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Full Length Research Paper

Combined pinch and exergy analysis for energy efficiency optimization in a steam power plant

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In this paper, the simulation of a 325 MW steam power plant was performed in a Cycle-Tempo 5.0 simulator and operational parameters of the Rankine cycle were optimized using the Exergy concept combined with a Pinch-based approach. The Combined Pinch and Exergy Analysis (CPEA) first considers the representation of the hot and cold Composite Curves of the Rankine cycle and defines the energy and Exergy requirements. The basic assumption of the minimum approach temperature difference (ΔT_{min}) required for the Pinch Analysis is represented as a distinct Exergy loss that increases the fuel requirement for power generation. The exergy composite curves put the focus on the opportunities for fuel conservation in the cycle. The application results of CPEA in the power plant showed that its fuel consumption could be reduced by 5.3% and the thermal cycle performance could be increased from 39.4 to 41.9%. In addition, the production drop problem in current power plants, due to the inefficiency of the cooling system, especially in warm seasons, could be eliminated, thanks to an 18.77 MW reduction in the cooling load of the condenser.

Key words: Rankine cycle, composite curves, exergy loss, fuel conservation, cooling system, condenser.

INTRODUCTION

Steam Power Plants (SPPs) are based on the Rankine cycle. However, after a century of research and development, current SPPs have become more complex than ideal Rankine cycles, in order to achieve thermal efficiencies above 40%, based on the Low Heating Value (LHV) of the fuel (Ataei, 2009). The SPP is known to feature high flexibility, a long lifetime, high reliability without complexity, and commercial applicability; SPPs have become quite popular, in particular, in countries where natural gas is sufficiently available for electricity generation. The recent increase in fuel prices, the necessity for better environmental performance, and the curbing of air pollution and greenhouse gases have stimulated the search for further improvements. The efficiency of the Rankine cycle can be improved by varying cycle parameters such as the turbine inlet pressure, inlet temperature, reheat pressure, reheat temperature, extraction pressure, and condenser pressure, with respect to their optimum values (Azhdari et al., 2009).

Process integration, especially Pinch Analysis (PA) and Exergy Analysis (EA), are powerful analytical methods for identifying and selecting concrete technical solutions for improving efficiencies and providing optimum manufacturing solutions (Ataei et al., 2009; Linnhoff, 1993). The first step in the energy integration analysis is the calculation of the minimum heating and cooling requirements for the heat exchanger network (HEN). A heat exchanger (HEX), exchanges heat between a hot and a cold process stream; the hot stream needs to be cooled and the cold stream needs to be heated (Linnhoff and Flower, 1978).

Thermodynamic approaches in the form of PA were first introduced in the late 1970s, with the idea of setting targets prior to design and were originally developed at

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Leeds University. PA reports significant changes in energy savings and has established a track record of numerous successful applications in the chemical process industries (Linnhoff and Flower, 1978; Smith, 2005). During the last decades, PA has been developed in other area of process industries, including power plants, and has shown satisfactory results, with respect to energy saving. Linnhoff and Alanis have done much research work on using PA in various power plants. Their research model simulated the modification of an existing site. EA, another useful method for process integration, predicts the thermodynamic performance of an energy system and the efficiency of the system components by accurately quantifying the entropy-generation of the components (Kotas, 1995).

In steam power plants, it can be observed from cycle thermodynamics that synthesis of an optimal HEN with minimization of utilities may reduce Exergy losses and improve the cycle efficiency (Kwak, 2003; Rosen and Dincer, 2003; Sanjay, 2007). Therefore, a Combined Pinch and Exergy Analysis (CPEA) can better make use of the Exergy concept instead of pure thermal analysis, with the aid of PA's design and targeting capabilities. CPEA may represent a whole system, including individual units on one diagram, which helps to screen the promising modifications quickly for improving a base-case design. Therefore, the design of relating HEN for minimum Exergy loss and optimum efficiency is one of the main aims of applying CPEA in a power plant optimization project (Feng and Zhu, 1997).

In this paper, we propose a method of improving certain operational parameters, such as the pressure and mass discharge of steam extractions, by using pinch and exergy analyses. Also reported is a cycle performance increase that was calculated after a correction of operational parameters following this method. It is noteworthy that the main problem of a power plant, that is, a production drop due to inefficiency of the cooling system (the cold end of the power plant), especially in warm seasons, can be completely resolved by correcting the cycle in a power plant using CPEA.

Indeed, for constant power plant production, correcting the power plant cycle using CPEA and reducing fuel consumption in the boiler result in a smaller amount of heat that needs to be discharged at the cold end of the power plant. The current capacity of the cooling towers is therefore higher than that required by the cycle, after correction. Thus, the cooling system is efficient, even in warm seasons.

MATERIALS AND METHODS

Exergy analysis (EA)

Exergy is the maximum theoretical useful work attainable from an energy carrier under the conditions imposed by an environment at given pressure P_o and temperature T_o, and with given amounts of chemical elements. The purpose of an EA is generally to identify the location, source, and magnitude of true thermodynamic inefficiencies in process plants such as power plants (Chao and Yan, 2006). Disregarding kinetic and potential energy changes, the specific flow Exergy of a fluid at any cycle state is given by Equation 1:

$$e = (h - h_o) - T_o(s - s_o) \tag{1}$$

The reversible work as a fluid goes from an inlet state to an exit state is given by the Exergy change between these two states, as follows (Kotas, 1995; Kwak, 2003):

$$e_{out} - e_{in} = (h_{out} - h_{in}) - T_o(s_{out} - s_{in}) \tag{2}$$

A simple Rankine cycle and the T-S diagram for it are shown in Figure 1. As seen in the Figure 1, the SPP consists of two major components: one is the heat transfer system and the other is the turbine system. The chemical energy in the fuel provides the total Exergy for the plant, which is the original exergy source (Rosen and Dincer, 2003). Part of the exergy from the fuel is lost in the heat transfer system, including the boiler, the bleeds heat exchangers, the economizer and the condenser. The rest of the exergy goes into the turbine system as the exergy input for generating power. Some of the exergy input is lost in running the turbines and pumps. The amounts of these losses are defined by their machine efficiency. Also, a certain amount of the exergy is lost with the exhausted gas. The remaining exergy gives the shaft work, which is received by the electrical generators, which become the final exergy sink (Sanjay et al., 2007).

