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Integrated Wastewater and Waste Heat Recovery System in Coal-Fired Power Plants Using Reverse Osmosis to Produce Clean Water and Increase Thermal Efficiency

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Abstract
Indonesian electricity supply is still dominated by coal-fired power plants (CPP) by more than 50%. Water consumption for CPP in Indonesia reaches 222 million kL/year. Meanwhile, 10% of Indonesia's population is predicted to experience a clean water crisis in 2045. Most of the water consumed by CPP will be disposed of as wastewater, such as cooling tower blowdown and boiler blowdown. Boiler blowdown temperature is still relatively high. Thus, it wastes a high-quality of energy. Therefore, these conditions open the opportunity for innovations in improving clean water supply and increasing CPP's thermal efficiency. In this research, a novel system that integrates wastewater recovery and waste heat recovery in CPP using reverse osmosis is proposed to produce clean water while increasing the CPP's thermal efficiency. In this system, the boiler blowdown is streamed to a heat exchanger as the feedwater preheater. Then, the boiler blowdown flows to a Pelton turbine to generate electricity. The boiler blowdown will then be mixed with the cooling tower blowdown and streamed to a reverse osmosis system to produce clean water. The brine is converted by an electrolyzer into NaClO and H_2. Thermodynamic and economic analyses are performed to assess the proposed system's technical and economic feasibility. Based on the thermodynamic analysis calculation using the Engineering Equation Solver, the system is able to produce 162 kL/hr of clean water and the thermal efficiency of the coal-fired power plant increases by 0.4%. The economic analysis showed that the additional system is feasible with a payback period of 4.9 years.

Keywords:
coal-fired power plant, reverse osmosis, waste heat recovery, wastewater recovery

1. Introduction

Water scarcity is one of the biggest problems that modern humanity is facing. In Indonesia, the need for clean water for the community is increasing every year in accordance with the population growth. Indonesian Central Bureau of Statistics (2018) projected that Indonesian population will grow by 63 million from 2015 to reach 318 million populations in 2045. However, this increase is not followed by a sufficient increase in water supply. According to Lowy Institute (2019), Indonesian Ministry of Public Works and Public Housing projected that Java's water levels will drop to 476 m^3/year per person by 2040, which is a situation considered as a "total scarcity". Moreover, almost 10% of Indonesian population is expected to experience a water crisis by 2045. This is an important problem as it can lead to conflicts over fighting for future water supply.

The power generation industry is one of the industries with the highest water consumption for operation. However, most of the consumed water is released into the environment as wastewater without any further utilization (Noroozian et al., 2017). Therefore, efforts have been made to minimize wastewater from power plants, especially by using membrane processes to utilize the wastewater.

Reverse osmosis (RO) is a widely used membrane process for various water desalination purposes (Noroozian et al., 2017). Qasim et al. (2019) reviewed the latest studies on various aspects of RO desalination, including updates on membrane transport theories, membrane module and characterization, and RO pretreatment technologies. Zhang et al. (2021) studied the pretreatment of brackish-water RO concentrate using direct contact membrane distillation to increase water recovery in a water desalination plant.

Despite their widespread implementation, RO systems still have challenges to overcome, including big energy demand and environmental issues related to disposing of high-salinity brine to the surrounding (Noroozian et al., 2017). To overcome the first challenge, various systems have been proposed to reduce the energy consumption of RO systems. Choi et al. (2019) studied the improvement of seawater RO efficiency using a membrane capacitive deionization-reverse electrodialysis system. Harby et al. (2021) proposed the combination of an absorption desalination-cooling system and reverse osmosis to improve energy efficiency and water recovery. Meanwhile, to overcome the environmental challenges of RO systems, recent studies have introduced the zero-liquid discharge concept. In this concept, the existing power plant is enhanced by adding a bottoming cycle which will reduce pollutants in the brine water through further brine utilization. Peters and Hankins (2020) combined thermo-responsive draw solutions and osmotically-assisted RO systems to eliminate the liquid discharge.

Coal-fired power plants (CPP) are the most dominant power plants in Indonesia in terms of installed capacity. According to National Energy Agency (2019), Indonesia's power plant installed capacity in 2018 came from coal (50%), gas (29%), renewable energy (14%) and oil (7%) power plants. Meanwhile, according to Asian Development Bank (2016), coal-fired power plant ranks second in the category of water consumption for fossil fuel power plants in Indonesia after oil-fired power plants, which consumes approximately 222 million kL of water annually. Similar to other power plants, coal-fired power plants also produce a large quantity of wastewater during operation.

A coal-fired power plant has two main wastewater sources, namely boiler blowdown and cooling tower blowdown (Noroozian et al., 2017). The temperature and pressure of cooling tower (CT) blowdown are relatively low and near the ambient condition. Meanwhile, boiler blowdown temperature and pressure are relatively high. As a result, it is considered a waste heat source in a coal-fired power plant since it contains a high-quality of energy that will be wasted which decreases the power plant's thermal efficiency. Therefore, these conditions open the opportunity for innovations in improving clean water supply and increasing the thermal efficiency of coal-fired power plants.

