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Abstract: This study evaluates and compared the performance of coal-fired power plants in ultra-supercritical (USC) versus integrated gasification combined cycle (IGCC). System execution in terms of net control created, exergy examination was performed to coordinate the vitality loss dispersion of this system. Base on the exergy adjust condition. The IGCC system is modeled and simulated with post-combustion capture and both used sub-bituminous coal from the Indramayu PLTU. The result display that with the same amount of raw materials (20 ton/h coal) the IGCC generated great net power than USC. IGCC produced net power of 42 MW and USC of 22 MW. The highest exergy loss in the gasifier, H_2S Removal and Carbon Capture for IGCC and in Boiler, Steam Turbine system, and condenser for USC. The total exergy efficiency for IGCC was 41.51% and 33.71% in USC.

1. Introduction

Electricity consumption increases regardless of the economic development stage of each country and region[1] included Indonesia. Indonesia's GDP per capita has increased rapidly in the 2000s and beyond. Indonesia's economic growth is expected to continue to increase electricity consumption to reach 491 terawatt hours (TWh) in 2030. Therefore, electricity generation capacity needs to be increased by 4.1 gigawatts (GW) per year, of which 50% of the total installed capacity is Coal Power Plant[2].

Combustion of fuel produced high exhaust emission especially CO_2 gases which increased pollutant concentration in air. Coal contributed 44% of total global CO_2 emissions and became the largest source of GHG (greenhouse gas) emissions[3] such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3), and chlorofluorocarbons (CFCs)[27]. To reduce these pollutants, it is very important to increase energy efficiency in coal-fired power plants[4].

Reducing CO_2 gas emissions from the energy sector in principle can be done in several ways, namely the use of energy-efficient technologies or use Clean Coal Technology (CCT), fuel substitutions from low carbon (C) to higher carbon (C) or fuels with lower carbon fractions, and the third is CO_2 or carbon capture and storage (CCS)[5].

Clean Coal Technology (CCT) does not eliminate emissions to zero or close to zero, but rather means that there are fewer emissions. Even so, clean coal technologies can reduce emissions from several pollutants and waste and increase the energy produced from each ton of coal. Thus, the CCT technology for a coal power plant is now more efficient and environmentally friendly. besides using clean coal technology, it is necessary to add carbon capture to increase its efficiency. the purpose of carbon capture is to collect from various streams and is usually liquefied to facilitate storage[26] or usually injected into the depths of the ocean and oil wells that are no longer in use.

The application of clean coal technology is useful for developing more efficient thermal systems, namely, to produce the same amount of energy, fewer coal inputs are needed, thus extending the availability of energy sources and producing emissions that are far lower than conventional technology. Various types of clean coal technology are still under development in order to provide a method that is environmentally satisfying in the use of

coal, especially for electricity generation such as USC[4, 6-11], IGCC [12-14], and Integrated Coal Gasification of Fuel Cell Combined Cycle (IGFC)[15]. In China use of coal as gasification is considered a promising technology and can handle energy needs and climate change[23].

For the IGCC plant, the fuel source is also derived from low-grade solid fuels (biomass, wood, refinery residues, and petroleum cokes)[11]. So, in this study will be used low-quality coal (sub-bituminous) from Indramayu PLTU. From report Huaneng Greengen Co the result shows that IGCC has higher efficiency thermal than USC but the generating capacity of both is different (USC is 1000MW and IGCC is 250 MW)[16] so it cannot be compared.

M Asif et al.[12] simulated and compared in three configurations: IGCC without CO_2 capture, IGCC with pre- combustion capture (IGCC-eCC), and IGCC with post-combustion capture (IGCC-oCC). IGCC-oCC is more efficient than IGCC-eCC, namely 561 MW and 518 MW, respectively. M. Knoope et al[25]. investigate the technological and economic prospects of IGCC and Fischer–Tropsch (FT) liquid production with and without CCS, results indicate that substantial cost reductions and performance improvements are possible, especially for IGCC with CCS. Y. Liu et al.[4] studied that thermodynamic analysis of a modified system for a 1000 MW single reheat ultra-supercritical thermal power plant, results show that the exit temperature of flue gas from the boiler can be reduced to a lower value without cold end corrosion and clog. The power generation efficiency of the power plant of 48.35% is achieved, which is 1.27% points higher than that of the reference unit at the same capacity. Zhou et al.[7] studied that Parametric analysis and process optimization of steam cycle in double reheat ultra-supercritical power plants, the results showed that the power generation efficiency of the double reheat power plant could increase by 0.49 percentage point by parametric and process optimization.

