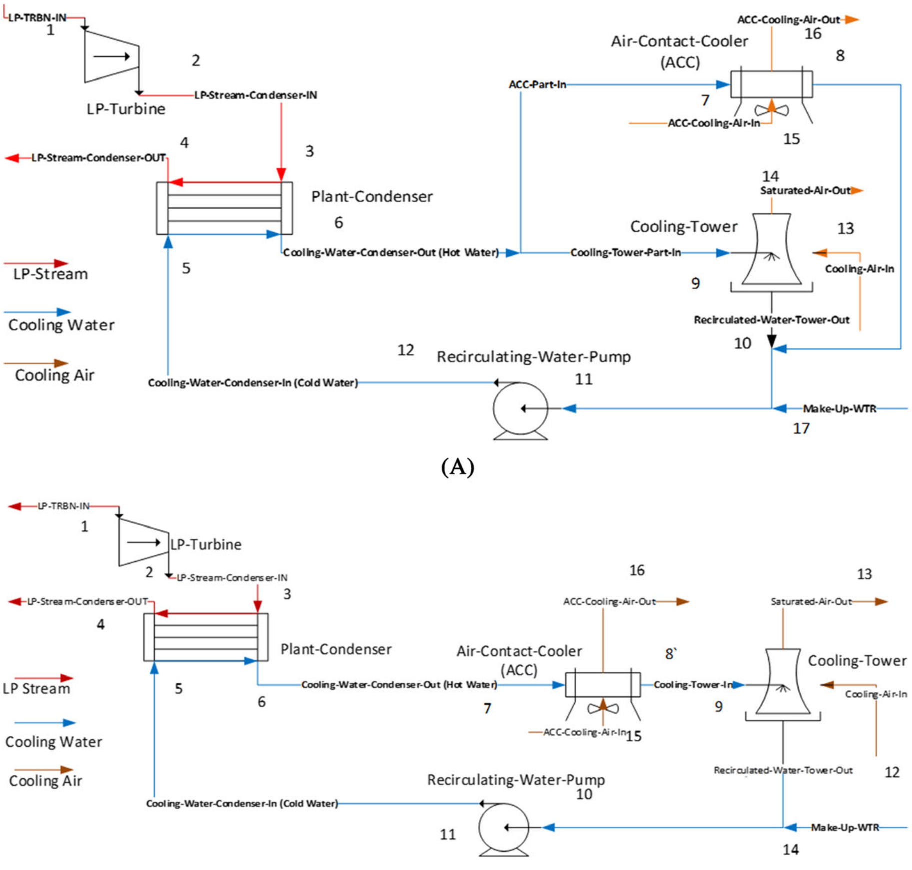


FIGURE 1 Hybrid cooling system configurations with the main condenser and circulating cooling water. A, Hybrid cooling system with a parallel air-cooled condenser (ACC) and cooling tower (CT) units (ACTD). B, Hybrid cooling system with ACC and CT units in the series [Colour figure can be viewed at wileyonlinelibrary.com]

streams merge after cooling (streams 8 and 10) and recirculating pumps (stream 12) return the cooling water supply (stream 5) to the main condenser to complete the cooling cycle.

2.2 | ACC-CT in the series hybrid cooling system (ACTS)

Similar to the ACTD design, in this configuration, the condensation is handled in the main condenser that is cooled with circulating cooling water. The downstream wet and dry cooling systems are arranged in series in which the cooling water flows through each unit (see Figure 1B). The dry cooling package (stream 7) is located before the wet cooling system (stream 9), and an equal loading condition is maintained via dry cooling system loading control. Due to the series assembly of ACC and CT units, maintaining equal load distribution can be achieved via controlling the ACC unit loading by regulating the air flow rate (stream 15).

$$Q_{\mathrm{ACC}} = \dot{m}_{\mathrm{C.air}} \times \left(H_{\mathrm{C.airout}} - H_{\mathrm{C.airin}}\right), \tag{2}$$

where Q_{ACC} is the removed cooling load in the ACC, $\dot{m}_{\mathrm{C.air}}$ is the cooling air mass flow rate, $H_{\mathrm{C.\ airout}}$ is the hot cooling air form the ACC, and $H_{\mathrm{C.\ airin}}$ is the cold cooling air to the ACC.

2.3 | Direct ACC-Wet cooling hybrid system (DACW)

