THIRD LIFE OF COAL POWER PLANTS ANALYSIS

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ABSTRACT

Due to climate change urgency coal power plants are under immense pressure. A wave of closures is present all around the world. Especially in the EU the community that we aspire to join. CO_2 tax is looming, and competitiveness with renewables is under decline. In this paper coal power plants are seen in future as a part of the energy storage system using excess electricity from renewables that would be otherwise curtailed. System consists of three parts: electricity to thermal energy conversion unit using heat pumps, and electric heaters as charging unit, then energy storage system, and existing power plant running on Rankine cycle as discharging unit. Emissions would be zero, no SO_2, no NOx, no CO_2, no ultra-fine and very harmful particles. Jobs would be saved. Intermittence of renewables solved. Integration with industry and residential sector for heating and cooling is of great importance for the round-trip efficiency. The objective of this paper is to determine the system's highest round-trip efficiency and least required work. An economic study of the investment costs for the PTES system, converting the current coal-fired power plant to a biomass boiler, and extending the life of the coal-fired power plant by investing in a Carbon Capture and Storage (CCS) system is conducted after the calculation. Analysis is performed using Engineering Equation Solver.

Keywords: decarbonization, energy storage, PTES, third life, just transition

1. INTRODUCTION

In this century, global warming has started to threaten. To minimize an increase in global average temperature of more than 2°C, greenhouse gas emissions must be regulated or reduced. Despite global initiatives to decarbonize the power industry, the production of electricity and heat accounts for more than 40% of all worldwide CO_2 emissions related to fuel combustion, with coal plants producing more than 70% of these emissions. The factors that affect CO_2 emissions from electricity generating include electrical output, generation efficiency, the proportion of fossil fuels in total generation, and the carbon intensity of fossil fuel generation [1]. Retrofitting or repowering a large number of existing coal thermal

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power plants is going to be important part in terms of decarbonization [2]. Getting to net-zero emissions by 2050 requires aggressive initiatives in several areas, including clean energy [3].

This implementation involves restructuring the existing coal power plant and requires appropriate policy support and sufficient investment in thermal energy storage (TES) infrastructure development. New coal-fired power plants should not be built, and the decommissioning of existing coal-fired power plants should be accelerated [4]. Over many years, power producers invested a lot in coal-fired generation. However, many plants are scheduled to close as coal becomes more of an economic and environmental liability [5].

However, far too much coal is still burnt and too many new coal-fired power plants are planned for the globe to maintain safe temperature limits. The number of coal-fired power facilities under development worldwide was felt last year. More than 2,400 coal-fired power plants with a total capacity of almost 2,100 GW are still in use in 79 different countries. There aren't enough plants scheduled for retirement in time to prevent global warming to 1.5°C, even if only 170 aren't planned to be phased out or have a carbon neutrality goal [6].

According to Global Energy Monitor data, 34 countries plan to build at least one coal-fired power plant by 2040. Figure 1-1 shows data on newly installed capacities from 2010 to 2021. China accounted for more than half (56%) of the 45 GW of newly-commissioned capacity globally in 2021 [7]. Outside of China, the coal fleet decreased for a fourth consecutive year, but more slowly than in 2020. Based on data, the total new coal power capacity dropped significantly, by approximately 19 percent, from 567GW to 457GW.

