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Impact of climate change on fossil fuel power-plant efficiency and water use

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A B S T R A C T

Thermoelectric plants consume large amounts of water for electricity generation, mainly for cooling purposes. The performance and cooling capacity of power plants is thus strongly dependent on rising ambient temperatures. This study investigates the effect of rising ambient temperatures on power-plant performance and water use. A natural gas combined-cycle and a coal power plant, using both recirculating and once-through cooling systems, have been analyzed under increasing cooling water temperature and increasing ambient air temperature. Higher ambient temperatures lead to higher pressure at the steam turbine outlet, decreasing power-plant performance. The efficiency of the power plants is found to be more sensitive to ambient temperature variations when a recirculating cooling system is used, as opposed to once-through cooling. For example, a 10 °C temperature increase leads to an efficiency decrease in coal plants of 0.5–0.7 percentage points, when they are equipped with recirculating systems, versus a 0.3–0.4 percentage-point decrease, when they are equipped with once-through systems. The cooling-water mass flow is also found to be more sensitive to temperature increases in plants with recirculating cooling than in plants with once-through cooling. When comparing coal to natural gas plants, it is seen that the cooling water quantity of coal-fired plants is more sensitive to temperature changes. On the other hand, the efficiency of natural gas plants is more sensitive to temperature changes overall. This is related to higher losses in gas turbine systems caused by increased ambient temperatures and to the fact that the gas turbine system delivers approximately two-thirds of the total power output in the natural gas plants.

1. Introduction

Electricity production and water resources are two sectors that have been considered interdependently until recently (Hadian and Madani, 2013; Gjorgiev and Sansavini, 2018). However, water is a vital component of several phases of electricity generation processes. The largest amount of water is used in the cooling systems of thermoelectric power plants (Ludzker, 2003). The energy sector is the highest source of withdrawals in many countries, above the agricultural sector, with a 44% share of the total water withdrawn in the European Union (EU) (Collins et al., 2009) and 15% of the world total water withdrawals (Mariya et al., 2018). This strong dependence of electricity generation on available water makes the energy sector particularly sensitive to changes in water quality and quantity due to climate change (He et al., 2019). These changes include, not only the reduction in river flows and available freshwater, but also a change in the properties of water due to increased water temperatures (Collins et al., 2009).

Water consumption is the amount of water withdrawn minus the water discharged. Both water withdrawal and consumption vary depending on the cooling method used in a power plant and determine a power plant's vulnerability to changes in water. Once-through cooling consists of an open system that takes large amounts of water from a nearby source to be used for cooling purposes and returns it to the source once it has been used. Withdrawal is particularly high for this cooling system, while consumption is kept at relatively low levels (Dodder, 2014). The necessity of available nearby water sources and the fact that the water used is at ambient temperature, makes this cooling method

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especially vulnerable to both water scarcity and water temperature increases due to climate change (Koch and Vögele, 2009). In recirculating cooling, on the other hand, the cooling water is brought into contact with ambient air in a cooling tower to lower its temperature and it is then used again for cooling purposes. This allows for a lower water withdrawal but implies a higher water consumption than once-through systems (Zhai and Rubin, 2010). Since wet-recirculating cooling requires less water, when compared to once-through systems, it is usually chosen in places with water shortages (Liu et al., 2017). Apart from these water-dependent cooling technologies, some power plants employ dry cooling systems that use air instead of water and avoid any water withdrawal or consumption. These systems, however, imply higher costs and lower efficiencies (Liqreina and Qoaider, 2014; Thopil and Pouris, 2016). Lastly, hybrid cooling systems that combine dry and wet-recirculating cooling can limit the water dependence significantly, when compared to simple wet-recirculating cooling systems (Rezaei et al., 2010).

Water consumption in thermoelectric power plants depends on the type of the power plant and the fuel used; so water changes due to climate change affect each plant in a different way. In solar-thermal power plants, the cooling water required strongly depends on the concentrating technology used and can be considerably higher than in coal-fired plants (Zhang et al., 2018). In non-renewable energy systems, nuclear energy is the most water consuming type, due to the higher mass flow of steam used (Parliament of Australia, 2006). Comparing natural gas and coal power plants, the amount of water consumed per unit of electricity is less for the natural gas plants, given their higher efficiency and that coal or lignite extraction is also water-consuming (Grubert et al., 2012). Furthermore, power plants including carbon capture are also highly water intensive (IEA, 2012).

Climate change is likely to exacerbate water scarcity issues in the near future, increasing the frequency and magnitude of droughts and affecting the power sector (Collins et al., 2009). In addition, economic growth is expected to increase electricity demand (Rijsberman, 2006), that will, in turn, require more water for cooling in thermoelectric power plants that will further accentuate the negative end-effects of water scarcity and water use in the energy sector. With this in mind, it is important to consider some trends that might make the energy sector less water demanding. Since large number of existing power plants will not be operative by the year 2060, new power plants can be constructed with less water-dependent cooling systems (dry and hybrid cooling). There is a high probability that the energy sector will include more renewable energy power plants in the future, some of which use negligible amounts of water (wind, solar photovoltaic) (Liu et al., 2017). Also, the majority of power plants that use once-through cooling today are very likely to substitute their cooling systems with recirculating wet, or even dry or hybrid cooling systems (Zhang et al., 2018).

