100 MWe COAL-FIRED DIRECT INJECTION CARBON ENGINE (DICE) GAS TURBINE COMPOUND REHEAT COMBINED CYCLE (GT-CRCC) WITH 90 PERCENT POST-COMBUSTION CO_2 CAPTURE

DESIGN BASIS REPORT

U. S. Department of Energy (DOE)
Contract No. 89243319CFE000025, Coal-Based Power Plants of the Future

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Section 1 Conceptual Design Study Results

1.1 DICE GT-CRCC CONCEPTUAL DESIGN CONFIGURATION

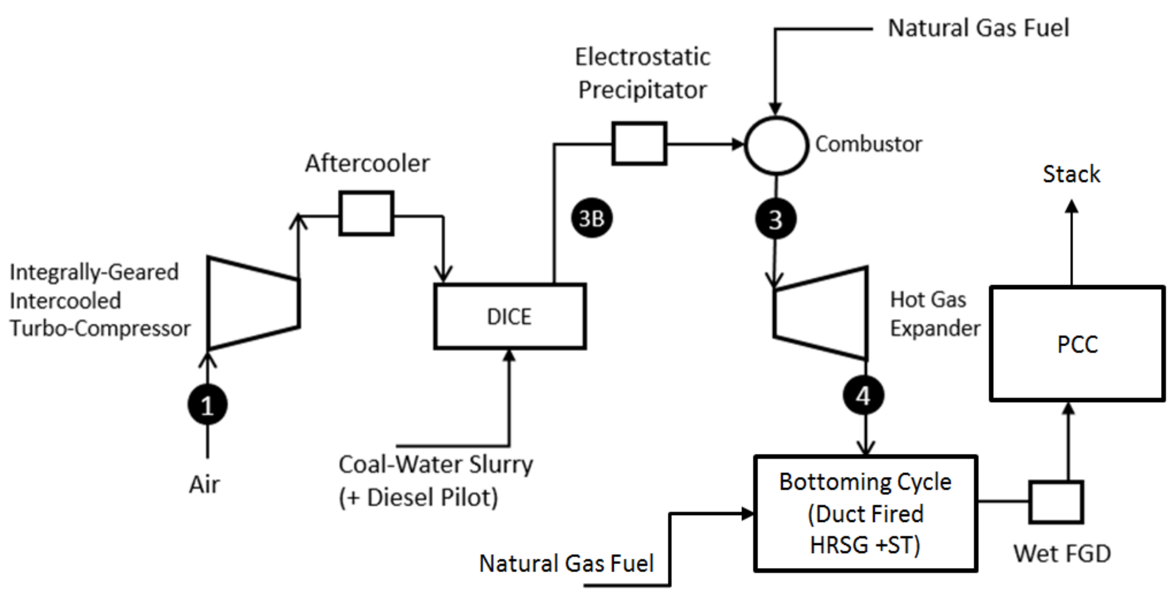
The power plant from the recently completed conceptual design study was configured as a 5x1x1x1 Direct Injection Carbon Engine (DICE) Gas Turbine-Compound Reheat Combined Cycle (GT-CRCC) generating nominal 100 MWe of net power while capturing 90 percent of the CO_2 in the flue gas. The breakdown of the process system and power blocks was as follows:

1. Five (5) DICE (nominal 15 MWe each)
2. One (1) hot gas expander
3. One (1) single pressure, no reheat heat recovery steam generator (HRSG)
4. One (1) non-condensing (back-pressure) steam turbine
5. One (1) 30 weight percent (wt percent) monoethanolamine (MEA) plant capturing 90 percent of the total CO_2 in the flue gas

The conceptual design for the DICE GT-CRCC plant was developed as a greenfield project with a Midwestern U.S location, burning low-sulfur sub-bituminous Montana Rosebud Powder River Basin (PRB) coal.

A simplified schematic of the DICE GT-CRCC plant is shown in Figure 1-1.

Figure 1-1
Simplified Schematic Diagram of Coal-Fired DICE GTCC with Hot Gas Expander and Duct-Fired HRSG



The ash content of the coal supplied is reduced by physical beneficiation to about 2 wt% on a dry basis, which is considered suitable for combustion in DICE. This process produces micronized refined coal (MRC), which is essentially finely ground low ash carbons in a slurry. For effective atomization when injected into the DICE cylinder, the MRC should have a maximum size of around 50 microns in a 55 percent coal and a 45 percent water mixture.

Multiple DICEs, operating in parallel, burn MRC to generate power. The DICE exhaust gas is sent to the hot gas combustor, which burns natural gas fuel to generate hot gas for expansion in the hot gas expander. A bottoming Rankine steam cycle comprising an HRSG and a backpressure steam turbine generator is included to generate additional power from the hot flue gas leaving the expander. Supplemental duct firing of natural gas in the HRSG is required in order to generate enough steam to meet the demand of the post-combustion capture (PCC) system.

