Pre-FEED – Performance Results

A Low Carbon Supercritical CO_2 Power Cycle / Pulverized Coal Power Plant Integrated with Energy Storage:

Compact, Efficient and Flexible Coal Power

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Project Partners

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1. Performance Summary

Performance Summary Metrics

This section details the calculation methodologies for the metrics reported in the performance summary.

Fired Heater Efficiency

The fired heater efficiency is equal to the amount of heat transferred to the CO_2 in the fired heater divided by the thermal input of the coal and natural gas (HHV basis). It is represented by the following equation:

$$\eta_{FE} = \frac{Q_{CO2}}{Q_{Coal} + Q_{NG}}$$

Where:

- η_{FE} – Fired heater efficiency
- Q_{CO2} – Heat transferred to the CO_2
- Q_{Coal} – Heat input of coal
- Q_{NG} – Heat input of natural gas into the fired heater

sCO_2 Power Cycle Efficiency

The power cycle efficiency is calculated by taking the gross power generated by the power turbine, subtracting the power cycle auxiliary loads, and dividing by the heat transferred to the CO_2 in the fired heater. It is represented by the following equation:

$$\eta_{PC} = \frac{W_{PT} - W_{cycle\ auxiliary}}{Q_{CO2}}$$

Where

- η_{PC} – Power cycle efficiency
- W_{PT} – sCO_2 power turbine gross power generated at generator terminals
- $W_{cycle\ auxiliary}$ – Auxiliary loads associated with the power cycle and fired heater

Generation Efficiency

The plant generation efficiency is calculated by taking the gross power generated by the power turbine adding the gross power generated by the combustion gas turbine, subtracting the power cycle and post combustion capture (PCC) auxiliary loads, and dividing by the heat transferred to the CO_2 in the fired heater and the heat input to the combustion gas turbine and heat recovery steam generator. It is represented by the following equation:

$$\eta_G = \frac{W_{PT} - W_{cycle\ auxiliary} + W_{GT} - W_{PCC\ auxiliary}}{Q_{CO2} + Q_{GT}}$$

Where

- η_G – Generation efficiency
- W_{GT} – Gas turbine gross power generated at generator terminals
- $W_{PCC\ auxiliary}$ – Auxiliary loads associate with the power cycle, fired heater, and the PCC system
- Q_{CO2} – Heat transferred to the CO_2
- Q_{GT} – Heat input of natural gas to the gas turbine and steam generator

Overall Plant Efficiency

The overall plant efficiency is calculated by adding the gross electric power produced sCO2 turbine and gas turbine and subtracting all plant auxiliary loads then dividing by the total heat input into the plant. It is represented by the following equation:

$$\eta_{Plant} = \frac{W_{PT} + W_{GT} - W_{PCC\ auxiliary} - W_{cycle\ auxiliary}}{(Q_{coal} + Q_{NG}) + \ Q_{GT}}$$

Where

- η_{Plant} – Net plant efficiency

Electrothermal Energy Storage (ETES) System Round Trip Efficiency

The round-trip efficiency of the ETES system is calculated by dividing electrical energy produced during the generating process by the electrical energy consumed during the charging process. It is represented by the following equation:

$$RTE = \frac{W_{generated}}{W_{charge}}$$

Where

- RTE – Round trip efficiency
- $W_{generated}$ – Electricity generated in generating cycle
- W_{charge} – Electricity consumed in the charging cycle.

Key System Assumptions

Table 1 shows key sCO$_2$ power cycle equipment performance values. Note, these values do not represent a solution that is optimized for only power cycle efficiency. Power cycle costs are considered during the cycle design and performance and cost are traded. There is potential to get approximately 0.5% points in power cycle efficiency if the heat exchangers are allowed to grow in size (UA). Echogen (EPS) typical design practices limit the effectiveness of the recuperators to 98% and both the low temperature recuperator (LTR) and high temperature recuperator (HTR) are below this limit. Turbomachinery efficiencies are scaled based shaft power (smaller sizer or shaft power corresponds to lower efficiency).

Table 1 sCO2 Power Cycle Equipment Performance Assumptions

Power Turbine	
Inlet Pressure (MPa)	27.4
Inlet Temperature (°C)	700
Isentropic Efficiency (%)	91.8
Low Temperature Compressor	
Inlet Pressure (MPa)	6.5
Inlet Temperature (°C)	21.7
Isentropic Efficiency (%)	88.3
Low Temperature Compressor Drive Turbine	
Inlet Pressure (MPa)	27.4
Inlet Temperature (°C)	700
Isentropic Efficiency (%)	86.4

High Temperature Compressor	
Inlet Pressure (MPa)	27.4
Inlet Temperature (°C)	700
Isentropic Efficiency (%)	86.6
High Temperature Compressor Drive Turbine	
Inlet Pressure (MPa)	27.4
Inlet Temperature (°C)	700
Isentropic Efficiency (%)	87.5
Low Temperature Recuperator	
Effectiveness (%)	97.1
Min. Approach Temperature (°C)	6.4
Overall Thermal Conductance, UA (kW/°C)	17,807
High Temperature Recuperator	
Effectiveness (%)	96.6
Min. Approach Temperature (°C)	11.2
Overall Thermal Conductance, UA (kW/°C)	14,136

Table 2 defines the assumptions applied to the fired heater, air quality control system (AQCS) equipment, and the post combustion carbon capture (PCC) systems.

Table 2 Fired Heater, AQCS, and Post Combustion Capture Equipment Assumptions

Fired Heater	
Coal	Montana Rosebud subbituminous (95% heat input)
Natural Gas	Natural Gas (5% heat input)
Fired Heater Efficiency (%)	84
Stack Temperature (°C)	33
AQCS Equipment	
SO2 Control	Circulating Dry Scrubber (CDS) and PCC flue gas pretreatment
Flue Gas Desulfurization Efficiency (% before / after PCC system)	92.2 / 99.9
NOx Control	Low NOx burners, over-fire air, and selective catalytic reduction (SCR)
SCR Efficiency (%)	70.7
Ammonia Slip (ppm) (end of catalyst life)	5
Particulate Control	Fabric filter
Fabric Filter Removal Efficiency (%)	99.8
Ash Distribution (% fly / bottom)	80 / 20
SO3 Control (%)	> 99% of SO3 is captured within the CDS

Mercury Control	Carbon injection at CDS
CO_2 Control	MHI KM CDR process ®
Overall Carbon Capture (%)	83.6

sCO_2 Fired Heater and PCC Heat and Mass Balance

The following section describes the sCO_2 fired heater and PCC system performance. The fired heater and air quality control system (AQCS) is described by the process flow diagram (PFD) shown in Figure 1 and the heat-and-mass balance (HMB) is summarized in Table 3 (line number therein corresponds to the stream number in the PFD). The flue gas constituents are summarized in Table 4. A dual-fuel system capable of firing pulverized coal and natural gas generates the hot flue gas, furnace and convective sections transfer heat to the CO2 working fluid and a tubular air heater transfers heat to combustion air. The system is designed to operate under full load with a 95% heat input from coal and 5% heat input from natural gas. The natural gas heat input is used for temperature trimming of the sCO2, as attemperation typical in steam systems is not utilized in this design.