The negative impact of climate change on electricity production has been demonstrated by heat waves such as the ones of 2003 and 2006, which had an effect on both supply and demand in many European countries (Tobin et al., 2018). In both instances, electricity production had to be curtailed during the summer months due to water shortages and high water temperatures (Koch and Vögele, 2009). During 2003 France suffered a 4000 MW capacity reduction due to increased temperatures of its freshwater resources (Añel et al., 2017) and in 2006, the Spanish power plant Garoña had to close for a week in July, due to the high temperature of the cooling water (Förster and Lilliestam, 2010). With climate change, the frequency and the impact of heat waves may increase, with more important effects on the electricity capacity of operating power plants (Ke et al., 2016).

Several studies have evaluated the effects of climate change on thermoelectric power plants. Tobin et al. (2018) evaluated the output changes of power plants due to increases of 1.5, 2 and 3 °C in water temperature from climate change in different regions. Results generally showed capacity reductions in thermoelectric power plants of 5% for a 1.5 °C increase in water temperature, 10% for a 2 °C increase and 15% for a 3 °C increase. Countries such as Spain are expected to be more affected by increasing water temperature, reaching a 20% capacity reduction for a 3 °C increase (Tobin et al., 2018). Förster et al. (2010) studied the capacity changes in a steam turbine power plant with once-through cooling, under water temperature increases of 1–5 °C and a 10–50% reduction in freshwater flow. Their results showed an average load reduction between 11.8% and 12.4% for the case of a 5 °C increase with between 10% and 30% flow reduction (Förster and Lilliestam, 2010). Chandel et al. (2011) estimated the impact of different climate change policies on power generation. They showed that a change in the power plant mix with all power plants using wet-recirculating cooling would cause a reduction in withdrawals. Increasing the wind and solar photovoltaic share from an approximately 4–7% to a 20% scenario, water withdrawal and consumption would be reduced by 18–23% and 14–21% (Chandel et al., 2011). Zheng et al. (2016) evaluated the impact of water scarcity on thermoelectric power generation in China, and recommend taking into account the future effect of climate change when choosing the location of power plants (Zheng et al., 2016). Turner et al. (2019) investigated the effects of climate change on both supply and demand in the Pacific Northwest of the US. Their results showed that power shortfalls in the studied location would decrease in number, length and intensity during winter, while they would become more frequent during the summer months because of climate change (Turner et al., 2019). Lim et al. (2012) evaluated different scenarios to reach a 50% share of clean energy supply in the United Arab Emirates by 2050. A first scenario that increases renewable penetration from 44% to 65% showed a water footprint reduction of 20% and a carbon emission reduction of 50%. Another scenario in which 80% of the natural gas power plants were retrofitted with carbon capture and storage was seen to be even less promising (Lim et al., 2012).

The present study evaluates the impact of climate change on power plant operation for a range of conditions. The novelty of this work is the special focus on two cooling technologies (once-through and wet-recirculating cooling), as well as on the variation of selected parameters, such as the cooling water temperature increase, to systematically evaluate how rising temperatures affect power plant operation in different scenarios. Two types of power plants (coal and natural gas) are considered, allowing the comparison of different fuel sources and revealing how cooling technologies and cooling system specifications affect water consumption and plant operation. The aim is to determine which cooling technology and power plant type would maintain high performance under climate change and how the plant parameters, and specifically the cooling system specifications, can help reduce the negative effects of global warming on power plant operation.

2. Methods

For the purpose of this study, a natural gas combined-cycle and a coal-fired power plant are simulated using the software EbsilonProfessional. EbsilonProfessional is commercial software used for the design and simulation of thermodynamic processes and it is widely used in industry and by researchers, as a modelling, simulation and optimization tool. The power plants designed and simulated in this study approximate real power plant operation. The operational parameters are chosen based on realistic thermodynamic conditions that can be considered representative of those found in real plants.

In the base coal plant, shown in Fig. 1 (15 °C ambient temperature, 9 °C temperature increase in the condenser and once-through cooling), a mass flow of 519 kg/s of air at 15 °C and 1.013 bar enters the combustion chamber (Stream 1). Coal is injected into the combustion chamber at a rate of 36 kg/s (Stream 3). The heat generated in the combustion chamber is used to generate superheated steam (Stream 6) from liquid water (Stream 12). The steam enters the steam turbine at 210 bar and 560 °C and exits at 0.041 bar and 29.5 °C (Stream 8), generating a gross power output of 400 MW. The expanded steam is condensed in the condenser of the plant. The condensate exits the condenser and after increasing its pressure in the pump of the plant, it is led to the boiler of the plant (Stream 12).

The 15,272 kg/s of cooling water (Stream 9) used in the once-through cooling system of the plant is assumed to be taken from a nearby source at 10.5 °C. Morrill et al. (2005) analyzed the relation between increasing air and water temperatures. They concluded that on average, for every 1 °C temperature increase of the air, the stream-water temperature increased by 0.6–0.8 °C. In the present study, a ratio of 0.7 has been assumed for simplicity (Morrill et al., 2005) . The temperature rise of the cooling water in this simulation is 9 °C, while the minimum temperature difference of the condenser (difference between the outlet of the steam turbine and the cooling water exiting the condenser) is 10 °C. This temperature difference is kept fixed in all simulations and it is the determining factor of the outlet pressure of the steam turbine of the plants. Here, it is assumed that the all of the cooling water used in the condenser is returned back to the water source.