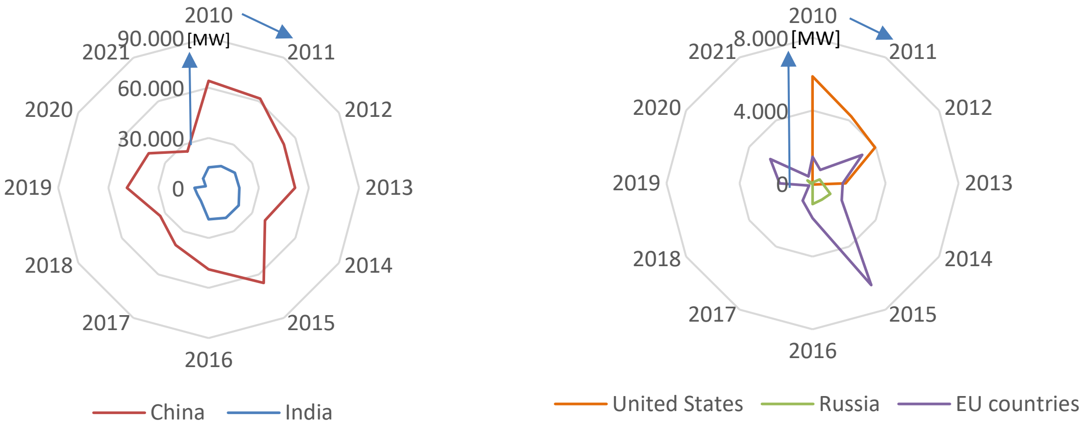


Figure 1-1 New coal-fired power capacity by region (MW)

Figure 1-2 shows retired coal power plant capacity by selected regions. The retirement of coal plants in the rest of the globe was almost completely offset by newly installed capacity in China (25.2 GW for 2021). For the second year in a row, the amount of U.S. coal capacity that was decommissioned in 2021 decreased from 16.1 GW in 2019 to 11.6 GW in 2020 to an expected 6.4 GW to 9 GW in 2021. In 2021, the 27-member European Union decommissioned a record 12.9 GW, with Germany (5.8 GW), Spain (1.7 GW), and Portugal accounting for the majority of those retirements (1.9 GW). Portugal stopped using coal in November 2021, nine years ahead of schedule for the 2030 phase-out [7].

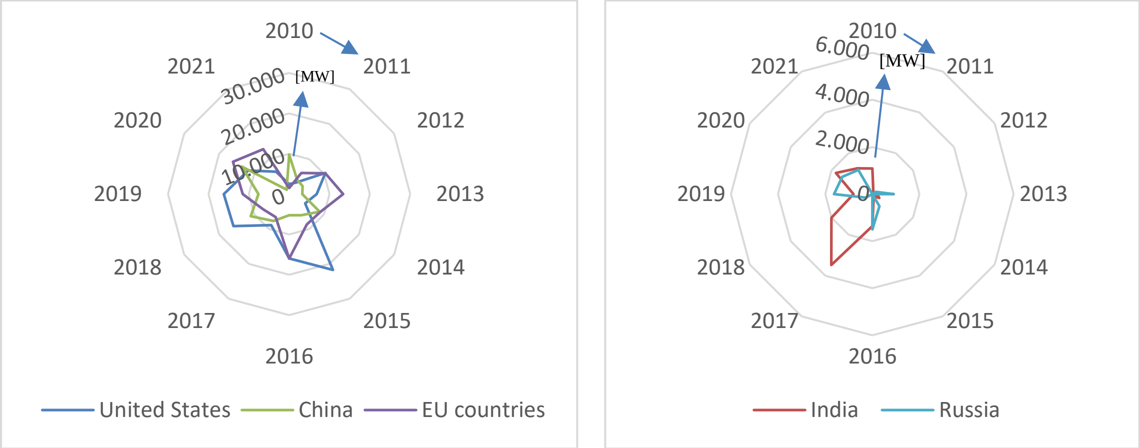


Figure 1-2 Retired coal-fired power capacity by selected region (MW)

Repowering is one opportunity. Repowering is broadly defined as an addition to or replacement of existing power plant equipment, retaining serviceable permitted components to improve generation economies, extend life, improve environmental performance enhance operability and maintainability, and more effectively use an existing site [8].

2. FROM SECOND TO THIRD LIFE OF A COAL POWER PLANT

2.1 SECOND LIFE OF COAL POWER PLANT

Typically, electric utility companies must decide what to do with outdated coal-fired power plants that are nearing the end of their design lives. Concerns about money, energy, and the environment are main problems [9]. There are two main decarbonization approaches that have been proposed for the equipment of existing coal power plants: retire the coal power plants and replace their function with a combination of energy efficiency and low-carbon energy production, or maintain the assets and decarbonize them by reducing direct emissions by adding carbon capture or lifecycle emissions by shifting fuel. Shifting to a lower emitting fuel is one way to reduce the carbon dioxide (CO_2) emissions from an existing coal power plant. The second life of thermal power plants involves using the existing infrastructure. The annual emissions can be minimized by increasing the use of a lower-emitting backup fuel and decreasing the use of a higher-emitting primary fuel. The second method is to mix or co-fire a fuel with a lower emission level with a fuel with a greater emission level. Repowering the power plant, or shifting the unit or the fuel system to allow the use of a lower-emitting fuel that hasn't been used before, is the third fuel-switching approach. One of the easiest and most technologically possible methods for lowering emissions is switching fuels, but it is not a simple task [10].