In this study, a novel system that integrates wastewater recovery and waste heat recovery in CPP using reverse osmosis is proposed to produce clean water while increasing the CPP's thermal efficiency without overlooking the environmental impact from the brine. The aim of this study is to assess the technical and economic feasibility of the proposed integrated wastewater and waste heat recovery system using reverse osmosis. This system is expected to be an appropriate and feasible process to produce clean water and increase the thermal efficiency of coal-fired power plants.

2. Methodology

2.1 System Description

In this study, Babelan Coal-Fired Power Plant Unit 1 is used as a case study for the implementation of the proposed integrated wastewater and waste heat recovery system. Babelan CPP Unit 1 is located in West Java, Indonesia, with a gross generation capacity of 140 MW and operates using the Rankine cycle. The electricity produced from Babelan CPP is used to fulfill the needs in the industrial area of

Jababeka and exported to the Java-Bali electrical grid (Ramdhan & Rangkuti, 2019). Figure 1 shows the schematic diagram of Babelan CPP Unit 1 with the base case system. The power plant has four feedwater heaters, which consist of two low-pressure heaters and two high-pressure heaters. The condenser uses seawater as the cooling water to condense the turbine's exhaust steam. The thermodynamic properties data of each stream in the base case (existing) system are obtained from a literature study of the research by Ramdhan & Rangkuti (2019).

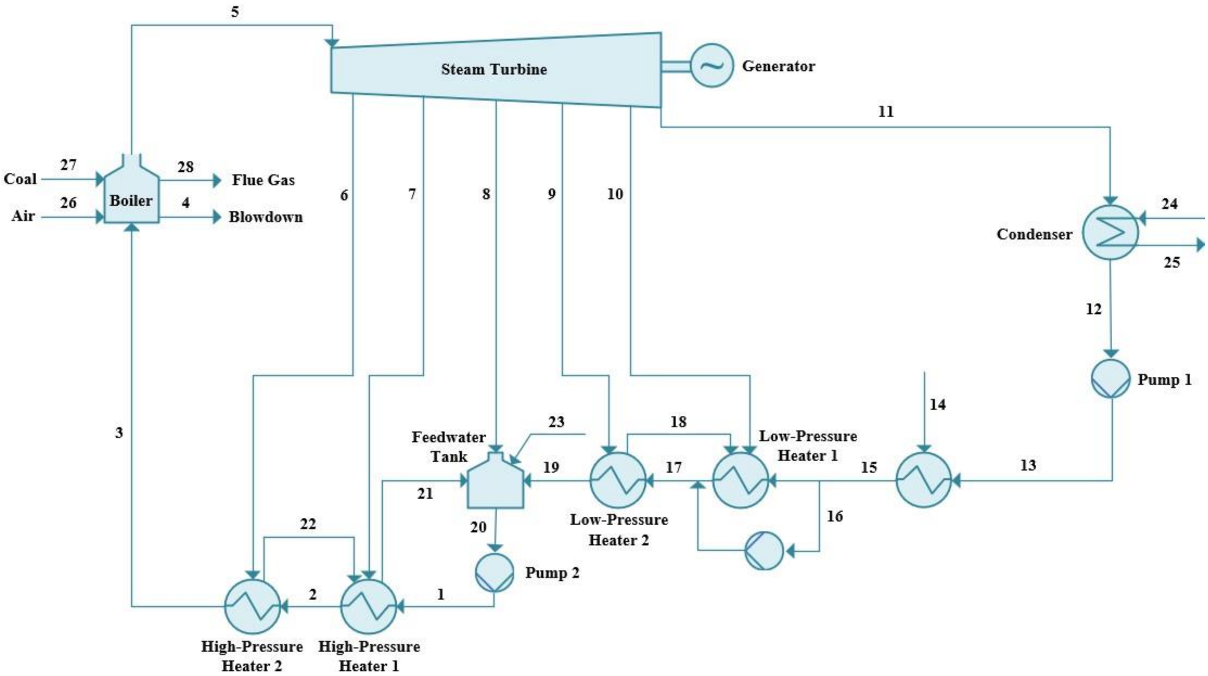

Figure 1. Schematic diagram of Babelan CPP Unit 1 with base case system (Ramdhan & Rangkuti, 2019).