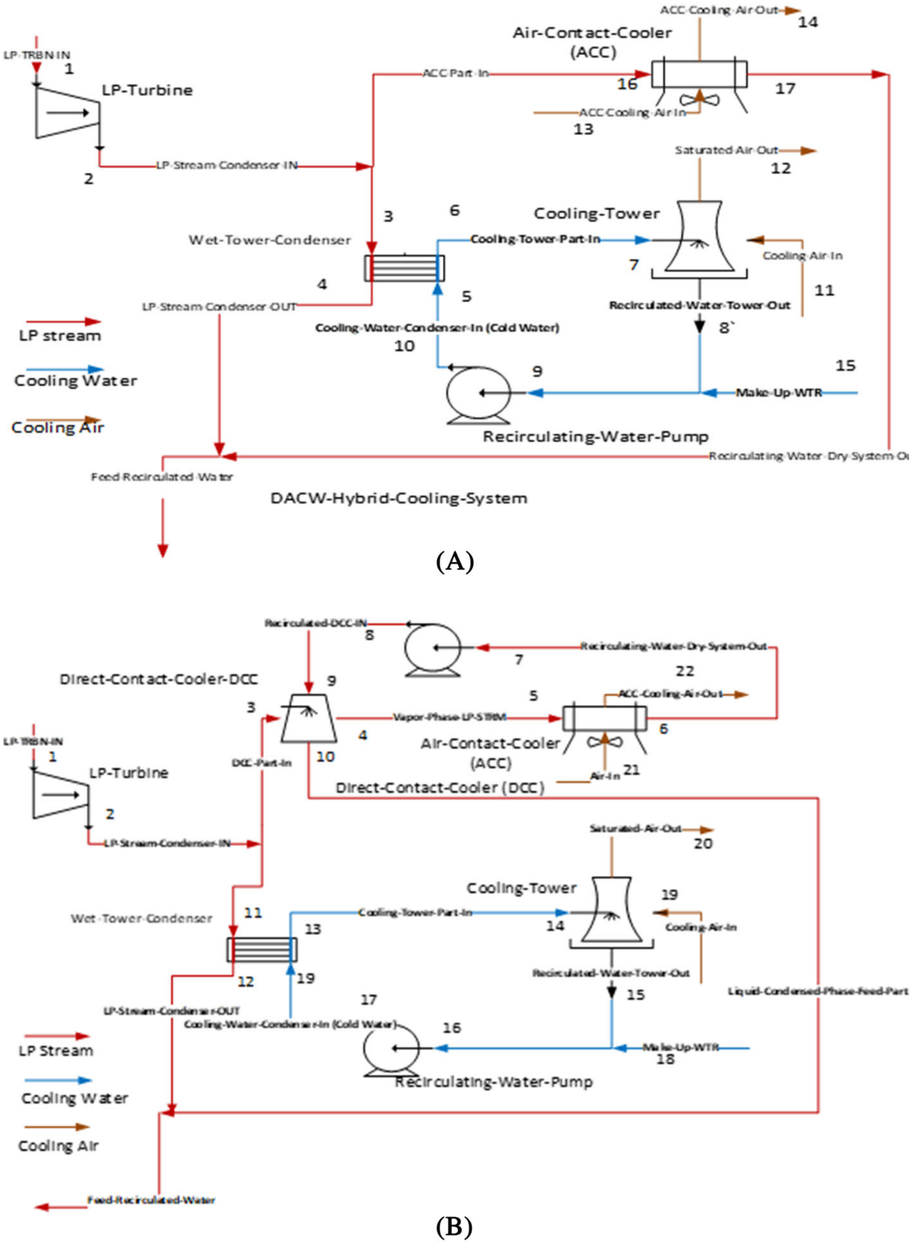
In this hybrid design, the stream leaving the LP turbine (stream 2) is directly fed to the cooling modules. The stream (saturated steam and water mixture) is divided between the ACC and wet cooling system (streams 16 and 3) without passing through any intermediate condenser heat exchanger except in the wet cooling system where a condenser is included in the wet cooling system; thus, the condensation process is handled within the cooling packages (streams 17 and 4; see Figure 2A). The phase change process (condensation) is handled at a constant temperature. The main difference in design parameters for the downstream cooling packages is that the hot side temperature remains constant throughout the cooling process. The stream leaving the LP turbine (stream 2) is a mixture of saturated steam and water with quality of about 91%. The downstream ACC and CT units are designed in a parallel assembly, and the cooling fluid splits in a manner to maintain equal cooling load for each cooling unit. The generated condensates leaving the cooling packages are mixed and returned to the condensate polishing plant for restarting the steam cycle. Equal cooling load distribution is controlled via the distribution of the flow rate of cooling fluid.

2.4 | Indirect air-CT hybrid cooling system (IDACT)

Similar to the DACW design, the stream leaving LP turbine (stream 2) is fed directly to the downstream cooling packages in the IDACT hybrid design. The condensation process is handled within the indirect dry and wet cooling systems unit. The indirect ACC unit is considered in parallel with CT cooling unit (see Figure 2B). For the indirect ACC, a DCC unit is used for phase separation and spraying the return condensate from ACC package for direct contact cooling and condensation of accumulated steam (streams 3 and 9). The separated steam is fed to the ACC (stream 5) for condensation, and returned condensate is sprayed in the DCC section (streams 6, 7, 8, and 9), the collected condensate (stream 10) is merged with wet cooling condensate (stream 12), and the whole stream is returned to the condensate polishing plant for steam cycle resumption.

Economically, the four proposed configurations need furthermore separated scientific work to be investigated to figure out the most feasible design. However, Zhai and Rubin[7] and Balogh and Szabo[27] have investigated the third and the fourth configurations, respectively, from economic point of view where LP stream is distributed between both dry direct and wet cooling systems in the third one and between the indirect dry and wet cooling system in the fourth one in combined cycle power plant as being shown in the table below.

Table 1 shows that using the third configuration leads to save 3.56 m € annually comparing to the based integrated cooling system (wet cooling technology), while cost saving is reduced with using the fourth configuration. This finding is expected because the fourth configuration has more piping system and construction than the third one. Furthermore, maintenance and operation costs for the fourth one are much higher than the third one.[28] Regarding the first and the second proposed configurations where the heated cooling water would be distributed equally between both cooling systems instead of distributing the LP stream, it has been expected that the cost would much lower than the third and the fourth once. This is likely expected because in the third and the fourth scenarios, the distributed LP stream has a high vapor content. Consequently, pipes and heat exchanger biofoulings are expected, and maintenance and operation cost are increasing as a result.



(A)

(B)

FIGURE 2 Hybrid cooling system configurations with condensation in cooling packages. A, The third proposed hybrid system (direct air-cooled condenser-wet cooling hybrid system [DACW]). B, The fourth proposed hybrid system (indirect air-cooling tower hybrid cooling system [IDACT]) [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 1 Comparing the cost saving (Euro Currency) between the indirect dry and wet hybrid cooling system and the based wet cooling system (the fourth configuration) for CCPP power plant according to Balogh and Szabo[27] and the direct dry and wet hybrid cooling system (The third configuration) according to Zhai[7]

Direct Dry and Wet Hybrid Cooling System[7] (Third Configuration)	Indirect Dry and Wet Hybrid Cooling System (Heller)[27] (Fourth Configuration)	Based Wet Cooling System
-4 m \$ = -3.56 m € (Gain)	-1.929 m € (Gain)	+9.653 m € (Cost)

Abbreviation: CCPP, combined cycle power plant.

3 | MATHEMATICAL AND GOVERNING EQUATIONS

The main governing equations, which are involved in the calculations of the present study, are divided into three parts; calculations of steam cycle, calculations of gas cycle, and calculations of the cooling system.