2.2 EXAMPLES OF SECOND LIFE

Other methods for repowering the coal power plant that can be applied are converting to: wind power, solar photovoltaic (PV) power, combination of wind power and solar PV, integrating to solar thermal power, switching out coal boiler for a nuclear reactor as a heat source or adding a geothermal heat source [11].

The U.S. Energy Information Administration (EIA) reports that between 2011 and 2019, 121 coal-fired power units in the country were converted to use alternative fuels, 103 of which were replaced by natural gas-fired facilities [12]. The business and energy secretary, Kwasi Kwarteng, said that importing wood to burn at the Drax power plant "is not sustainable" and "doesn't make any sense." The UK government's net zero goal includes burning biomass to create energy, which has benefited from £5.6 billion in subsidies over the last ten years [13].

With the help of the American business E3 International, Elektroprivreda Srbije (EPS) has started a pilot project for the use of biomass from energy plants, especially quickly growing willow, to generate electricity in coal-fired thermal power plants. At three places in Vojvodina and close to the EPS mining pit, these solutions are now being tested via pilot projects [14].

According to the U.S. Energy Information Administration, almost 600 coal-burning units with a combined 85 gigawatts of generating capacity have been decommissioned during the last two decades [15].

3. THIRD LIFE OF COAL POWER PLANT

Third life of coal power plant means a conversion of coal power plant to pumped energy storage. Pumped Thermal Electricity Storage (PTES) is the most promising large-scale energy storage technology currently under development because it has a long cycle life, has no geographic restrictions, doesn't require fossil fuel streams, and can be integrated into conventional fossil-fueled power plants. Based on these arguments, a literature review on the subject of "pumped thermal electricity storage" is offered in the current study with the intention of analyzing its current configurations and stage of development [16].

There are lots of energy storage technology options available for load-shifting. The necessity for deploying large-scale Energy Storage units is being emphasized by the increasing integration of variable renewables into the electric grid. The commercially available large-scale energy storage technologies include pumped hydro storage, compressed air energy storage, and flow batteries. However, several of these technologies have geographical limitations (such as compressed air energy storage and pumped hydro storage), depending on fossil fuel sources, or have short cycle lives (Flow Batteries). Therefore, it is necessary to have, large-scale Energy Storage Technologies that do not have the aforementioned flaws [17].

The central concept behind a PTES system is to convert electrical energy into thermal energy and store it in a high-temperature heat storage device using a pump (HP) cycle (charging process) (see Figure 3-1). A heat pump cycle that operates between an energy storage with a temperature of T_1 and the ambient temperature T_o. When electrical energy is required, a heat engine (HE) cycle then converts thermal energy back into electrical energy (discharging process). The fundamental idea behind a PTES system is to convert electrical energy into thermal energy and store it in a high-temperature heat storage device using a pump (HP) cycle (charging process). When electrical energy is required, a heat engine (HE) cycle then converts thermal energy back into electrical energy (discharging process) [18][17].

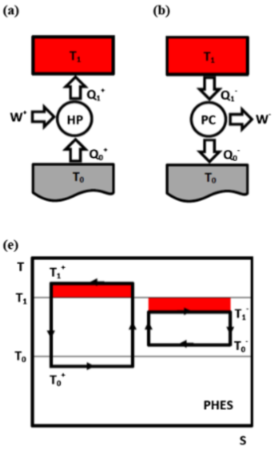


Figure 3-1 Conceptual representation of PTES system (a) charging and (b) discharging cycle [17]

Rankine cycles are the basis of the main section of PTES technology when it comes to generating electricity. Rankine PTES, which typically produces better energy densities and stores energy at a considerably lower temperature than the Brayton cycle, may be a viable option. This is preferred for heat losses, the selection of the materials for the reservoir and machinery, and it could permit the use of phase-change materials as a storage medium [19].