The AQCS includes NO_x control using SCR, SO_2 control using a CDS and particulate control using a fabric filter. Tubular air preheaters are proposed for combustion air heater, and there is no air leakage present in the preheater.

The PCC system PFD and HMB are shown in Figure 2. Note only flue gas inlet and CO_2 capture conditions are shown.

Table 3 sCO_2 Fired Heater - HMB

Line	Media	Temp	Pressure	Draft	Fluid Flow	Solids	Flow	Flow
#		°C	bar(a)	mm H20	kg/hr	kg/hr	(A) L/min	(S) L/min
1	Coal	15	N/A	N/A	0	50,954	N/A	N/A
2	Coal / Primary Air	66	N/A	508	104,033	50,954	3,202,437	1,414,933
3	Natural Gas	15	3.4	N/A	1,040	N/A	14,314	21,219
4	Primary Air (Cold)	15	N/A	1,270	104,033	N/A	1,424,242	1,414,933
5	Primary Air (Hot)	371	N/A	1,143	104,033	N/A	3,183,600	1,414,933
6	Secondary Air (Cold)	15	N/A	381	312,299	N/A	4,275,477	4,247,532
7	Secondary Air (Hot)	288	N/A	254	312,299	N/A	8,374,645	4,247,532
8	Secondary Air (Hot)	288	N/A	254	83,266	N/A	2,232,879	1,132,493
9	Secondary Air (Hot)	288	N/A	254	229,033	N/A	6,141,766	3,115,039
10	CO2	209	295.1	N/A	281,656	N/A	N/A	N/A
11	CO2	520	292.1	N/A	281,656	N/A	N/A	N/A
12	CO2	503	292.1	N/A	3,124,457	N/A	N/A	N/A
13	CO2	700	275.1	N/A	3,124,457	N/A	N/A	N/A
14	Flue Gas / Fly Ash	414	N/A	-127	464,168	3,742	15,092,199	6,371,377
15	Flue Gas / Fly Ash	346	N/A	-203	464,168	3,742	12,844,424	6,371,377
16	Flue Gas / Fly Ash	346	N/A	-318	464,375	3,742	13,804,717	6,374,210
17	Flue Gas / Fly Ash	174	N/A	-406	464,375	1,339	9,921,255	6,374,210

18	Flue Gas / Fly Ash	79	N/A	-533	488,097	198,385	5,898,350	6,699,840
19	Flue Gas	79	N/A	-762	488,097	5	8,878,460	6,699,840
20	Flue Gas	88	N/A	25	488,097	5	8,422,022	6,699,840
21	Byproduct (Ash/Lime)	79	N/A	-533	0	197,041	N/A	N/A
22	Byproduct (Ash/Lime)	79	N/A	-406	0	195,701	N/A	N/A
23	Water	15	5.9	N/A	23,723	N/A	N/A	N/A
24	Lime	15	1.4	N/A	0	1,339	N/A	N/A
25	Ammonia	15	6.6	N/A	206	N/A	N/A	N/A

Table 4 sCO2 Fired Heater - Flue Gas Constituents

Line	**N2**	**O2**	**CO2**	**H2O**	**SO2**	**SO3**	**HCl**	**NOx as NO2**	**Ash**	**NH3**
#	**vol % (wet)**	**vol % (wet)**	**vol % (wet)**	**vol % (wet)**	**PPM$_v$ (wet)**	**PPM$_v$ (wet)**	**PPM$_v$ (wet)**	**PPM$_v$ (wet)**	**g/m^3**	**PPM$_v$ (wet)**
14	71.52	3.13	11.60	13.65	723.6	5.8	9.2	187.6	4.28	0.00
15	71.52	3.13	11.60	13.65	723.60	5.80	9.20	187.60	4.28	0.00
16	71.53	3.15	13.63	11.61	721.3	7.2	9.2	56.1	4.27	5.00
17	71.53	3.15	13.63	11.61	721.3	7.2	10.4	-	5.13	4.6
18	68.72	2.96	10.82	17.23	105.9	1.7	1.0	-	441.74	4.3
19	68.75	3.03	10.85	17.17	53.0	0.3	1.0	-	0.01	0.8
20	68.75	3.03	10.85	17.17	53.0	0.3	0.8	-	0.01	0.8