In the gas cycle, the main governing equations are the equations that involve calculating gas net produced power and cycle efficiency where:

$$\text{Net Produced Power} = \text{Gas Turbine Power-Air Compressor Power} \\ = \left(m^{\cdot}_{\text{Combusted}-\text{Fuel}} \times \left(h_{\text{g.in}} - h_{\text{g.out}}\right)\right) - \left(m^{\cdot}_{\text{Compressed}-\text{air}} \times \left(h_{\text{air.out}} - h_{\text{air.in}}\right)\right), \tag{3}$$

$$\text{Gas Cycle Efficiency} = \frac{\text{Net Produced Power}}{(\text{Fuel Heating Value(High, or Low)}) \times \text{m}^{\cdot}_{\text{fuel.mass.Inlet}}}. \tag{4}$$

The main equations in the steam cycle calculations are

$$\begin{aligned}\text{Net Produced Power} = {} & \text{HP turbine power} \\ & + \text{IP turbine power} \\ & + \text{LP turbine power},\end{aligned} \tag{5}$$

where:

$$\text{Turbine Power} = m^{\cdot}_{\text{feed.Suh.Stm}} \times \left(h_{\text{in}} - h_{\text{out}}\right) \tag{6}$$

The steam cycle efficiency is equal to

$$\eta_{\text{steam}} = \frac{\text{Turbines Net Produced Power}}{Q_{\text{HRSG.in}}}$$

where:

$Q_{\text{HRSG. in}}$ is the heat input to HRSG system and this is equal to

$$Q_{\text{HRSG.in}} = m^{\cdot}_{\text{gas.fuel.HRSG.in}} \times \left(h_{\text{g.fuel.HRSG.in}} - h_{\text{g.fuel.HRSG.out}}\right). \tag{7}$$

In case of integrating CC unit, η_{steam} is expected to be increased and the equation will be

$$\eta_{\text{steam.CCS}} = \frac{\text{Turbines Produced Power} - \text{The penalty because of integrating the CCS unit}}{Q_{\text{HRSG.in}} - Q_{\text{ccs}}\ (\text{The extracted heat for the CCS reboiler})}, \tag{8}$$

where $m^{\cdot}$,η_{steam},h,and Q are mass flow rate, efficiency, enthalpy, and heat duty, respectively. Regarding the cooling system, a number of calculations have been shown in the previous sections; the rest evaporative cooling calculations are shown in the next sections.

4 | RESULTS AND DISCUSSION

4.1 | Validation

Numerical simulations were conducted using the COCO.3.3 software for a complete NGCC power cycle together witch auxiliaries, including the cooling system. Peng Robinson property method was used as an equation of state to calculate the physical properties of gases. The calculations were performed for the processed feed water and steam using the IAE steam property method. A closed cooling system type was considered for the cooling section. The CT was modeled using an equilibrium RADFRAC block with a design temperature of 15.5°C according to the reference case. Using the RADFRACK block as a tower was first used by Queiroz et al[29] with the following assumptions:

1. A non-random two liquid property method has been set to calculate thermophysical properties.
2. Murphree efficiency was set to calculate the ideality of the phases at each stage as

$$\text{Eff}^{m}_{i,j} = \frac{y_{i,j} - y_{i,j+1}}{y^{*}_{i,j} - y_{i,j+1}}, \tag{9}$$

where $\text{Eff}^{m}_{i,j}$ represents Murphree efficiency and y represents the vapor phase for component i at stage j according to Joao A. Queiroz's notation.[29]

A validation test was conducted using a reference 630 MW NGCC plant with a closed cooling system, as documented in the 2015 NETL's report.[30] The combined cycle includes a gas turbine package with a 422-MW capacity. The flue gas leaves the gas turbine package at 603°C before entering a downstream Heat Recovery Steam Generator (HRSG) package. The heat of the flue gases is recovered in the HRSG to generate superheated steam for the combined steam cycle. Generated steam expands in three pressure level steam turbines (high pressure [HP], intermediate pressure [IP], and LP) for completion of the combined Rankine cycle. The steam leaving the LP turbine is condensed in a main condenser unit, which is cooled with a closed loop cooling system.

The results of the validated simulation of the referenced plant and cooling system are provided in Tables 2 and 3. The results predicted by the present study are in good agreement with the documented values in the NETL report[30]; indicating the model and method utilized are validated.

TABLE 2 The results of simulations for the actual NGCC plant referenced in the NETL report[30]

Description	NETL Report Reference Case	Simulation Results
Gas power (MW)	422	422.3
Fuel-gas-flow-rate (kg/s)	23.37	23.37
Steam power (MW)	219	219.95
Gross electric power (MW)	641	642.25
Net electric power (MW)	630	630.25
Air in mass flow rate (kg/s)	1,006.32	1,006.32
Mass flow rate to HRSG (kg/s)	1,029.7	1,029.69
Temperature of HRSG inlet (°C)	603	603.12
Steam cycle efficiency	39.1%	39.2%
Gas cycle LHV efficiency	38.1%	38.3%
Gas cycle HHV efficiency	34.5%	34.5%
LHV net efficiency	57.0%	57.1%
HHV net efficiency	51.5%	51.6%
HP turbine temperature (°C)	565.55	565.56
IP turbine temperature (°C)	565.55	565.56
LP turbine temperature (°C)	272.22	272.23
Condenser temperature (°C)	38.33	38.33

Note. The predicted results are compared to those documented in NETL report.[30]

Abbreviations: HHV, high heating value; HP, high pressure; HRSG, heat recovery steam generator; IP, intermediate pressure; LHV, low heating value; LP, low pressure; NETL, National Energy Technologies Laboratory; NGCC, natural gas combined cycle.

4.2 | Comparison among the hybrid cooling system configurations

The proposed hybrid cooling system configurations were simulated, and performance criteria regarding water consumption, water withdrawal, and power penalty were compared. The power penalty, which has been considered in the calculations of the present study, is the consumed power through air fans and water pumps of the cooling system. Water withdrawal and consumption amounts in this study represent the amount of water that would be made up to the tower as a result of evaporative, drift, and blowdown losses. The following assumptions were considered in the simulations:

- A constant ambient air condition was considered, representing a 10.8°C wet bulb temperature and 60% relative humidity.
- A natural draft tower was considered for all simulations to reduce power penalty.
- The cooling water inlet temperature was set at the design tower temperature.
- The air to water ratio in the CT was set to 0.803 according to Queiroz.[29]
- The approach temperature for all heat exchangers was set to not exceed 6°C.