3.1 Examples of third life

Three pilot projects are now being developed by E2S Power in the U.S. and Europe. Several commercial size initiatives are also being discussed by E2S Power in Europe, the U.S. and Canada. The Traveling Wave Energy Storage Technology (TWEST) system, which combines electric radiating heaters, MGA storage blocks, and steam generators into an one module, would be installed as part of the solution for the existing coal power plants. The system stores heat from solar or wind power plants, which, when needed, is transformed into steam to power steam turbine engines that currently create electricity [20].

The Electric Thermal Energy Storage (ETES) method was developed by Siemens Gamesa in Germany and uses rocks that are kept inside a structure. When power has low price, air is directly passed through the rock bed and resistively heated. In order to heat steam for a Rankine power cycle, the rocks are heated and air is occasionally passed through them [21]. Similar to Siemens Gamesa, MAN-ETES is going to install by the end of 2022, two heat pump units in the Danish city of Esbjerg, replacing the existing coal-fired power plant by the middle of 2023 to provide all nearby communes district heating and achieve neutral carbon emission [22]. Researchers at German Aerospace Center (DLR), National Renewable Energy Laboratory (NREL), and the Bill Gates-funded start-up Malta are looking at turning coal plants into low-cost heat "batteries" that may be used as grid-scale thermal energy storage. Most of a coal plant's assets would be used again after conversion. Tanks of molten salts would be heated electrically to "charge" the storage instead of burning coal for heat. This storage could then be "discharged" back to the grid as needed utilizing the old coal plant's existing power generating and transmission resources [23].

One of Chile's strategic initiatives to address climate change and attain carbon neutrality by 2050 is the Plan de Retiro del Carbón (Coal Phase-Out Plan). All of Chile's coal-fired power stations will be shut down by 2040, the government promised in 2019 [24]. The most feasible solution for Chile, according to a GIZ research, is to convert coal-fired power stations into thermal energy storage units. They will be fueled by changing renewable sources, ensuring a steady supply of energy. Investments in renewable energy facilities will be more profitable, and transmission line investments won't be necessary. Additionally, it is possible to avoid the high costs and detrimental environmental effects of decommissioning while maintaining employment at the locations of the power plants [25].

4. LITERATURE REVIEW

Desrues et al. were the first to report research on a pumped thermal energy storage system based on the Brayton cycle for large-scale electric applications in 2010. [16].Also, several authors engaged in various sorts of optimization. First, using finite-time thermodynamics models, Zhag et al. optimized round-trip efficiencies (RTEs) of PTES and pumped cryogenic energy storage (PCES) under whole process ecological optimization are developed [18]. Vinnemeier et al. investigated at the temperature difference from 50 to 700°C maximum heat pump range [26]. The focus of authors White et al. were on the thermodynamics of PTES, including energy and power density, as well as the numerous causes of irreversibility and their effects on round-trip efficiency [27]. Guo et al. also examined a PTES' performance in an investigation to establish how the output power and round-trip efficiency are related [28]. In order to theoretically analyze the PTES system's thermodynamic efficiency, Thess constructed a model of the PTES system using the finite time thermodynamic model [17]. Similar to that, a numerical analysis of the performance of an Argon-based Brayton type PTES system was conducted by Albert et al. [29]. The implementation of packed thermal energy storage powered by a heat pump, a high-temperature electric heater, or a combination of the aforementioned two was investigated by Brutto and Perez. In their work there were five potential system configurations that are suggested and discussed [30].

This paper presents a way of providing a third life to existing thermal power plants. The model is based on thermal energy storage, heat pump and a high-temperature electric heater. Goal is to find the minimum required work and maximum round-trip efficiency for system. The calculation is followed by an economic analysis of the comparison of investment costs between the PTES system, the conversion of the existing coal-fired power plant with a biomass boiler, and the extension of the life of the coal-fired power plant with an investment in the Carbon Capture and Storage (CCS) system.