Superheated steam generated in the HRSG is expanded in the backpressure steam turbine for additional power generation. The expanded steam leaves the backpressure turbine at 60 psia and is desuperheated to saturated conditions. This steam is consumed in the PCC stripper reboiler, which uses the latent heat of the steam to generate the vapor needed to strip CO_2 from the MEA solution. The reboiler returns hot condensate to the HRSG, where it is heated to generate steam again and the cycle continues.

The flue gas leaving the HRSG contains about 300 ppm of SOx. It is first desulfurized in a standard wet flue gas desulfurization (WFGD) scrubber system that uses limestone to react with and remove about 95 percent of the SOx in the flue gas, and lowering the SOx content to around 15 ppmv.

The desulfurized flue gas is then sent to the PCC plant for CO_2 removal. This is a standard amine-based chemical absorption-desorption process where 90 percent of the CO_2 in the flue gas is absorbed by lean amine in an absorber column. The treated, CO_2-depleted flue gas exits at the overhead of the absorber column to the stack for release into the atmosphere. The rich amine containing the absorbed CO_2 is sent to the MEA stripper column where it is stripped of CO_2 with heat supplied by LP steam from the backpressure turbine. The regenerated lean amine is then pumped, cooled, and routed to the absorber column for CO_2 absorption again.

1.2 DICE GT-CRCC CONCEPTUAL STUDY RESULTS

1.2.1 Operating Performance

Table 1-1 summarizes the overall performance of the nominal 100 MWe DICE GT-CRCC power plant based on the conceptual design as shown in Table 1-1. The fuel mix to the plant is 70 percent coal and 30 percent natural gas, on a LHV basis. The efficiency is 32.2 percent on an LHV basis (30.4 percent HHV) with 90 percent CO_2 capture. This is higher than even a PRB coal-based ultra-supercritical pulverized coal (PC) plant with CO_2 capture at 29.8 percent LHV efficiency (28.7 percent HHV).

Table 1-1
100 MWe Nominal DICE GT-CRCC Performance

Power Summary	
POWER GENERATION, kWe	
5 x DICE	78,790
Turboexpander	40,250
Steam Turbine	16,192
Total Power Generation	**135,232**
AUXILIARY LOAD SUMMARY, kWe	
Coal Handling and Conveying	71
Coal Beneficiation	incl w/ BOP
DICE Pumps	6
Main Air Compressor	27,776
SCR	107
Cyclone	163
Boiler Feed Water Pump	325
Economizer Recirculation Pump	9
Steam Turbine Auxiliaries	34
WFGD	428
CO_2 Capture	4,316
CO_2 Compression	8,292
Circulating Water Pumps	840
Ground Water Pumps	20
Cooling Tower Fans	540
Miscellaneous Motors	79
Miscellaneous Balance of Plant (incl MRC Fuel Prep)	3,776
Transformer Losses	676
Total Auxiliaries, kWe	**47,627**
Net Power, kWe	**87,605**
As-Received PRB Coal Feed, lb/hr	79,044
Natural Gas Feed Flow, lb/hr	13,719
Coal LHV Thermal Input, MMBtu/hr	650
Gas LHV Thermal Input, MMBtu/hr	279
Total LHV Thermal Input, MMBtu/hr	**928**
LHV Efficiency, %	**32.2%**
Coal HHV Thermal Input, MMBtu/hr	674
Gas HHV Thermal Input, MMBtu/hr	308
Total HHV Thermal Input, MMBtu/hr	**983**
HHV Efficiency, %	**30.4%**

1.2.2 Capital Costs (Capex)

Table 1-2 provides a breakdown of the DICE GT-CRCC total plant cost (TPC), in 2018 dollars, reported in a similar format, with similar code of accounts as the NETL baseline reference cases for combustion-based coal and natural gas-fired power plants.

Table 1-2
100 MWe Nominal DICE GT-CRCC Capital Cost Breakdown

DICE GT-CRCC w/ CO2 Capture Total Plant Cost Details (Jun 2018 Basis)