According to Figure 1, the exergy loss and exergy efficiency for each of the Rankine cycle components can be calculated as follows:

Boiler

The Exergy loss in the boiler can be calculated as follows (Kotas, 1995):

$$e\dot{l}_{Boiler} = \dot{E}_{in} - \dot{E}_{out} = \sum(\dot{m}e)_{in} - \sum(\dot{m}e)_{out} \tag{3}$$

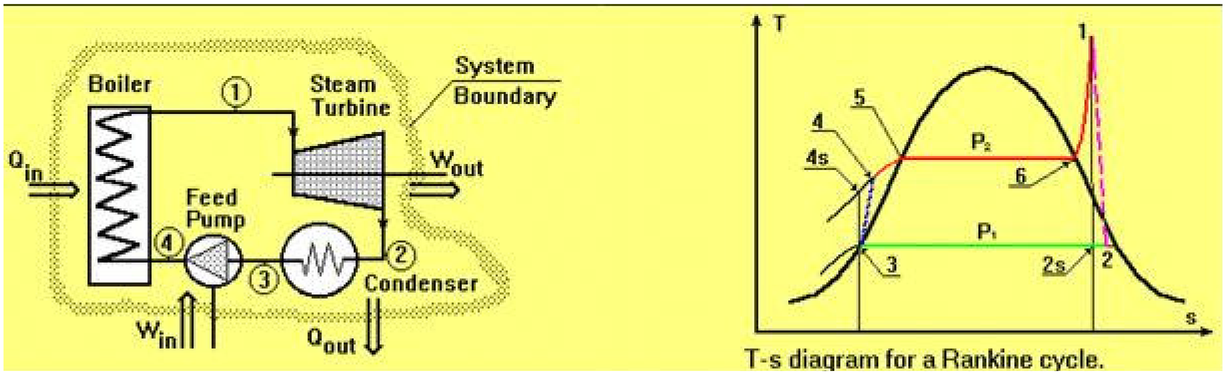
$\dot{E}_{in}$ is the sum of the fuel Exergy and air Exergy that is input to the boiler. $\dot{E}_{out}$ is Exergy of the combustion that produces in the boiler.

Steam turbine

The Exergy loss in the steam turbine is defined as follows (Sanjay et al., 2007):

$$e\dot{l}_{Turbine} = \sum(\dot{m}e)_{in} - \sum(\dot{m}e)_{out} - \dot{W}_{out} \tag{4}$$

Where, $\dot{W}_{out}$ is the actual produced shaft work, as shown in Figure 1. The maximum shaft work of the steam turbine is equal to the difference of the input and output steam enthalpies. Accordingly, the exergetic efficiency of the turbine is defined as the ratio of the



T-s diagram for a Rankine cycle.

Figure 1. A simple Rankine cycle and its T-S diagram.

actual shaft work to the maximum one as equation 5:

$$\varepsilon_{Turbine} = \frac{\dot{W}_{out}}{\sum(\dot{m}e)_{in} - \sum(\dot{m}e)_{out}} \tag{5}$$

Heat exchangers

Feed-Water Heaters (FWHs) and condensers are essentially heat exchangers designed to perform different tasks. An Exergy balance written on the heat exchanger should express the Exergy destroyed in the system as the difference of Exergies of incoming and outgoing streams, as follows (Chao, 2006):

$$e\dot{l}_{FWH} = \dot{E}_{in} - \dot{E}_{out} = \sum(\dot{m}e)_{in} - \sum(\dot{m}e)_{out} \tag{6}$$

The exergetic efficiency of a heat exchanger (HEX) is defined as the ratio of the increase in the exergy of the cold fluid to the decrease in the exergy of the hot fluid (Equation 7).

$$\varepsilon_{HEX} = \frac{\sum[\dot{m}e_{out} - \dot{m}e_{in}]_{Cold\ Streams}}{\sum[\dot{m}e_{in} - \dot{m}e_{out}]_{Hot\ Streams}} \tag{7}$$

Pump

The Exergy loss in the pump can be expressed as follows (Chao, 2006):

$$e\dot{l}_{Pump} = \sum(\dot{m}e)_{in} - \sum(\dot{m}e)_{out} + \dot{W}_{in} \tag{8}$$

$\dot{W}_{in}$ is the actual power consumed in the pump, as shown in Figure 1. The Exergetic efficiency of the pump can be defined as the ratio of the minimum work input to the actual work input, using the following equation:

$$\varepsilon_{Pump} = \frac{\sum(\dot{m}e)_{out} - \sum(\dot{m}e)_{in}}{\dot{W}_{in}} \tag{9}$$

Rankine cycle

The total exergy loss in the Rankine cycle is simply the sum of exergy losses in the boiler, steam turbines, heat exchangers, and pump. The overall exergetic efficiency of the cycle can be calculated as follows (Kwak, 2003):

$$\varepsilon_{Cycle} = \frac{\dot{W}_{net}}{\dot{E}_{fuel}} \tag{10}$$

Where $\dot{W}_{net}$ is expressed by Equation. 11:

$$\dot{W}_{net} = \dot{W}_{out} - \dot{W}_{in} \tag{11}$$

Pinch analysis (PA)

PA has become a general methodology for the targeting and design of thermal and chemical processes, and associated utilities. When considering the energy efficiency of a process, pinch-based approaches target the identification of the possible energy recovery by heat exchange, and define the Minimum Energy Requirement (MER) of the process. The Composite Curves (CC) and the Grand Composite Curve (GCC) are two basic tools in PA, and they are constructed using temperature versus enthalpy axes (Ataei et al., 2009; Polley and Panjeshahi, 1991; Smith, 2005). The MER targeting procedure with CC is shown in Figure 2.

The energy targeting in PA set by the CC and GCC are only in terms of heat loads. However, to deal with systems involving heat and power, the concepts of both the CC and the GCC should be extended.

Combined pinch and exergy analysis (CPEA)

By allowing the comparison of the quality of the different forms of energy, exergy is a rigorous way of analyzing energy conversion systems such as SPPs. In the context of process integration analysis, the exergy concept is combined with pinch analysis for reducing the fuel requirement and optimizing the Rankine cycle in SPPs. The Exergy Composite Curve (ECC) and Exergy Grand Composite Curve (EGCC) concepts have been introduced by Feng