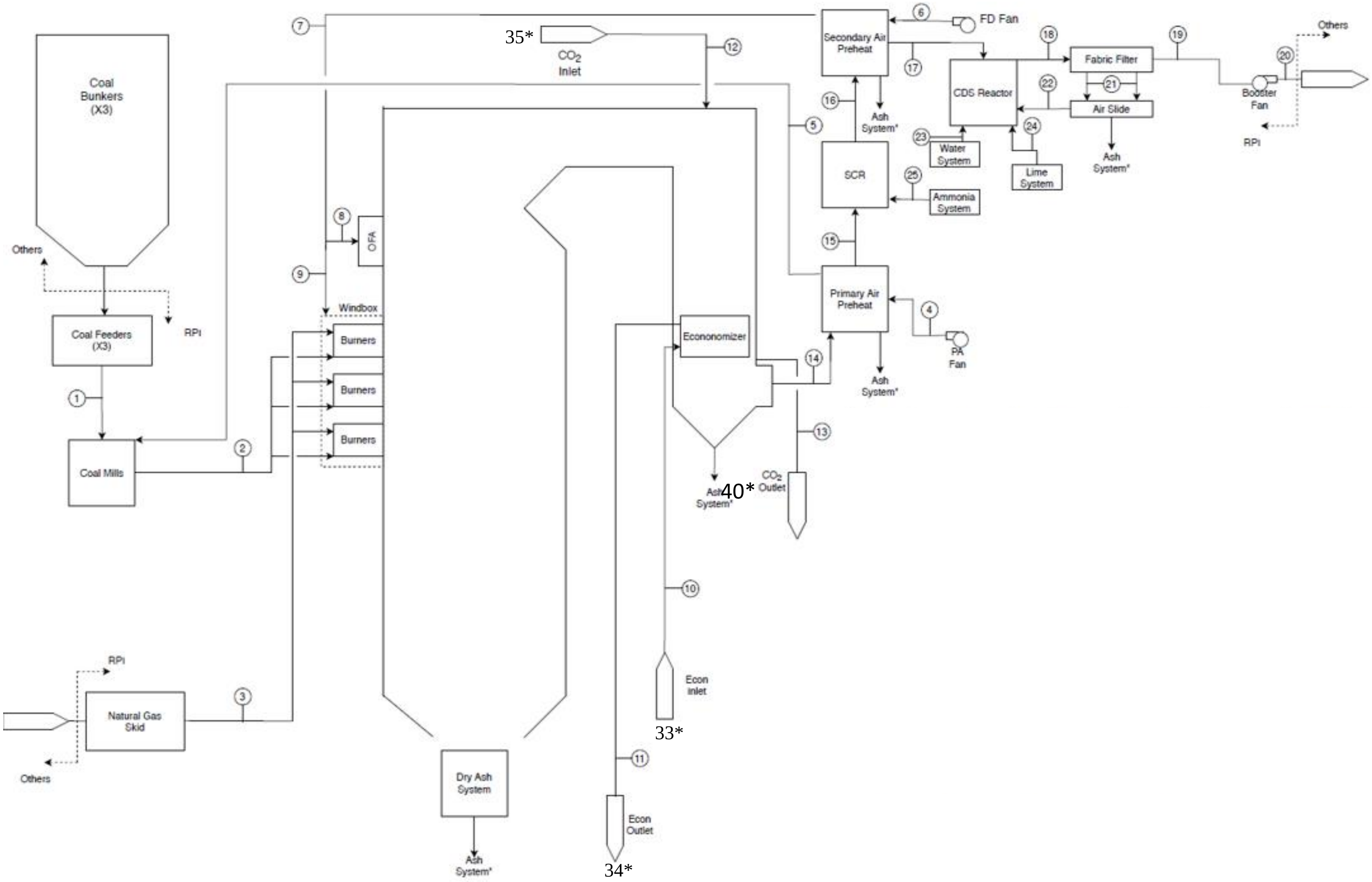
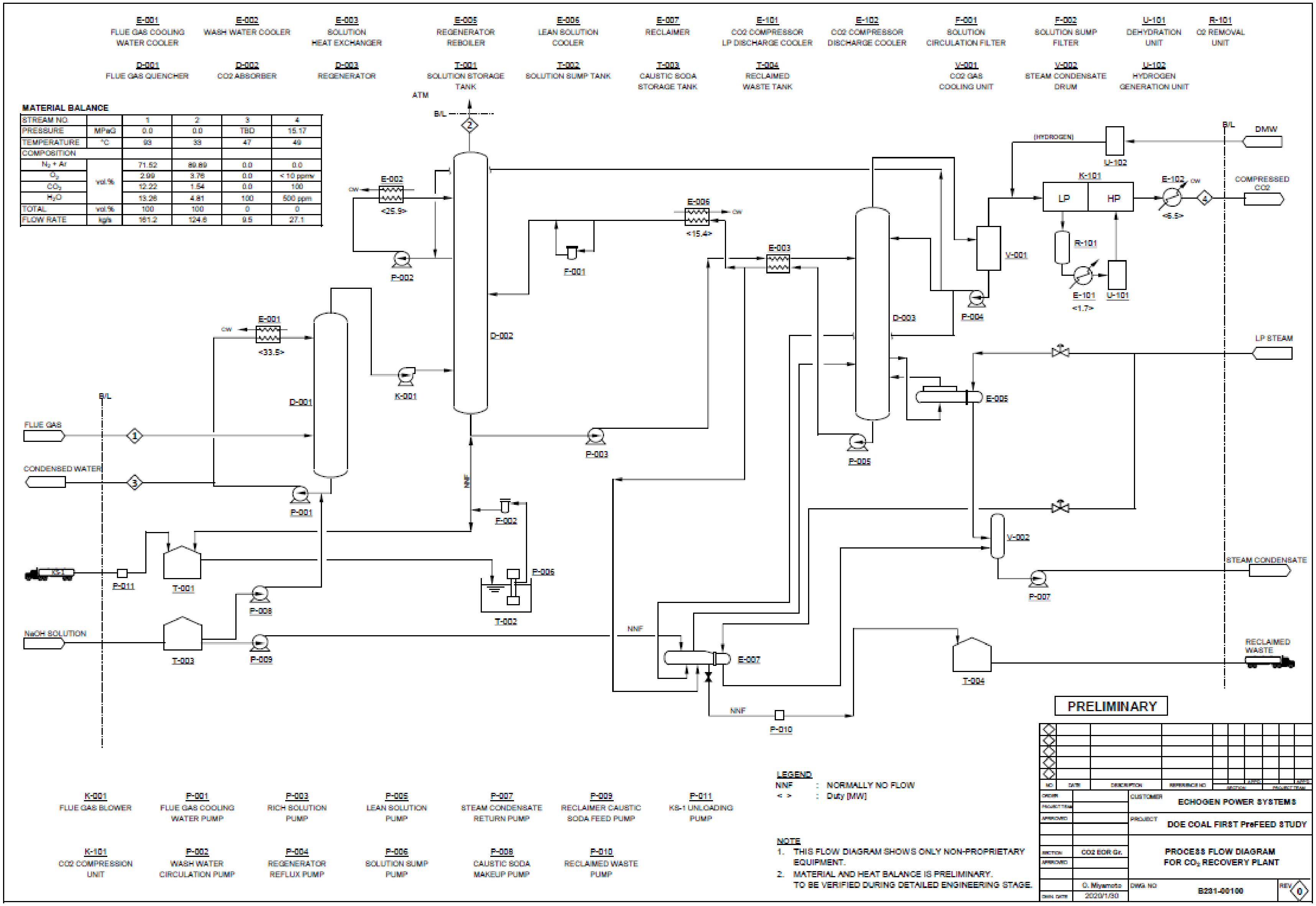


*Figure 1 sCO2 fired heater PFD (note; streams marked with * correspond to stream numbers from sCO2 power cycle)*



MATERIAL BALANCE

STREAM NO.		1	2	3	4
PRESSURE	MPaG	0.0	0.0	TBD	15.17
TEMPERATURE	°C	93	33	47	49
COMPOSITION					
N_2 + Ar	vol.%	71.52	89.89	0.0	0.0
O_2		2.99	3.76	0.0	< 10 ppmv
CO_2		12.22	1.54	0.0	100
H_2O		13.26	4.81	100	500 ppm
TOTAL	vol.%	100	100	0	0
FLOW RATE	kg/s	161.2	124.6	9.5	27.1

LEGEND

NNF : NORMALLY NO FLOW
< > : Duty [MW]

NOTE

1. THIS FLOW DIAGRAM SHOWS ONLY NON-PROPRIETARY EQUIPMENT.
2. MATERIAL AND HEAT BALANCE IS PRELIMINARY. TO BE VERIFIED DURING DETAILED ENGINEERING STAGE.

CUSTOMER: ECHOGEN POWER SYSTEMS
PROJECT: DOE COAL FIRST PreFEED STUDY
SECTION: CO2 EOR Gr.
PROCESS FLOW DIAGRAM FOR CO_2 RECOVERY PLANT
O. Miyamoto
DWN. DATE: 2020/1/30
DWG. NO: B231-00100
REV. 0

Figure 2 MHI PCC HMB

Combined Heat and Power Plant and Air-fired PC Exhaust Flow

The proposed plant includes two separate heat (exhaust) sources. A combined-heat-and-power (CHP) plant, consisting of a natural gas (NG) combustion turbine (CT) and heat recovery steam generator (HRSG), and the air-fired PC heater. The full exhaust of the air-fired PC heater is sent to the PCC system, while only a partial amount of exhaust from the CHP plant is sent. There is a cap on the amount of 30% heat input (HHV) for the NG in the total plant. To meet this requirement only fraction of the total CHP exhaust can be processed in the PCC system, while the remainder is exhausted through a stack. A simplified flow diagram of the exhaust flows is shown in Figure 3, and the state points are defined in Table 5.