An integrated wastewater and heat recovery system using reverse osmosis is applied to the power plant. The schematic diagram of the proposed system can be seen in Figure 2. The boiler blowdown temperature is higher than the operating ability of the RO system. Therefore a heat exchanger is needed to reduce its temperature before the stream enters the RO system. This heat exchanger enables the boiler blowdown to reject its heat to the feedwater. Hence the heat exchanger conversely acts as a preheater for the feedwater. The pressure of the boiler blowdown is also too high for the RO system. In general, RO systems require a high-pressure inlet stream of high-salinity water. However, the salinity of both boiler and CT blowdowns is low since feedwater and cooling water have been pretreated in desalination and demineralization facilities before entering the CPP system. As a result, a Pelton turbine is added to the system to reduce the stream's pressure while also generating electricity. Afterward, the boiler blowdown will be combined with the CT blowdown in a mixer. However, since the CT blowdown pressure is lower than the boiler blowdown pressure, a pump is required to increase the CT blowdown pressure. This blowdown mixture will be filtered in the RO system to produce clean water.

The pressure of the remaining brine from the RO system is still relatively high. Therefore, in order to recover the stream's energy, another Pelton turbine is utilized to generate more electricity. Furthermore, the outlet stream from the second Pelton turbine already has low energy, but it has high salinity and it is harmful to release it into the environment. Therefore, an electrolyzer is used to convert the brine into sodium hypochlorite (NaClO) and hydrogen (H2), which can be sold to increase the system's economic performance. NaClO can be used to produce bleaching chemicals and disinfectants. This research uses an alkaline electrolyzer with an efficiency of 77%, according to the electrolyzer model studied by Sun et al. (2012) and Zeng and Zhang (2010). In order that the electrolyzer can operate, all electricity generated by the two Pelton turbines will be used to power the electrolyzer.

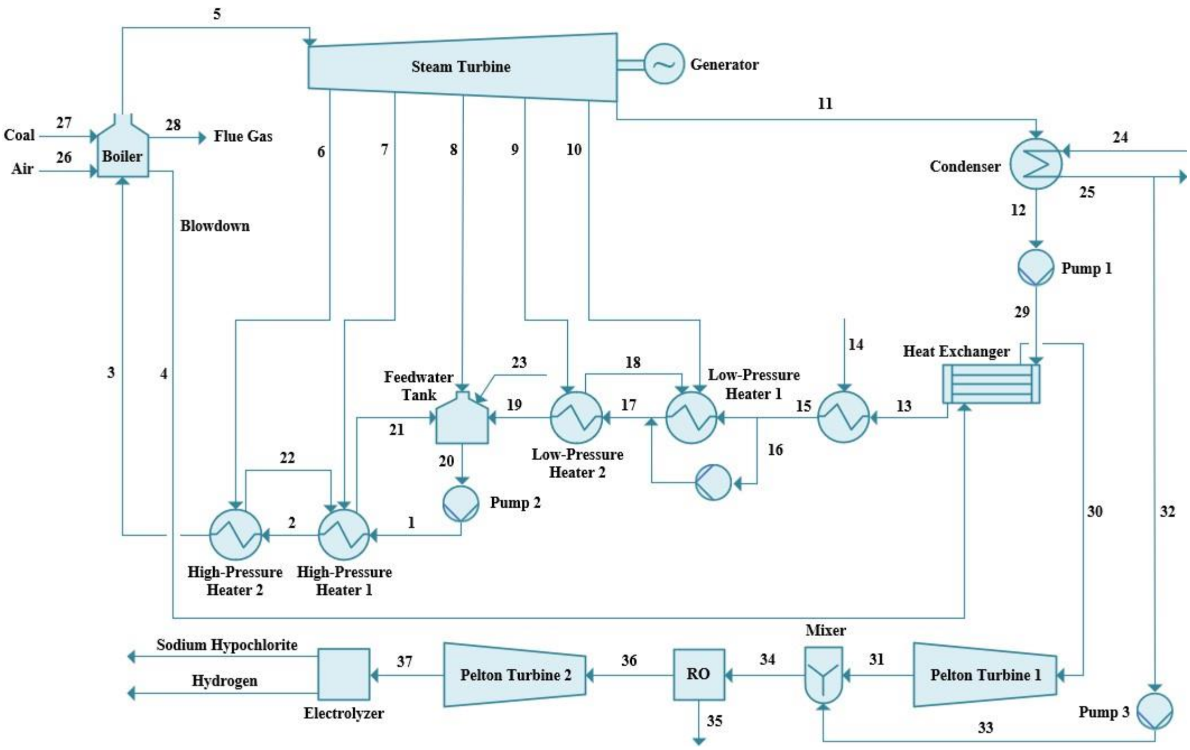

Figure 2. Schematic diagram of the proposed system applied to the power plant.