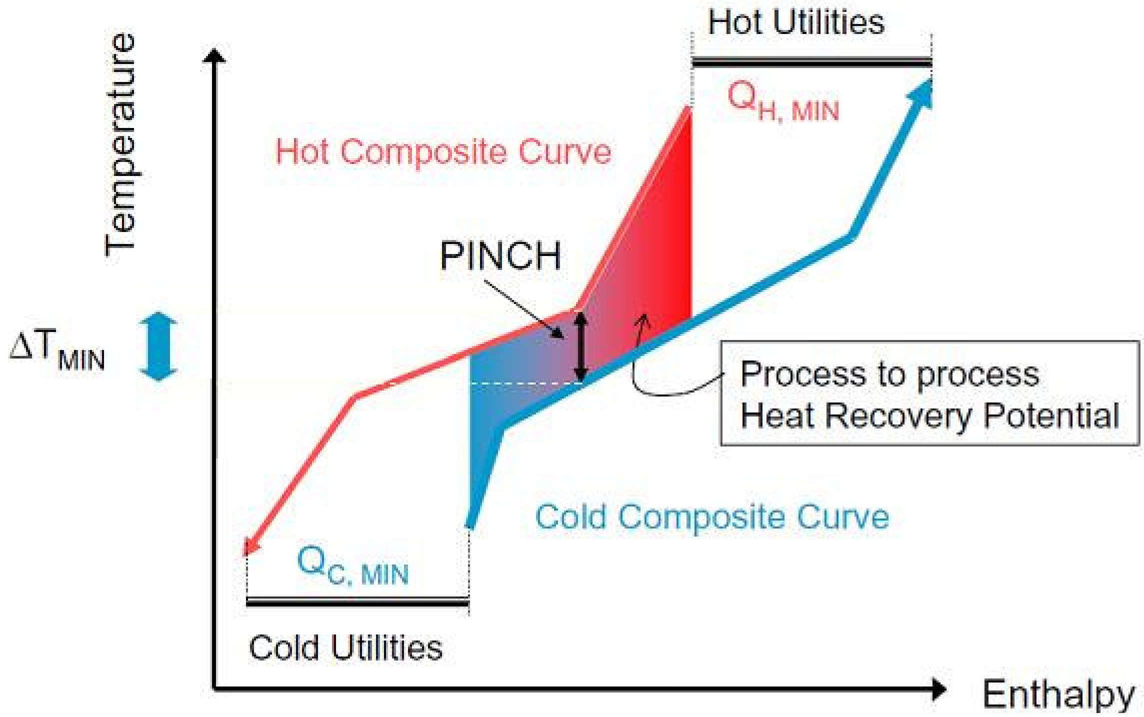


Figure 2. MER targeting procedure with cold and hot CC.

and Zhu (1997) for this purpose. For each linear segment in the CC, the heat Exergy delivered (e) by a stream delivering a heat load (Q) from the inlet temperature (T_{in}) to the outlet temperature (T_{out}) is computed by Equation 12 (Feng and Zhu, 1997):

$$e = Q(1 - \frac{T_o}{T_{lm}}) \tag{12}$$

Where, T_{lm} is the logarithmic mean of temperatures computed by Equation 13 (Polley et al., 1990):

$$T_{lm} = \frac{T_{in} - T_{out}}{Ln(\frac{T_{in}}{T_{out}})} \tag{13}$$

When considering the hot CC, the heat delivered is represented by the T-H diagram; the exergy delivered is computed by replacing the temperature axis by the Carnot factor, as expressed in Equation 14. It then corresponds to the area between the CC and the enthalpy axis (Feng and Zhu, 1997). The same procedure is followed for the cold streams, to define the Exergy required by the cold streams (Kotas, 1995).

$$\eta_c = 1 - \frac{T_o}{T} \tag{14}$$

Figure 3 shows how the CC (T-H diagram) for a heat transfer system can be converted into the ECC and the EGCC. The shaded areas in Figure 3 indicate the Exergy loss associated with the heat transfer process.

The graphical representation of process units involving energy in terms of heat and power has been made possible with the introduction of a variable referred to as energy level (Ω) defined as follows (Feng and Zhu, 1997):

$$\Omega = \frac{Exergy}{Energy} \tag{15}$$

Thus, for the work, Ω is equal to 1 but for the heat can be calculated as follows (Feng and Zhu, 1997):

$$\Omega = 1 - \frac{T_o}{T} \tag{16}$$

In the case of steady-state flow system, the Ω is expressed as follows (Feng and Zhu, 1997):

$$\Omega = \frac{\Delta E}{\Delta H} \tag{17}$$

In addition, all economic limitations and power generation process constraints can be considered in retrofit study of SPPs using CPEA (Feng and Zhu, 1997). To achieve this aim, ECC and EGCC as two basic tools of this combined analysis should be calculated. Data required for those plots can be extracted by simulation of the SPP using Cycle Tempo 5 (2006), which is powerful power plant simulation software.

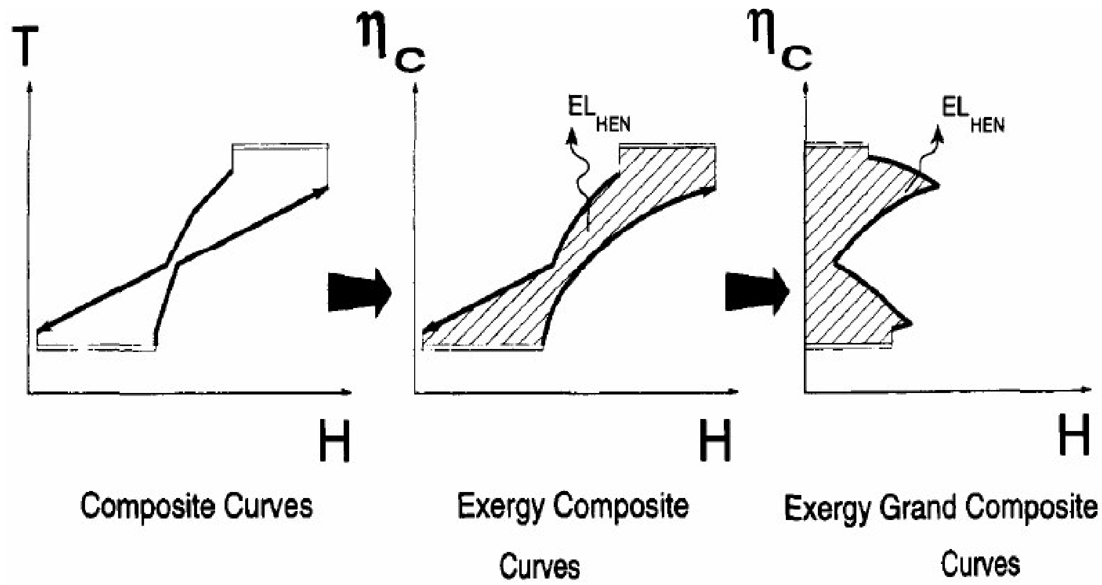


Figure 3. Exergy transformation from CC to ECC and EGCC.

RESULTS AND DISCUSSION

Plant description

A 325 MW SPP was considered as a case study. It included eight steam extraction stages and one steam reheating stage. Details related to the Rankine cycle of the power plant are shown in Table 1. In most cases, the maximum load of the sample SPP is less than 325 MW. Thus, cycle conditions were studied for a 312-MW load. In other words, all data related to water, steam, boilers, and so on were recorded and studied for such a load. As shown in Table 1, a flow rate of 83530 m^3/h of fuel was required to obtain a sufficient heating load for the thermal cycle of the power plant to generate 325 MW of electricity. Thus, taking into account the LHV of the fuel, it was found that 823.77 MW of energy was transferred to the feed water of the boiler. To compare the modified cycle with the actual cycle, the cycle of the power plant was simulated using the software cycle tempo for a 325 MW load. The value of transferred energy that was obtained was the reference value in our study.

Taking into account the gross cycle as well as the fuel LHV, it was estimated that the electricity generation performance was 39.453% for a full load, under the conditions of our study. Data related to fuel analysis and combustion calculations are given in Table 2.

Figure 4 shows the power plant cycle flow diagram. Hot and cold flows that were extracted from the flow chart are reported in Table 1. The data from Table 1 were used to plot the CC and ECC. These two curves are shown in Figures 5 and 6, respectively. According to the current load of the boiler, the minimum approach temperature difference (ΔT_{min}) in the current CC and ECC should be 5.8°C.