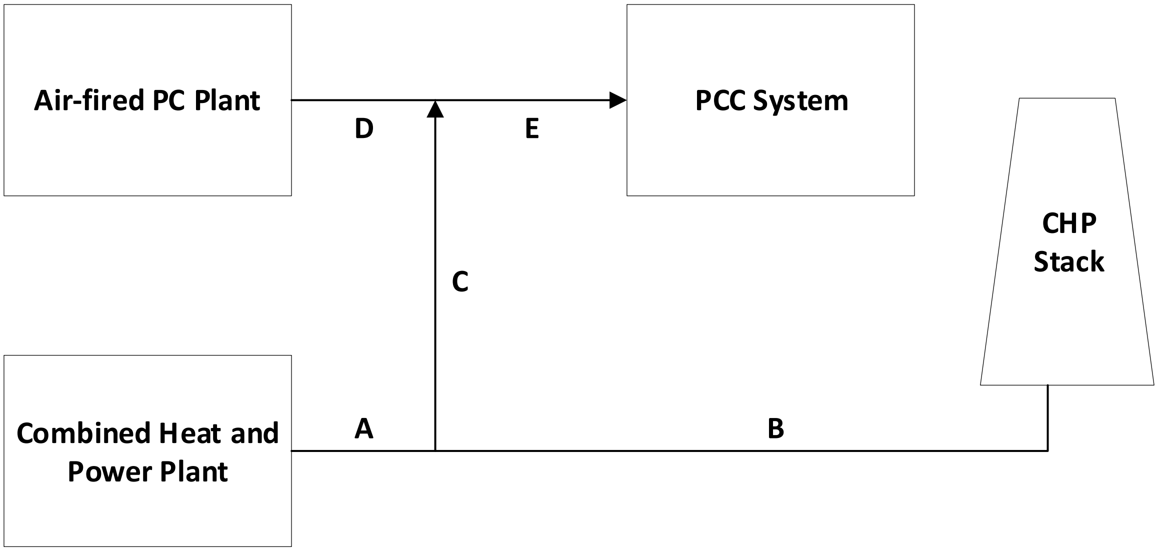


Figure 3 Combined Heat and Power Plant / Air-fired PC Heater Exhaust Flow Diagram

Table 5 CHP / Air-fired PC Heater Exhaust HMB

State	Description	Temperature (°C)	Mass Flow (kg/s)	Enthalpy (Wet Gas) (kJ/kg)
A	CHP plant exhaust	113	57.3	93.4
B	CHP plant exhaust to stack	113	24.3	93.4
C	CHP plant exhaust to PCC	125	33.0	93.4
D	Air-fired heater exhaust (State 20, Figure 1)	88	128.9	66.6
E	PCC Inlet (State 1, Figure 2)	93	161.9	72.0

sCO_2 Power Cycle Heat and Material Balance

The sCO_2 power cycle and plant performance are summarized in the following section. The modified recompression Brayton (mRCB) cycle described in the Design Basis Report is used for the power cycle. This cycle allows for more efficient use of the heat produced in the fired heater, with little effect on power cycle performance (approximately 0.1% change in power cycle efficiency). The specific state points for the proposed cycle are based on a cycle optimization in which both fired heater an sCO2 power cycle performance and sCO2 power cycle costs are considered. This combined optimization results with the HTC and LTR high pressure outlets having slightly different temperatures. The power cycle PFD is shown in Figure 4, with the HMB summarized in Table 6.

Plant electrical loads are summarized in Table 7. These loads encompass the main power generation portion of the plant, but do not include the ETES system. Generating loads include both the sCO_2 power cycle and combustion turbine (CT) generators. The total net generating capacity of the plant is 120.7 MW_e. Auxiliary loads for the fired heater include fans, coal pulverizers, and atomizers. sCO_2 power cycle auxiliary loads include gearbox and generator losses, air-cooled condenser fans and turbomachinery auxiliaries. Also included were transformer losses and a balance-of-plant allowance for buildings, coal conveying, ammonia pumps and vaporizers, and ash transport systems. The PCC system auxiliary loads and CT electrical generation have been combined into a single line item. The auxiliary loads associated with this include the following: cooling tower fans, cooling water pumps, condensate return and HRSG boiler feedwater pumps, and make-up water pumps.

A summary of the power cycle component size and performance is shown in Table 8.

The plant performance summary for both the plant without and with PCC is shown in Table 9 and Table 10, respectively. In both cases the fired heater efficiency is 84% and the power cycle has a gross thermodynamic efficiency of 48%. Without PCC the net plant efficiency, excluding CT generating and PCC auxiliary loads as shown in Table 7, is 40.3% HHV. With PCC the net plant efficiency is 29.9% HHV.

Table 6 sCO_2 power cycle heat and mass balance

State	Description	Temperature (°C)	Pressure (MPa)	Flow (kg/s)	Enthalpy (kJ/kg)
10	CHX Outlet - LTC Inlet	21.7	6.52	568.0	258.3
20	LTC Outlet	50.2	30.00	568.0	290.3
21	HTC Outlet	201.7	29.58	318.1	573.8
22	Turbomachinery Bearings	50.2	30.00	18.0	290.3
23	LTR High Pressure Inlet	50.2	29.97	550.0	290.3
30	LTR High Pressure Outlet	214.2	29.58	550.0	592.4
31	HTR High Pressure Inlet	209.5	29.50	789.9	585.6
32	HTR High Pressure Outlet	500.9	29.29	789.9	967.3
33	PHX-2 Inlet	209.5	29.51	78.3	585.6
34	PHX-2 Outlet	520.0	29.21	78.3	991.4
35	PHX-1 Inlet	502.6	29.21	868.2	969.5
40	PHX-1 Outlet	700.0	27.51	868.2	1220.9
41	LTC Turbine Inlet	700.0	27.41	91.7	1220.9
42	HTC Turbine Inlet	700.0	27.41	156.8	1220.9

43	Power Turbine Inlet	700.0	27.41	619.7	1220.9
50	HTR Low Pressure Inlet	523.5	7.02	868.2	1013.8
51	LTC Turbine Outlet	531.3	7.12	91.7	1023.1
52	HTC Turbine Outlet	529.3	7.12	156.8	1020.6
53	Power Turbine Outlet	521.0	7.12	619.7	1010.7
54	HTR Low Pressure Outlet - LTR Low Pressure Inlet	220.6	6.92	868.2	666.5
60	LTR Low Pressure Outlet	60.4	6.77	868.2	475.1
61	CHX Inlet	56.2	6.69	568.0	469.3
62	HTC Inlet	59.8	6.69	318.1	475.1
A1	Air Inlet	15.0	0.101 Fan dP (20.3 mm H_2O)	9868.2	288.4
A2	Air Outlet	27.1		9868.2	300.6

Table 7 Summary of plant auxiliary and generating loads

Plant Electrical Loads	**Value (kW$_e$)**
Generating Loads	
sCO2 Power Turbine	130,212
NG CT – PCC parasitic loads	700
Gross Power	**130,912**
Auxiliary Loads	
Gearbox & Generator Losses	1,666
ACC Fan (CHX)	2,707
Primary Air Fan	1,147
Forced Draft Fan	875
Induced Draft Fan	1,860
Pulverizer Seal Air Fan	110
Pulverizers	513
Atomizer	238
Turbine Auxiliaries (Dry gas seal conditioning and lube oil)	156
Transformer Losses	440
Miscellaneous Balance of Plant	500
Total Auxiliary Power	**10,212**
System Net Power (with PCC)	**120,700**

