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# COAL-FIRED POWER PLANTS ENERGY EFFICIENCY AND CLIMATE CHANGE-CURRENT STATE AND FUTURE TRENDS

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**Abstract**. *Coal-fired power plants emit large amounts of $CO_2$, which constitutes one of the largest causes of global warming. Reducing $CO_2$ emissions in the energy sector has become a top priority for national governments. On the other hand, fossil energy production is also affected by air and water temperatures. Local weather conditions affect the capacity of cooling towers and natural water bodies to transfer waste heat from steam condensers to the atmosphere. Without technology-based improvements in cooling system efficiency, the steam-cycle energy efficiency would decrease. This again leads to increased consumption of fossil fuels and thus increasing emissions of $CO_2$. Increasing in global energy demand aggravates this issue. In this paper, the overview of currently actual methods for $CO_2$ reduction is given. The main objective, however, is to find a cost-effective solution for increasing the energy efficiency of existing plants in Serbia. The overview of cooling water temperature increase impact on the energy efficiency in Serbian power plants is given, based on meteorological data and numerical simulation. This study is done for both, power plants with once-through and with closed cycle cooling system. Obtained results could be used as useful guidelines in design of the new power plants and also in improving existing power plants performances.*

**Key words**: *power plant, energy efficiency, cooling system, $CO_2$ emission, global warming*

## 1. INTRODUCTION

Global warming is the term used to describe a gradual increase in the average temperature of the Earth's atmosphere and its oceans, a change that is believed to be permanently changing the Earth’s climate. The scientific consensus on climatic changes related to global warming is that the average temperature of the Earth has risen between 0.4 and 0.8 °C over the past 100 years. The increased volumes of carbon dioxide and

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other greenhouse gases released by the burning of fossil fuels, land clearing, agriculture, and other human activities, are believed to be the primary sources of the global warming that has occurred over the past 50 years.

Climate change resulting from global warming are reflected in the change of air temperature, the amount of atmospheric precipitation, changes in water resources, the occurrence of storms and droughts, rising sea levels, etc. To study the impact of the global warming or climate change parameters in the future, it is necessary to predict the direction and intensity of these changes. For this purpose 'Earth models' are used, based on an advanced mathematical approaches and the latest computer technology. Accurate simulations provide insight into the progress of these processes throughout the countries and in the course of one day, years, decades, even centuries. "The Community Climate System Model", version 3 (CCSM3) that includes atmospheric components and components of land, currently gives the values of variables such as temperature, precipitation and flow of water courses every 6 hours from 1870 to 2100. This model at the level of a decade or century monitors and assesses demographic, economic and technological change [1]. Figures 1 and 2 give insight into predicted global temperature changes in the world until 2100, and annual stream flow changes in the Europe until 2050.

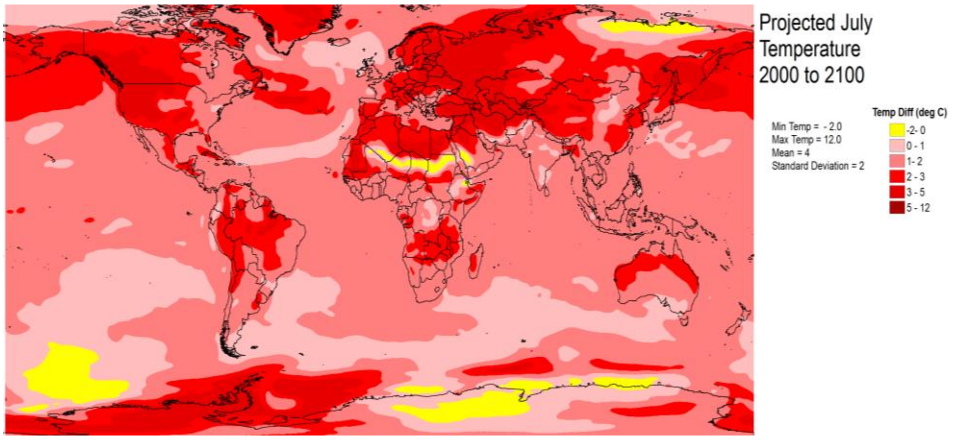

**Fig. 1** Global temperature changes in the world until 2100,
*Courtesy of Oak Ridge National Laboratory, U.S. Department of Energy.