Plant modification

The stream data for the HEN in the sample power plant, calculated with Cycle Tempo 5, are shown in Table 3.

To modify the cycle, the steps of CPEA analysis were performed as follows:

Bringing pinches closer together

Resolving the uncoordinated distribution of stimulant forces is the first step in bringing the system to ideal conditions and reducing fuel consumption. Figures 7 and 8 display the CC and ECC after modification.

As a result of the modification, the input boiler water temperature was increased. It follows that the heating load for generating steam was decreased. The boiler-heating load was changed to 782.22 MW (that is, a 5.3% reduction relative to the base cycle). Fuel consumption was reduced to 79290 m^3/h (that is, a 5.3% reduction relative to the current cycle). Figure 9 shows the temperature driving force at a selected working point of the HEN in the power plant. This figure clearly indicates that the heat exchangers are placed on the network temperature driving force plot. Such a placement was used to minimize error from non-vertical heat transfer between hot and cold flows.

Table 1. Primary information of the sample power plant.

Power plant nominal capacity (MW)	325	
Turbine isentropic performance (%)	High pressure turbine	82.14
	Medium pressure turbine	89.85
	Low pressure turbine	86.17
Feed water pump performance (%)	82	
Boiler heating performance (%)	92.34	
Ambient temperature (℃)	10	
Air pre-heater output temperature (℃)	269	
Boiler flue gas temperature (℃)	126	
Fuel demand (m^3/h)	83530	
Nominal performance (%)	39.453	

Table 2. Important results from analyzing gas fuel and combustion calculations.

Consumable fuel analysis (Mole %)	Methane	88
	Ethane	4.5
	Propane	1.48
	Iso butane	0.24
	Normal butane	0.35
	Iso pentane	0.11
	Normal pentane	0.07
	Normal hexane	0.05
	Carbon dioxide	0.2
	Hydrogen sulfide	3 ppm
	Nitrogen	5
Fuel molecular mass (kg/kmol)	18.13	
Fuel volume mass (kg/Nm^3)	0.765	
LHV (mJ/Nm^3)	35.502	
HHV (mJ/Nm^3)	38.6	
Air required for full combustion (Nm^3/kgfuel)	31	
Excess air average percentage (%)	5	
Combustion gas mass discharge (kg/h)	2095800	
Flame adiabatic temperature (℃)	2200	
Flue gas density (kg/Nm^3)	1.2906	
Flue gas specific heat capacity (kJ/kg℃)	1.10825	

Optimization of extraction levels

In this step, the pressure (or saturated temperature) and extraction mass flows were determined so that the minimal amount of fuel necessary to generate 325 MW of electricity were consumed.

It was found that the minimum temperature difference was $\Delta T_{\min} = 5.6^{o}C$. Table 4 lists different extraction amounts, the optimal saturated temperatures, and the amount of consumed fuel.

Economical cycle optimization

Accurate economical information is important. Indeed, if the information is inaccurate, the estimated and fore-casted return on investment cannot be met. For example, considering an energy cost that is higher than the actual value results in a targeted investment that is higher than the maximal value. Thus, although more energy is saved, the value for the return on the investment will be higher. On the other hand, lower energy costs will not promote

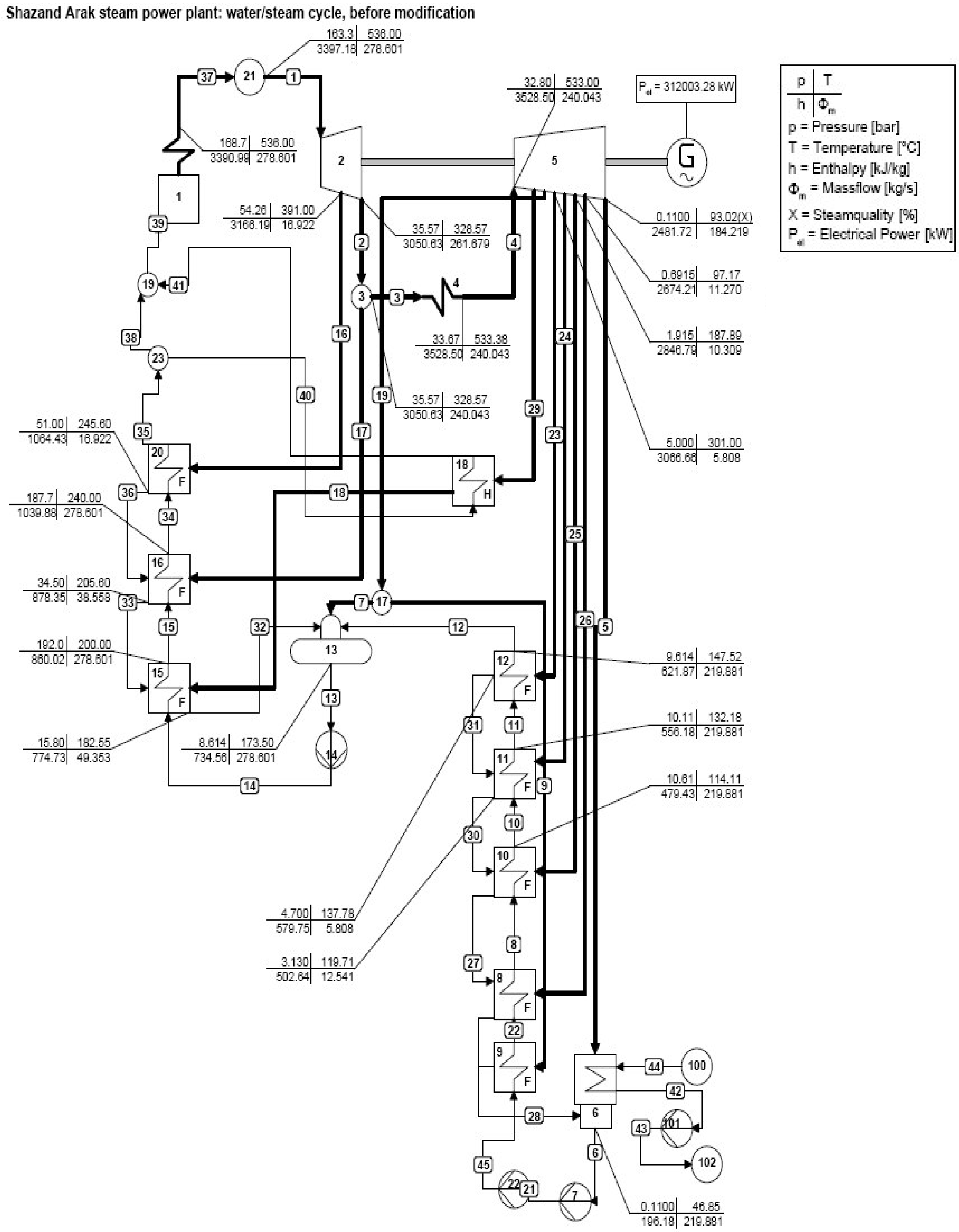


Figure 4. The process flow diagram of the sample power plant; before modification.

energy savings, as it will be hard to convince managers to fund new energy-saving, network-heating areas in process units. In sum, energy costs must be precisely determined (Ataei et al., 2009).