2.2 Thermodynamic Analysis

The system's technical performance is studied using the first law of thermodynamics energy analysis. Engineering Equation Solver software is used to simulate both base case and proposed systems based on the mathematical model of the system using energy equations. It is assumed that the system operates at the steady-state conditions and all components, except for the boiler, are adiabatic. Equations (1) and (2) address the energy and mass balances at steady-state conditions, respectively (Noroozian & Bidi, 2016):

$$\dot{Q} - \dot{W} = \sum_{i=1}^{n} \dot{m}_{out} h_{out} - \sum_{i=1}^{n} \dot{m}_{in} h_{in} \tag{1}$$

$$\sum_{i=1}^{n} \dot{m}_{in} = \sum_{i=1}^{n} \dot{m}_{out} \tag{2}$$

2.2.1 Coal-Fired Power Plant

The following are the necessary equations to analyze the equipment in the power plant:

- Boiler

$$\dot{m}_3 \times h_3 + \dot{m}_{27}(\eta_{boiler} \times LHV) + \dot{m}_{26} \times h_{26} = \dot{m}_4 \times h_4 + \dot{m}_5 \times h_5 + \dot{m}_{28} \times h_{28} \tag{3}$$

In the equation above (Mohapatra & Sanjay, 2014), η_{boiler} is the boiler efficiency which is assumed to be 90%, while LHV is the lower heating value of the coal.

- Steam turbine (ST)

$$\eta_{ST,is} = \frac{h_{inlet} - h_{outlet}}{h_{inlet} - h_{outlet,is}} \tag{4}$$

In the equation above (Noroozian et al., 2017), $\eta_{ST,is}$ is the steam turbine isentropic efficiency which is assumed to be 85%. The steam turbine in Babelan CPP Unit 1 has six steps, which consist of five extraction steam outlets and one exhaust outlet. Using Equation (4), the net power output of the steam turbine could be computed which is equal to the total power output generated in every turbine step as formulated below (Noroozian et al., 2017):

$$\dot{W}_{ST,step(n)} = \dot{m}_{step(n)}(h_{inlet} - h_{outlet})_n \tag{5}$$

$$\dot{W}_{net,ST} = \sum_{n=1}^{6} \dot{W}_{ST,step(n)} \tag{6}$$

- Condenser

The rate of heat rejection by in the condenser is formulated according to Equation (1) as follows:

$$\dot{Q}_{condenser} = \dot{m}_{11}(h_{11} - h_{12}) \tag{7}$$

- Condensate pump (pump 1)

$$\eta_{pump1,is} = \frac{h_{29,is} - h_{12}}{h_{29} - h_{12}} \tag{8}$$

In the equation above (modified from Noroozian et al., 2017), $\eta_{pump1,is}$ is the condensate pump isentropic efficiency which is assumed to be 85%. Furthermore, the required power for the condensate pump can be calculated as follows (modified from Noroozian et al., 2017):

$$\dot{W}_{pump1} = \dot{m}_{12}(h_{29} - h_{12}) \tag{9}$$

- Low-pressure heater 1

Applying the energy and mass balances for the low-pressure heater 1 according to Equation (1) and Equation (2), respectively, results in:

$$\dot{m}_{10} \times h_{10} + \dot{m}_{15} \times h_{15} + \dot{m}_{18} \times h_{18} = \dot{m}_{16} \times h_{16} + \dot{m}_{17} \times h_{17} \tag{10}$$

$$\dot{m}_{16} \times h_{16} = \dot{m}_{10} \times h_{10} + \dot{m}_{18} \times h_{18} \tag{11}$$

- Low-pressure heater 2

Applying the energy and mass balances for the low-pressure heater 2 according to Equation (1) and Equation (2), respectively, results in:

$$\dot{m}_{9} \times h_{9} + \dot{m}_{17} \times h_{17} = \dot{m}_{18} \times h_{18} + \dot{m}_{19} \times h_{19} \tag{12}$$

$$\dot{m}_{9} \times h_{9} = \dot{m}_{18} \times h_{18} \tag{13}$$

- Feedwater tank

The feedwater tank supplies the feedwater which comes from the pretreatment plant into the boiler. Applying the energy balance for the feedwater tank according to Equation (1) results in:

$$\dot{m}_8 \times h_8 + \dot{m}_{19} \times h_{19} + \dot{m}_{23} \times h_{23} = \dot{m}_{20} \times h_{20} + \dot{m}_{21} \times h_{21} \tag{14}$$

- Feedwater pump (pump 2)

$$\eta_{pump2,is} = \frac{h_{1,is} - h_{20}}{h_1 - h_{20}} \tag{15}$$

In the equation above (modified from Noroozian et al., 2017), $\eta_{pump2,is}$ is the feedwater pump isentropic efficiency which is assumed to be 85%. Furthermore, the required power for the feedwater pump can be calculated as follows (modified from Noroozian et al., 2017):

$$\dot{W}_{pump1} = \dot{m}_{12}(h_{29} - h_{12}) \tag{16}$$

- High-pressure heater 1

Applying the energy and mass balances for the high-pressure heater 1 according to Equation (1) and Equation (2), respectively, results in:

$$\dot{m}_1 \times h_1 + \dot{m}_7 \times h_7 + \dot{m}_{22} \times h_{22} = \dot{m}_2 \times h_2 + \dot{m}_{21} \times h_{21} \tag{17}$$

$$\dot{m}_7 \times h_7 + \dot{m}_{22} \times h_{22} = \dot{m}_1 \times h_1 \tag{18}$$