For the performance comparison of the four proposed hybrid configurations, it was assumed that the cooling load is divided equally between the dry and the wet cooling systems for all design configurations. The amount of withdrawn and consumed water and the power penalty of the hybrid cooling configurations considered in this study are listed in Table 4 and depicted in Figure 3. It is demonstrated that the IDACT yields the lowest amount of raw water withdrawal, raw water consumption, and power penalty with 2.038 (gal/min)/MW$_{net}$, 572 (gal/min)/MW$_{net}$ and 12.19 MW, respectively. The IDACT is found to be the best hybrid cooling system compared to the other proposed hybrid cooling systems. However, despite having the best performance, IDACT cooling system is a cost-effective design due to a number of additional equipment added.[28-31] Having more equipments increases both capital and operating and maintenance costs. Also, the large dependence of the dry cooling system to the ambient conditions should be considered as one of the intrinsic drawbacks of the system. It is important to note that the water rates are within close range for four hybrid systems within 6.5% deviation,

TABLE 3 Simulation results for the cooling system of the reference NGCC plant

Parameter	NETL Reference Case	Simulation Results
Condenser duty (GJ/hr)	1,281	1,345.0
Water consumption (gal/min)/MWnet	3.3	3.2
Water withdrawal (gal/min)/MWnet	4.2	4.2
Inlet temp. of condenser (°C)	16	16
Outlet temp. of condenser (°C)	27	27.3
Tower exit temperature(°C)	15.5	14.7

Note. Predicted results are compared against those documented in the NETL report.[30]

Abbreviations: NETL, National Energy Technologies Laboratory; NGCC, natural gas combined cycle.

TABLE 4 Comparison of raw water withdrawal, water consumption, and power penalty among proposed hybrid cooling systems for the reference NGCC plant

Parameter	ACC + CT (Parallel) ACTD	ACC + CT (Series) ACTS	Direct ACC + CT (Parallel) DACW	Indirect + CT (Parallel) IDACT
Raw water withdrawal (gal/min)/MWnet	2.18	2.14	2.10	2.04
Raw water consumption (gal/min)/MWnet	1.68	1.65	1.61	1.57
Power penalty (MW)	25.68	13.88	24.55	12.29

Abbreviations: ACC, air-cooled condenser; CT, cooling tower; ACTD, ACC-CT hybrid cooling system; ACTS, ACC-CT in series hybrid cooling system; DACW, direct ACC-wet cooling hybrid system; IDACT, indirect air-CT hybrid cooling system; NGCC, natural gas combined cycle.

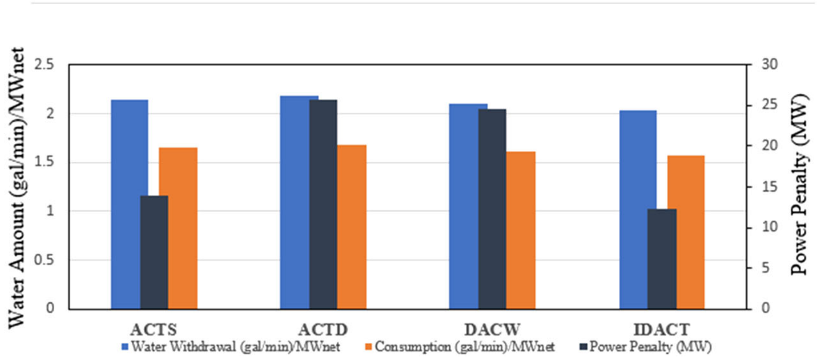


FIGURE 3 Comparison of the proposed hybrid cooling system configurations in terms of water consumption, water withdrawal and power penalty. A, The water withdrawal and consumption for conventional cooling systems and indirect air-cooling tower hybrid cooling system (IDACT) hybrid cooling design. B, The power penalty for conventional cooling systems and IDACT hybrid cooling design. [Colour figure can be viewed at wileyonlinelibrary.com]

which represents the difference between each value at each case as shown in Figure 3. The rate of water consumption and withdrawal per net generated power (gal/min)/MW$_{net}$) depends on the power penalty. An increase in the power penalty leads to a decrease in the net power; consequently, it increases the rate of required raw water per net generated power where net generated power is calculated from:

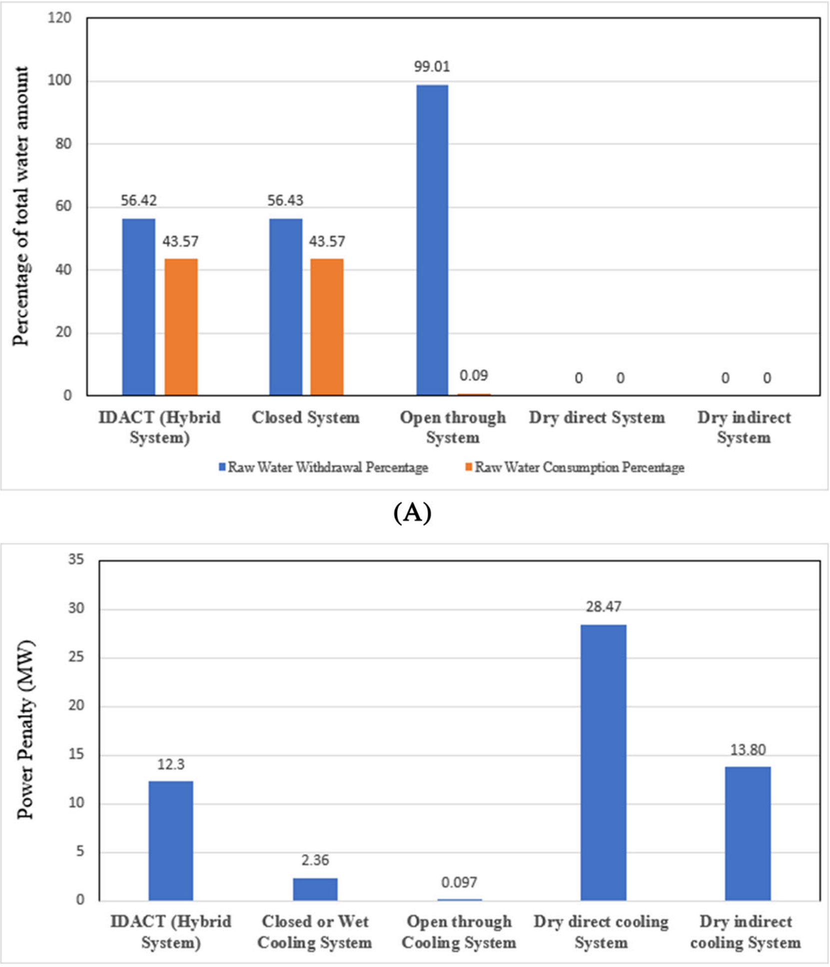
$$\text{Net generated power} = \text{Plant gross power–Auxiliary load} \tag{10}$$

4.3 | The effect of retrofitting cooling system

The performance of the most effective hybrid cooling system (IDACT) was compared to the conventional cooling systems in Figure 4. The open through system, closed-loop wet cooling system, direct dry cooling system, and indirect dry cooling system were the selected conventional cooling systems for the comparison analysis. There is no water withdrawal and consumption for dry cooling systems (both direct and indirect), while they have a high-power penalty as the cooling requires maintaining an air flow rate.