The operation costs of heating in the boiler and cooling in the condenser were assumed to be 12 and 3.17 \$/kWyr, respectively. In addition, the hours of operation per year (h/yr) were assumed to be 8000 h/y. The results

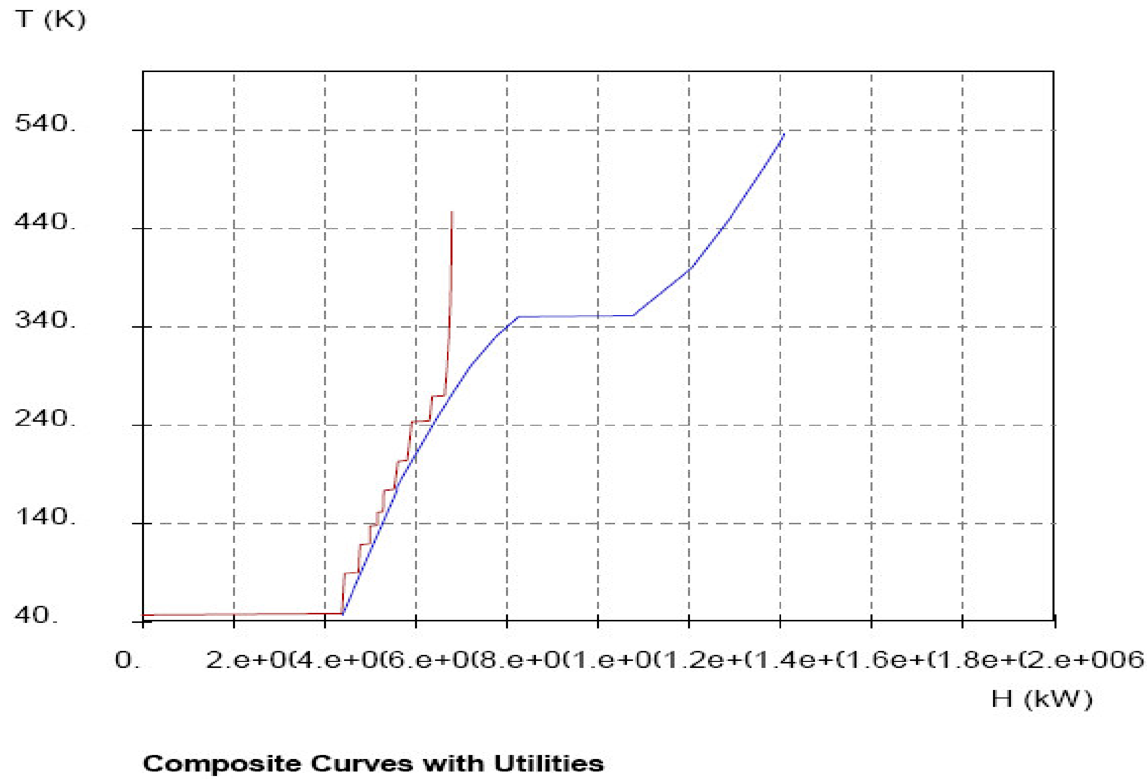


Figure 5. Cycle CC; before modification.

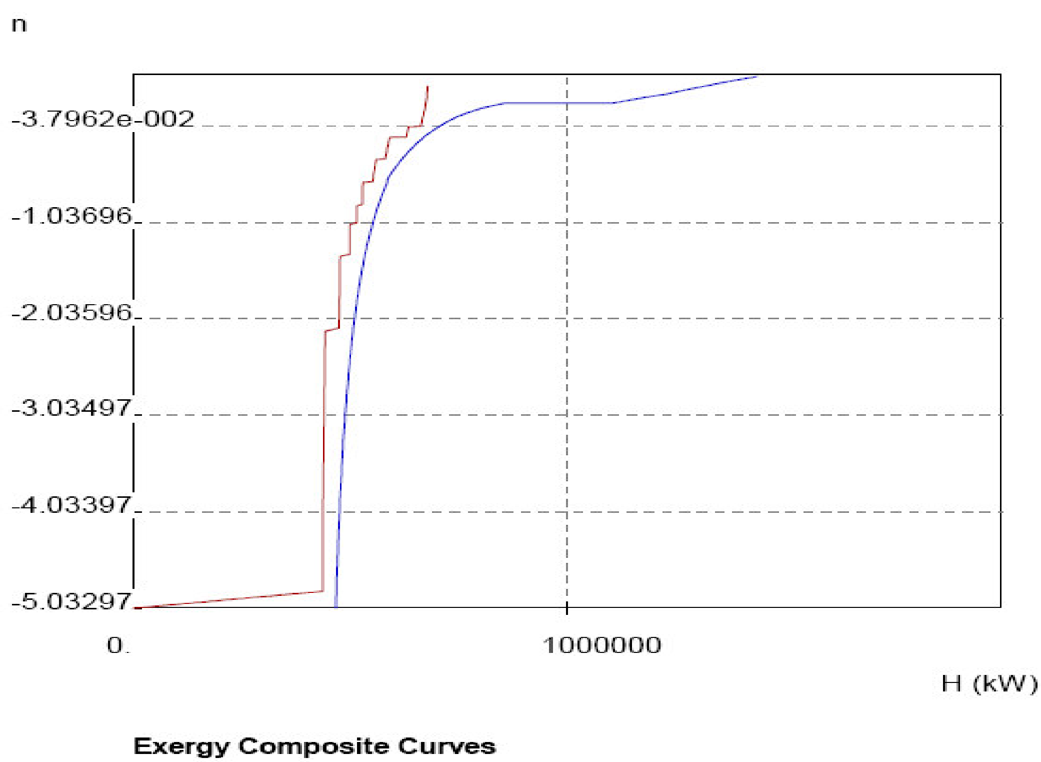


Figure 6. Cycle ECC; before modification.

Table 3. Stream data for the HEN in the sample power plant; before modification.