Most of the works depended adjust investigation on energy based. These considers based on the vitality base strategies are simple to get it, but as it were the quantitative variety of vitality is considered, and its subjective variety is ignored. Subsequently, the application of such a strategy for surveying the enhancement conceivable outcomes of a prepare can result in a mutilated vision of the inquired about the framework and the irreversibility of forms inside the framework cannot be characterized[9]. By differentiate, exergy examination can characterize the work potential of a framework. Exergy is characterized as the most extreme hypothetical valuable work gotten with the reference or dead state, exergy investigation based on the moment law of thermodynamics can precisely appear the development and utilization of a device[6, 9].

The purpose of this study to perform of an IGCC-oCC and USC process was developed using UniSim Design® R450 and Promax® 4.0. IGCC and USC technology was evaluated and compared. Performance of the system in terms of net power produced, to performed energy loss distribution of this system use the exergy analysis. Base on the exergy balance equation, exergy efficiency, exergy distribution and efficiency of the unit were determined.

2. Description and Calculation Models

2.1 Description process of IGCC

The Process flow diagram of the IGCC prepare utilized within the investigation is shown in Fig. 1. The process consists of five main blocks: coal measuring and slurry planning, gasification unit, syngas cooling and cleaning unit, Acid Gas Removal (AGR) unit, CO_2 gas cleaning unit and combined cycle power segment. In the step one of the preparation coal with crushing and mixing of coal with water. The coal slurry is fed to the gasifier unit added with pure O_2 95% and steam to produce raw syngas, raw syngas is fed to syngas cooling and cleaning to remove H_2S gas using an absorption unit with MDEA solvent. syngas that has been separated will be burned in the combustor unit using dry air then the combustion gas will be used as a driving force in the turbine gas unit to produce electricity. The turbine output gas will be used as a heater in the Heat Recovery Steam Generation (HRSG) unit to produce steam. Steam produced will be used as a driving force for steam turbines to produce electricity. the gas used to produce steam will be fed to the CO_2 removal unit.

The reason for utilizing unadulterated oxygen within the gasifier is to extend the warming esteem of the syngas and to diminish the syngas volume. The low volume of raw syngas is moderately simple to handle within the heat recuperation area and in acid gas removal unit. Also, the by and large taken a toll of the IGCC framework diminished due to the little hardware measure in gasification, AGR, and syngas cooling units[12].

The traditional Sulphur removal processes utilize a variety of commercial solvents, which be categorized into three general types: chemical, physical, and hybrid solvents[18].

Steam produced in the HRSG unit is divided into three parts related to pressure, namely high pressure (HP), intermediate pressure (IP), low pressure (LP). To drive the steam turbine used the HP superheated steam from HRSG. And then to produce superheated steam used the IP and LP steam reheated in the HRSG [12].

2.2 Description Process of USC

The Process flow diagram of the USC process used in the analysis is shown in Fig. 2. The process consists of two main blocks: boiler subsystem and turbine subsystem[8]. The coal is fed to the boiler, where the feed water from the regenerative system from the steam turbine is heated to the specified conditions. The power plant comprises high-pressure turbines (HPT1, HPT2), intermediate-pressure turbines (IPT1, IPT2), and low- pressure turbines (LPT1-4). The Flue gas prepares to CO_2 Capture to separate CO_2

and H_2S with the DEA solvent[24].