The comparative percentage of water withdrawal and consumption is depicted in Figure 4A to avoid the disparity in water withdrawal amount between the open-through system and the other conventional cooling systems.

The largest water withdrawal is obtained for the open-through cooling system. The water rate, 183.3 (gal/min)/MWnet, is consistent with the value documented in the NETL report. This relatively high value of water withdrawal is due to the limited admissible temperature difference between cooling water supply and return that requires a higher flow rate to handle the related cooling load. On the other hand, the open-through cooling system has the lowest power penalty, and the dry direct cooling system has the highest power penalty among the conventional cooling systems considered. This is due to the fact that a dry direct cooling system uses air as a cooling medium, while the open-through cooling system is a water-based system. The heat capacity of water is about four times greater than that of air, and the compressibility factor of air is much greater than the corresponding value for water; leading to more power consumption in the dry system as compared to the wet system. The open through the cooling system has a positive impact on raw water withdrawal and consumption. Although the open-through cooling system has no or little water consumption, it has a significant environmental impact. The admissible temperature difference between cooling water supply and return temperature in the open-through



(A)

(B)

FIGURE 4 Comparison of raw water withdrawal and consumption (water consumption for open-through system = 1% of the total withdrawal for the open-through condenser[32]) for conventional cooling systems and indirect air-cooling tower hybrid cooling system (IDACT) hybrid design. [Colour figure can be viewed at wileyonlinelibrary.com]

system is 11°C.[2] Any further increase in return water temperature will result in a temperature rise of the water resource. The source temperature rise is strictly limited to 1.5°C.[33] Exceeding these critical limits will result in “thermal pollution” causing profound environmental side effects Rutberg[32] and Caissie et al.[34] Regarding the performance of dry cooling systems, the power penalty for the indirect cooling system is nearly half of that of a direct cooling system. In an indirect dry cooling system, the steam leaving the LP turbine is condensed in the ACC and returned to the DCC where the cooled returned condensate is directly sprayed into the stream resulting in more steam phase condensation. This configuration leads to a reduction of required air flow rate and thus reducing required fan power according to the ideal gas law:

$$\text{Fan Power} = \text{Pr} \times (\Delta \text{Vol}), \tag{11}$$

$$\text{Pr} \times \text{Vol} = \text{Mass} \times R \times T, \tag{12}$$

where Pr is air pressure, Mass is air mass flow rate, T is temperature, and R is the universal gas constant. It is shown that the IDACT configuration has the lowest value of water withdrawal and consumption, as well as power penalty, as compared to the other conventional cooling systems. The power penalty of IDACT is about half the amount of power penalty for the DACW configuration, which confirms that IDACT is the best option in terms of both water consumption and power saving.

4.4 | The effect of PCCC integration on cooling system

4.4.1 | Validation with PCCC integration

Reducing the negative impact of NGCC power plants on global warming requires removing carbon dioxide gas from the flue gas stream leaving the HRSG system. CO_2 gas has the largest contribution to greenhouse gases. In order to remove CO_2 from the flue gas leaving the HRSG package, a separate PCCC needs to be considered. In CC unit, the flue gas is cooled down to 35.85°C within a heat exchanger before the absorber section. Temperature control of the flue gas is necessary to prevent solvent degradation inside the absorber.[35] A FD fan (forced draft fan) is used to pressurize the flue gas stream in order to maintain the pressure in the absorber at a certain design level and compensate the pressure drop throughout the process. In the absorber unit, a new way has been used in the carbon capture simulation where the lean solvent stream and the flue gas enter the absorber having two stages. In the first stage, the mainstream of the absorber enters a chemical compound splitter. In the present model, the mole fraction of each compound was set according to the NETL report to get the same value of the parameters listed in the report (see Tables 5 and 6). Then, the absorption stage was set by absorbing the CO_2 by an methyl ethanol amine (MEA) solvent, where the MEA is a 15 wt.% of the MEA-water mixtures, and the $CO_{2\ mole}/MEA_{\ mole}$ loading was about 0.314. A regenerative heat exchanger is used in the model to heat the rich solvent leaving the absorber by the hot lean solvent that comes from the stripper at about 116°C. After passing the regenerative heat exchanger, the rich heated solvent is fed to the stripper in which the stream is further heated to release the absorbed CO_2. The released CO_2 is collected and fed to a compressor package for delivery to a disposal facility. The flow diagram of the considered PCCC is based on the NETL report,[30] and it is provided in Figure 5. The stripper column has a built-in reboiler heat exchanger in which the heat of extracted steam from the LP turbine is used for heating the solvent for the regeneration process.

TABLE 5 Parameters of the integrated CCS compared to the corresponding values in the NETL report[30]

Parameter	NETL Report -2015	The Current Study
Steam power (MW)	179	178.12
Net power (MW)	559	559.46
Net HHV efficiency%	45.7%	45.777%
Net LHV efficiency%	50.6%	50.72%
CO_2 mass flow rate enters to the compressor (Ib/hr)	448 649	448 624.11
Capture rate %	90%	90.10%
Gas mass flow rate in the sack (Ib/hr)	7 514 952	7 529 198.10

Abbreviations: CCS, carbon capture system; HHV, high heating value; LHV, low heating value; NETL, National Energy Technologies Laboratory.