Table 8 sCO_2 power cycle equipment summary

Component	**Duty (kW) - (kW/°C)**	**Efficiency / Effectiveness**
LTC - Shaft Power (T – C)	18,135	86.4% – 88.3%
HTC - Shaft Power (T – C)	31,392	87.5% – 86.6%
PT - Shaft Power	130,212	91.8%
CHX - Heat Transferred – UA	119,788 – 16,426	90.3%
HTR - Heat Transferred – UA	301,498 – 14,136	96.6%
LTR - Heat Transferred – UA	166,183 – 17,807	97.1%
PHX1 - Heat Transferred to CO_2	218,244	84% Fired Heater Efficiency
PHX2 - Heat Transferred to CO_2	31,756	

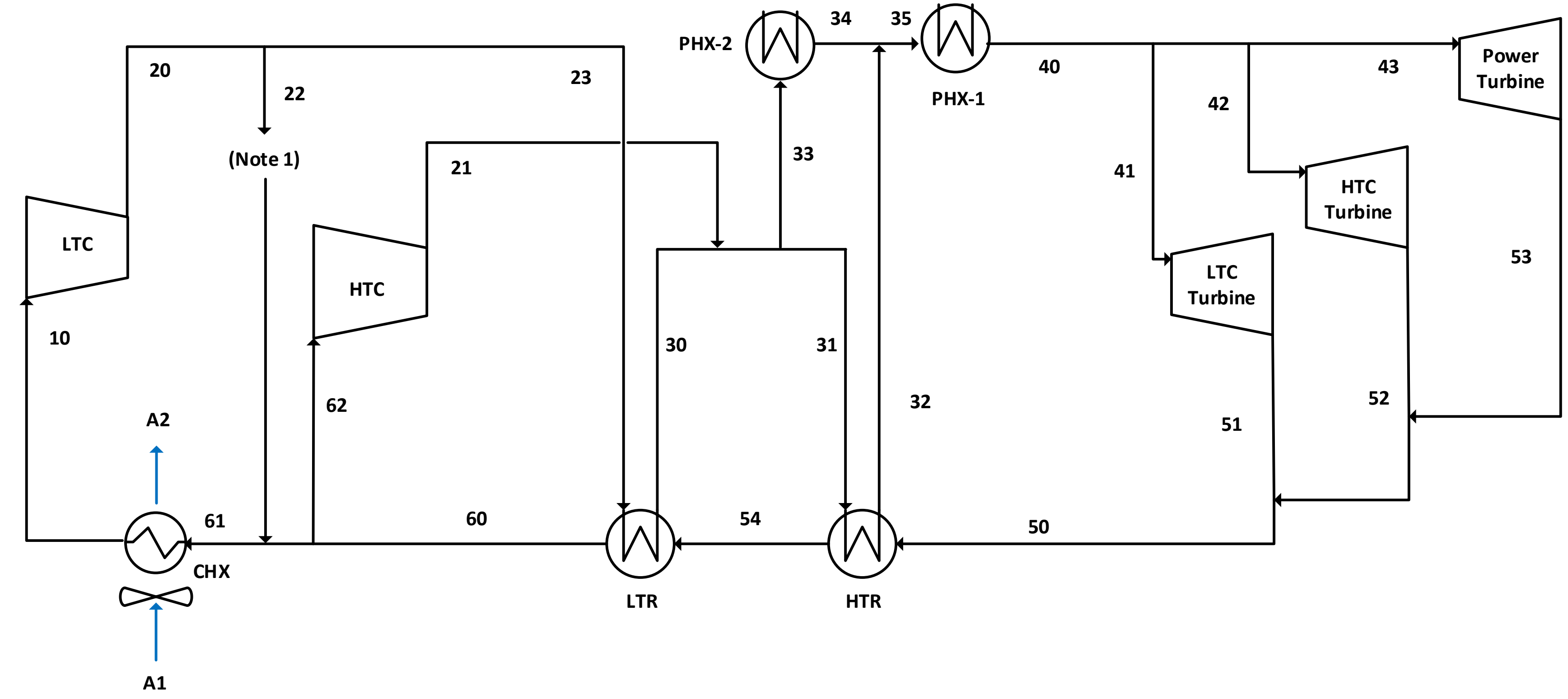


Figure 4 sCO_2 Power Cycle Process Flow Diagram

LTC – Low temperature compressor

HTC – High temperature compressor

PHX-2 – Fired heater convective section

PHX-1 – Fired heater radiant section

HTR – High temperature recuperator

Note 1 – Estimated parasitic CO_2 flow for turbomachinery auxiliaries

LTC Turbine – Low temperature compressor drive turbine

HTC Turbine – High temperature compressor drive turbine

Power Turbine – Power turbine, coupled to synchronous generator

CHX – Air cooled CO_2 condenser/chiller

LTR – Low temperature recuperator

Table 9 Plant efficiency summary without PCC

System (without PCC)	Energy In (kW)	Energy Out (kW)	Efficiency
Fired Heater	297,619	250,000	84.0%
Power Cycle	250,000	120,000	48.0%
Overall Plant (without PCC)	297,619	120,000	40.3%

Table 10 Plant efficiency summary including PCC

System (with PCC)	Energy In (kW)	Energy Out (kW)	Efficiency
Fired Heater	297,619 (Thermal)	250,000 (Thermal)	84.0%
Power Cycle (incl. PCC Aux.)	250,000 (Thermal)	120,000 (Electric)	48.0%
Combustion Gas Turbine and Duct Burner and PCC	106,292 (Thermal)	600 (Electric)	n/a
Overall Plant (with PCC)	403,912 (Thermal)	120,600 (Electric)	29.9%

ETES System Heat-and-Mass Balance

The following section summarizes the performance of the ETES system. The PFD's for the generating and charging cycles are shown in Figure 5 and Figure 6, respectively. The ETES system utilizes CO_2 as the working fluid. Concrete is used as the high temperature storage medium and Duratherm HF ® is used as the heat transfer fluid (HTF) between the concrete and CO2. The cold storage uses an ice-on-coil system in which a large storage tank has a tube bundle installed inside. Cold CO2 flows through the tubes and freezes a water/glycol mixture in the tank during the charge cycle and warm CO2 (> 0°C) and melting the ice slurry mixture.

The ETES system is represented as two separate cycles (generating and charging), but share the following components:

- High temperature storage cold reservoir (HTSc)
- High temperature storage intermediate reservoir (HTSi)
- High temperature storage hot reservoir (HTSh)
- High temperature oil to CO2 heat exchangers (HTX1 and HTX2)
- Recuperator (RCX)
- Low temperature ice slurry to CO2 heat exchanger and slurry storage (LTX/ISG)

The generating cycle (Figure 5) is a simple recuperated power cycle, with a recompression step occurring at an intermediate pressure in the power turbine expansion. Liquid CO2 is pumped to a high pressure from the cold state at the discharge of the low temperature heat exchanger (LTX/ISG) and heated with the RCX using heat that is not used during the expansion of the CO2 across the turbine. HTF heated from the high temperature concrete reservoir is then used to heat the CO2 in the high temperature heat exchangers (HTX1 and HTX2) before it is expanded across the high pressure and low-pressure stages of the power turbine. A small split stream is taken at an intermediate pressure in the power turbine expansion and recompressed and added back to cycle between the RCX and HTX2. The low-pressure CO2 leaving the lower pressure section of the power turbine passes through the RCX before finally rejecting heat through the LTX/ISG. The generating cycle state points are described in

Table 11 and the associated major equipment performance summary is shown in Table 12.