Summer temperatures across Europe depict the uniform increase until 2050 by about 1°C-2°C, except in the West where the temperature will rise by about 2°C-3°C. Large changes in the average monthly temperature of 8°C-9$^{o}$C, refer to the countries of the Balkan region, Austria, as well as some parts of the Italian Alps. All Europe, excluding Scandinavia and parts of northern Germany, Belgium, Scotland and Northern Polish, will record a significant decline in the annual flow of water to 2050. This will have the most impact on the Danube that flows through Serbia and Bulgaria, on the river Seine in France and several rivers on the Iberian Peninsula.

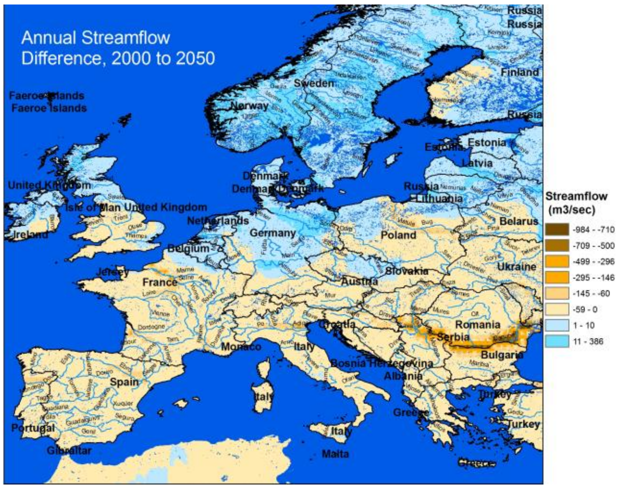

**Fig. 2** Global temperature changes in the world until 2100,
*Courtesy of Oak Ridge National Laboratory, U.S. Department of Energy

## 2. COAL FIRED POWER PLANTS AND $CO_2$ EMISSION

Some authors estimated the commitment to future emissions and warming represented by existing carbon dioxide–emitting devices. They calculated cumulative future emissions of 496 (282 to 701 in lower- and upper-bounding scenarios) gigatonnes of $CO_2$ from combustion of fossil fuels by existing infrastructure between 2010 and 2060 [2].

Coal-fired power plants emit large amounts of $CO_2$, which constitutes one of the largest causes of global warming. The global climate challenge requires the stabilization of atmospheric $CO_2$ levels as a matter of urgency. Given the rising energy demand, this implies the need for a massive reduction in $CO_2$ emissions from fossil fuels.

Meanwhile, according to the latest data, coal-fired power generation is one of the main sources of electric power, accounting for roughly 45% of the power in the United States and 40% in Germany, while the share in Japan is around 25%. The share is as high as approximately 80% in China and approximately 70% in India [3]. In Serbia, the share (Fig.3) is approximately 70%, [4].

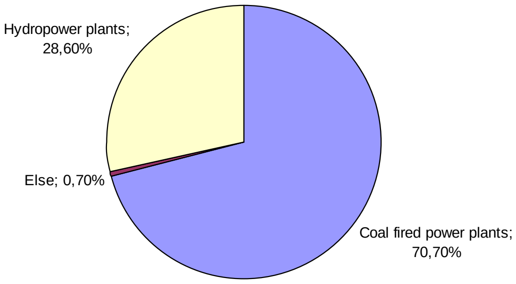

**Fig. 3** Structure of electricity production in the Republic of Serbia, 2013

For fossil fuel power plants in the short term, significant reductions in $CO_2$ emissions can be achieved by replacing older power plants with the new, higher efficiency plants now available. However, in the medium to long term, fossil energy usage will require technologies to achieve zero emissions.