In the base natural gas combined-cycle plant, shown in Fig. 2, a mass flow of 628 kg/s of air at 15 °C and 1.013 bar enters the gas turbine (Stream 1). Natural gas is injected into the combustion chamber at a rate of 14.7 kg/s (Stream 3). The combustion products leaving the gas turbine at a rate of 642 kg/s and a temperature of 618 °C (Stream 5) are then led to a heat recovery steam generator (HRSG) that includes a high-pressure superheater (HPSH), an evaporator (HPEV) and an economizer (HPEC). Superheated steam at 560 °C and 124 bar (Stream 16) enters the high-pressure steam turbine (HPST) and exits at its low-pressure end (LPST) at 29.5 °C and 0.041 bar (Stream 21), generating a gross output of 400 MW. There is a reheating stage (RH) between the high- and intermediate-pressure ST. After the steam leaves the steam turbine, it is led to the once-through cooling system, where 4150 kg/s of water (Stream 22) enters the condenser at 10.5 °C. As in the coal plant, the cooling water temperature increase in the condenser of the base simulation is 9 °C. Also, the minimum temperature difference in the condenser in all variations of these plants is fixed at 10 °C, as well.

Fig. 3 shows the ensemble of reference scenarios tested in this study. A main variation considered is the replacement of the once-through systems with wet-recirculating systems. In the wet-recirculating system cooling (Fig. 4) water coming from the cooling tower (Stream 14) is circulated with a pump (Stream 9) back to the condenser. After the water leaves the condenser (Stream 10), it goes back to the cooling tower, where it is cooled down by coming into contact with ambient air (Stream 15). Some of the water (around 2 or 3%) is lost due to evaporation, creating the necessity for a make-up water stream of the same quantity (Stream 17).

An internal programming script in the simulation software is used to vary the ambient temperature from the initial reference scenarios (15, 20 and 25 °C) to a temperature 10 °C higher with steps of 2 °C, representing six different scenarios for each of the reference scenarios. This leads to a total of 216 simulations.

The chosen ambient temperatures represent climatic conditions in Mediterranean countries. Power plants in these locations are particularly sensitive to increasing ambient temperatures due to climate change and the particularly warm and dry weather

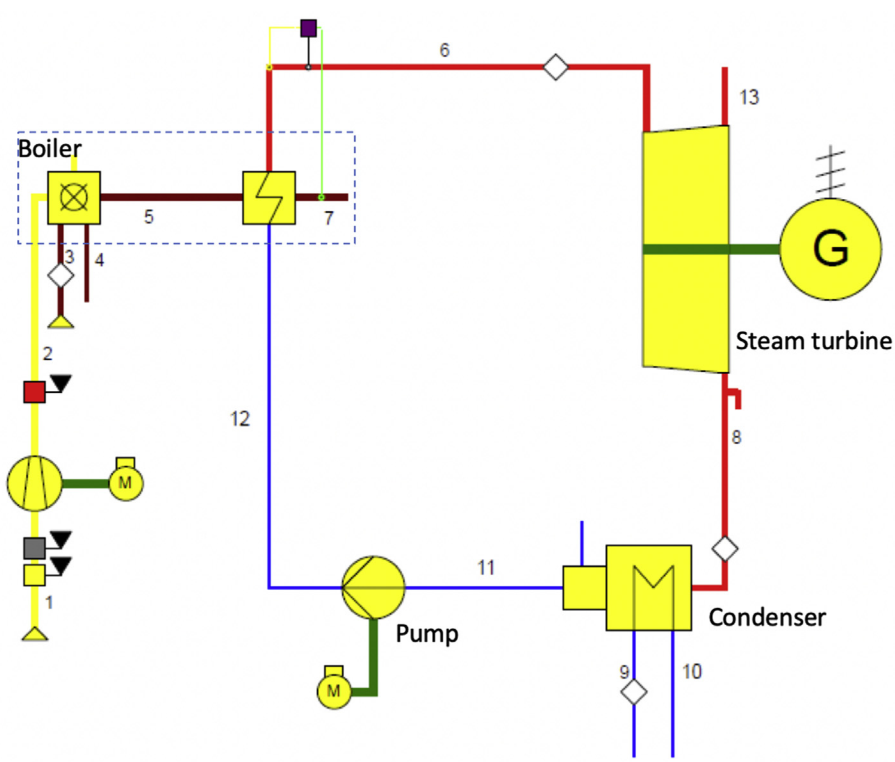

Fig. 1. Flow diagram of the coal power plant.