The charging cycle (shown in Figure 6), used to generate the hot and cold potential for the generating cycle, is a modified heat pump cycle. It takes AC power in and converts it to hot and cold that can be stored in the HTS (concrete) and LTX/ISG (ice slurry) reservoirs. A CO_2 compressor compresses (and heats) the CO_2 to 22.6 MPa. The high temperature CO_2 leaving the compressor rejects heat to the HTF and the HTS. The CO2 then goes through the RCX to pre-heat the CO2 at the compressor inlet. An air-cooled chiller (Chg ACC) is used to reject heat prior to expansion across a low temperature turbine (LT turbine). The Chg ACC is used to balance the hot and cold storage and decrease the temperature going into the turbine expansion. From the LT Turbine cold CO2 enters the LTX/ISG and generates the ice slurry mixture and then goes through RCX prior to entering the charge compressor. The charging cycle state points are described in Table 13 and the associated major equipment performance summary is shown in Table 14.

This system utilizes a three-tank high temperature storage system, consisting of a hot tank (HTSh), an intermediate temperature tank (HTSi), and a cold tank (HTSc). This is done because of the mismatch and curvature of the specific heat between CO2 and the HTF (Figure 7). The addition of a third tank allows for tight approach temperatures between the CO2 in both the charging and generating cycles (shown in Figure 8).

The ETES system performance is summarized in Table 15. The system is designed to charge and discharge at 30 MW_e, with a 15-hour charge time and 8-hour discharge time. The generating cycle has an efficiency of 30.4%, and the charging cycle has a coefficient of performance (COP) of 1.73. The overall RTE for the ETES system is 52.7%.