- High-pressure heater 2

Applying the energy and mass balances for the high-pressure heater 2 according to Equation (1) and Equation (2), respectively, results in:

$$\dot{m}_2 \times h_2 + \dot{m}_6 \times h_6 = \dot{m}_3 \times h_3 + \dot{m}_{22} \times h_{22} \tag{19}$$

$$\dot{m}_6 \times h_6 = \dot{m}_{22} \times h_{22} \tag{20}$$

2.2.2 Reverse Osmosis Desalination Plant

- Heat exchanger

The heat from the boiler blowdown is transferred to the feedwater. Applying the energy balance for the heat exchanger according to Equation (1) results in:

$$\dot{m}_4(h_4 - h_{30}) = \dot{m}_{29}(h_{29} - h_{13}) \tag{21}$$

- Pelton turbine 1

The isentropic efficiency and power output of Pelton turbine 1 (PT1) are formulated as follows (modified from Ramdhan & Rangkuti, 2019):

$$\eta_{PT1,is} = \frac{h_{30} - h_{31}}{h_{30} - h_{31,is}} \tag{22}$$

$$\dot{W}_{PT1} = \dot{m}_{30}(h_{30} - h_{31}) \tag{23}$$

- Cooling tower blowdown pump (pump 3)

$$\eta_{pump3,is} = \frac{h_{33,is} - h_{32}}{h_{33} - h_{32}} \tag{24}$$

In the equation above (modified from Noroozian et al., 2017), $\eta_{pump3,is}$ is the cooling tower blowdown pump isentropic efficiency, which is assumed to be 85%. Furthermore, the required power for the cooling tower blowdown pump can be calculated as follows (modified from Noroozian et al., 2017):

$$\dot{W}_{pump1} = \dot{m}_{32}(h_{33} - h_{32}) \tag{25}$$

- Mixer

The salinity of streams 31, 33 and 34 is assumed to be equal to 1500 ppm. Applying the energy and mass balances for the mixer according to Equation (1) and Equation (2), respectively, results in:

$$\dot{m}_{31} \times h_{31} + \dot{m}_{33} \times h_{33} = \dot{m}_{34} \times h_{34} \tag{26}$$

$$\dot{m}_{31} + \dot{m}_{33} = \dot{m}_{34} \tag{27}$$

- Reverse osmosis system

Mass and salt balances of the RO system are expressed by Equations (28) and (29) (Banchik & Lienhard, 2012; Eshoul et al., 2016), where $\dot{m}_{34}$, $\dot{m}_{35}$ and $\dot{m}_{36}$ are the feed, clean water and brine flow rates, respectively. X_f, X_{cw} and X_b are the salinity of the feed, clean water and brine, respectively. The values of X_f and X_p are assumed to be 1,500 ppm and 0 ppm (freshwater), respectively.

$$\dot{m}_{34} = \dot{m}_{35} + \dot{m}_{36} \tag{28}$$

$$X_f \times \dot{m}_{34} = X_{cw} \times \dot{m}_{35} + X_b \times \dot{m}_{36} \tag{29}$$

In the equation below (modified from Mohapatra & Sanjay, 2014), R is the recovery ratio, which is the ratio of permeate (clean water) flow rate and RO feed flow rate, and the value is assumed to be 0.8.

$$R = \dot{m}_{35}/\dot{m}_{36} \tag{30}$$

- Pelton turbine 2

The isentropic efficiency and power output of Pelton turbine 2 (PT2) are formulated as follows (modified from Ramdhan & Rangkuti, 2019):

$$\eta_{PT2,is} = \frac{h_{36} - h_{37}}{h_{36} - h_{37,is}} \tag{31}$$

$$\dot{W}_{PT2} = \dot{m}_{36}(h_{36} - h_{37}) \tag{32}$$

- Electrolyzer

The total power output of both Pelton turbines is delivered to the electrolyzer, which can be formulated as follows (Noroozian et al., 2017).

$$\dot{W}_{el} = \dot{W}_{PT1} + \dot{W}_{PT2} \tag{33}$$

Finally, the thermal efficiency of the coal-fired power plant considering the blowdown, could be computed as follows (modified from Vandani et al., 2015):

$$\eta_{thermal} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{W}_{net,ST} - \dot{W}_{pump,total}}{\dot{m}_5(h_5 - h_3) + \dot{m}_4(h_4 - h_{30})} \tag{34}$$

2.3 Economic Analysis

Economic analysis is performed to assess the economic feasibility of the additional system. This study considered net present value (NPV), internal rate of return (IRR), capital expenditure (CAPEX), and payback period ($t_{payback}$) as the economic indicators. These are calculated by developing cost functions of each component in the system along with the assumptions as mentioned in Table 1 based on literature studies of the research by Bachtiar et al. (2021), Mwagomba (2016) and Kesieme et al. (2013).