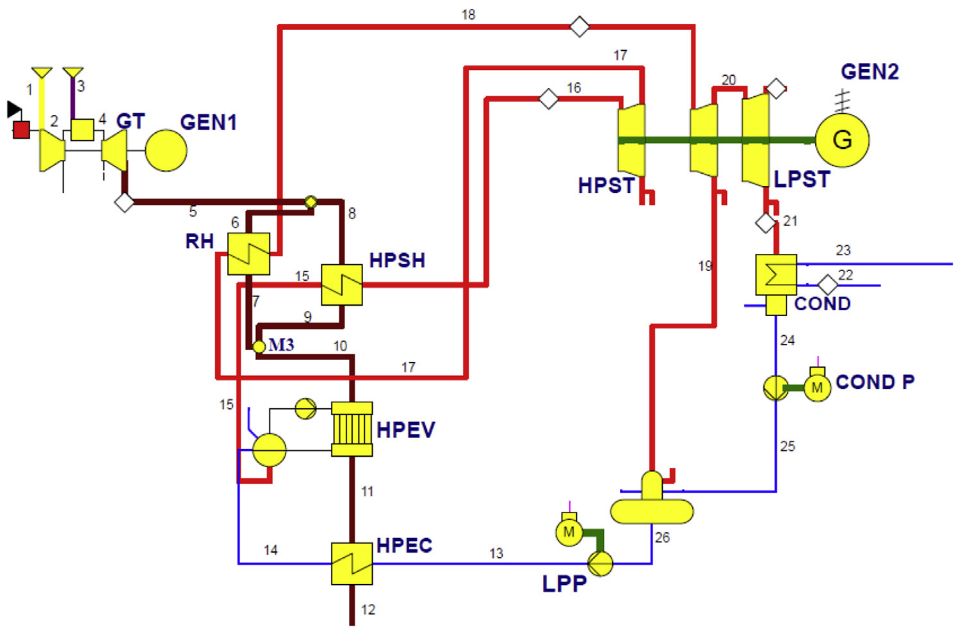

Fig. 2. Flow diagram of the natural gas combined-cycle power plant.

conditions. Average monthly temperatures in Athens, Greece go from 10 °C in January to 28 °C in July, similar to those in Barcelona, Spain (10–25 °C in January and August) and Naples, Italy (9 °C in January and 24 °C in August) (Climate-data.org, 2019). The scenarios in this project cover a temperature range from 15 to 35 °C. This maximum temperature represents the extremely high temperatures reached during the summer period in these countries (AEMET, 2018), as well as temperature increases due to climate change.

When the inlet temperature of cooling water changes, the outlet temperature of the water changes as well, as it depends on the cooling water temperature rise of the condenser (5, 9 or 15 °C, in this study). Given that the minimum temperature difference in the condenser remains constant and equal to 10 °C in all cases, the pressure of the steam turbine outlet needs to be accordingly adapted to ambient temperature variations. To achieve this, the steam turbine outlet stream pressure is modified until it reaches a value at which the minimum temperature difference in the condenser is 10 °C.

For the plants that incorporate a recirculating cooling system, the program calculates the air wet bulb temperature at the inlet of the cooling tower from the ambient temperature and pressure of the stream, using the respective thermodynamic tables of the simulation software. The temperature of the incoming cooling water to the condenser from the cooling tower is then set assuming a temperature difference with the wet bulb temperature of the air of 2.8 °C: $T_{in,cond} = T_{wb,air} + 2.8$.

3. Results and discussion

The efficiency of both coal and natural gas plants decreases with increasing ambient temperature due to increased fuel consumption, regardless of the cooling system used. The main driver of this result is the reduced efficiency of the Rankine cycle at higher temperatures. Rising ambient temperatures (air and water streams) force the increase of the pressure at the outlet of the steam turbine (Fig. 5). As the ambient temperature rises, both inlet and outlet temperatures of the cooling water increase as well. To achieve a minimum temperature difference in the condenser of 10 °C, the temperature of the steam exiting the steam turbine needs to be increased as well. A higher temperature at the outlet of the steam turbine implies a pressure increase for both natural gas combined-cycle and coal-fired power plants. This increase is between 43 and 48% per 10 °C of ambient temperature increase, when using once-through cooling systems and between 55 and 60%, when using recirculating cooling systems. This pressure increase causes a decrease in the efficiency of the plants.

The efficiency of coal plants (Fig. 6) decreases at a rate of 0.5–0.7 percentage points per 10 °C of temperature increase with a recirculating cooling system, and 0.3–0.4 percentage points with the once-through cooling system. The mass flow of both make-up and cooling water increases as temperature rises (Fig. 7). The increase in make-up water in the case of recirculating cooling systems is found to be 8–10 percent per 10 °C ambient temperature rise, while in the case of once-through cooling systems, it is approximately 3 percent. It is seen that the efficiency of the plants is less sensitive to temperature changes when once-through cooling systems are used. This is due to the use of a recirculating pump at the outlet of the cooling tower to make up for pressure losses in the case of the wet-recirculating systems. The higher power consumption of the recirculating pump increases the fuel mass flow of the plant. Nonetheless, fuel mass flow increases in plants with once-through systems are less pronounced, when compared to plants with wet-recirculating cooling systems.

Natural gas plants show similar results to coal power plants. The consumption of fuel in the plants increases as the ambient temperature rises, due to a reduction in the efficiency of both the gas turbine and the steam cycle of the plant. The efficiency of the overall plant (Fig. 8) decreases at a rate of approximately 0.6–0.7 and 0.5–0.6 percentage points per 10 °C of temperature increase with a recirculating and a once-through cooling system, respectively. The mass flow of both make-up and cooling water (Fig. 9) tends to increase with increasing ambient temperature. Considering an ambient temperature increase of 10 °C and an allowed temperature rise of 9 °C between cooling water inlet and outlet, the make-up water mass flow in the case of the recirculating cooling system increases by 10–12%, while in the case of once-through cooling its increase is around 5–6%, relative to its reference value.