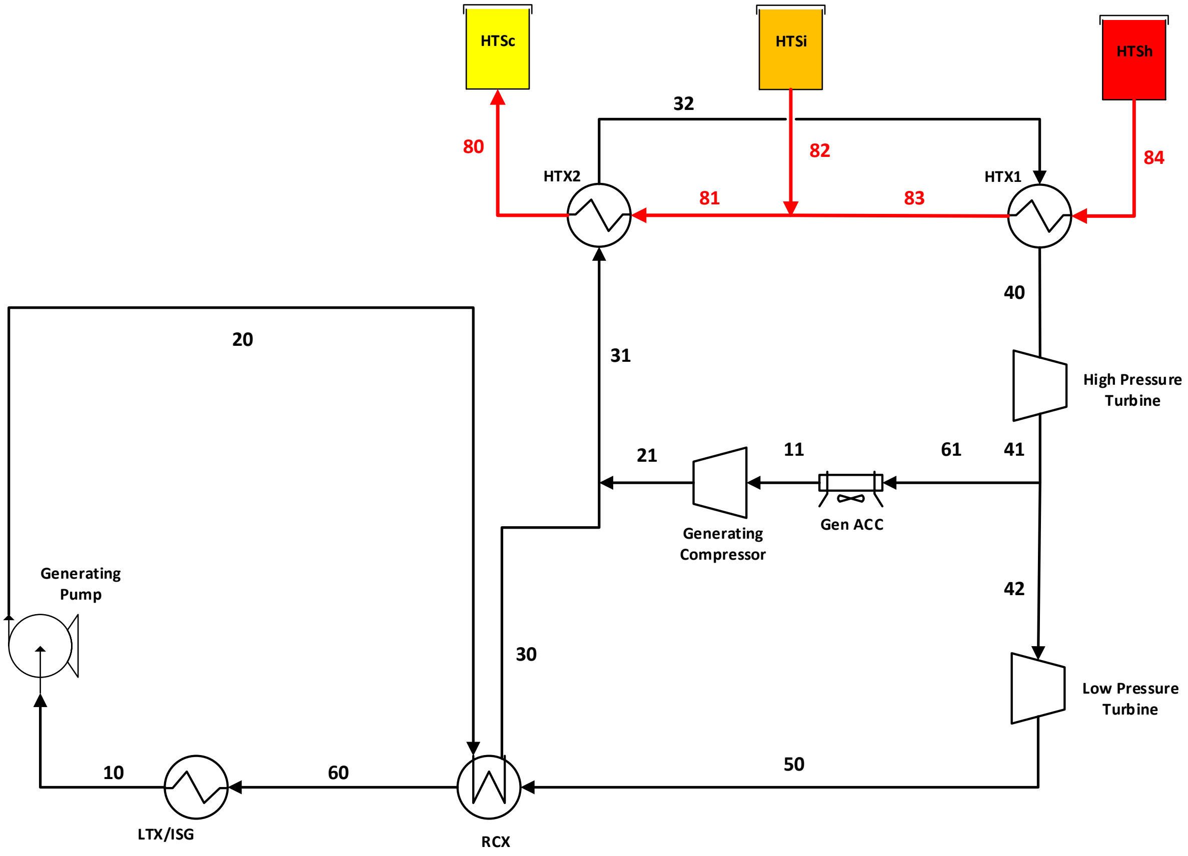


Figure 5 ETES system power generating cycle

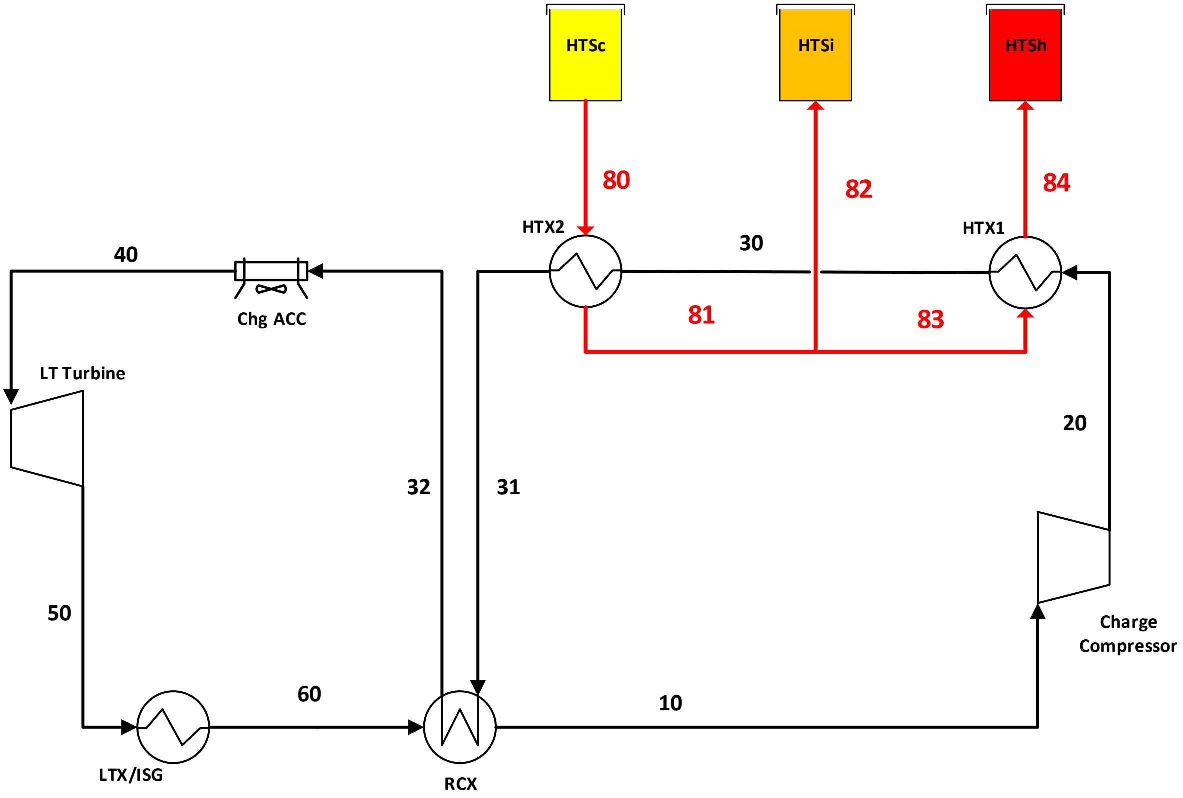


Figure 6 ETES system charging cycle

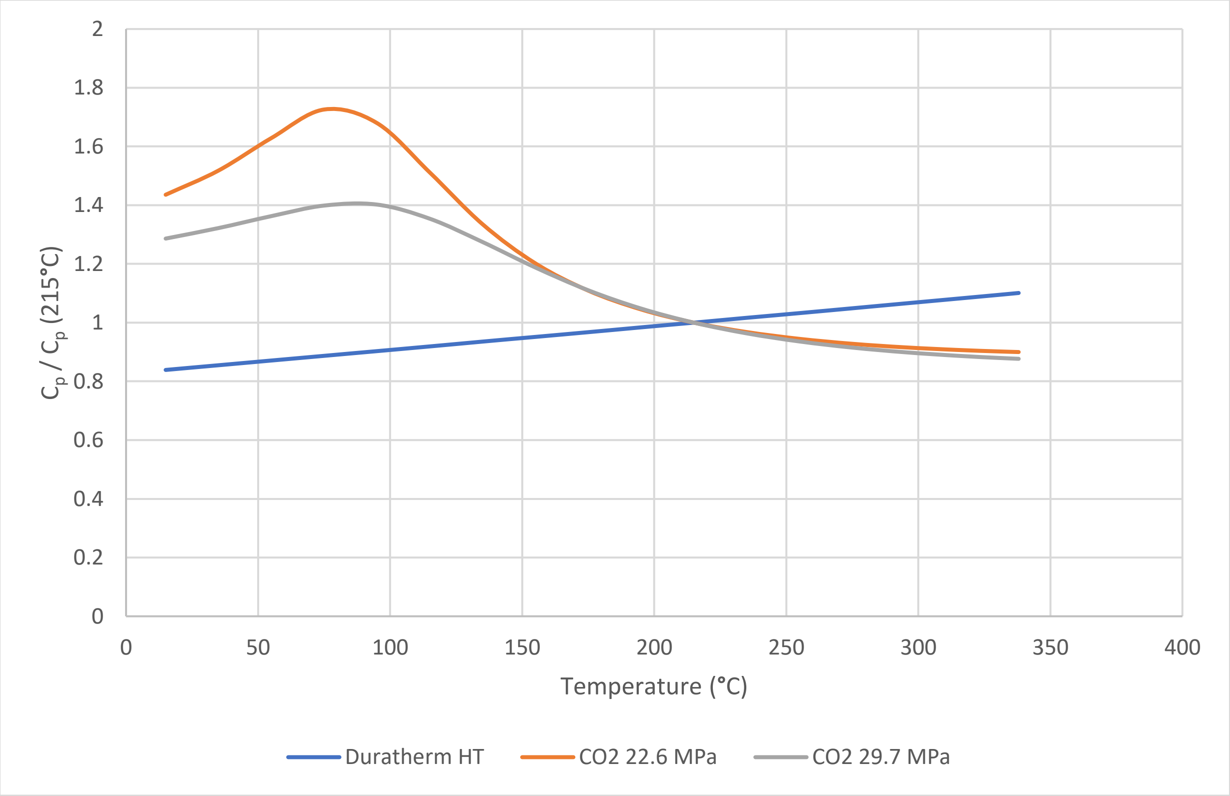


Figure 7 Specific Heat Variation of CO_2 and Duratherm HF® (215°C Reference)