5x1x1x1 90 MW DICE GT-CRCC PLANT WITH 30 WT% MEA CO2 CAPTURE

Cost Basis 2018 ($x1000)
Plant Size 88 MWe, net

Acct		Equipment	Material	Labor		Sales	Bare Erected	Eng'g CM	Contingencies		TOTAL PLANT COST	
No.	Item/Description	Cost	Cost	Direct	Indirect	Tax	Cost $	H.O & Fee	Process	Project	$	$/kW
1	COAL HANDLING	$5,806	$1,687	$3,887	$0	$0	$11,379	$1,138	$0	$1,878	$14,395	$164
2	COAL & SORBENT PREP & FEED		included in coal feed cost									
3	FEEDWATER & MISC BOP SYSTEMS	$8,266	$523	$1,108	$0	$0	$9,898	$990	$0	$1,605	$12,493	$143
4	DICE AND GAS TURBINE	$54,900	$8,250	$9,895	$0	$0	$73,045	$7,305	$9,948	$13,545	$103,843	$1,185
5	FLUE GAS CLEANUP	$26,000	$7,975	$11,950	$0	$0	$45,925	$4,593	$0	$5,052	$55,569	$634
5B	CO2 REMOVAL & COMPRESSION	$29,180	$20,717	$32,292	$0	$0	$82,188	$8,219	$0	$18,081	$108,488	$1,238
7	HRSG, DUCTING & STACK	$5,900	$1,001	$1,168	$0	$0	$8,069	$807	$0	$54	$8,929	$102
8	STEAM TURBINE GENERATOR	$7,618	$999	$2,049	$0	$0	$10,666	$1,067	$0	$1,365	$13,098	$150
9	COOLING WATER SYSTEM	$3,014	$3,786	$3,281	$0	$0	$10,081	$1,008	$0	$1,642	$12,732	$145
10	ASH/SPENT SORBENT HANDLING SYS	$3,064	$94	$3,803	$0	$0	$6,961	$696	$0	$789	$8,445	$96
11	ACCESSORY ELECTRIC PLANT	$6,900	$1,025	$1,250	$0	$0	$9,175	$918	$0	$1,110	$11,203	$128
12	INSTRUMENTATION & CONTROL	$5,257	$595	$4,457	$0	$0	$10,309	$1,031	$0	$1,701	$13,041	$149
13	IMPROVEMENTS TO SITE	$1,074	$583	$3,041	$0	$0	$4,698	$470	$0	$1,034	$6,201	$71
14	BUILDINGS & STRUCTURES	$0	$2,181	$2,076	$0	$0	$4,257	$426	$0	$702	$5,385	$61
	CALCULATED TOTAL COST	$156,980	$49,415	$80,257	$0	$0	$286,651	$28,665	$9,948	$48,557	$373,822	$4,267

The estimated TPC for the 100 MWe DICE GT-CRCC plant is $374MM, or $4,267/kW-net. On a per kilowatt basis, this is comparable to large-scale, 550 MWe type coal-fired plants with CO_2 capture, estimated to be about $4.167/kW-net, even though these large plants have a cost advantage due to their economies- of-scale.

Table 1-3 presents the breakdown of the additional costs required to develop the TPC to total overnight cost (TOC), based on the assumptions used in the NETL coal and natural gas baseline power plant cases. The resulting TOC, at $5,273/kW-net, is used for the calculation of the first-year cost of electricity (COE).

Table 1-3
100 MWe DICE GT-CRCC Total Overnight Cost Breakdown

Description	$/1,000	$/kW
Preproduction Costs		
6 months All Labor	$3,299	$38
1 Month Maintenance Materials	$357	$4
1 Month Non-Fuel Consumables	$525	$6
1 Month Waste Disposal	$12	$0
25% of 1 Months Fuel Cost at 100% CF	$784	$9
2% of TPC	$7,476	$85
Total	**$12,454**	**$142**
Inventory Capital		
60 day supply of fuel at 100% CF	$4,518	$52
60 day supply of non-fuel consumables at 100% CF	$982	$11
0.5% of TPC (spare parts)	$1,869	$21
Total	**$7,369**	**$84**
Other Costs		
Initial Cost for Catalyst and Chemicals	$1,940	$22
Land	$150	$2
Other Owner's Cost	$56,073	$640
Financing Costs	$10,093	$115
Total Overnight Costs (TOC)	**$461,901**	**$5,273**

1.2.3 Operating Costs (Opex)

Table 1-4 presents a breakdown of the DICE GT-CRCC fixed and variable operating costs, including the cost of fuel, in 2018 dollars, similar in format to the NETL baseline reference cases. The delivered cost of PRB coal to the power plant is estimated at $36.6/ton. Coal beneficiation to MRC is expected to add $2.50/MMBtu, resulting in a fuel cost that is estimated to be $79.4/ton. This beneficiated coal cost has the largest impact on the overall annual operating costs.

Table 1-4
100 MWe Nominal DICE GT-CRCC Annual Operating Cost Breakdown

INITIAL & ANNUAL O&M EXPENSES

Case:	DICE GT-CRCC		
Plant Size (MWe)	**88**		
Primary/Secondary Fuel:	**Wyoming PRB**	**Fuel Cost ($/MMBtu):**	
Design/Construction	3 years	**Book Life (yrs):**	20
TPC (Plant Cost) Year	Jun-18	**TPI Year:**	2018
Capacity Factor (%)	85	**CO2 Captured (TPD)**	1965

OPERATING & MAINTENANCE LABOR

Operating Labor

Operating Labor Rate (base):	$39.70	$/hr
Operating Labor Burden:	30.0	% of base
Labor Overhead Charge	25.0	% of labor

Operating Labor Requirements per Shift	**units/mod**	**Total Plant**
Skilled Operator	1.0	1.0
Operator	3.3	3.3
Foreman	1.0	1.0
Lab Tech's etc	1.0	1.0
TOTAL Operating Jobs	6.3	6.3