5. MODEL DESCRIPTION

Figure 5-1 shows a schematic representation of the PTES model with a heat pump and an electric heater. The model may be divided into three separate parts. One represents the functioning of the thermal energy storage (TES) which include hot and cold storage system, while the other two represents the charging and discharging units. The system consists of a conventional system for producing electricity using the Rankine cycle. In this configuration a heat pump and electric heater are used as charging system. Two-stage compression and turbo-expander were used as a charging system in heat pump circuit and a steam Rankine cycle as a discharging unit. The system is coupled with a high temperature hot and cold thermal storage in order to store the energy. Intercooling between two compressors takes place in the exchanger where heat is transferred from gas to gas. After the heat exchange in hot exchanger, the air expands in the turbo-expander to a pressure of 1 bar and is then heated in the cold heat exchanger to the initial state. In this way, the circulation circuit of the heat pump is complete. In the storage system, there is a hot and a cold side in the system. On the hot side, the air at a temperature of 20°C leaves the hot TES and is first heated by the intercooler to 80°C and then the air is reheated by the hot air leaving the two-stage compression. The role of the electric heater is to heat the air to a temperature of 650°C. The air heated in this way is directed by means of a three-way valve to the storage or from the storage to the Heat Recovery System Generator (HRSG).

The steam turbine function, feed water pump, and HRSG are the elements of discharging unit configuration. The water is heated up from 24°C to super-heater steam 525°C which is standard operating temperature at inlet of turbine [31]. For a simpler approach, the connection between the charge, TES and discharge circuit is based on temperature differences. These differences represent the temperature difference of working fluid at the exit from the second compressor and the temperature of the air used to charge the TES ($T_{3hotc} = T_{HP4} + \Delta t_1$, where Δt_1 is assumed to be 8 K). As well as the temperature difference between the HRSG and the air temperature during discharge ($T_{4HoTc} = T_{RC2} + \Delta T_2$, where Δt_2 is assumed to be 83 K). Superheated steam expands in a high-pressure turbine. The steam is then fully condensed and returned to the HRSG by the feed pump.

The cooling system is performed using cooling water that is cooled using cold TES. The air receives its heat from a 60/40 mixture of water and ethylene-glycol in favor of the ethylene-glycol [32]. The mixture fills the storage tank by cooling it to -5°C using a heat exchanger. On the other side of the cold TES there is water that is used when the process of discharging the system is in order to obtain cooling water for steam condensation in the condenser.