Some of the main approaches that will be used to reduce $CO_2$ emissions are increasing the efficiency of energy conversion and utilization and capturing and storing $CO_2$ from fossil fuel combustion. Carbon Dioxide Capture and Storage (CCS) is a technology with the potential to reduce the greenhouse gas problem and facilitate the continued use of fossil fuels, but it is still technological and commercial challenge.

$CO_2$ capture involves the separation of $CO_2$ from combustion gases and compressing it so that it is suitable for safe transport and storage. There are three basic capture systems to isolate $CO_2$ from the combustion process: post-combustion separation, oxy-fuel firing, and pre-combustion separation.

Post-combustion Capture. In this process, the $CO_2$ is separated from the flue gases after combustion has taken place. Instead of being discharged directly to the atmosphere, the flue gas is passed through an absorbent or a selective membrane, which separates most of the $CO_2$. The $CO_2$, previously compressed, is fed to a storage reservoir and the remaining flue gas is discharged into the atmosphere.

Pre-combustion Capture. Pre-combustion capture involves reaction between fuel and oxygen or air, and possibly also with steam, to produce a 'synthesis gas (syngas)' or 'fuel gas', composed mainly of carbon monoxide and hydrogen. The carbon monoxide is then reacted with steam in a catalytic reactor, called a shift converter, to give $CO_2$ and more hydrogen. Next, the $CO_2$ is separated, usually by a physical or chemical absorption process, resulting in a hydrogen-rich fuel which can be used in many applications, such as boilers, furnaces, gas turbines, engines and fuel cells.

Oxy-fuel Firing. In oxy-fuel combustion, nearly pure oxygen is used for combustion instead of air, resulting in a flue gas that is mainly $CO_2$ and $H_2O$. This simplifies the separation process as the water vapour can readily be condensed to liquid, leaving the $CO_2$ for subsequent treatment.

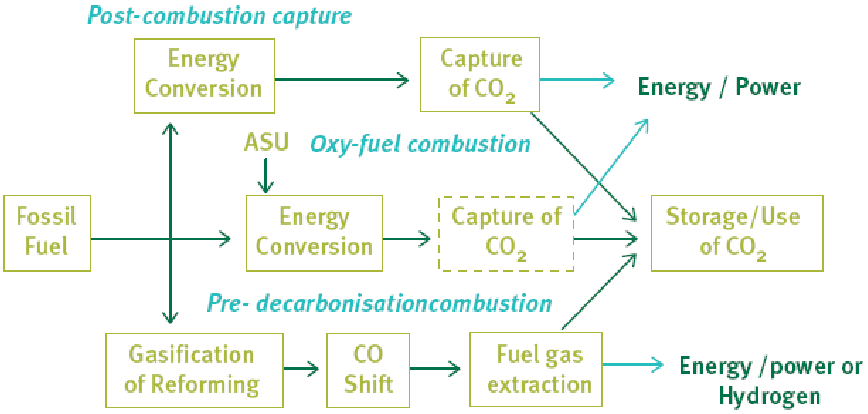

**Fig. 4** $CO_2$ Capture options

Research and development are needed to establish adequate transport infrastructures for $CO_2$ in Europe. In fact, $CO_2$ is already transported in pipelines, but work is still needed to clarify particular requirements for captured $CO_2$. Once captured and transported, most $CO_2$ will be stored in geological reservoirs. Detailed knowledge and understanding are needed as to where and how $CO_2$ can be stored. This understanding must include, for example, geographical locations, capacities, future behaviour in reservoirs, and associated risks, together with both national and international legal constraints [5].

## 3. ENERGY EFFICIENCY OF THE POWER PLANTS AND CLIMATE VARIABILITY

Every existing source of energy is affected by climate variability. Renewable energy sources tend to be more sensitive to global warming, but fossil energy production is also affected by air and water temperatures.

The most direct impact of climate change caused by global warming on electricity production in conventional thermal power plants using fossil fuels is reflected in the operating conditions of the cooling system. As anticipated, climate change will lead not only to an increase in air temperature, but also to a reduction in available water for cooling, all of which increases the effect of reducing the efficiency and reliability of the electricity production in the near future.