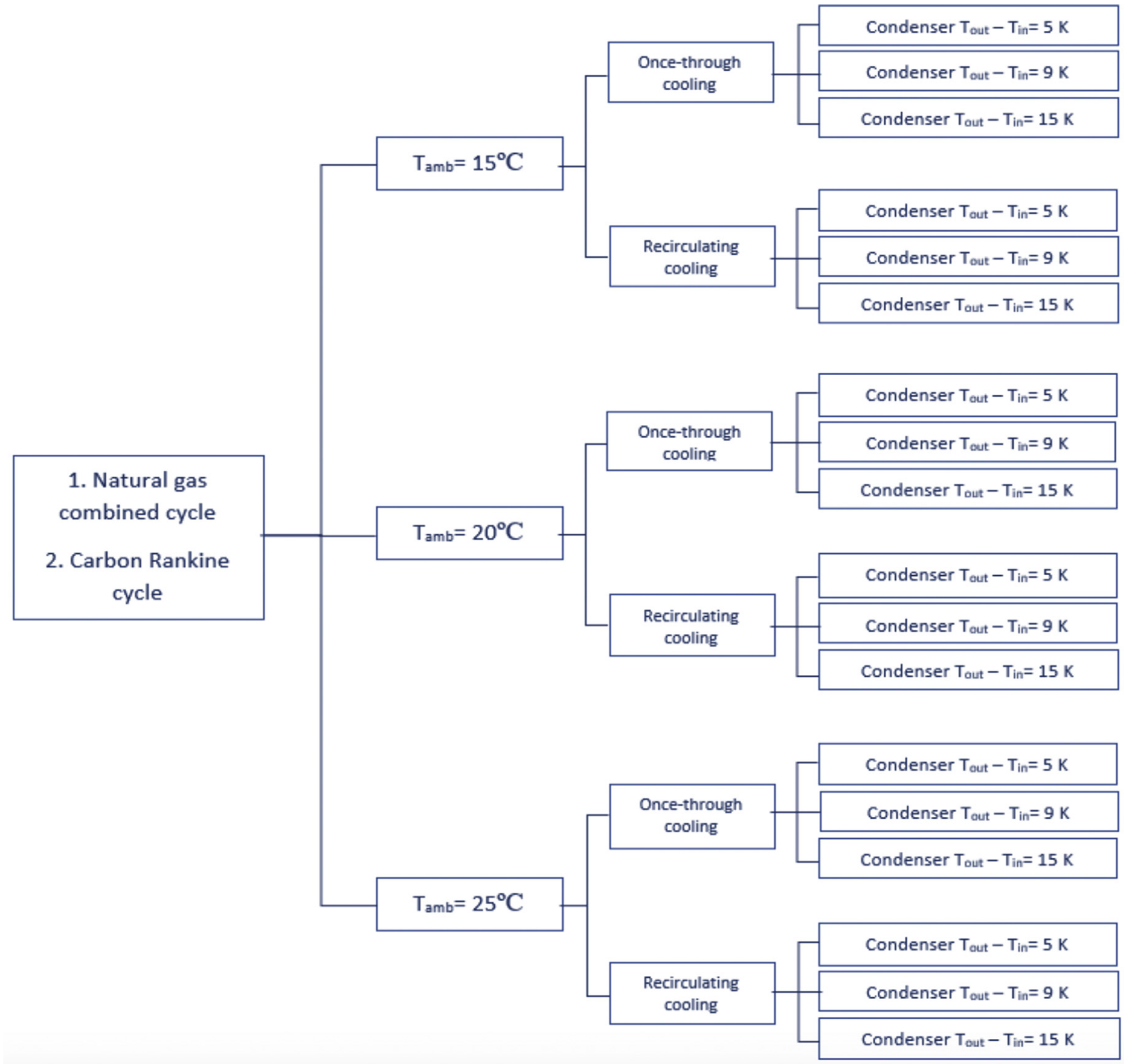

Fig. 3. Ensemble design for simulations of natural gas combined-cycle and coal power plants.

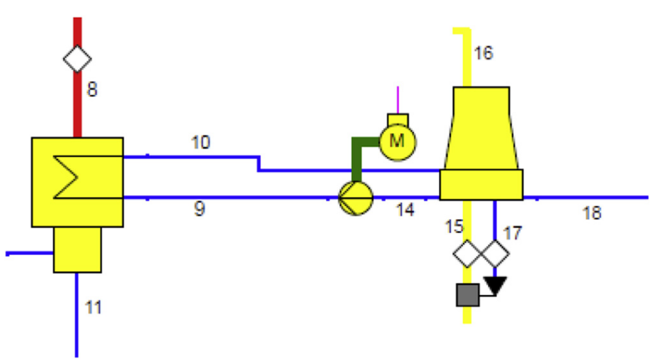

Fig. 4. Flow diagram of the wet-recirculating cooling system.

A lower sensitivity of the cooling water mass flow to temperature changes is found when a once-through system is used. Generally, once-through cooling systems show slightly higher efficiency than recirculating systems, due to the temperature at the inlet of the condenser. In once-through systems the inlet temperature of the cooling water is defined as the temperature of the air multiplied by a factor of 0.7. In the case of recirculating systems, the temperature at the inlet of the condenser (*in,cond*) is determined by the wet bulb (*wb*) temperature of the air in the cooling tower, assuming an approach temperature of 2.8 °C: $T_{in,cond} = T_{wb,air} + 2.8$. The resulting temperature in the case of the recirculating cooling system is higher, when compared to the case of the once-through system, also resulting in a higher cooling water outlet temperature. As explained above, a higher cooling water temperature produces a decrease in the outlet pressure of the steam turbine, considering a fixed 10 °C minimum temperature difference in the condenser (Fig. 10).