	Annual Cost $
Annual Operating Labor Cost	$2,848,253
Maintenance Labor Cost	$2,430,408
Administration & Support Labor	$1,319,665
Property Taxes and Insurance	$7,476,439
TOTAL FIXED OPERATING COSTS	**$14,074,764**

VARIABLE OPERATING COSTS

Maintenance Material Cost **$3,645,612**

Consumables	Consumption Initial	Consumption /Day	Unit Cost	Initial Fill Cost	
Water(/1000 gallons)	0	237	1.87	**$0**	**$137,545**
Chemicals					
MU & WT Chem (lb)	0	1148	0.30	$0	$106,527
Limestone (ton)	0	21	40.50	$0	$267,383
Lube Oil for DICE					$469,336
Carbon (Mercury Removal) (lb)	0	1	1518.23	$0	$260,051
MEA Solvent (ton)	643	4.0	2721.80	$1,749,531	$3,410,649
Corrosion Inhibitor				$125,501	$432,628
MEA Reclaimer Additive (ton)	361	4.0	181.44	$65,450	$225,621
SCR Catalyst	0	0.01	9979.00	$0	$18,929
Ammonia (19% NH3) (ton)	0	0.23	368.40	$0	$25,784
Subtotal Chemicals				**$1,940,481**	**$5,216,909**
Waste Disposal:					
Ash from Coal Beneficiation	0	64	0.00	$0	$0
Fly Ash (ton)	0	14	28.03	$0	$122,271
Subtotal Waste Disposal				**$0**	**$122,271**
TOTAL VARIABLE OPERATING COSTS				**$1,940,481**	**$9,122,338**
PRB Coal (ton)	**0**	**949**	**79.39**	**$0**	**$23,362,999**
Natural Gas (MMBtu)	**0**	**7401**	**3.75**	**$0**	**$8,610,904**

1.2.4 First Year Cost of Electricity

Based on the overall performance, TOC, and annual operating costs of the 100 MWe DICE GT-CRCC plant, its first year COE is estimated to be $163.2/MWh. The assumptions used in estimating the COE are listed in Table 1-5.

At about $163/MWh, the COE for the 100 MWe DICE GT-CRCC is only about 14 percent higher than a large, 550 MWe-scale supercritical plant with CO_2 capture burning similar PRB coal. The high plant net efficiency, at 32.2 percent LHV after factoring in CO_2 capture, coupled with the low costs of the highly modular design, DICE is able to mitigate the inherent economies-of-scale disadvantages of a small 100 MW-scale plant versus a large, baseload power plant, from a Capex and fixed Opex (labor) perspective. It is assumed and expected that no other conventional combustion-based technology is able to achieve such low costs at this scale.

Table 1-5
First Year Cost of Electricity (COE) Parameters and Cost Breakdown

Plant	DICE GT-CRCC
Size	88 MWe
Capacity Factor (CF)	**85%**
Years of Construction	**3**
Capital Charge Factor (CCF)	**0.111**
Total Overnight Cost, $MM	462
Fixed Operating Cost, $MM/yr	14.1
Variable Operating Cost @ 100 % CF, $MM/yr	10.7
Fuel Cost @ 100% CF, $MM/yr	48.2
Annual 1000 MWh (100% CF)	767
COE (excl. CO2 T&S), $/MWh	**163.2**
COE Breakdown, $/MWh	
Fuel (incl. coal beneficiation)	49.0
Variable O&M	14.0
Fixed O&M	21.6
Capital Charges	78.6
Total COE, $/MWh	**163.2**

Note: 3 year construction for DICE GT-CRCC is consistent with a natural gas combined cycle (NGCC) construction period assumption as used by NETL in its reference reports. CCF used for COE evaluation for such 3 year, high-risk investor owned utilities (IOU) projects is 0.111

Section 2 Pre-FEED Study Design Basis

2.1 POWER PLANT DESIGN CRITERIA

2.1.1 General

Similar to the plant in the recently completed conceptual design, the DICE GT-CRCC plant in this pre-FEED study is designed to generate a nominal 100 MWe on a net basis. It is to be equipped with a CO_2 capture plant that captures 90 percent of the total CO_2 in the flue gas. Based on the requirements of the Pre-FEED study as stated in the executed contract, the design criteria and assumptions are consistent with the Quality Guidelines for Energy Systems Studies (QGESS), and the QGESS documents are used as references to the greatest extent possible.