It is important to note that even if the efficiency loss is small in percentage terms, the overall effect of relatively small changes in efficiency could still be substantial as the change applies to the major share of power production. For example, such an effect could be important: a1% reduction in electricity generation due to increased temperatures would amount to a drop in supply of 25 billion kWh in the USA [6].

For cooling its condenser, steam power plants use basically two types of cooling systems: open-cycle and closed cycle [7].

Open-cycle or once-through cooling systems withdraw large amounts of circulating water directly from and discharge directly to streams, lakes, reservoirs, and embayment through submerged diffuser structures or surface outfalls. Open-cycle systems depend upon adequate cool ambient water to support generation at full capacity. Circulating water requirement in a thermal power plant is a major water resource issue and has tremendous effect on the surrounding environment, population, and animal and aquatic life. In an open cycle systems the most important environmental effect is the discharge temperature. As the cooling water passes through the condenser, it picks up heat. The amount of temperature rise depends on the amount of water flow.

Closed-cycle or recirculating cooling systems transfer waste heat from circulating water to air drawn through cooling towers. Conventional wet cooling towers depend on evaporative heat exchange and require a continuous source of freshwater to replace evaporation losses. The ability of cooling towers to provide cold water to steam condensers of thermoelectric unit decreases with increasing air temperatures and, for wet cooling tower, increasing humidity.

Whether a power plant cooling system is closed or open cycle, energy efficiency of the power plant is determined by its cold end performances.

Predicted decline in the annual flow of water is more severe problem in open cycle systems where the quantity of water requirement is very high. In closed cycle systems the effect is less severe since the raw water quantity requirement is only 5 % of the open cycle system.

Anticipated global increase in air temperatures is however important problem for systems with closed cooling system. With increasing temperature of the atmospheric air, heat and mass transfer conditions in a cooling tower deteriorates. This results in higher cooling water temperature at the inlet of the condenser and thus reduces the energy efficiency of plant.

## 4. REFERENCE POWER PLANTS IN SERBIA

This paper presents a comparison of operating conditions and energy efficiency of the coal fired power plants 348 MW "Kostolac B2" (open-cycle cooling system) and 110 MW "Kolubara A5" (closed-cycle cooling system). Flow diagram of the both plants are similar, and it's represented in figure 5.

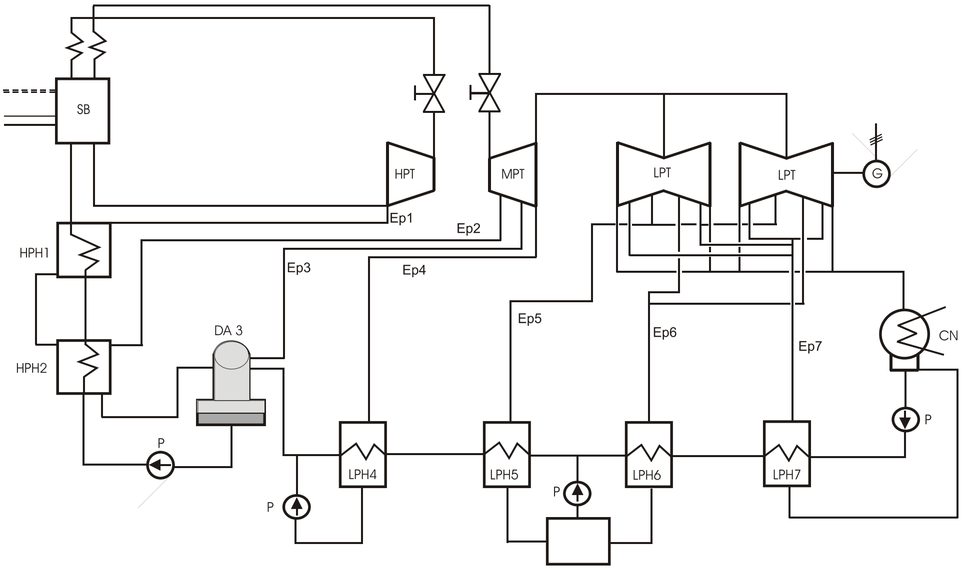

**Fig. 5** Flow diagram of the coal fired power plant

Heat rate and generated power output of a turbo generator unit strongly depend on the condenser pressure. The pressure in the surface steam condenser will depend on condenser design, an amount of latent heat to be removed, cooling water temperature and flow rate, maintenance of the condenser and air removal system. At any given time these operating conditions will determine the relationship between the heat rate and the power output.