2.3 Simulation Models and Main Assumptions

An IGCC and USC plant integrated with CO_2 capture are simulated using UniSim Design® R450 and Promax® 4.0 program simulation software. The following are some of the design parameters and assumptions used in this study:

- The model is based on a steady state
- Coal particles feed in standard conditions (30 °C and 1 atm)
- Feed coal use rheology of coal-water slurries[17]
- A chemical reaction occurs in a state of equilibrium, and there is no decrease in pressure
- In the heat exchanger, there is a pressure drop of 5 psi

- The composition of syngas products and process model based on experimental data [12, 18]
- The boiler model is based on a reference model of Yang, et al. and Zhou, et al.[8, 7]
- The Air Separation Unit (ASU) is not modeled
- The Cryogenic is based on a reference model (Air Liquide Indonesia. PT)
- In the Gasification Reactor used a UniSim Design® R450
- Pump efficiency of 65%
- Turbine efficiency and compressor of 75%
- Coal specification was obtained from the Indramayu PLTU (Table 1)

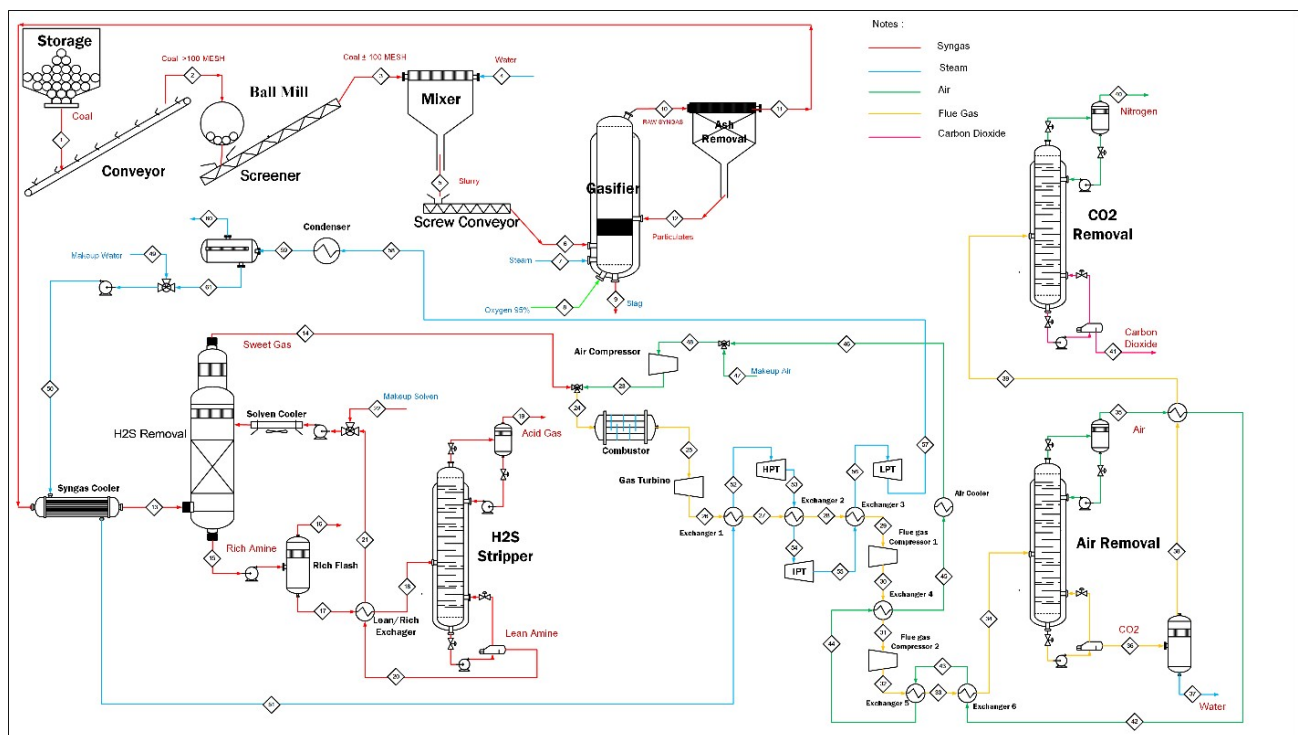The operating conditions and design used of the IGCC plant shown in Table 2 and USC plant shown in Table 3.