2.1.2 Site-Related Conditions

The DICE GT-CRCC plant in this Pre-FEED study is assumed to be located at a generic plant site in the Midwestern USA, with site-related conditions as shown below:

▪ Location	Midwestern USA
▪ Elevation, ft above sea level	0
▪ Topography	Level
▪ Size, acres	300
▪ Coal delivery	Rail
▪ Gas delivery	Pipeline
▪ Ash/slag disposal	Off Site
▪ Water	Municipal (50 percent)/Groundwater (50 percent)
▪ Access	Landlocked, having access by train and highway
▪ CO_2 disposition	Compressed to 2,200 psig at battery limit before being transported 50 miles for sequestered in a saline formation at a depth of 4,055 ft (Study scope limited to delivery at the plant battery limit (B/L) only)

2.1.3 Meteorological Data

The design ambient conditions for the material balances, thermal efficiencies, system design, and equipment sizing are:

▪ Atmospheric pressure, psia	14.7
▪ Maximum ambient dry bulb temperature (DBT)	59 °F
▪ Maximum ambient wet bulb temperature (WBT)	51.5 °F
▪ Design ambient relative humidity, percent	60

- Cooling water temperature 60 ºF

Air composition based on published psychrometric data, mass percent	
N_2	75.055
O_2	22.998
Ar	1.280
H_2O	0.616
CO_2	0.050
Total	100.00

2.1.4 Coal Feed Characteristics

The design coal is Montana Rosebud PRB coal. The coal properties stated in Table 2-1 are from the 2019 revision of the QGESS document "Detailed Coal Specifications".

Table 2-1
As-Received PRB Coal Properties

Coal seam nomenclature	Montana Rosebud
Coal field	PRB, Area D
Mine	Western Energy Co.
ASTM D388 Rank	Subbituminous

Proximate Analysis[2]	**As-Received**	**Dry**
Moisture[3]	25.77%	0.00%
Volatile Matter	30.34%	40.87%
Ash	8.19%	11.04%
Fixed Carbon	35.70%	48.09%
Total	100.00%	100.00%

Ultimate Analysis[2]	**As-Received**	**Dry**
Carbon	50.07%	67.45%
Hydrogen	3.38%	4.56%
Nitrogen	0.71%	0.96%
Sulfur	0.73%	0.98%
Chlorine	0.01%	0.01%
Ash	8.19%	11.03%
Moisture[3]	25.77%	0.00%
Oxygen	11.14%	15.01%
Total	100.00%	100.00%

Heating Value[1,2]	**As-Received**	**Dry (Dulong calc.)**
HHV (Btu/lb)	8,564	11,516
LHV (Btu/lb)	8,252	11,096
HHV (kJ/kg)	19,920	26,787
LHV (kJ/kg)	19,195	25,810

Hardgrove Grindability Index	57

2.1.5 **Coal Beneficiation Characteristics**

The DICE GT-CRCC conceptual design utilizes the physical beneficiation to remove the minerals and sulfate/pyritic sulfur in the PRB coal. Physical beneficiation, depending on the feedstock and process, is able to bring the coal ash content down to a few percent by weight. The process is expected to reduce the ash content of the coal to about 2 wt% on a dry basis, which is considered suitable for combustion in DICE.

The physical beneficiation process produces MRC, which is essentially finely ground low ash carbons in a slurry, similar in consistency to an acrylic paint. For effective atomization when injected into the DICE cylinder, the MRC should have a maximum size of around 50 microns in a 55 percent coal and a 45 percent water mixture.

There are a number of steps required to produce MRC. In general, the process comprises of:

- Coal washing
- Micronizing (fine grinding/milling)
- Froth flotation (de-ashing)
- Partial dewatering to 55 wt% coal MRC

For the design coal, it is assumed that the cleaned coal ash content is reduced to 2 percent on a dry weight basis, while also assuming that 20 percent of the sulfur in the coal is inorganic and is thereby removed during physical beneficiation. The expected resulting coal properties are shown in Table 2-2. Actual beneficiated coal properties will be based on the inputs from the coal beneficiation technology developer/original equipment manufacturer (OEM). Disposition of the tailings from the beneficiation process will also be addressed based on the technology developer/OEM inputs.

Table 2-2
PRB MRC Coal Properties

Ultimate Analysis, wt%	As Is (% wt)	Washed	Dry	Dry (% wt)	Slurry	MRC (% wt)
Moisture	25.77	25.77	0.00	0.00	81.82	45.00
Carbon	50.07	50.07	50.07	74.31	74.31	40.87
Hydrogen	3.38	3.38	3.38	5.02	5.02	2.76
Nitrogen	0.71	0.71	0.71	1.05	1.05	0.58
Chlorine	0.01	0.01	0.01	0.01	0.01	0.01
Sulfur	0.73	0.58	0.58	0.87	0.87	0.48
Ash	8.19	1.49	1.49	2.21	2.21	1.21
Oxygen	11.14	11.14	11.14	16.53	16.53	9.09
Total	100.00	93.15	67.38	100.00	181.82	100

2.1.6 **Natural Gas Characteristics**

Natural gas is the co-fired fuel in the DICE GT-CRCC plant, being burned in the hot gas combustor to generate hot gas for expansion in the hot gas expander, and for the supplemental duct firing in the HRSG. The natural gas properties are shown in Table 2-3. The natural gas composition to be used was specified in Appendix B of the Pre-FEED study contract, while the natural gas delivery conditions (temperature and pressure) were specified in the NETL Bituminous Baseline Report.