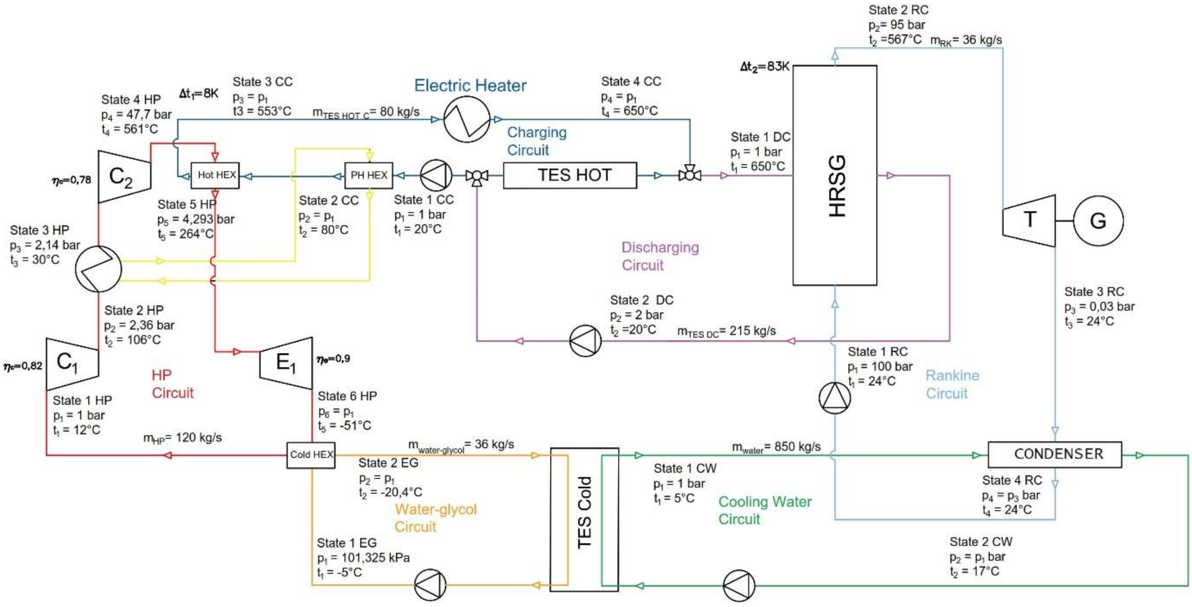


Figure 5-1 PTES system coupled with electric

6. STUDY SCOPE

Figure 5-1 also shows the constants and calculated states in the model. The heat supplied by the heat pump is evaluated based on maximum pressure at 47,7 bars. Nevertheless, the necessary heat pump components may be regarded as being commercially available. The investigated approaches work on the presumption that the environment air serves as the heat source for the heat pump [26]. The compressor is the primary source for irreversible energy conversion inside the heat pump process. Therefore, isentropic compressors efficiencies are assumed of respectively 80 and 78%. Also, the turbine efficiency is assumed at 90% [33].

Other states, such as the total work of the compressor and the total work of the turboexpander, as well as the exchanged amount of heat on both hot and cold exchangers, are determined based on the efficiency of the compressor, turbo-expander, maximum and intermediate pressure, and the temperature of the air at the exit from the intercooler.

Once the system's states have been identified, it is possible to calculate the heat pump's coefficient of performance (COP). The COP can be calculated with and without a supply of air pre-heating using equations, taking into account the availability for producing that heat for COP only the heat given in the hot exchanger was used for calculating COP (Eq.1). When it comes to COP_{DH} both heat from exchangers were used (Eq.2).

$$COP = \frac{\dot{Q}_{charge}}{\dot{W}_c - \dot{W}_t} \tag{1}$$

$$COP_{DH} = \frac{\dot{Q}_{charge} + \dot{Q}_{DH}}{\dot{W}_{c,\,\mathrm{tot}} - \dot{W}_t} \tag{2}$$

Where $\dot{W}_c$ is the work of the compressor for single stage, $\dot{W}_t$ is the work of the turbo-expander, $\dot{Q}_{charge}$ is the total heat power transferred to the hot heat exchanger after the compression, and $\dot{Q}_{DH}$ is the heat exchanger from intercooler for preheating air.

The round-trip efficiency is determined by an equation since it accounts for the energy supplied for district heating (Eq.3).

$$\eta_{\mathrm{roundtrip}} = COP_{DH} \cdot \eta_{RK} \tag{3}$$

Where η_{RK} is the efficiency of Rankine cycle. The Eq. 4 is used to determine the Rankine cycle efficiency (Eq. 4).

$$\eta_{RK} = \frac{\dot{W}_{st} - \dot{W}_p}{\dot{Q}_{HRSG}} \tag{4}$$

Where W_{st} is the work of the steam turbine and W_p is the work of pump. Based on the amount of electricity used to charge the system, the input electricity to output electricity efficiency ratio determines how much electricity is returned to the grid. It is determined using an equation in which the heat pump's COP is taken into account without district heating (Eq.5).

$$\eta_{el,el} = COP \cdot \eta_{RK} \tag{5}$$

7. RESULTS AND DISCUSSION

The system's performance is simulated using Engineering Equation Solver (EES). In order to find the highest round-trip efficiency, the pressure in the intercooler was varied from the initial 2.36 bar to 20 bar. The maximum pressure in the system is set at 47,7 bar, which corresponds to a temperature of 884 K. The temperature distribution also depends on the pressure of the intercooler is shown in Figure 7-1.