When compared to coal plants, the effect of different cooling systems on the efficiency of natural gas plants is lower with changing ambient temperature. This is because the gas turbine system, that remains unchanged, delivers approximately two-thirds of the total power output, while the steam turbine accounts for the remaining one-third. This implies that coal-fired plants of the same capacity have a much higher steam mass flow in the steam cycle than natural gas plants. The higher the steam mass flow passing through the cooling system, the larger the

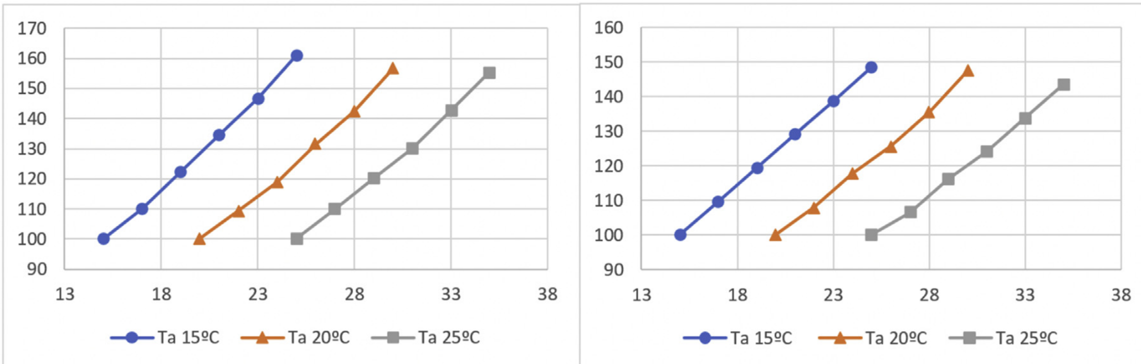

Fig. 5. ST outlet pressure variation (%) with ambient temperature (°C) using a wet-recirculating cooling system (left panel) and a once-through cooling system (right panel), starting from the reference ambient temperature.

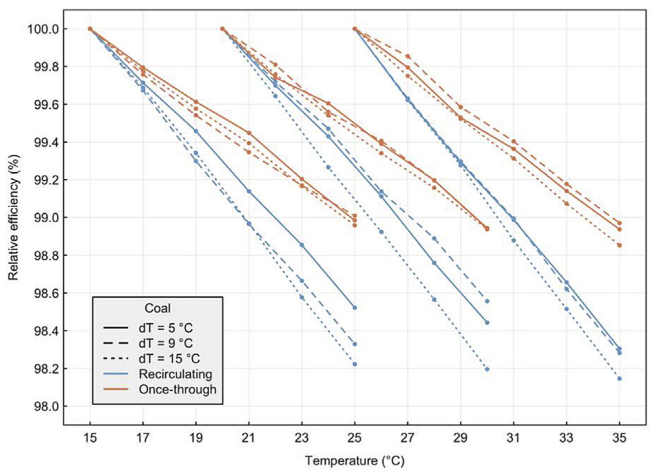

Fig. 6. Efficiency variation (%) of coal plants with rising ambient temperature (°C).

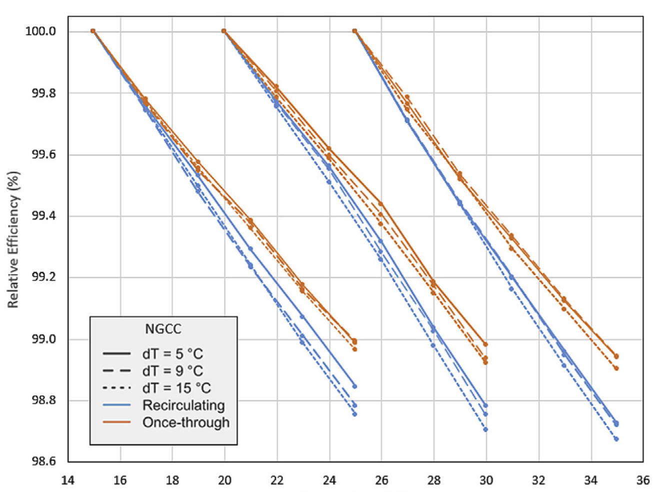

Fig. 7. Efficiency variation (%) of natural gas plants with rising ambient temperature (°C).

required cooling water quantity. This results in higher water consumption and a higher sensitivity to changes in water properties. The amount of cooling water that coal-fired power plants need is thus found to be more sensitive to temperature changes, when compared to natural-gas combined cycles. The efficiency of combined-cycle power plants, however, is seen to be more sensitive to temperature increases than that of coal plants. This is related to the operation of the gas turbine systems that shows higher losses with increasing ambient temperatures than the steam turbine. The gas turbine experiences approximately 0.5 percentage points efficiency loss, when the ambient temperature rises from 15 to 25 °C; 0.6 percentage points efficiency decrease, when the temperature is increased from 20 to 30 °C; and 0.75 percentage points, when the temperature is increased from 25 to 35 °C.