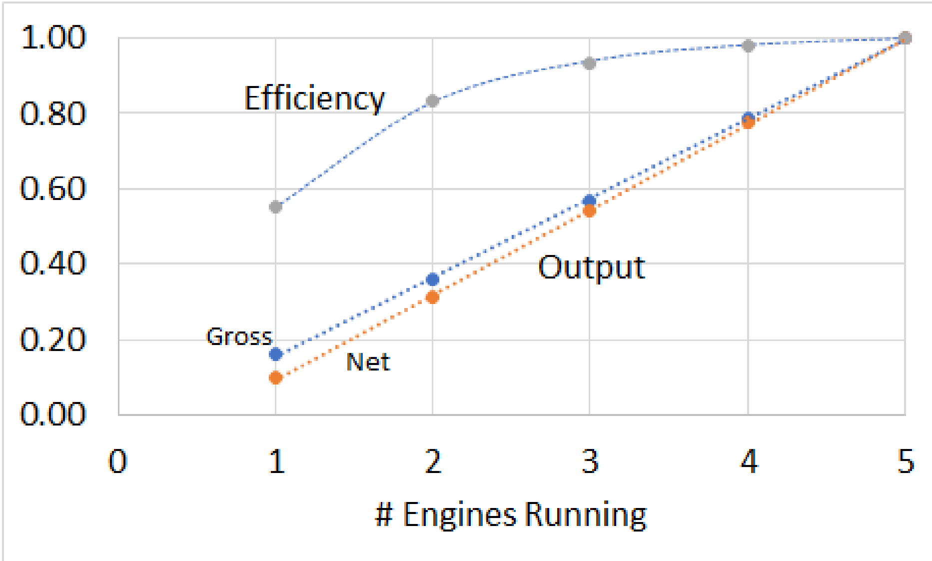
Table 2-3
Natural Gas Properties

Natural Gas Composition		
Component		**Volume Percentage**
Methane	CH_4	93.1
Ethane	C_2H_6	3.2
Propane	C_3H_8	0.7
n-Butane	C_4H_{10}	0.4
Carbon Dioxide	CO_2	1.0
Nitrogen	N_2	1.6
Methanethiol	CH_4S	$5.75x10^{-6}$
	Total	**100.00**
	LHV	**HHV**
Btu/lb	20,410	22,600
Btu/scf	932	1,032
Natural Gas Delivered Conditions		
Pressure, psia	430	
Temperature, ºF	80	

2.1.7 Flexible Plant Performance Targets

The DICE GT-CRCC power plant shall be designed with a flexible plant performance target of being capable of turning down to 20 percent of full capacity. This can be achieved by turning off up to four of the five engines. This was explored in the conceptual design, per Figure 2-1, that indicated the number of DICE running at full load (horizontal axis) and the corresponding gross power output, net power output, and plant efficiency on a normalized basis. A similar evaluation will be performed for the pre-FEED study based on information from the DICE OEM.

Figure 2-1
DICE-GT CRCC Part Load Performance



2.1.8 Water Requirements

The water supply is 50 percent from a local publicly owned treatment works and 50 percent from groundwater and is assumed to be in sufficient quantities to meet plant makeup requirements.

The raw water undergoes filtering to remove sediments, after which it is suitable for to be used as makeup water for process water, cooling water, and WFGD makeup.

The filtered raw water go through demineralization unit to produce demineralized water suitable for use as boiler feed water makeup.

2.1.9 Waste Water Treatment

Wastewater recycle will be maximized to reduce waste water disposal requirement and to minimize overall net fresh water makeup requirement. Blowdowns from cooling tower, steam drum, and demineralization regeneration will be considered for use as part of the makeup to the coal beneficiation plant and the WFGD plant. Flue gas condensate from the PCC direct contact cooler will be considered for use as part of the overall plant makeup water supply.

Net water purges from WFGD, PCC, and raw water treatment will be used to transport coal and ash solid wastes. Net decanted water from transport will either be exported to the local publicly owned treatment plant, or onsite evaporation ponds, consistent with NETL baseline studies.

Sanitary waste water will be exported to the local publicly owned treatment plant for disposal.