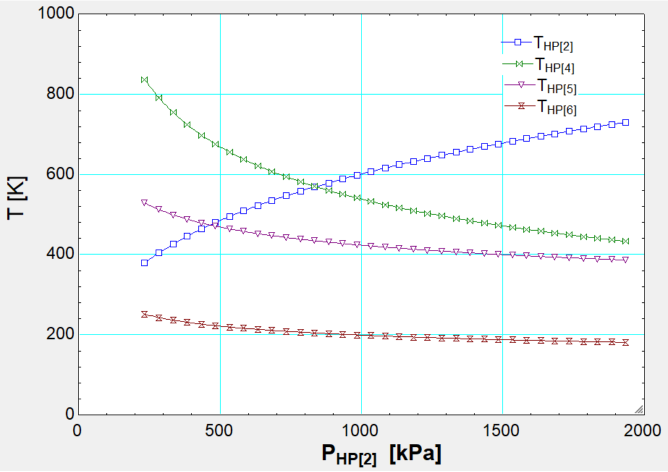
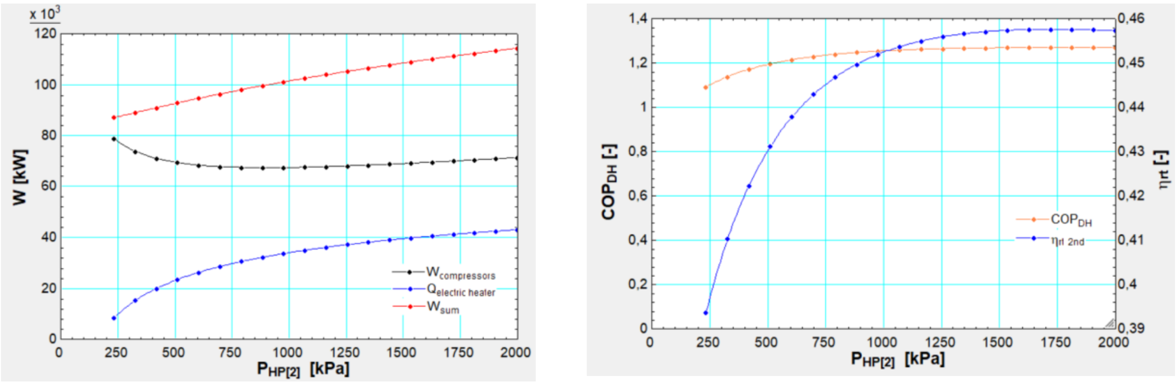


Figure 7-1 Temperature distribution based on different intercooler

Intercooling pressure is a very important element for determining the round-trip efficiency of the system. Figure 7-2 shows two diagrams of the total required work depending on the intermediate pressure (P_{HP2}) and COP_{DH} and roundtrip efficiency.



(a) *(b)*

Figure 7-2 Required work of compressors and heat needed from electric heater (a) change of COP_{DH} and η_{RT} based on intermediate pressure (b)

Analyzing Figure 7-2 (b), we see that the highest η_{RT} is reached at a pressure of 1700 kPa, and it should be noted that there is a very small difference in efficiency between them at 1350 kPa. Also, the change in COP_{DH} does not change significantly after 1000 kPa. The total work of the compressor has minimum 885 kPa (a), while the largest is at 236 kPa. However, that optimum pressure will not lead to maximum round trip efficiency and therefore comprise must be done.

Depending on the pressure, the required area of the heat exchanger also varies (see Figure 7-3), which additionally affects the investment costs. With a change in intermediate pressure, the exchanged amount of heat energy delivered in the exchanger changes and, accordingly, the required surface of the exchanger. The total heat transfer coefficient from gas to gas is adopted to be 50 W/m^2 K for all exchangers [34]. The biggest impact of pressure changes is on the surface of the hot exchanger compared to the cold one.

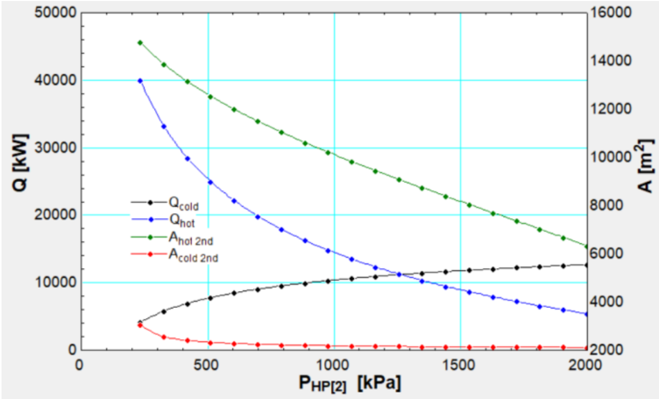


Figure 7-3 Total heat delivered to heat exchangers

7.1 ECONOMY ANALYSIS

The capital cost of the investment in this system was made on the basis of available data in the literature. It should be noted that the specific costs for the capital investment are given in Table 7-1. Only the largest equipment elements are included in the costs. The investment in extending the life of a coal-fired power plant is not that expensive compared to the price for a new construction of the biomass power plant (see Table 7-1). However, it should be borne in mind that the average age of thermal power plants in Serbia is 46 years and the question arises only of benefits. The oldest coal-fired power station in Serbia is the Kolubara A (239 MW), which was built in 1956. The 'youngest' plant is the Kostolac B (697 MW), which began operating in 1987. This price does not include the total investment price for Carbon Capture and Storage (CCS) which raises the total costs significantly [35].