Fig. 1: Process flow diagram of the IGCC

2.4 Calculation method

exergy is a form of the second law of thermodynamics related to energy quality, where not all energy produced can be used or produce 100% work, but there will be a loss of good environment. The exergy loss can be form of chemical exergy, physical exergy, potential exergy and kinetic exergy. For the exergy-based analysis, the physical, chemical, potential, kinetic and total exergies of all streams are calculated based on the results from the simulation [12, 19,21-22].

$$Ex_{total} = Ex_{ph} + Ex_k + Ex_p + Ex_{ch} \qquad (1)$$

Because there is no kinetic and potential exegesis so the

two exergy can be ignored and the equation becomes:

$$Ex_{total} = Ex_{ph} + Ex_{ch} \qquad (2)$$

The following is the equation used to calculate physical exergy:

$$Ex_{ph} = (h - h_0) - T_0(s - s_0) \qquad (3)$$

The following is the equation used to calculate chemical exergy for gas mixture:

$$Ex_{ch,gas} = \sum x_i Ex_{ch,i} + RT_0 \sum x_i ln x_i \qquad (4)$$

The equation used to calculate Chemical exergy of the

coal is [12]:

$$Ex_{ch, \ fuel} = (LHV + w_{H2O}LH_w)\emptyset_{dry} + 9417w_s \quad (5)$$

$$\emptyset_{dry} = 0.1882\frac{w_h}{w_c} + 0.061\frac{w_{ox}}{w_c} + 0.0404\frac{w_n}{w_c} \ +$$

$$1.0437 \quad (6)$$

The following is the equation used to calculate exergy efficiency:

$$\eta = \frac{Exergy \ Product}{Exergy \ Input} \quad (7)$$

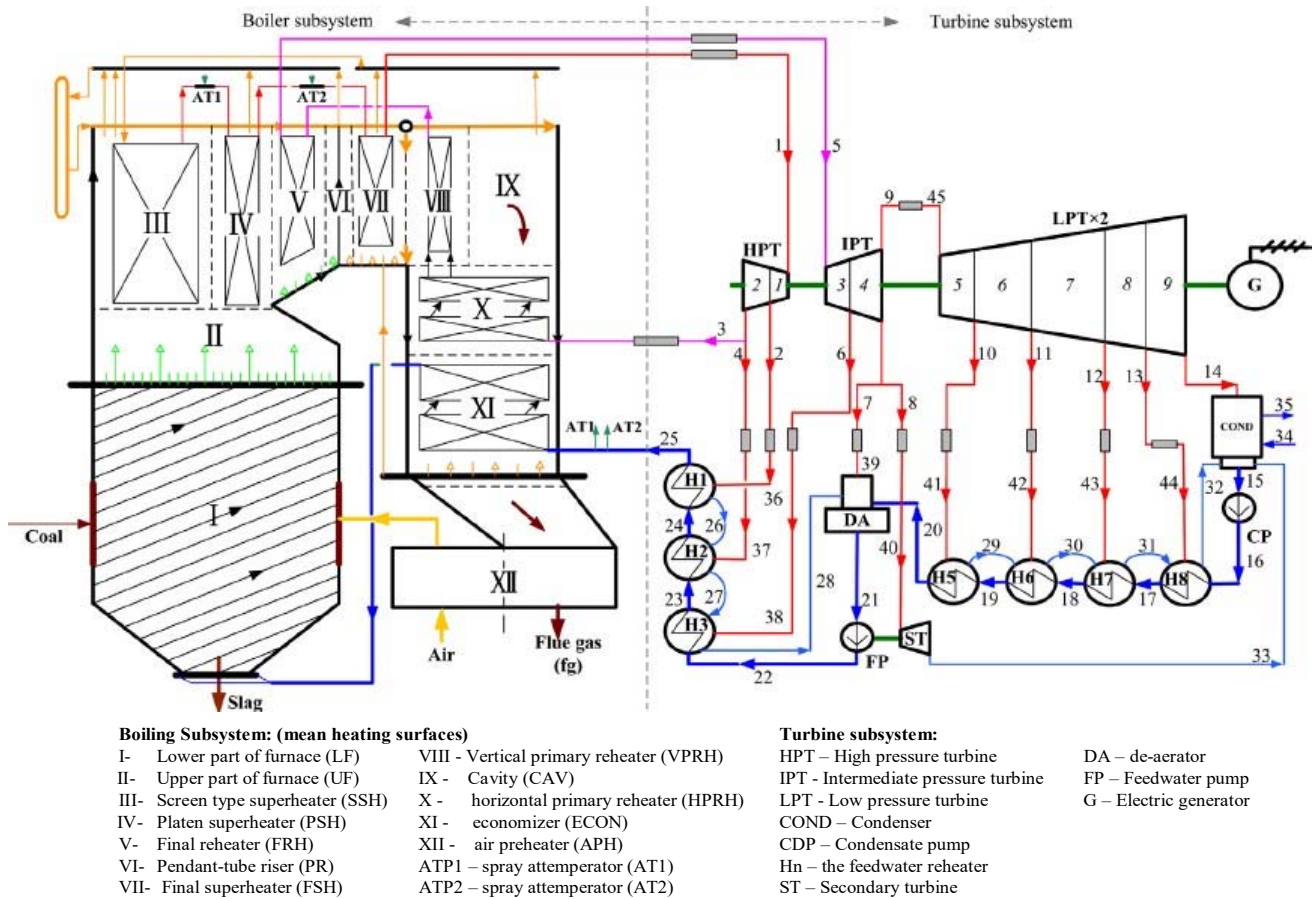**Fig. 2:** Process flow diagram of the USC