TABLE 6 Component fractions of the integrated CCS compared with the corresponding values in the NETL report[30]

Component	NETL Report -2015	The Present Study
H_2O fraction in the stream that enters the CCS	0.0841	0.0841
CO_2 fraction in the gas in the stack	0.0042	0.00418
H_2O fraction in the gas in the stack	0.0468	0.0497
N_2 fraction in the gas in the stack	0.8054	0.803
O_2 fraction in the gas in the stack	0.134	0.1335
CO_2 fraction in the stream from stripper to compressor	0.9824	0.982
H_2O fraction in the Stream from stripper to compressor	0.0176	0.0178
CO_2 fraction in the stream that enters the CCS	0.0391	0.39

Abbreviations: CCS, carbon capture system; NETL, National Energy Technologies Laboratory.

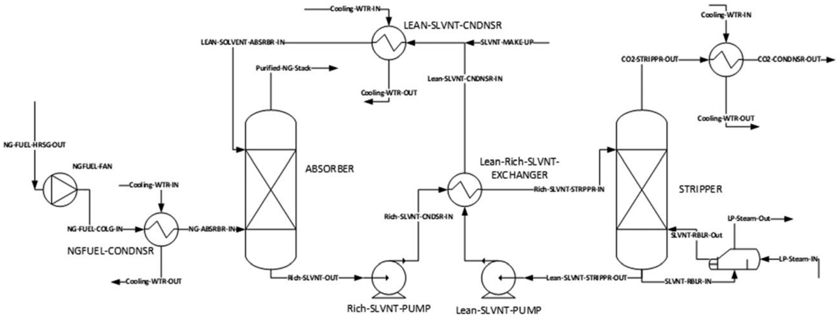


FIGURE 5 The carbon capture system (CCS) process flow diagram. A, Raw water withdrawal. B, Raw water consumption. C, The effect of adding CCS on power penalty for the proposed hybrid cooling configurations

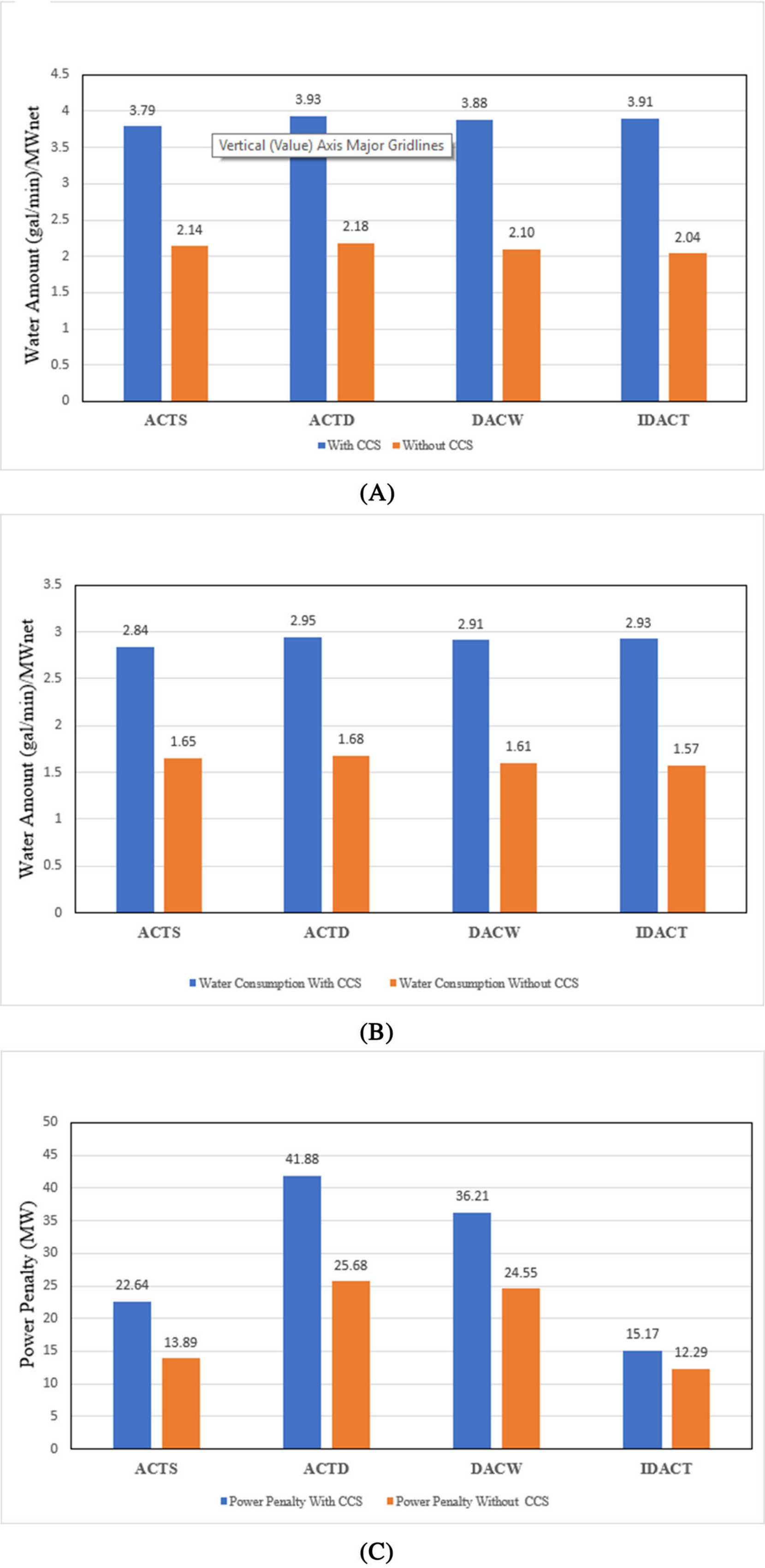


FIGURE 6 Comparison of water withdrawal, water consumption, and power penalty among proposed hybrid cooling systems considered in this study. A, Raw water withdrawal with and without carbon capture system (CCS). B, Raw water consumption with and without CCS. C, Power penalty with and without CCS. [Colour figure can be viewed at wileyonlinelibrary.com]