No.	Flow title	Mass flow (kg/h)	Supply temperature (℃)	Target temperature (℃)	Inlet pressure (atm)	Saturated temperature (℃)
1	Feed water from ejector steam condenser	219.881	47.18	173.5	8.614	173.5
2	Feed water from pump to the boiler	278.6	176.95	270	186.7	359.9
3	Steam reheat	0.42240	328.56	533	32.8	238.8
4	Steam extraction 1	216.9	391	245.6	54.26	269.08
5	Steam extraction 2	21.695	328.5	205.6	35.57	243.4
6	Steam extraction 3	7910	457	182.55	16.8	203.7
7	Steam extraction 4	9010.9	353.4	173.5	8.614	173.5
8	Steam extraction 5	8.085	301	137.6	5	151.85
9	Steam extraction 6	2376	217	119.6	2.553	128.13
10	Steam extraction 7	10.309	195.83	92.59	2.074	121.39
11	Steam extraction 8	11.27	97	87.99	0.6915	89.63
12	Input flow to the condenser	184.229	48.1	46.7	0.112	48.06

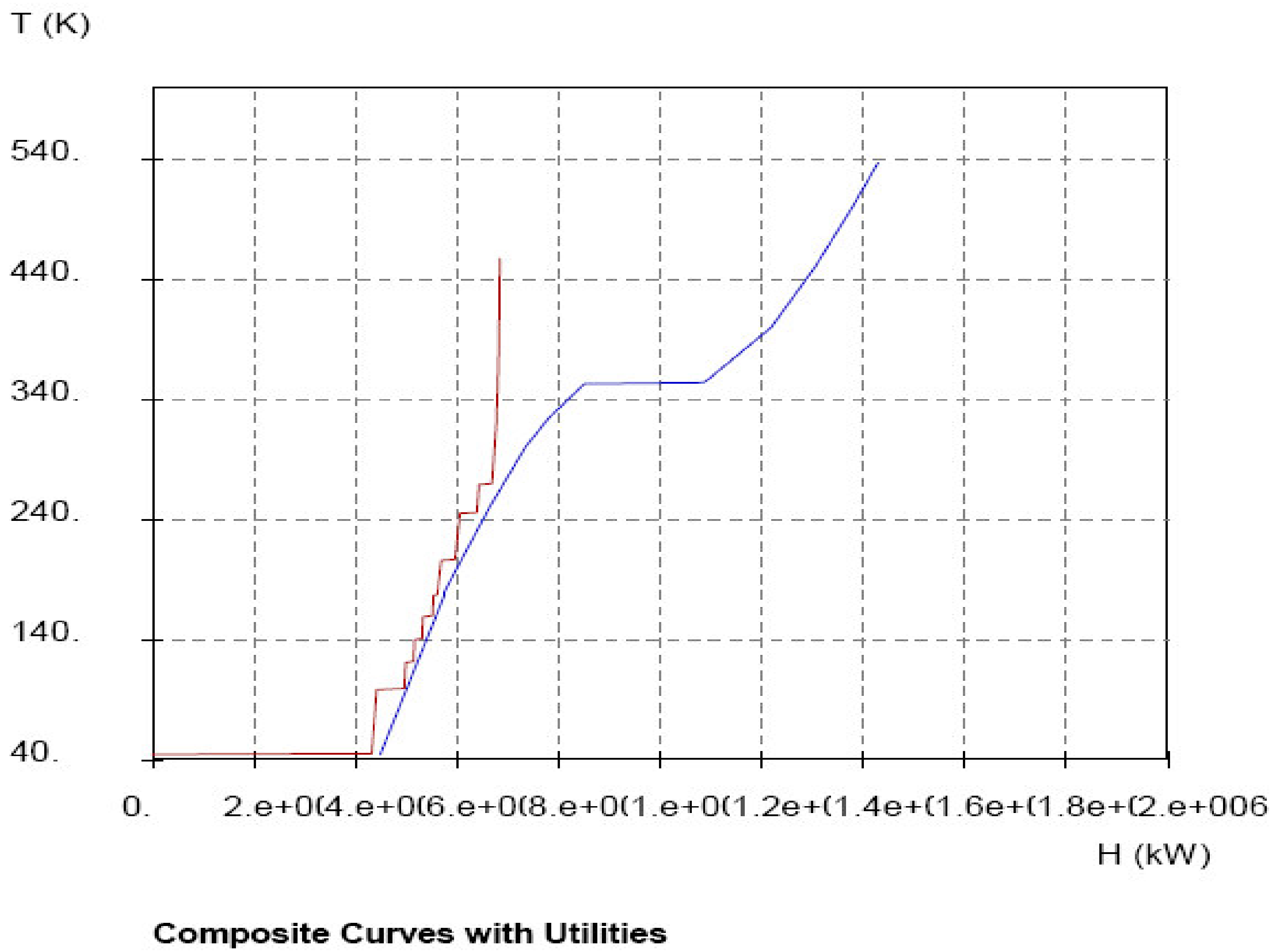


Figure 7. Cycle CC; after modification.

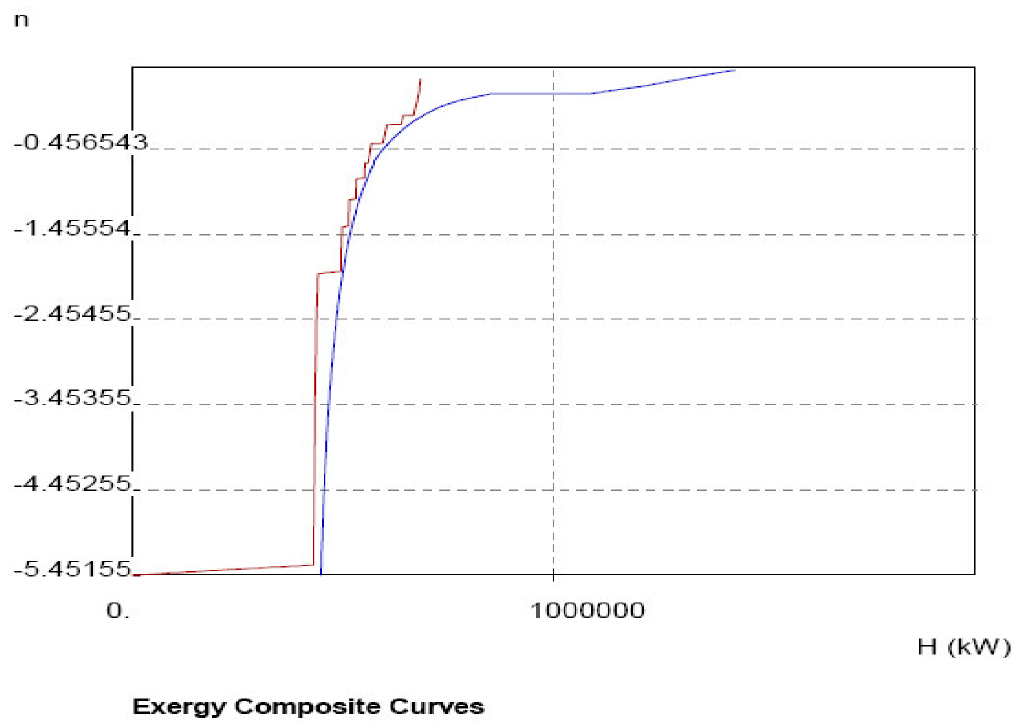


Figure 8. Cycle ECC; after modification.