Boiling Subsystem: (mean heating surfaces)

I- Lower part of furnace (LF)	VIII - Vertical primary reheater (VPRH)
II- Upper part of furnace (UF)	IX - Cavity (CAV)
III- Screen type superheater (SSH)	X - horizontal primary reheater (HPRH)
IV- Platen superheater (PSH)	XI - economizer (ECON)
V- Final reheater (FRH)	XII - air preheater (APH)
VI- Pendant-tube riser (PR)	ATP1 – spray attemperator (AT1)
VII- Final superheater (FSH)	ATP2 – spray attemperator (AT2)

Turbine subsystem:

HPT – High pressure turbine	DA – de-aerator
IPT - Intermediate pressure turbine	FP – Feedwater pump
LPT - Low pressure turbine	G – Electric generator
COND – Condenser	
CDP – Condensate pump	
Hn – the feedwater reheater	
ST – Secondary turbine	

Table 1. Composition analysis of coal

Composition	Value (% wt.)
Moisture	14.34
Fixed carbon	37.63
Volatile matter	43.47
Ash	4.56
C	55.42
H	4.20
N	0.71
S	0.1
O	20.67
Ash	4.56
Calorific value, HHV (kcal/kg)	4236

Table 2. Assumptions and operating conditions for simulation of IGCC

Units	Model Simulation	Parameters	Value
Reactor	Gasifier Reactor	Pressure (kPa)	2000
		Temperature (°C)	1063
		Composition:	
		Coal 65% wt. (kg/h)	20000
		Air 35% wt. (kg/h)	7000
		Oxygen (95%), 35% wt. (kg)	7000
		Steam (Kg/h)	8000
		Syngas out (kg/h)	40696.13
Combustor	Combustor	Pressure (kPa)	1800
		Temperature (°C)	763.8
		Composition:	
		Syngas (kg/h)	26557
		Air (kg)	978393
		Type Combustor (Gibs Minimization) Gibs set (burner)	
H_2S Removal	H_2S absorber	Mass solvent (MDEA) (kg)	43830.63
		Temperature (°C)	30
		Pressure (kPa)	1965.53
		Ideal Stage Column Type (TSWEET Kinetics)	
		Pressure Drop per tray (Psi)	5
		Number of trays	7
		Diameter (m)	1.3
		Tray Spacing (m)	0.6
		Weir Height (cm)	7
		Total Height (m)	12.6
	Stripper	Temperature (°C)	100
		Pressure (kPa)	172.37
		Ideal Stage Column Type (TSWEET Stripper)	
		Number of trays	10
		Pressure Drop per tray (Psi)	4
	HE,	Pressure Drop (Psi)	5
	Cooler,	Pressure Drop (Psi)	5
	Pump,	Pump Efficiency (%)	65
	Makeup Solvent	Mass (Kg/h)	5481.31
HRSG	preheater, economizers, evaporator superheater	Pressure Drop (Psi)	5
CO2 Removal	Distillation Cryogenic 1	Temperature (°C)	-70
		Pressure (kPa)	480
		Number of trays	10
	Distillation Cryogenic 2	Temperature (°C)	-120
		Pressure (kPa)	480
		Number of trays	5
		Mass CO2 (kg/h)	40097.12