The cooling-water temperature rise in the condenser has a strong impact on the consumption of cooling water. A lower cooling-water temperature rise implies higher cooling-water mass flow and higher sensitivity to changes in ambient and water temperatures. In the case of coal plants with once-through cooling systems and with an ambient temperature of 15 °C, for example, when the cooling range is 5 °C, the cooling water mass flow is 26,972 kg/s. When the cooling range is changed to 9 °C and 15 °C, the cooling-water mass flows are 15,272 and 9427 kg/s, respectively. The efficiency, however, gets lower with higher temperature ranges in the condenser. This is related again to the fixed 10 °C minimum temperature difference in the condenser.

Similar results have been observed in other studies on this topic. Attia (2015) studied the efficiency losses caused by rising ambient temperatures on a nuclear power plant revealing a 0.152 percent efficiency decrease per 1 °C of temperature increase. It is found that the efficiency in power plants with once-through cooling decreases approximately 0.1 percent per 1 °C of temperature increase. While these values are comparable, their discrepancy is most likely due to the higher amount of water required in the plant they studied, making the plant efficiency more sensitive to water temperature changes (Attia, 2015). The results of this study are slightly higher than the power output decrease (0.15–0.5 percent per degree of temperature) reported by Meng and Sanders (2019), most likely because their study is highly based on coal plants (Meng and Sanders, 2019). Furthermore, Klimenko et al. studied the efficiency loss of a gas turbine system due to changes in ambient temperature, obtaining temperature changes increases from 0.5 to 1 percent per 10 °C. The efficiency of the gas turbine of the study presented here decreases by 1.4 percent per degree of temperature, for temperatures between 15 and 25 °C and 2 percent per degree of temperature, for temperatures between 25 and 35 °C. The higher decrease in efficiency found here might thus be due to the assumed higher ambient temperatures. The temperatures used in this work are between 15 and 35 °C, while many of the regions Klimenko et al. use have mean temperatures well below 5 °C. This effect of the

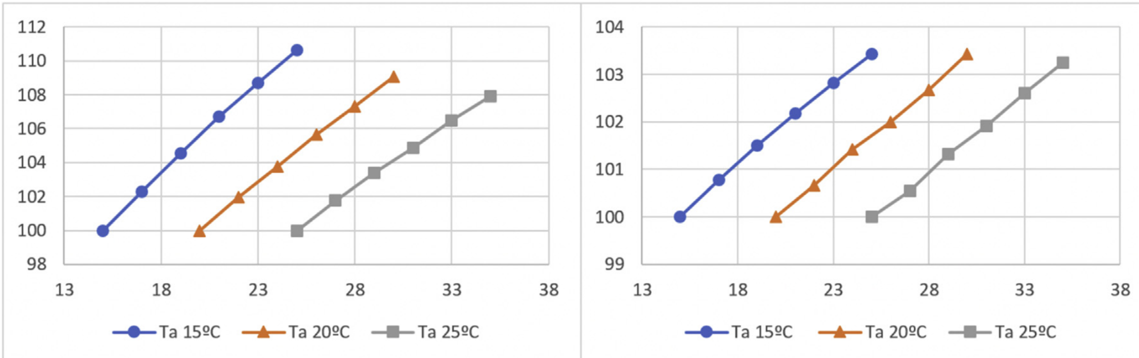

Fig. 8. Make-up and cooling water mass flow variation (%) with ambient temperature (°C) for coal plants with recirculating cooling systems (left panel) and once-through cooling systems (right panel), starting from the reference ambient temperature.

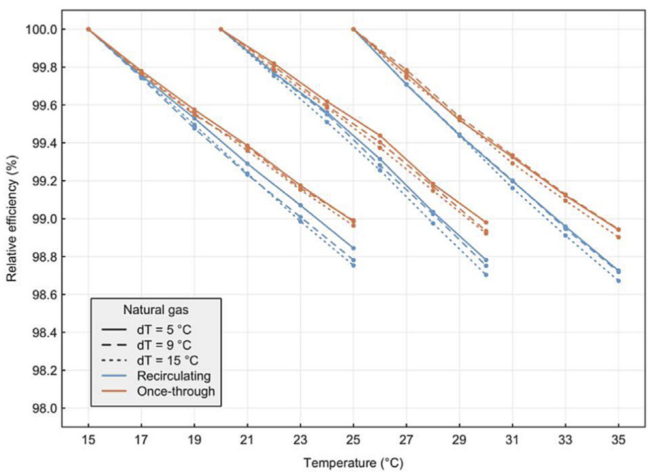

Fig. 9. Efficiency variation (%) of the natural gas plant with rising ambient temperature (°C).

temperature range on the efficiency can also be seen in Fig. 1 of Klimenko et al., (2016) (Klimenko et al., 2016).

Finally, the CO_2 emissions of the power plants are also compared here with a 9 °C cooling-water temperature rise in the condenser. The coal plant has CO_2 emissions of 134 kg/s at 15 °C ambient temperature, and shows an increase in emissions of 1–2% per 10 °C rise in ambient temperature. The released CO_2 of natural gas plants at 15 °C ambient temperature is 41 kg/s and results in an increase in emissions of 7–8% with a 10 °C rise in ambient temperature. In both plants, the released CO_2 mass flow is slightly higher when a recirculating system is used. Overall, the power plants with lower fuel consumption and higher efficiencies present less CO_2 emissions. That is, CO_2 emissions are lower for: lower cooling ranges in the condenser; once-through cooling systems over recirculating system; and natural gas combined cycles over coal plants. CO_2 emissions increase as temperature rises, further highlighting the environmental impact of climate change.