Table 1. Basic financial assumptions used for economic analysis.

Parameter	Unit	Value
Project length	Year	20
Discount rate	%	10
Tax	%	25
Depreciation period (linear)	Year	20
Construction duration	Year	3
CAPEX distribution for 1st, 2nd, and 3rd year of construction	%	20/30/50
OPEX	% of CAPEX	50
System capacity factor	%	47.5
Cost of heat exchanger	USD/m^2	500
Cost of Pelton turbine	USD/kW	750
Cost of cooling tower blowdown pump	USD/kW	450
Cost of reverse osmosis	USD/kg.s	19,500
Cost of electrolyzer	USD/kW	675
Cost of electricity (c_{elec})	cent/kWh	6
Cost of clean water (c_{cw})	USD/kL	1.13
Cost of hypochlorite (c_{hypo})	USD/kg	2.94
Cost of hydrogen (c_{hydro})	USD/kL	62.68

A project or system is feasible if the NPV is positive. NPV is formulated below (Bachtiar et al., 2021), where i is the discount rate, t is the project life in years, and CF_t is the cash flow in the T-th year:

$$NPV = \sum_{T=0}^{T} CF_T/(1+i)^T \tag{36}$$

IRR is a discount rate that makes total present value equal to capital expenditure (Achinas & Euverink, 2019). A project is feasible if the IRR is equal to or higher than the expected return. CAPEX consists of equipment costs and additional costs, such as construction and project management costs, which are assumed to be 65% of total equipment costs. The payback period calculation includes construction duration, CAPEX, additional net power output after implementing the proposed system ($\dot{W}_{add}$), OPEX, tax and the sales income, which are formulated as follows (modified from Noroozian et al., 2017):

$$t_{payback} = t_{construction} + \frac{FC}{(Sales - OPEX) \times (100\% - tax\%)} \tag{37}$$

$$Sales = (\dot{W}_{add} \times c_{elec}) + (\dot{m}_{35} \times c_{cw}) + (\dot{m}_{hypo} \times c_{hypo}) + (\dot{m}_{hydro} \times c_{hydro}) \quad (38)$$

3. Results and Discussions

3.1 Thermodynamic Analysis

Thermodynamic properties data of every stream in the base case system are shown in Table 2, which are obtained from the monthly operational report of Babelan CPP Unit 1 as reviewed in the study by Ramdhan & Rangkuti (2019). The data include mass flow rate, pressure, temperature and enthalpy of each stream. As shown in Table 2, the boiler blowdown stream (stream 4) is at the boiler operating pressure at 151 bar and at the temperature of 300 °C, which is near to the boiler saturation temperature at 342 °C. Therefore, the boiler blowdown has a huge energy content with an enthalpy of 1,339.2 kJ/kg.

Table 2. Thermodynamic properties data of every stream in the base case system.

Stream	Flow rate (kg/s)	Pressure (bar)	Temperature (°C)	Enthalpy (kJ/kg)
1	135.40	157.19	160.0	684.36
2	135.40	152.09	190.0	814.05
3	135.40	151.00	218.0	938.36
4	0.40	151.00	300.0	1,339.20
5	135.0	124.12	540.0	3,454.10
6	6.95	25.83	320.0	3,056.60
7	7.40	14.50	282.0	3,000.40
8	6.75	6.94	172.0	2,781.80
9	6.93	2.38	125.0	525.06
10	7.77	0.70	91.0	2,661.90
11	99.20	0.11	49.8	2,591.30
12	99.20	0.11	49.8	208.55
13	99.20	16.67	49.9	210.87
14	0.18	0.40	150.0	2,780.90
15	99.20	16.33	55.7	234.13
16	14.70	1.76	83.0	347.60
17	99.20	16.33	86.0	361.35
18	6.93	16.33	92.0	385.58
19	113.90	3.39	129.0	543.03
20	135.40	16.33	160.0	675.60
21	14.35	6.68	167.0	706.50
22	6.95	14.50	191.0	790.60
23	0.40	24.70	30.0	127.47
24	2,308.00	0.83	16.0	67.18
25	2,308.00	0.83	36.0	150.37
26	151.25	1.02	25.0	298.18
27	23.04	-	-	-
28	181.29	1.02	167.0	315.30