For cooling its condenser, the “Kostolac B” power plant uses cooling water from the Danube. The temperature of this cooling water varies from around 4°C in winter up to 28°C in summer. At this moment, the cooling water flow rate cannot be controlled in wider range. Mathematical model and detailed numerical simulation is given in [8].

Figure 6 shows histograms of characteristic water temperature for perennial period.

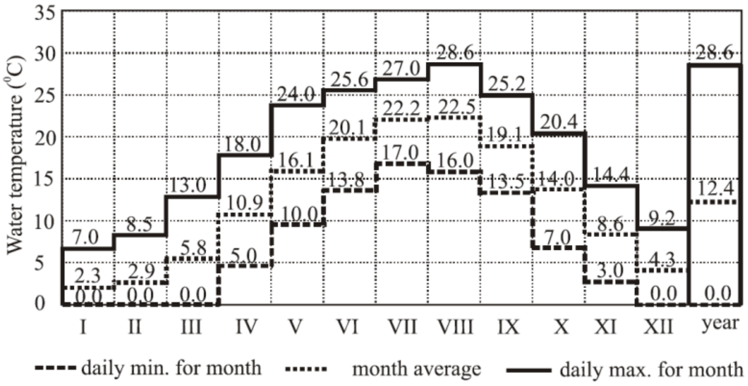

**Fig. 6** Histograms of characteristic Danube water temperature for perennial period

Using the known assumption, from the literature [9], that with increasing pressure in the condenser of 1 kPa, efficiency decreases to 1.0-1.5% and considering that in this particular case the reduction is 1.2%, dependence of the energy efficiency (generated power divided by an amount of energy consumed) in the function of the cooling water temperature rise is obtained and is shown in fig. 7.

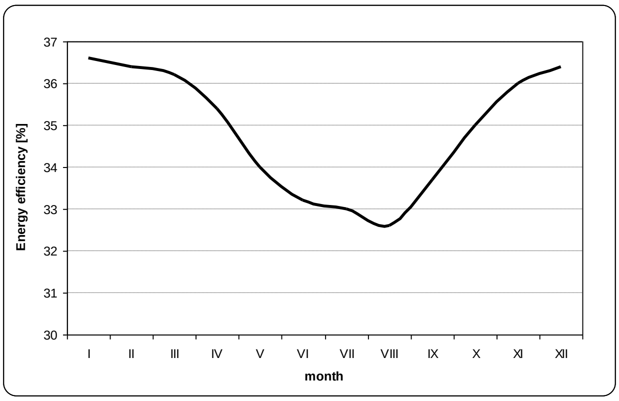

**Fig. 7** Energy efficiency of the plant due to annual cooling water temperature change

Power plants with once-through cooling system using cooling water from natural water bodies are susceptible to the influence of seasonal changes in atmospheric parameters. Summer period, with high air and water temperatures is a critical period in terms of achieving the nominal power, but also in terms of energy efficiency.

The cooling system of the"Kolubara A5" power plant is made with two condensers, each of which has exchange surface of 3450m$^2$. The chambers are crossed by cooling pipes inside of which circulate the water that is afterwards sent to the evaporative cooling towers. The towers are made of 10 cells which are structurally the same, but only 8 currently are in function. Mathematical model and detailed numerical simulation is given in [10].