Table 3. Assumptions and operating conditions for simulation of USC

Unit	Model Simulation	Parameter	Value
Boiler	Combustor	Pressure (kPa)	465.53
		Temperature (°C)	1568
		Composition:	
		Coal (kg/h)	20000
		Air (kg/h)	336000
	Type Combustor (Gibs Minimization) (WSPSH), (FRH), (FSH), Economizer, (PRH), (APH)	Gibs set(burner) Pressure Drop (Psi)	5
		Pressure (kPa)	30000
H_2S dan CO_2 Removal	Absorber	Mass solvent (DEA)(kg/h)	756000
		Temperature (°C)	30
		Pressure (kPa)	465.53
		Ideal Stage Column Type (TSWEET Kinetics)	
		Pressure Drop per tray (Psi)	5
		Number of trays	15
		Diameter (m)	4
		Tray Spacing (m)	0.6
		Weir Height (cm)	7
		Total Height (m)	27
	Stripper	Temperature (°C)	120
		Pressure (kPa)	175.53
		Ideal Stage Column Type (TSWEET Stripper)	
		Number of trays	10
		Pressure Drop per tray (Psi)	4
	HE	Pressure Drop (Psi)	5
	Cooler,	Pressure Drop (Psi)	5
	Pump	Pump Efficiency (%)	65
	Makeup Solvent	Mass (Kg/h)	3311.53
HPT	2 Turbine	P in (kPa)	29212.1
		P out (kPa)	4601.47
IPT	2 Turbine	P in (kPa)	4498.05
		P out (kPa)	1000
LPT	4 Turbine	P in (kPa)	1000
		Pout (kPa)	40

3. Results and Discussions

Fig. 3. Display the simplified schematic as a result of the simulation with IGCC technology and Fig. 4. Display the simplified schematic as a result of the simulation with USC technology.

Total power produced, and the total power consumed in IGCC and USC system is shown in Fig. 5. And The power consumed, and the power produced in IGCC and USC section are shown in Fig. 6 and Fig. 7. in IGCC net power produced was 42 MW and 22 MW in USC. The results indicated that the power produced from IGCC was highest than USC. In research conducted by Asif et. al.[12], coal is needed at 157860 kg/h to produce a net power of 561 MW using IGCC technology. while Y. Yang et.al[8] requires coal of 250740 kg / h to produce a net power of 670 MW. So that in the next study optimization of coal flow rate is needed to produce a more optimum net power.

The maximum power produced in the GT was 148.48 MW. 20.63 MW and 22.14 MW in consecutive contained in ST IGCC and USC. 1.022 MW consumed in the gas turbine compressor of the Combustor for IGCC, for O_2 compression for IGCC was 0.95 MW and consumed in Cryogenic CO_2 Separation was 125 MW. Nearly 73.92% of the total power produced consumed in Cryogenic CO_2 Separation, consumed in pumps 0.04 MW, 0.0008 MW for coal slurry preparation and consumed in the main CO_2 compressor for USC was 20.84 MW Shown in Fig. 6. The results 73.92% was consumed in the Cryogenic CO_2 Separation of the total power produced and in USC is illustrated in Fig. 7. The results shown that 0.6 % consumed in the pump of the total power produced.
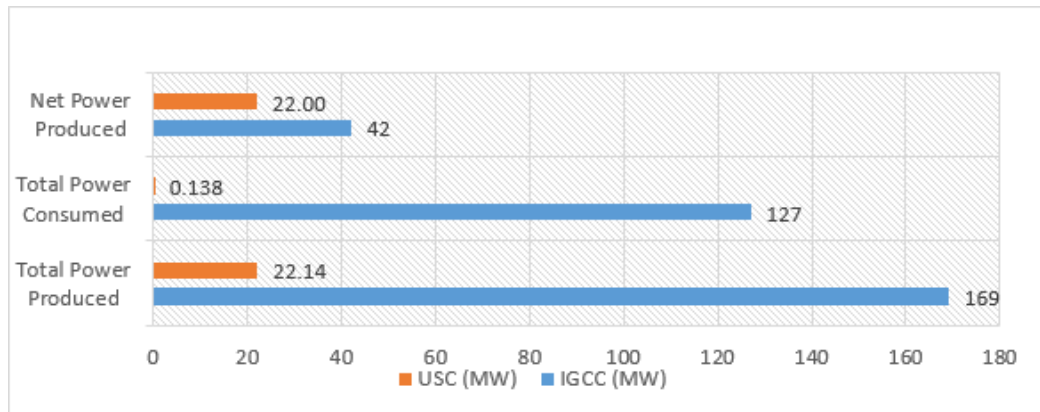
Fig. 3: Schematic of the IGCC system with Promax® 4.0