As for the investment of the system and conversion to biomass, the investments themselves are lower compared to a coal-fired power plant, but the issue of CO_2 neutrality arises. Many of the examples listed show that certain countries are shutting down biomass power plants due to the large amount of biomass required. Also, the only way for biomass to be neutral is to use residues, but the question of supplies remains uncertain. Another problem is the operating costs of biomass power plants are high and without additional subsidies the power plant itself is not profitable, the best example is the Drax power plant in Great Britain, the situation is similar in Belgium. Based on a report the advisory council of the Dutch government proposed that the country should phase out the use of biomass for power production as soon as possible. Although burning biomass is inefficient, it is an “indispensable” resource for the circular economy [36]. The total costs of the PTES system when investing in the existing thermal power plant are higher than the conversion to biomass, but the benefit in the form of all emissions is significantly higher and exceeds the higher initial investments.

Table 7-1 Investment cost of specific technology

PTES system				
Technology	Nominal investment	Required capacity /area	Cost (M€)	Reference
Wind turbine	1.12 (M€/MW)	87.34 (MW)	97.82	[37]
Compressor	5840 · $(\text{Capacity})^{0,82}$ (EUR/kW)	78,578 (kW)	60.33	[38]
Turbo-expander	500-2,500 (EUR/kW)	37,907 (kW)	56.86	[39]
Heat-exchanger	9,096 +120·S (EUR/m^2)	5,671 (m^2)	0.69	[40]
Heat-exchanger for hot charging	40,000+500·S (EUR/m^2)	13,768 (m^2)	6.9	[41]
Heat-exchanger for cold charging	≈ 250·S (EUR/m^2)	4,871 (m^2)	1.21	[42]
Electric heater	240 (EUR/kW)	8,766 (kW)	2.1	[43]
Hot thermal storage	40-50 (EUR/MWh)	1,000 MWh	0.2	[44] [45]
Cold thermal storage	500 (EUR/kW)	8,303 (kW)	4.15	[46]
Total investment		Σ=	230.3	
Convert Coal Power Plant to biomass using existing plant				
Technology	Nominal investment	Required capacity /area	Cost (M€)	Reference
New boiler	1,6 (M€/MW)	123.67 (MW)	197.87	[37]
Coal power plant life extension + CCS				
Technology	Nominal investment	Required capacity /area / tonne CO$_2$ stored	Cost (M€)	Reference
Plant life extension	0.24 (M€/MW)	123.67 (MW)	29.68	[37]
CCS technology	3 (M€/MW)	123.67 (MW)	371	[37]
CCS storage	4 (€/tonne CO$_2$ stored)	0.89 (tonne CO$_2$ stored)	3.49	[47]
Total investment:		Σ=	404.2	

**S – required area of heat exchanger*

8. CONCLUSION

Coal-fired power plants account for the largest share of CO$_2$ emissions. Therefore, it is necessary to pay the greatest attention to them. Giving a second life to the thermal power plant will have a contribution but will not solve the problem in general. Many countries are abandoning the transition to biomass because CO$_2$ neutrality can only be achieved by burning residues and subsides for operating are expensive. On the other hand, extending the life of the power plant is not a high investment compared to building a new one on biomass, but the construction of CCS significantly increases investment costs. In addition, there is also the question of the location of the warehouse itself.

A study of providing a third life to thermal power plants has been presented. The model is designed from three parts: charging, discharging and energy storage. Based on thermodynamic aspects PTES technology is one of the most suitable energy storage systems, given that it does not depend on geographical locations. The influence of intercooler pressure on COP$_{DH}$ and the round-trip efficiency has been analyzed. According to parametric research, some design variables have optimum values, while others either force a trade-off between efficiency and required work. A factor that can be used when deciding can be the price of the investment in a particular system.

Parametric study was preformed analyzing the change of intermediate pressure. Optimum intermediate pressure does not necessary implies to best efficiency.

A factor that can influence the decision can be the price of the investment in a particular system. From the investment costs, the most expensive part is only the CCS storage, while the cheapest is to extend the life of the existing power plant

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