4.4.2 | Impact of PCCC integration on hybrid cooling system

In this section, the performance of the four hybrid configurations including the incorporation of a PCCC to the NGCC plant is summarized. To supply the required heat duty when the PCCC is integrated into the IDACT hybrid system, the PCCC heat duty is processed by using a direct dry cooling system. The total amount of heat load removed by both direct and indirect dry cooling system is equal to the total amount of heat removed by the CT. Thus, the cooling load is equally divided between both the dry and wet cooling systems. To evaluate the evaporative mass loss properly, an empirical correlation, developed by Perry and Green,[36] is utilized:

$$\dot{m}_{\text{evp.los}} = 0.00085 \times \Delta T_{\text{tower}} \times \dot{m}_{\text{cwcdsr}} \times 1.8, \tag{13}$$

where $\dot{m}_{\text{evp.los}}$ is the evaporated water loss through the tower, ΔT_{tower} is the temperature difference across the tower, and $\dot{m}_{\text{cwcdsr}}$ is the cooling water mass flow rate across the condenser. Drift losses was assumed to be 0.1% of the cooling water mass flow rate. The blowdown losses rate can be calculated according to the NETL report[30] as

$$\text{Blowdown} = \frac{\dot{\text{m}}_{\text{evp.los}}}{\text{COC} - 1}, \tag{14}$$

where COC represents a number of cycles of concentrations. Cycles of concentrations can be calculated according to EDF[37]:

$$\text{COC} = \frac{C_B}{C_M}, \tag{15}$$

where CB represents the concentration of solids and salts in the blowdown and CM is the concentration in the makeup water.

The results related to water consumption, water withdrawal, and power penalty for the four proposed hybrid cooling systems, including PCCC integration, are listed in Table 6 and depicted in Figure 6, for comparison. The ACTS has the lowest water usage with 3.789and 2.841 (gal/min)/MWnet for water withdrawal and consumption, respectively. The part of the PCCC heat duty was separated and distributed equally between the dry and wet cooling system. Hence, the water circulation rate is slightly less than the corresponding cooling system without integrated CC unit. Despite having slightly higher water consumption, the IDACT system with integrated PCCC has a much lower power penalty, 15.177 MW, compared to the other hybrid cooling configurations. The integration of PCCC nearly doubles the water withdrawal and consumption of the proposed hybrid cooling system configurations, as shown in Figures 6A and 6B. The results presented here are consistent with the results reported in related references.[3,38,39] As shown in Figure 6 C, integration of the PCCC increases the power penalty significantly in all hybrid cooling system configurations, except in the IDACT design, which was selected as the most effective cooling system without PCCC integration. This is due to the fact that the condenser duty in the IDACT case is reduced by about 30% when carbon capture is included, since the extracted steam from the LP turbine used in the stripper reboiler results in decreasing the cooling air mass flow rate in the indirect cooling system. Moreover, the PCCC waste heat is not dissipated by the DCC and ACC in the indirect dry cooling system for the IDACT design; instead, it is drawn from the hot gases, and there is no vapor content to be extracted in the DCC. The PCCC waste heat when removed by a closed cooling system, where the water is the only cooling media; results in a further decrease in the power penalty as compared to the air-cooled systems. The small amount of waste heat, not exceeding 18%, is added to the direct dry cooling system to distribute heat equally between both the dry and wet cooling systems. Thus, a small power penalty is added to the case without CC unit. As a result, the power penalty for IDACT with integrated PCCC is only 3 MW higher than the design case without carbon capture, as listed in Table 7 and depicted in Figure 6C.

4.4.3 | Comparison of IDACT hybrid design against conventional cooling systems with and without CC unit

In this section, the performance of the conventional cooling systems with integrated PCCC is reported, and

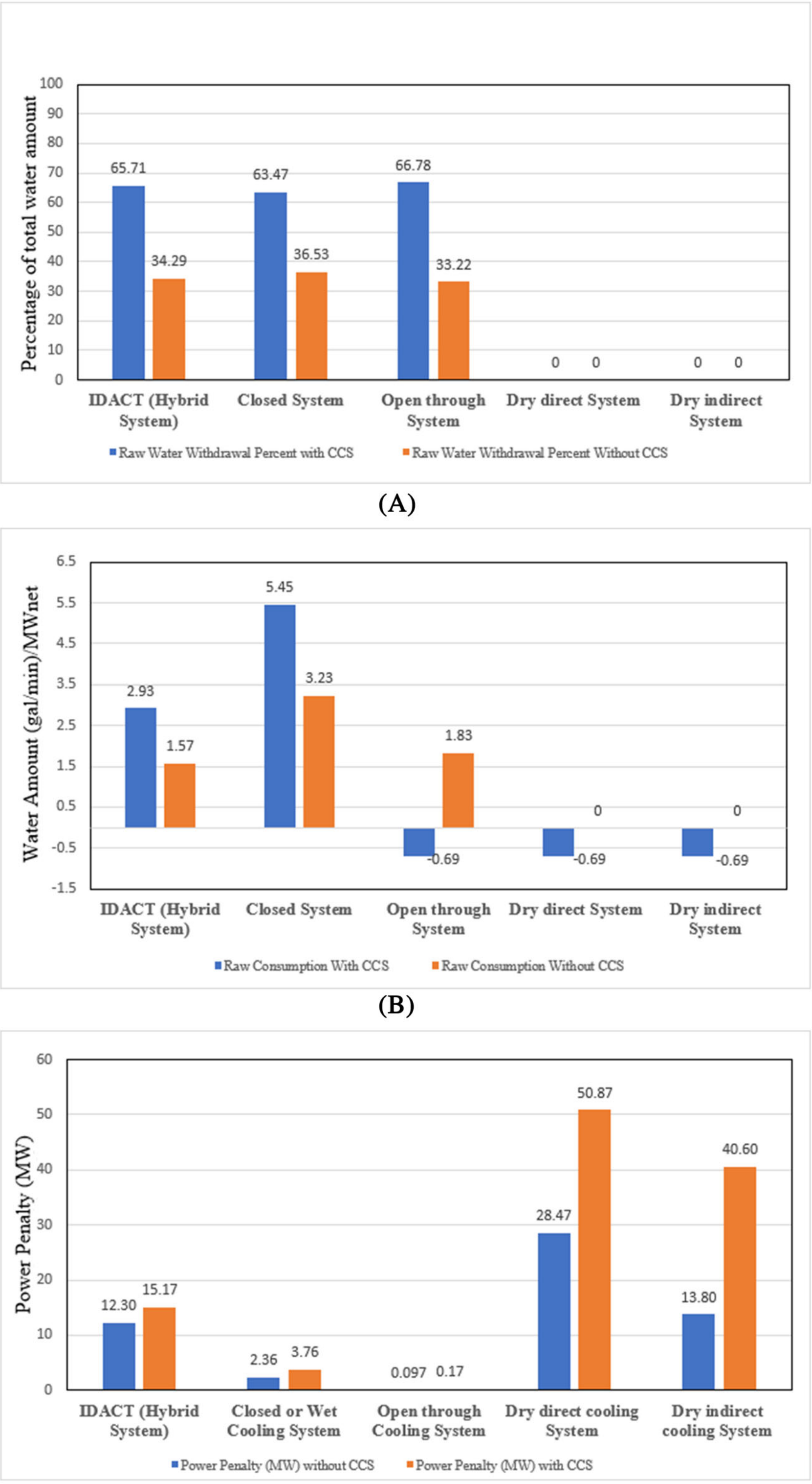
TABLE 7 Raw water withdrawal, water consumption, and power penalty of hybrid cooling systems with integrated CCS