Thermodynamic properties data of every stream after using the proposed integrated wastewater and waste heat recovery system can be seen in Table 3. As the boiler blowdown temperature is too high for the RO, a heat exchanger is added to lower the temperature of the boiler blowdown (stream 4) by rejecting its heat to the feedwater (stream 13). Conversely, the temperature of the feedwater increases. This reduces the needed heat in the low-pressure heater 1. Hence flow rate of the fifth-step extraction steam (stream 10) reduces from 7.77 kg/s to 1.65 kg/s. Accordingly, the steam flow rate in the steam turbine increases, as well as the power output of the steam turbine. Therefore, the heat exchanger improves the existing system by increasing the power output of the steam turbine and lowering the boiler blowdown temperature. Two Pelton turbines and a cooling tower blowdown pump are added to adjust the pressure of the streams. The first Pelton turbine reduces the boiler blowdown pressure before entering the RO system (stream 31). Meanwhile, the second Pelton turbine reduces the brine's pressure before entering the electrolyzer (stream 36). The cooling tower blowdown pump increases the cooling tower blowdown pressure (stream 32) to enable mixing with the boiler blowdown.

Table 3. Thermodynamic properties of every stream after the proposed system is applied.

Stream	Flow rate (kg/s)	Pressure (bar)	Temperature (°C)	Enthalpy (kJ/kg)
1	135.40	157.19	160.0	684.36
2	135.40	152.09	190.0	814.05
3	135.40	150.05	218.0	938.36
4	0.40	140.86	300.0	1,339.20
5	135.00	124.12	540.0	3,454.10
6	6.95	25.83	320.0	3,056.60
7	7.40	14.50	282.0	3,000.40
8	6.75	6.94	172.0	2,781.80
9	6.93	2.38	125.0	525.06
10	1.65	0.70	91.0	2,661.90
11	105.30	0.11	49.8	2,591.30
12	105.30	0.11	49.8	208.55
13	105.30	16.67	55.0	215.00
14	0.18	0.40	150.0	2,780.90
15	99.20	16.33	76.3	320.20
16	8.58	1.76	83.0	347.60
17	99.20	16.33	86.0	361.35
18	6.93	16.33	92.0	385.58
19	113.90	3.39	129.0	543.03
20	135.40	16.33	160.0	675.60
21	14.35	6.68	167.0	706.50
22	6.95	14.50	191.0	790.60
23	0.40	24.70	30.0	127.47
24	2,308.00	0.83	16.0	67.18
25	2,207.37	0.83	36.0	150.37
26	151.25	1.02	25.0	298.18
27	23.04	-	-	-
28	181.29	1.02	167.0	315.30
29	99.20	16.67	49.9	210.87
30	0.40	140.90	58.0	254.12
31	0.40	8.00	57.6	241.30
32	100.63	0.83	36.0	150.37
33	100.63	8.00	36.0	151.43
34	101.03	8.00	36.1	151.79
35	44.90	0.80	36.1	151.79
36	56.13	7.00	36.1	151.79
37	56.13	2.00	35.0	146.64

The power plant has two blowdown streams, namely boiler blowdown (stream 4) and cooling tower blowdown (stream 32). The total flow rate of both blowdown streams is 101.03 kg/s. In the base case condition, these streams were going to be disposed of without any utilization. Meanwhile, in the proposed system, the blowdown streams are utilized further in the RO system, which filters the blowdown to produce clean water. The system is able to produce clean water (stream 35) with a rate of 44.9 kg/s or 162 kL/hr as shown in Table 3 and Table 4. The brine then flows to the electrolyzer to be converted into NaClO and H_2. As mentioned in Section 2.1, this research uses an alkaline electrolyzer with an efficiency of 77%, according to the model by Sun et al. (2012) and Zeng & Zhang (2010). The electrolyzer is able to produce NaClO and H_2 at the rates of 18.86 kg/hr and 3.96 L/s, respectively.

Table 4. Production rates of clean water, sodium hypochlorite and hydrogen.

Product	Production rate	Unit
Permeate (clean water)	161.70	kL/hr
Sodium hypochlorite	18.86	kg/hr
Hydrogen	3.96	L/s

In the base case condition, the net power output generated by the power plant is 140,393 kW, as seen in Table 5. As aforementioned, the utilization of boiler blowdown to preheat the feedwater reduces the steam extraction required by low-pressure heater 1. Thus steam flow rate in the steam turbine is higher. Therefore, power generated by the steam turbine increases from 140,675 kW to 141,924 kW. The power consumed (input) and generated (output) by each component in both base case and proposed systems are shown in Table 5. In the proposed system, there is an increase in the consumed power since the proposed system requires the addition of a cooling tower blowdown pump. Also, the flow rate entering the condensate pump is higher, so that the duty of the pump increases. However, the proposed system still yields a higher net power output than the base case system, with a net power output of 141,573 kW, which gives an incremental power output of 1,180 kW. The thermal efficiency of the system increased by 0.4% from 41.3% to 41.7% after the implementation of the proposed system.

Table 5. Comparisons of power input/output of each equipment, net power output, and thermal efficiency between the base case and proposed systems.