2.1.10 Plant and Instrument Air Supply

Plant air will be compressed and cooled ambient, and will be supplied to the DICE GT-CRCC plant at the following conditions:

Nominal Temperature, ºF	100
Maximum Temperature, ºF	120
Nominal Pressure, psig	125
Maximum/Minimum Pressure, psig	150 / 100

Part of the plant air will be dried to -40ºF dew point for use as instrument air for the DICE-GT CRCC plant. Instrument air will be supplied to it at the following conditions:

Nominal Temperature, ºF	100
Maximum Temperature, ºF	120
Nominal Pressure, psig	100
Maximum/Minimum Pressure, psig	150 / 80

2.1.11 Environmental/Emissions Requirements

Design emissions requirements and limits for the DICE GT-CRCC power plant with PCC in this study are per Appendix B of the Pre-FEED study contract as follows:

- SO_2 1.00 lb/MWh-gross
- NOx 0.70 lb/MWh-gross
- Particulate Matter (Filterable) 0.09 lb/MWh-gross
- Hg 3×10^{-6} lb/MWh-gross
- HCl 0.010 lb/MWh-gross
- CO_2 90 percent removal from flue gas

2.1.12 Major Equipment Performance Assumptions

The assumptions used in the design of the following major equipment of the DICE GT-CRCC plant are as shown:

- Main air compressor
  - Intercooled/integrally-geared
  - Deliver 5 bar/70C charge air to the engines (with an aftercooler)
  - Performance calibration based on Kobelco budgetary quote

- Hot Gas Expander
  - Maximum pressure ratio 4:1
  - Maximum inlet gas temperature: 1,400 ºF
  - Performance calibration per GE (formerly Baker-Hughes) quote

- Steam Turbine
  - Two casing, condensing, no reheat
  - Performance per modified Spencer, Cotton and Cannon in Thermoflow THERMOFLEX
  - Air-cooled condenser

- HRSG
  - Duct-fired
  - Single-pressure
  - Steam conditions TBD

- Particulate removal
  - Equipment, exact location and performance TBD subject to system optimization

2.2 PCC DESIGN CRITERIA

Guidelines for the PCC plant design include the following:

2.2.1 General

The PCC plant is designed as an integral part of the DICE GT-CRCC plant to recover up to 90 percent of the CO_2 in the flue gas.

The projected largest-single train size equipment will be used to maximize economy-of-scale. The vessels exceeding transportation size limits (as specified in the Project Transportation Size Limitation section of this document) will be field fabricated. The equipment is designed for a 30-year plant life.

The rotating equipment (including turbomachinery) critical to the continuous plant operation will be provided with the required spare (or redundant) capacity. Where sparing capacity is not feasible, alternate operation will be identified to maintain continuous power plant operation.

2.2.2 Flue Gas Feed Specification

The flue gas exiting the WFGD is the design feed for the PCC plant. The corresponding flue gas feed composition and flow rate to the PCC plant will be specified after the design of the DICE GT-CRCC plant is completed.

2.2.3 CO_2 Product Specifications

The recovered CO_2 is delivered at the plant B/L that meets enhanced oil recovery (EOR) specifications as listed in Table 2-5, per the 2019 version of the DOE QGESS CO_2 Impurity Design Parameters (NETL-PUB-22529).

Table 2-4
Recovered CO_2 Product Properties

Compositions:		
CO_2	Vol% (Min)	95
N_2	Vol% (Max)	1
Ar	Vol % (Max)	1
O_2	ppmv (Max)	10
H_2O	ppmv (Max)	500
SO_2,	ppmv (Max)	100
NOx	ppmv (Max)	100
CO	ppmv (Max)	35
B/L pressure, psig		2,200
B/L Temperature, ºF		70

2.2.4 Utility Commodity Specifications

Low Pressure Steam

Low pressure (LP) steam for the PCC stripper reboiler is the DICE GT-CRCC backpressure steam turbine exhaust desuperheated to meet the following PCC B/L conditions:

Min pressure, psia	60
Temperature, °F	Saturated + 10 (303 ºF)

The LP steam is assumed to be desuperheated to 10°F above saturation temperature to allow positive control of desuperheater condensate injection. The degree of LP steam superheat can be varied to meet minimum desuperheater design requirement.

Medium Pressure Steam

The medium pressure (MP) steam for amine reclaiming is to be extracted intermittently from the power plant steam cycle at the following B/L conditions:

Minimum pressure, psia	100
Temperature, °F	Saturated + 10
Equivalent frequency, percent of time	~ 15percent

The MP steam is assumed to be desuperheated to 10°F above saturation temperature to allow positive control of desuperheater condensate injection. The degree of MP steam superheat can be varied to meet minimum desuperheater design requirement.

PCC Return Condensate

The reboiler steam condensate will be pumped back to the power plant hot at the following conditions:

Minimum pressure, psia	175
Temperature, °F	To be determined by PCC Design

Cooling Tower Water

It is assumed that cooling water is available from the plant cooling towers at the following conditions:

Maximum supply temperature, °F	60
Maximum return temperature, °F	100
Maximum supply pressure, psia	70
Maximum PCC pressure drop, psi	30

PCC Plant Water Supply

The plant water will be filtered water from the groundwater/municipal water supply. The water will be supplied to the PCC facility where it is filtered and pumped to the internal subsystem battery limits at the following conditions:

Supply Temperature, °F	60
Return Temperature, °F	100
Nominal Pressure, psia	As Required

2.3 PROJECT TRANSPORTATION SIZE LIMITATIONS

The maximum overland transportable dimension is 100 feet long by 15 feet wide by 15 feet height (including carriage height). The maximum equipment height is 13.5 feet assuming using 1.5 feet height low boy carriage. The maximum overland transportable weight is 120 tons.