Fig. 4: Schematic of the USC system with Promax® 4.0

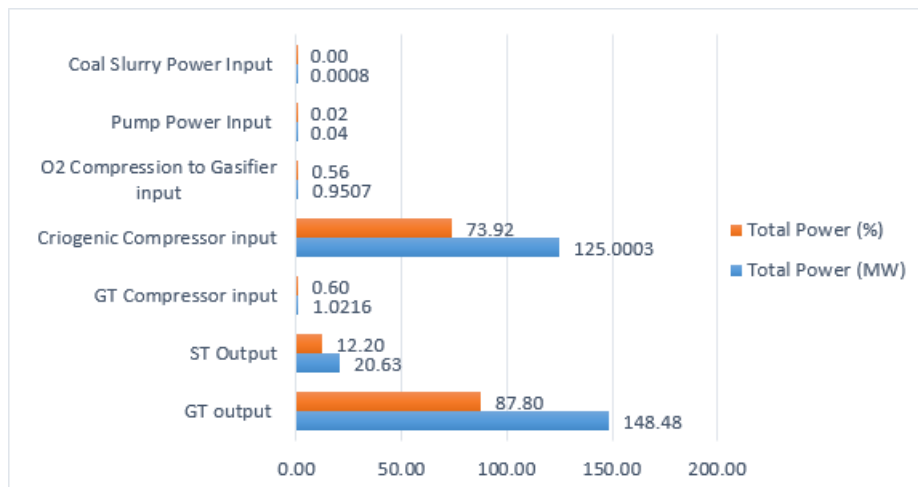**Fig. 5:** Comparison of the total power generated and consumed in IGCC and USC

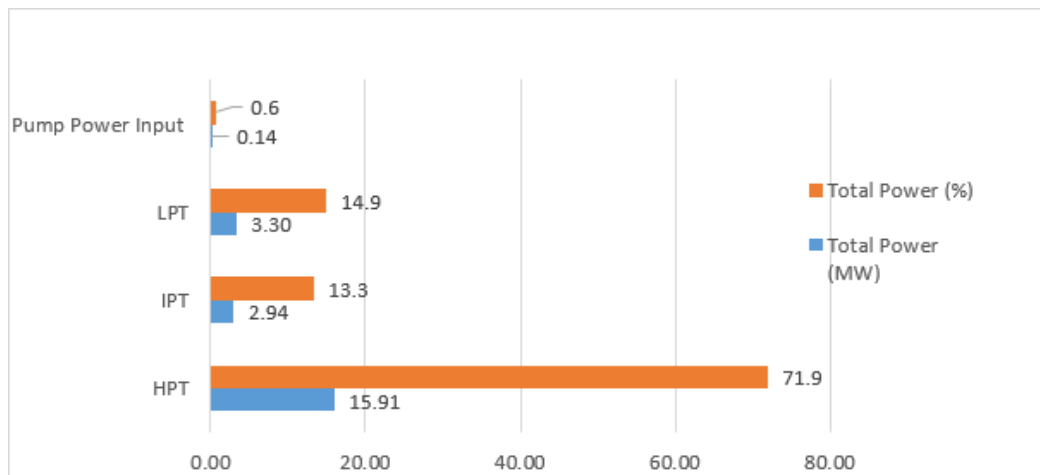**Fig. 6:** The power consumed and produced in IGCC section

Fig. 7: The power consumed, and the power produced in USC section

The results indicate that 43.19 % of the efficiency exergy in the gasifier, 99.29 % in the syngas Cooler, 66.845 % in the H_2S Removal, 98.966 % in the combustor, 71.286 % in the Air Compressor, 94.747 % in the Gas Turbine, 44.115 % in the Steam Turbine system, 94.057% in the HRSG and then 92.034% in the Carbon Capture.