Parameter	Unit	Base case	Proposed system
Power output of steam turbine	kW	140,675.00	141,924.00
Power input of condensate pump	kW	204.20	216.80
Power input of feedwater pump	kW	65.53	65.53
Power input cooling tower blowdown pump	kW	-	57.35
Power output of Pelton turbine 1	kW	-	5.20
Power output of Pelton turbine 2	kW	-	255.90
Power input of electrolyzer	kW	-	261.10
Net power output	kW	140,393.00	141,573.00
Additional net power output	kW	-	1,180.00
Thermal efficiency	%	41.30	41.70

3.2 Economic Analysis

This study performed an economic analysis for the additional system to assess its feasibility from the economic point of view. From the economic analysis, the CAPEX, NPV, IRR and payback period of the proposed system are obtained, as can be seen in Table 6. These economic parameters are used to decide whether the system is economically feasible. In addition, the cumulative cash flow profile of the additional system can be seen in Figure 3, which is used as the basis for the calculation of NPV and IRR.

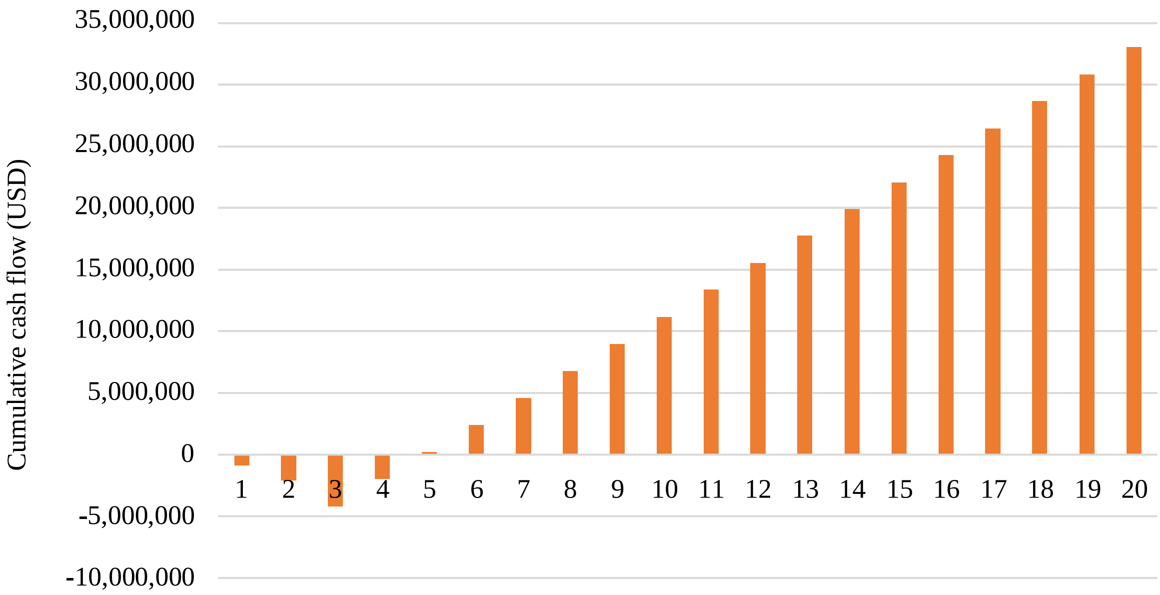

Figure 3. Cumulative cash flow of the proposed system.

The amount of CAPEX needed to develop the proposed integrated wastewater and waste heat recovery system is USD 4,171,537. The project yields a positive NPV of USD 9,893,457 with an IRR of 39.9%. Furthermore, the payback period is 4.9 years, calculated since the beginning of the project or 1.9 years after finishing the construction phase. The positive NPV, high IRR and short payback period show that the additional system is economically feasible to implement.

Table 6. Results of economic analysis.

Economic parameter	Unit	Value
CAPEX	USD	4,171,537.00
NPV	USD	9,893,457.00
IRR	%	39.90
Payback period	Year	4.90

4. Conclusions

A novel system that integrates wastewater and waste heat recovery systems in coal-fired power plants using reverse osmosis is proposed to produce clean water and increase the thermal efficiency of the power plants. The proposed system is technically proven to produce clean water by recovering boiler blowdown and cooling tower blowdown streams using reverse osmosis. The system produces clean water at a rate of 162 kL/hr. Also, it converts the reverse osmosis brine into sodium hypochlorite and hydrogen to prevent environmental issues from high-salinity brine. Furthermore, the system is proven to increase the thermal efficiency of the coal-fired power plant by 4%, from 41.3% to 41.7%. Economic analysis showed that the NPV and IRR of the additional system are USD 9,893,457 and 39.9%, respectively, with a payback period of 4.9 years. The positive NPV, high IRR and short payback period indicate that the additional system is economically feasible to implement.

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