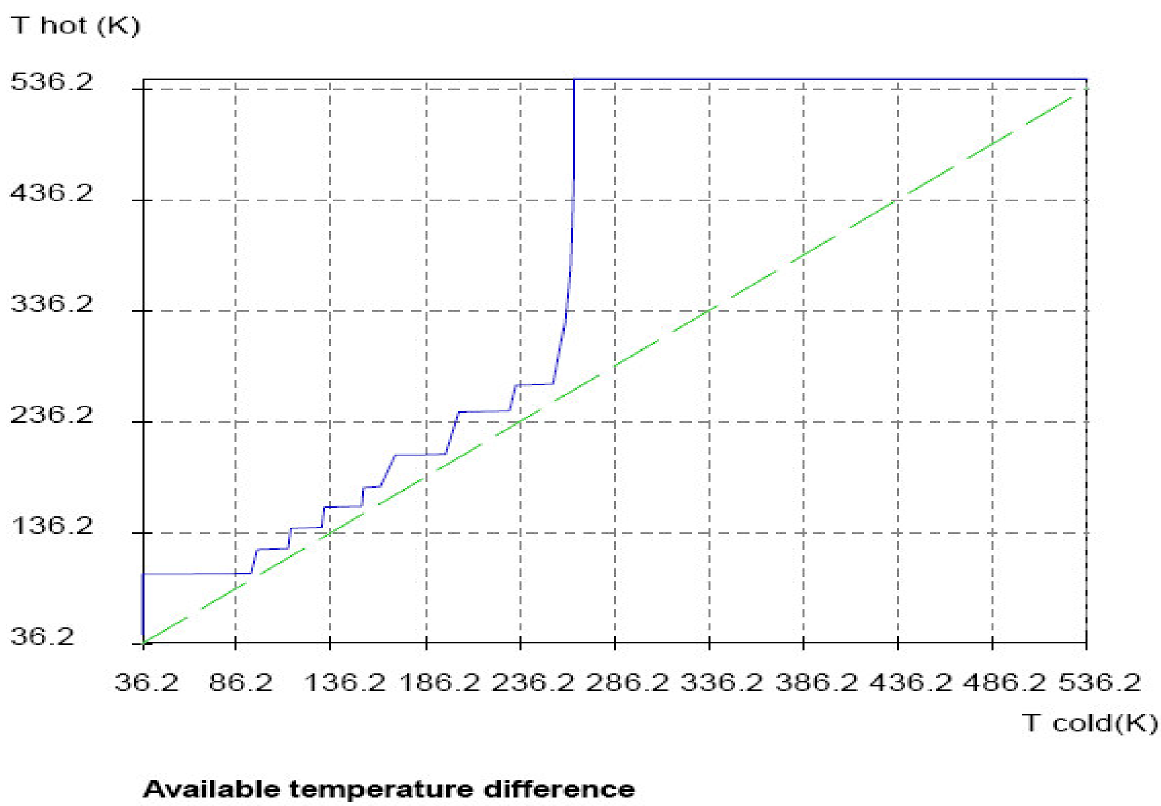


Figure 9. Temperature driving force in HEN of the cycle.

Table 4. Stream data for the HEN in the sample power plant; after modification.

No.	Flow title	Mass flow (kg/h)	Supply temperature (℃)	Target temperature (℃)	Inlet pressure (atm)	Saturated temperature (℃)	Optimum pressure drop (atm)
1	Feed water from ejector steam condenser	228.54	44.63	176.6	9.27	176.62	4.604
2	Feed water from pump to the boiler	280.558	179.79	537	173.4	353.84	1.6
3	Steam reheat	245.8	324.6	537	33.35	239.77	3.33
4	Steam Extraction 1	15.662	376.4	247.8	54.68	269.57	Negative
5	Steam Extraction 2	19.12	323.6	215	36.68	245.24	Negative
6	Steam Extraction 3	14.206	457	185.59	17.7	206.27	Negative
7	Steam Extraction 4	4.075	352.5	176.6	9.27	176.62	Negative
8	Steam Extraction 5	9.15	305.2	158.85	6.12	159.62	Negative
9	Steam Extraction 6	7.184	246	132.27	6.617	140.1	Negative
10	Steam Extraction 7	7.618	185.1	113.29	2	120.24	Negative
11	Steam Extraction 8	23.782	119.3	97.29	0.97	98.78	Negative
12	Input flow to the condenser	179.787	45.45	44.6	0.098	45.45	Negative

Table 5. Targeting results for the power plant.

Selected working point: $\Delta T_{\min} = 5.6^o C$		
Gross cycle power generation	MW	325
Cycle efficiency, after modification	%	41.9
Increase in cycle efficiency	%	2.5
Boiler load, after modification	MW	782.22
Fuel consumption, after modification	Nm^3/h	79290
Condenser pressure, after modification	atm	0.0968
Input feed-water temperature to the economizer, after modification	℃	271
Condenser load, after modification	MW	420238
Minimum heat transfer area, according to the working point	m^2	7279
Reduction in the boiler load	MW	41.55
Reduction in the fuel consumption	Nm^3/h	4240
Reduction in the condenser load	MW	18.775
Area efficiency coefficient	%	80
Addition heat transfer area	m^2	1132
Fuel savings	$/yr	518514
Condenser load savings	$/yr	38266
Total savings	$/yr	558177
Required investment	$	323116
Simple payback time	yr	0.58

of targeting and economic calculations at the selected working point ($\Delta T_{\min} = 5.6^o C$) for the power plant are given in Table 5.

Retrofit of HEN

After targeting, the HEN can be modified using the Pinch Design Method (PDM) (Polley and Panjeshahi, 1991; Polley et al., 1990). In this study, the HEN of feed-water heaters was modified and simulated using the cycle tempo software and systemic parameters were obtained. Figure 10 displays the process flow diagram of the cycle after modification. As indicated by Figure 10, new heat transfer areas have to be placed in the network in order to maintain an allowable feed-water pressure drop in the