Plants using the closed-cycle cooling systems are susceptible to daily and seasonal changes in operating conditions due to changes of parameters of atmospheric air. The lowest water temperature can be achieved in the winter months, while the increase in atmospheric air temperature in summer leads to reducing of cooling tower capability to remove waste heat, and an increase in water temperature at the exit from a tower (and thus at the entrance of the condenser) is inevitable. Specific hydraulic load of the fill has also great influence on the temperature of the cooled water. As the climatic parameters are constantly changing without any established rules, most realistic picture of the impact of these changes in plant operation can be obtained using the measured air temperature and relative humidity for the one year period. For one year, air temperature and relative humidity were measured every day at 00:00, 3:00, 6:00, 12:00, 15:00, 18:00 and 21:00. For each parameter the mean value for each day were obtained, and these mean values were used in the simulation of plant cold end. Cooling tower simulation output parameter is the cooled water temperature. This value is then input value for the condenser operation simulation. For each day of the considered period for the given weather conditions condensation pressure value was obtained. Annual change of the water temperature at the exit from the cooling tower is shown in Figure 8.

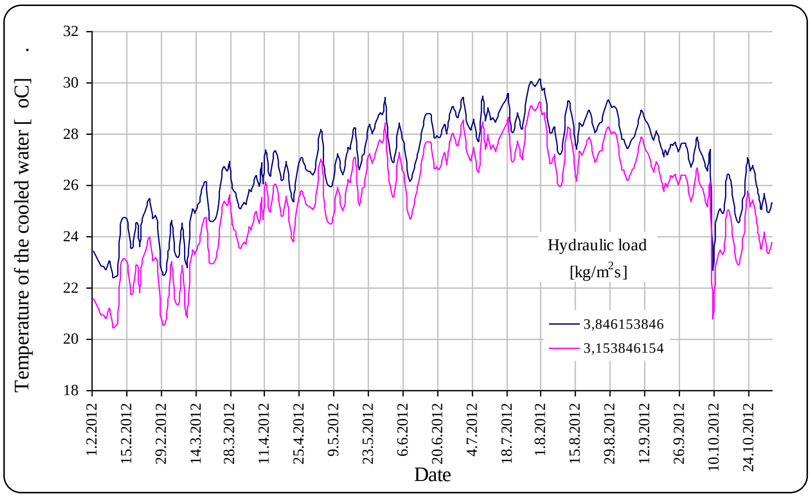

**Fig. 8** Annual change of the cooled water temperature

Annual change of energy efficiency of the power plant with closed-cycle cooling system is obtained for two cases, current state with 8 working cooling towers (8CT) and with 10 cooling towers (10 CT) as it is shown in figure 9. Annual change of energy efficiency is obtained using data obtained from [11] on the mean annual relative humidity and mean maximum and mean normal temperature of atmospheric air for the 2012.

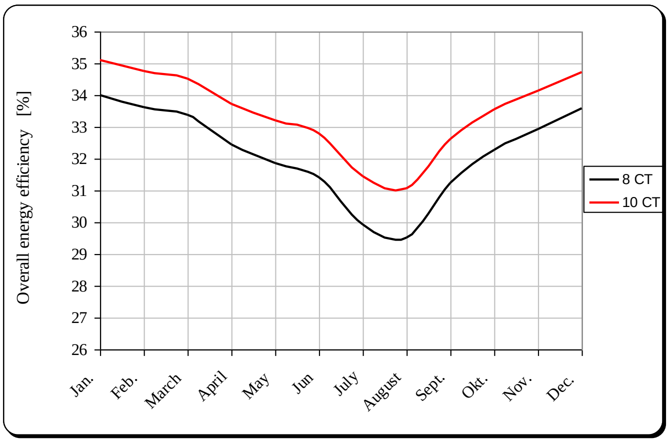

**Fig. 9** Annual change of energy efficiency of the plant A5 „Kolubara A"

Power plants which are using wet cooling towers for cooling condenser cooling water usually have higher design temperature of cooling water, thus the designed condensing pressure is higher compared to plants with once-through cooling system. Daily and seasonal changes further deteriorate energy efficiency of these plants, so it can be concluded that these plants have up to 5% less efficiency compared to systems with once-through cooling [12].