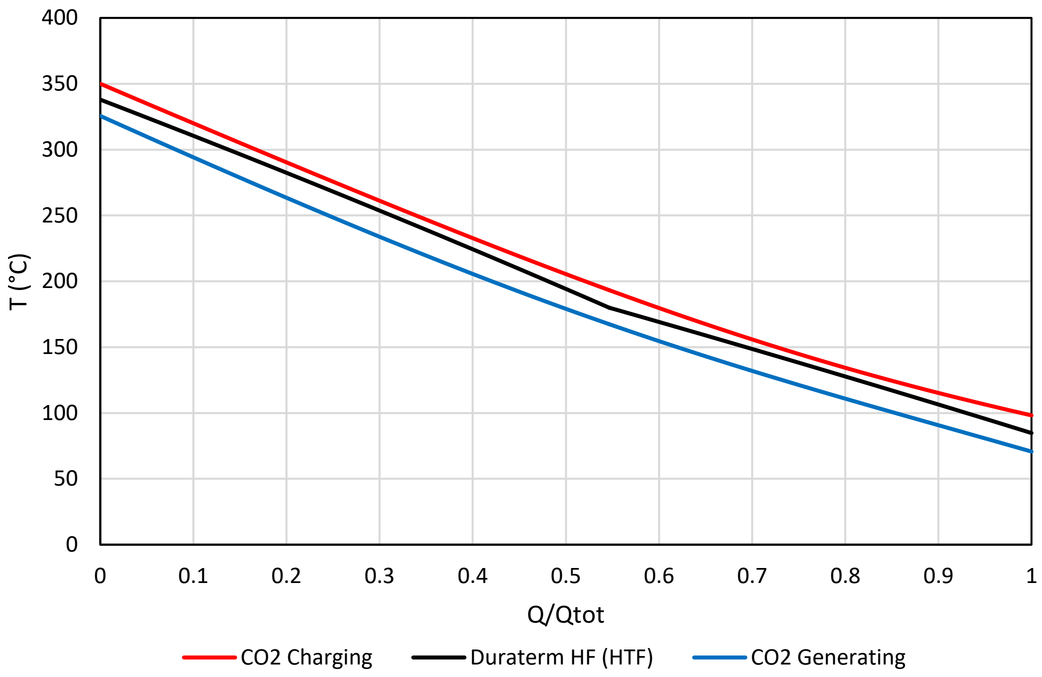


Figure 8 Temperature - Heat Transfer (T-Q) Plot of HTX1 and HTX2

Table 11 State point table for ETES power generating cycle, Figure 5

State	Description	Temperature (°C)	Pressure (MPa)	Flow (kg/s)	Enthalpy (kJ/kg)
10	LTX Outlet - Pump Inlet	-6.1	3.1	214.8	185.5
20	Pump Outlet - RCX HP Inlet	13.1	30.0	214.8	218.6
30	RCX Outlet	72.1	29.9	214.8	334.4
31	HTX2 Inlet	70.7	29.9	237.9	331.7
32	HTX2 Outlet - HTX1 Inlet	167.4	29.8	237.9	332.4
40	HTX Outlet - HPT Inlet	325.6	29.7	237.9	744.2
41	HPT Outlet	185.4	7.0	237.9	627.0
42	LPT Inlet	185.4	7.0	214.8	627.0
50	LPT Outlet - RCX LP Inlet	123.0	3.3	214.8	576.9
60	RCX LP Outlet - LTX Inlet	15.9	3.2	214.8	461.0
61	Gen ACC Inlet	185.4	7.0	23.1	627.0
11	Gen ACC Outlet - Gen Comp Inlet	25.0	6.9	23.1	269.7
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

84	HTSh Outlet - HTX1 HTF Inlet	338.0	0.3	149.9	702.5
83	HTX1 HTF Outlet	180.0	0.2	149.9	344.6
82	HTSi Outlet	180.0	0.2	79.3	344.6
81	HTX2 HTF Inlet	180.0	0.2	229.2	344.6
80	HTX2 HTF Outlet - HTSc Inlet	84.8	0.1	229.2	150.5

Table 12 ETES power generating cycle equipment summary, Figure 5

Component	**Duty (kW) – (kW/°C)**	**Efficiency / Effectiveness (%)**
Generating Pump	7,103	82.0
HP Turbine	27,883	88.0
LP Turbine	10,758	
Generating Compressor	840	79.0
HTX1	54,347 - 9,639	93.4
HTX2	43,488 - 8,358	90.1
RCX	25,029 - 1,722	97.0
Gen ACC (thermal / electric)	8,265 / 64	-
LTX	59,184	-
Hot Oil Pumps	99.6	80.0

Table 13 State point table for ETES charging cycle, Figure 6

State	**Description**	**Temperature (°C)**	**Pressure (MPa)**	**Flow (kg/s)**	**Enthalpy (kJ/kg)**
10	RCX LP Outlet - Chg Comp Inlet	95.8	2.3	139.6	555.0
20	Chg Comp Outlet - HTX1 Inlet	350.0	22.6	139.6	785.3
30	HTX1 Outlet	193.3	22.4	139.6	580.7
31	HTX2 CO2 Inlet - RCX HP Inlet	98.2	22.2	139.6	410.9
32	RCX HP Outlet - Chg ACC Inlet	49.4	22.1	139.6	295.5
40	Chg ACC Outlet - LTT Inlet	20.0	22.1	139.6	233.1
50	LTT Outlet - ISG Inlet	-13.5	2.4	139.6	168.7
60	ISG Outlet - RCX LP Inlet	-12.5	2.3	139.6	439.6
[redacted]			[redacted]		

80	HTSc Outlet - HTX2 HTF Inlet	84.8	0.3	122.1	150.5
81	HTX2 HTF Outlet	180.0	0.2	122.1	344.6
82	HTSi Inlet	180.0	0.2	42.2	344.6
83	HTX1 HTF Inlet	180.0	0.2	79.8	344.6
84	HTX1 HTF Outlet - HTSh Inlet	338.0	0.1	79.8	702.5

Table 14 ETES charging cycle equipment summary, Figure 6

Component	**Duty (kW)**	**Efficiency / Effectiveness (%)**
Charge Compressor	32,644	84.0
LT Turbine	2,647	84.3
HTX1	28,467 - 3,282	95.5
HTX2	22,779 - 2,718	93.5
RCX	5,339 - 795	98.0
Charge ACC (thermal / electric)	8,717 / 116	-
ISG	31,517	-
Hot Oil Pumps	54	80

Table 15 ETES performance summary

Generating Cycle	Heat Input (kW_{th})	98,146
	Heat Rejected (kW_{th})	59,184
	Electricity Generated (kW_{e})	29,833
	Net Cycle Efficiency (%)	30.4
	Time to Full Discharge (hrs)	8
Charge Cycle	Electricity Consumed (kW_{e})	30,167
	Heat Generated (kW_{th})	52,269
	Cooling Generated (kW_{th})	31,517
	COP	1.73
	Time to Full Charge (hrs)	15
Round Trip Efficiency (%)		**52.7**

Environmental Performance

The plant emissions of SO_2, NO_x, particulate matter (PM), Hg, HCl, and CO_2 are presented in Table 16.

Table 16 Air emissions

Emission	lb/MMBTU	lb/MWh (gross)	ton/year
SO_2	1.69E-03	.013	7.3
NO_x	0.074	0.700	335.2
PM	9.50E-03	0.090	43.1
Hg	3.16E-07	3.00E-06	1.4E-03
HCl	1.10E-03	0.010	5.0
CO_2	30.52	290.5	184,634

SO_2 emissions (as well as SO_3, HCl, and HF) are controlled using a CDS that requires a dedicated hydrated lime injection, water injection, byproduct ash recycle and flue gas recirculation. This system achieves a removal efficiency of 92.2%. The byproduct of this process is “dry ash”, which will have calcium content and cannot be used for typical beneficial uses and hence will need to be disposed off-site. SO_2 is further removed during the carbon process bringing the overall removal rate to 99.9%.

NO_x heater emissions are controlled to 0.3 lb/MMBtu using low NOx burners and over fire air. An SCR is then used to further reduce the NO_x concentration to 0.074 lb/MMBtu.

Particulate emissions are controlled using a pulsed jet fabric filter, operating with a removal efficiency of 99.8%.

The total reduction in mercury emission through the combined control equipment (SCR, fabric filter, and CDS) brings the overall emissions to 3.16E-07 lb/MMBtu.

83.6% of the CO_2 present in the flue gas is removed in the PCC process with the remainder being emitted at a rate of 30.52 lb/MMBtu.

Table 17 shows the overall water balance for the plant. The water demand represents the amount of water required for a particular process. The difference between the demand and what is recycled in the process is water withdrawal. Raw water consumption is defined as what is removed from the source and not returned. There are 4 processes that require water: the CDS, evaporative cooling tower, boiler feedwater make-up, and the PCC process.

Cooling tower water losses considered are evaporative (2.3% of circulating flow), drift (0.1% of circulating flow), and blowdown (EL + drift / (cycles of concentration – 1)).

Because of sensitivities to proprietary information, the boiler feedwater and PCC process water use has been grouped together.

Table 17 Water balance

Water Use	**Water Demand**	**Internal Recycle**	**Raw Water Withdrawal**	**Process Water Discharge**	**Raw Water Consumption**
	L/min	L/min	L/min	L/min	L/min
CDS	395	0	395	0	395
Cooling Tower **(Drift, Evaporation, and Blowdown)**	124	0	124	31	93
Boiler Feedwater and PCC process	723	0	723	0	723