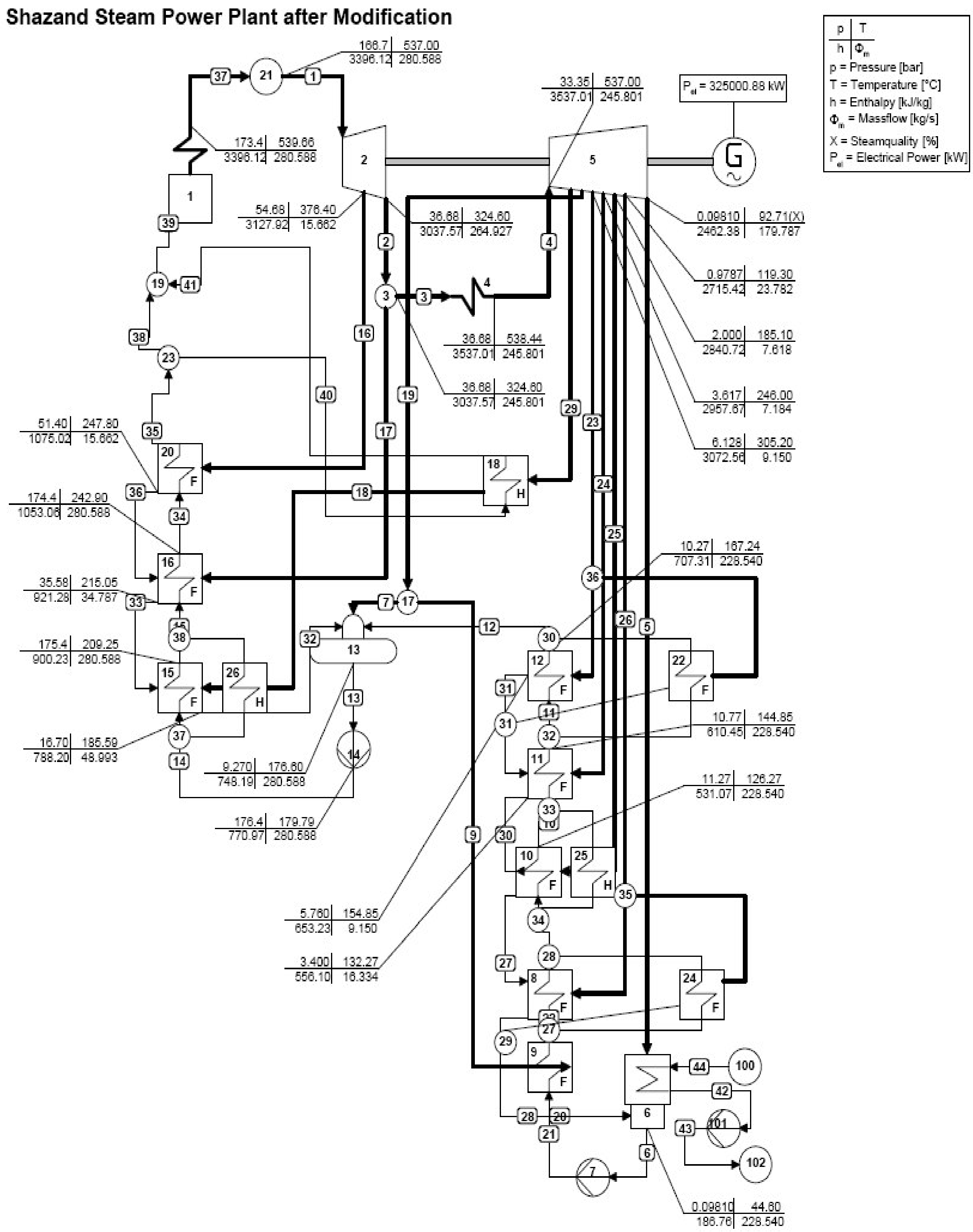


Figure 10. The process flow diagram of the sample power plant; after modification.

preheating network. More specifically, one heater must be placed in parallel with heater 8, one in parallel with heater 5, one in series with heater 6, and one in series with heater 3.

Simulation of the corrected design with the afore-mentioned software showed that, by changing the steam extraction levels as described above and installing the aforementioned new heaters, the performance of the studied power plant can be increased by exactly 5.3% for the chosen energy target. Thus, without modifying the electricity that is generated in the power plant, the natural gas (fuel) consumption and load on the cold side of the power plant can be reduced by 4240 m^3/h and 18.77 MW, respectively. These results indicate that the main problem of the power plant, that is, an insufficient efficiency of the cold side of the plant (at around 11 MW) can be solved.

If the aforementioned modifications were applied in the Rankine cycle of the sample power plant, a 33.92 million cubic meters yearly reduction in the fuel demand of the power plant would be achieved. Applying RETscreen software showed that 63226 tons of greenhouse gas (GHG) emissions-reduction per year would be obtained by this method. According to the RETscreen software, that amount of reduction in GHG emissions is equivalent to that of not using 11580 cars and light trucks.

Conclusion

The Pinch analysis and Exergy analysis concepts were used to design a power plant installation. The addition of four heaters, as shown in the modified process flow diagram, resulted in a 5.3% reduction in fuel consumption in the Rankine cycle of the sample SPP. It was found that the fuel consumption could be reduced by 4240 m^3/h. This reduction leads to considerable savings in the power plant running costs. In addition to a 2.5% increase in cycle performance, a condenser-cooling load reduction of 18.77 MW in the modified cycle of the power plant was determined. This result indicates that the main cooling tower is more efficient and no longer limits production during warm seasons.

Applying the proposed modification to power plants may result in a yearly reduction of GHG emissions of about 63226 tons, which is equivalent to not using 11580 cars and light trucks.

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NOMENCLATURE

CC*,* Composite curves; **PDM,** pinch design method; **CPEA,** combined pinch and exergy analysis; Q, Heat load (kJ); ***e*,** exergy (kJ); **s,** entropy (kJ/°K); $\dot{E}$**,** exergy rate (kW); ***s*$_o$,** entropy at ambient condition (kJ/°K); $\dot{E}_{fuel}$, exergy rate from fuel (kW); **SPP,** steam power plant; **EA,** exergy analysis; **T,** temperature (°K); **ECC,** exergy composite curves; **T_o,** ambient temperature (°K); **EGCC,** exergy grand composite curves; **T_{lm},** logarithmic mean of temperatures (°K); $e\dot{l}_{Boiler}$, rate of exergy loss in the boiler (kW); **W,** Work (kJ); $e\dot{l}_{FWH}$**,** rate of exergy loss in the feed-water heater (kW); $\dot{W}_{in}$**,** rate of inlet work (kW); $e\dot{l}_{Pump}$**,** rate of exergy loss in the pump (kW); $\dot{W}_{net}$**,** rate of net work (kW), $e\dot{l}_{Turbine}$**,** rate of exergy loss in the turbine (kW), $\dot{W}_{out}$**,** rate of outlet work (kW); **FWH,** feed-water heater; ***GCC*,** grand composite curve.

Greek letters

ΔE, Exergy changes (kW); **GHG,** greenhouse gases**; ΔH,** Heat load (kW); **h_o,** enthalpy at ambient condition (kJ); **ΔT_{min},** minimum temperature approach on composite curves (°C); **h,** enthalpy (kJ); ε_{Cycle} **,** cycle overall Exergetic efficiency; **H,** enthalpy rate (kW); ε_{HEX} **,** heat exchanger exergetic efficiency; *HEN,* Heat exchanger network; $\varepsilon_{Turbine}$**,** turbine exergetic efficiency; **HEX,** heat exchanger; **Ω,** energy level; **HHV,** high heating value (mJ/Nm^3); η_c **,** carnot factor; **LHV;** low heating value (mJ/Nm^3).

Subscripts

$\dot{m}$**,** Mass flow rate (kg/s) **cold streams,** streams need to be heated; **MER,** maximum energy recovery (kW) **Hot streams,** streams need to be cooled; **P_o,** ambient pressure (atm); **in,** Inlet**; P_1,** supply pressure (atm); **out,** Outlet; **P_2,** Target pressure (atm); **PA,** pinch analysis.

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