Climate change is likely to constrain thermoelectric generation in the 21st century by degrading cooling capability and power plant efficiency. Having in mind the tendency of temperature increase by 2050 to around 3-4°C in the Balkan countries, and even 8-9˚C until 2100, it is obvious that it is necessary give full attention to improving the operation of existing plants. One of the ways to increase the efficiency of thermal power plants in the event of an increase in temperature of the cooling water is the optimization of the flow of cooling water condenser [13]. According to the results shown in this paper, for the reference plant with closed-cycle cooling system, there is an easy low cost way for energy efficiency increasing. Two of ten built cooling tower are not currently in function. The small investments are required to put into operation those two cooling towers, in order to increase overall energy efficiency of the plant by 1.5%.

## 4. CONCLUSION

Weather-induced increases in the temperature of water supplied by close-cycle or open-cycle systems to steam condensers reduce generation efficiency and capacity because turbine backpressure increases. Power output loss due to cooling water constraints is critical because it coincides with peak summertime demands for energy to cool the buildings.

In the near future, due to the global warming, the greater energy losses will occur in the existing thermal power plants. The lower energy efficiency of these plants in turn leads to higher $CO_2$ emissions, and thus worsens the problem of global warming. This means that it is necessary to revitalize the existing plants in order to increase their energy efficiency, which will bring economic and environmental benefits. Few low-cost ways for improving energy efficiency in the reference power plants are given in this paper.

Also, in the design of new capacities it is necessary to incorporate new technologies that would reduce the impact of the increase in ambient temperature on plant operation to a minimum and reduce the consumption of cooling water in the power plants. Moreover, the attention should be paid to planning at local and regional level in order to prevent the impacts of storms and droughts, improved forecasting that would predict the impact of global warming on energy resources at regional and local levels, as well as to the creation of action plans and reports for the conservation of energy and water. Taking into account the increasingly stringent environmental requirements and increased energy demand, it is necessary to introduce new technologies to reduce $CO_2$ emissions. Research in this field is currently necessary for the commercialization of zero emission plants.

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# ENERGETSKA EFIKASNOST TERMOELEKTRANA I KLIMATSKE PROMENE - SADAŠNJE STANJE I BUDUĆNOST

*Termoelektrane na fosilna goriva, pre svega ugalj, emituju velike količine ugljen dioksida, koji se smatra glavnim uzročnikom fenomena globalnog zagrevanja. Smanjenje emisije* $CO_2$ *u energetskom sektoru je postalo jedan od osnovnih prioriteta svih nacionalnih vlada. Sa druge strane, globalno zagrevanje direktno utiče na proizvodnju energije. Ovaj uticaj se pre svega ogleda u mogućnosti odvođenja otpadne toplote, neophodnog za rad postrojenja. U doglednoj budućnosti efikasnost rada postojećih termoenergetskih postrojenja opadati, ukoliko se ne ulože dodatni napori kako bi se unapredio njihov rad, posebno imajući u vidu optimizaciju rada kondenzacionog dela postrojenja, a ovo opet vodi povećanoj emisiji* $CO_2$*. Predviđeni porast potrošnje energije dodatno podvlači ovaj problem.U radu je dat pregled današnjih metoda za smanjenje emisije CO2 u atmosferu, ali je osnovni cilj rada da ukaže na mogućnosti povećanja energetske efikasnosti postojećih postrojenja, uz relativno mala ekonomska ulaganja, čime bi se smanjili i ekološki problemi. Prikazan je uticaj porasta temperature rashladne vode i vazduha na energetsku efikasnost termoelektrana u Srbiji sa protočnim i povratnim sistemom hlađenja. Rezultati su dobijeni na osnovu originalnih matematičkih modela i numeričkih simulacija, koje su autori predstavili u drugim radovima. Dobijeni rezultati mogu biti od koristi kako pri revitalizaciji postojećih, tako i pri projektovanju novih termoenergetskih kapaciteta.*

Ključne reči: *termoelektrana, energetska efikasnost, rashladni sistem, emisija* $CO_2$