4. Conclusions

Water scarcity and more frequent heat waves, expected in the near future, create the necessity to evaluate power generation strategies under climate change. This article studied the effect of rising ambient temperatures on the performance and cooling capacity of coal and natural gas power plants. The power plants were simulated with variations of their cooling system (once-through and recirculating), cooling range and reference ambient temperature (15, 20 or 25 °C). The reference ambient temperature was increased in steps of 2 °C up to 10 °C.

Rising ambient temperatures caused an efficiency decrease in both natural gas and coal-fired power plants. The study assumed a constant minimum temperature difference in the condenser of the steam cycle (difference between the steam turbine outlet and the cooling water outlet). This means that when the ambient temperature was increased, the steam turbine outlet pressure was

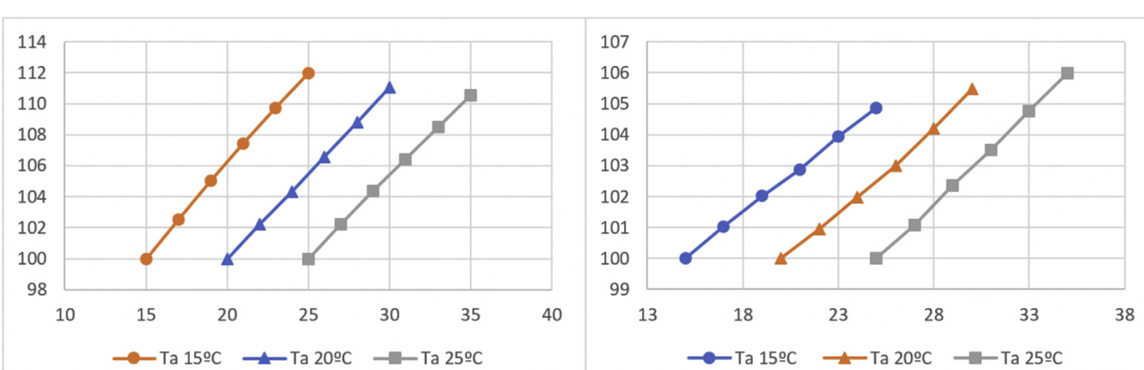

Fig. 10. Make-up and cooling water mass flow variation (%) with ambient temperature (°C) for the natural gas plant using a recirculating cooling system (left panel) and a once-through cooling system (right panel), starting from the reference ambient temperature.

adjusted to satisfy the fixed minimum temperature difference. The steam turbine outlet pressure increased by 43–48% per 10 °C increase in the ambient temperature in coal and combined-cycle plants with recirculating cooling, leading to a reduction in efficiency of 0.5–0.7 percentage points; the pressure increased by 55–60% in coal and combined-cycle plants with once-through cooling systems, leading to efficiency reductions of 0.3–0.4 and 0.5–0.6 percentage points, respectively. The reason why the efficiency of the combined-cycle plants showed higher sensitivity to temperature changes is the higher proportion of the total power output generated in the gas-turbine system (two-thirds, while only one-third of the output is obtained by the steam turbine), and the fact that the gas turbine shows higher sensitivity to changes in ambient temperature than the steam turbine. The sensitivity of water consumption to temperature changes was found to be higher in the case of coal plants, given the higher steam mass flow passing through the cooling system, when compared to the combined-cycle power plants.

The efficiency of the plants with once-through cooling systems was found to be less sensitive to temperature changes, when compared to plants with wet-recirculating cooling systems. On the other hand, the make-up water mass flow in recirculating cooling systems was more sensitive than the cooling water mass flow in once-through cooling systems.

The effect of the cooling range of the condenser on water consumption and efficiency changed with rising ambient temperature. A lower cooling range led to increased water consumption and a higher sensitivity to rising ambient temperatures. However, lower cooling ranges also increased the efficiency, and implied a smaller efficiency loss with increasing ambient temperature.

Overall, natural gas plants achieved higher efficiencies and lower CO_2 emissions with lower cooling ranges and once-through cooling. However, the lower the cooling range, the higher the water consumption and withdrawal, as well as the sensitivity to ambient temperature changes. The CO_2 emissions of the natural gas plants were more sensitive to increasing ambient temperature than those of coal plants, due to their strong dependence on the gas turbine.

The study revealed which type of power plants (coal or natural gas combined cycles), and water-based cooling systems (once through or wet recirculating cooling) maintain higher efficiencies with rising ambient temperatures due to climate change. These results can be very useful in the decision making of the design of future power plants in locations where water scarcity or extremely high temperatures are expected to affect the performance of power plants. To progressively change the global power-plant mix, in order to shift to more efficient plants that can adapt to ambient temperature changes, it is necessary to have information about how power-plant characteristics can help mitigate the effects of rising temperatures.

Future work on this topic could include the consideration of other types of power plants, apart from fossil-fuel power plants. An analysis of renewable power plants in this context would highlight the necessity of developing power generation systems with low or zero harmful emissions to the environment. Also, an additional analysis of dry-cooling systems would complement this study, as they are a potentially good option in areas with intense water scarcity, even if they require a larger investment and penalize the power plant efficiency.

Credit author statement

Fontina Petrakopoulou: Conceived of the research and developed the methodology, Formal analysis, Writing - original draft. Alexander Robinson: Formal analysis, Writing - original draft. Marina Olmeda-Delgado: Formal analysis, Writing - original draft.

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.

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