Parameter	ACTD	ACTS	DACW	IDACT
Raw water withdrawal (gal/min)/MWnet	3.933	3.789	3.884	3.905
Raw water consumption (gal/min)/MWnet	2.946	2.841	2.913	2.928
Power penalty (MW)	41.878	22.641	36.208	15.177

Abbreviations: ACTD, air-cooled condenser-cooling tower (ACC-CT) hybrid cooling system; ACTS, ACC-CT in series hybrid cooling system; CCS, carbon capture system; DACW, direct ACC-wet cooling hybrid system; IDACT, indirect air-CT hybrid cooling system.

the results are compared with the results of the IDACT hybrid design. As it is expected, dry direct and indirect cooling systems have no withdrawn water. The amount of water withdrawal doubles with PCCC integration for the open-through cooling, closed cooling, and the hybrid cooling system. Figure 7A depicts the percentage of water withdrawal with and without PCCC integration. The percentage of water withdrawal is plotted to avoid the disparity between the open-through system and the other conventional systems.

There are small gains in water usage as indicated by the negative amount of raw water withdrawal for open through, direct and indirect dry cooling systems with integrated CC unit, as illustrated in Figure 7B. The gain



(A)

(B)

(C)

FIGURE 7 Water withdrawal, water consumption, and power penalty for conventional cooling systems and the indirect air-cooling tower hybrid cooling system (IDACT) hybrid cooling design. [Colour figure can be viewed at wileyonlinelibrary.com] in the withdrawn water with a PCCC has a positive impact of on the total amount of water coming from the condenser in the DCC part of the CC unit, which cools the flue gas before entering the absorber. This finding is consistent with the results of Magneschi et al.[16] The amount of water gain is small compared to the added heat by the reboiler, but it could still be retreated and reused together with process condensate. The power penalty of the conventional cooling designs doubles when the PCCC is integrated (see Figure 7C). The significantly large increase in power penalty for conventional cooling systems with PCCC integration makes the IDACT hybrid design more attractive.

The condenser duty, 373.62 MW for the reference power plant and 261 MW for the plant with CC unit, is for condensing the saturated steam leaving the LP turbine. Integration of a PCCC considerably increases the net cooling load, since cooling is required for the flue gas, solvent, and CO_2 in the carbon capture processing in the CC unit. In dry cooling systems, the added cooling load is dissipated using a direct cooler since the single-phase condition of the flue gas makes the DCC unit not applicable. Using the direct dry cooling system for handling the excess cooling load requires a considerable amount of extra power, and thus, the power penalty increases significantly. For indirect cooling systems, a separate direct dry cooling unit should be used for cooling the flue gas since there is no phase change during the cooling process. Having DCC in indirect dry cooling system has a major influence on reducing the required cooling air amount and related power penalty, but it is not applicable for flue gas cooling.

5 | CONCLUSIONS

Four different hybrid cooling system configurations have been proposed and investigated in this study regarding their impact on water withdrawal and consumption, and power penalty for a NGCC power plant; ACTS, ACTD, DACW, and IDACT. The novelty is concentrated on investigating these parameters for the ACTS, ACTD, and IDACT configurations and compares the results against the most considered studied one in the literature (DACW). Constant tower inlet temperature, constant approach temperature, and constant air to water ratio parameter are considered for simulations. The cooling load is distributed equally between the wet and dry systems in the proposed hybrid cooling configurations. Natural draft CT with 0.1% draft losses has been assumed in the cooling system to minimize power penalty. It has been demonstrated that among the proposed hybrid cooling systems, the IDACT is the best performing configuration with water withdrawal and consumption amounting to 2.038 and 1.573 (gal/min)/MW_{net}, and power penalty of 12.29 MW. The IDACT hybrid system has been compared with the other conventional types of cooling systems regarding performance parameters. It was shown that the IDACT configuration outperforms the conventional cooling systems. The effect of PCCC integration on cooling system performance was also studied for all proposed hybrid design configurations. Despite not having the least levels of water withdrawal and consumption when a PCCC is integrated with the IDACT design, it is still the best configuration due to having much lower power penalty compared to the other designs. The IDACT performance with PCCC integration was calculated 3.9 (gal/min)/MW_{net}, 2.928 (gal/min)/MW_{net}, and 15.177 MW for water withdrawal, consumption, and energy penalty, respectively. The PCCC integration doubles the amount of water withdrawal and consumption from the plant for all types of designs except dry cooling systems, as compared to without the PCCC case. Additionally, there is a small amount of water that would be gained from the PCCC in the DCC part of cooling the flue gas before entering the absorber and cooling the CO_2 gas after the stripper. These water savings can be retreated and reused again to decrease the total amount of the consumed water. The mathematical model and numerical method employed in this study were validated using a reference NGCC plant with and without CC unit, as documented by NETL report.[30]

As future work, a parametric study of the best hybrid cooling system design should be analyzed to form the basis for plant system design optimization. Also, due to the difference in temperature of the required cooling for the condenser and CC unit, the condenser cooling return can be used as a cooling source for the PCCC heat exchanger, which would considerably reduce the amount of required water. This can be considered for future improvement of the proposed hybrid cooling system. Furthermore, an economic investigation should be studied extensively for the proposed configurations to figure out the most feasible design economically

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