For USC the efficiency exergy, was 80.98 % in the Boiler subsystem, 96.37 % in the Steam Turbine system, 98.75 % in the Regenerative Heating System, 5.33 % in the Condenser and 99.75 % in the Carbon Capture. For IGCC the highest exergy losses is in the unit gasifier, H_2S Removal, and Carbon Capture, and the USC the highest exergy losses in the Boiler ST system and condenser.

The low efficiency of the gasifier and boiler or combustor besides being caused by the loss of chemical exergy related to chemical reactions is also caused by the quality of coal fuel, especially in the water content. In coal gasifier which is fed in the form of slurry which still contains a lot of water. The water content causes heat loss due to the evaporation process of the water content in the fuel. The higher the water content in the fuel, the greater the heat loss [20].

Table 4. Exergy Loss in the IGCC Technology

Unit	Ex in (MW)	Ex out (MW)	Ex loss (MW)	Efficiency Exergy (%)
Gasifier	240.8101	104.006	136.8041	43.190
Syngas Cooler	130.8023	129.873	0.929	99.290
H2S Removal	1372.542	917.4821	455.0601	66.845
Combustor	107.4737	106.3621	1.111616	98.966
Air Compressor	269.5452	192.1483	77.39697	71.286
Gas Turbine	107.4737	101.8279	5.645845	94.747
Steam Turbine system	179.9273	79.37548	100.5518	44.115
HRSG	681.6483	641.1367	40.51166	94.057
Carbon Capture	2661.872	2449.836	212.0361	92.034
Total	101.41	42.09	59.32	41.51

Table 5. Exergy Loss in the USC Technology

Unit	Ex in (MW)	Ex out (MW)	Ex loss (MW)	Efficiency Exergy (%)
Boiler	1223.36	990.64	232.72	80.98
Steam Turbine	610.40	588.26	22.14	96.37
Regenerative Heating system	806.12	796.08	10.03	98.75
Condenser	26.45	1.409	25.045	5.33
Carbon Capture	1726.36	1722.13	4.23	99.75
Total	65.26	22.003	43.26	33.71

4. Conclusion

This study to evaluate and compare the performance of coal fire power plants between IGCC and USC. Both of them processes are modeled and simulated with Unisim and Promax program, and exergy analysis and net power produced used to evaluate the results. The following conclusions can be derivate:

- The net power produced in IGCC was 42 MW and in USC was 22 MW. While the power produced with USC is the lowest[8, 12]. That is the next study optimization of coal flow rate is needed to produce an optimum net power.
- The relatively higher exergy losses for IGCC in the gasifier, H2S Removal, and Carbon Capture, this is caused by the chemical exergy that is lost and the occurrence of chemical reactions in the gasifier and Gas Turbine combustor. For USC the relatively higher exergy losses in the Boiler Steam Turbine system and condenser.
- The total exergy efficiency for IGCC was 41.51% and 33.71% in USC.

for further research needed an economic calculation to determine the feasibility of coal fire power plants between ultra-supercritical (USC) and integrated gasification combined cycle (IGCC).

Nomenclature

Ex	exergy (MW)
LHV	low heating value (J kg^{-1})
T_0	temperature of the dead state (K)
P_0	pressure of the dead state (kPa)
h	specific enthalpy (J kg^{-1})
s_0	entropy of the dead state (J kg^{-1} K^{-1})
s	entropy of initial state
h_0	enthalpy of the dead state (J kg^{-1})
w	weight fraction (–)
x	Mole fraction of syngas (–)

LH	latent heat (kJ/kg)
R	Gas law constant (m^3 kPa kmol^{-1} K^{-1})

Greek symbols

η	Efficiency exergy (–)
$\emptyset$	Coefficient to solid fuel composition (–)

Subscripts

ch	chemical
ph	physical
k	kinetic
p	potential
i	Component index
c	carbon
f	fuel
h	hydrogen
n	nitrogen
s	sulfur
w	water
ox	oxygen

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