2.4 CAPEX COST ESTIMATION METHODOLOGY

Based on the requirements stated in the executed contract, the Capex for the pre-FEED study shall be reported at a level of detail similar to that found in DOE/NETL Baseline studies.

The DOE/NETL Bituminous Baseline Report report provided a cost estimate for 14 major subsystems of a reference 650 MWe supercritical PC plant with CO_2 capture. It is expected that the cost of the 100 MW DICE GT-CRCC plant be broken down into these same categories.

2.4.1 Coal Beneficiation and DICE GT-CRCC Power Island

For the pre-FEED design, additional cost details will be provided for the pertinent systems associated with the DICE GT-CRCC plant. In particular, the Capex for the coal beneficiation and DICE GT-CRCC power island will be better defined, with costs based on inputs from the DICE and coal beneficiation OEMs.

The costs for commercialized equipment associated with the DICE GT-CRCC plant, such as the air compressor, hot gas combustor, hot gas expander and the various generator equipment, will be estimated and verified with quotes from equipment vendors. These will then be developed up to the total plant cost level, which includes bulk material, labor, and construction indirect costs based on historical factors for similar equipment type.

2.4.2 PCC Plant

The Capex for the 30wt% MEA-based PCC for the DICE GT-CRCC plant is a major equipment (ME) factored estimate with a target accuracy of ±30 percent.

For an ME-factored estimate, the ME material and labor costs were developed from equipment sizes, quantities, and design parameters defined by the PCC design from CCS. The bulk material and labor costs were factored from the ME costs. The sum of the ME and bulk material costs, including shipping costs, forms the total direct cost (TDC).

The construction indirect cost, factored from total direct labor cost, is added to the TDC to come up with the total field cost (TFC). Using factors consistent with the DOE/NETL report for the Case 12 total plant cost (TPC), the Engineering and Construction Management Fees and Home office cost, and contingencies are added to the TFC to come up with the TPC.

Upon generating the size estimates for the individual equipment, the costs for the equipment were generated using commercial estimation software (ASPEN ICARUS) with adjustments based on past quotes for similar equipment where necessary. Installation labor for each ME was factored from historical data by equipment type.

The costs for bulk materials such as instrumentation, piping, structure steel, insulation, electrical, painting, concrete and site preparation associated with the major equipment were factored from ME costs based on historical data for similar services. The installation labor for each bulk commodity was factored from historical data by type.

The construction indirect cost was factored from total direct labor costs based on historical data. The construction indirect cost covers the cost for setup, maintenance and removal of temporary facilities, warehousing, surveying and security services, maintenance of construction tools and equipment, consumables and utilities purchases, and field office payrolls.

2.4.3 Balance of Plant

Cost estimates for the DICE GT-CRCC balance of plant (BOP) systems, will be based on major equipment factored costs, wherever possible. For potential DICE GT-CRCC BOP systems that have virtually identical counterparts in the NETL Bituminous Baseline Report PC and NGCC cases, with only differences in capacity, cost estimates that follow the QGESS Capital Cost Estimation guidelines that is based on capacity-factoring may be used.

2.5 O&M COST ESTIMATION METHODOLOGY

The operations and maintenance (O&M) costs pertain to those charges associated with operating and maintaining the power plant over their expected life. These costs include:

- Operating labor
- Maintenance – material and labor
- Administrative and support labor
- Consumables
- Fuel

- Waste disposal

There are two components of O&M costs; fixed O&M, which is independent of power generation, and variable O&M, which is proportional to power generation. The base case variable O&M costs are estimated assuming that the DICE GT-CRCC plant is operating as a baseload plant, with a plant capacity factor of 85 percent. A range of O&M costs will also be estimated across a range of flexibility conditions.

2.5.1 Operating Labor

Operating labor cost is determined based on the number of operators required to work in the plant. Other assumptions used in calculating the total labor cost include, per the 2019 revision of the NETL Bituminous Baseline Report:

- 2018 Base hourly labor rate, $/hr — $38.50
- Length of work-week, hrs — 50
- Labor burden, percent — 30
- Administrative/Support labor, percent O&M Labor — 25

2.5.2 Consumables and Waste Disposal

The cost of consumables, including fuel, is determined based on the individual rates of consumption, the unit cost of each specific consumable commodity, and the plant annual operating hours. The waste quantities and disposal costs are evaluated similarly to the consumables.

The unit costs for major consumables and waste disposal are based on the values reported in the DOE/NETL Bituminous Baseline report. These costs are reported in Dec 2018 cost basis.

2.6 FINANCIAL MODELING BASIS

2.6.1 Economic Assumptions

The pre-FEED study deliverable calls for an estimate of the COE based on the technology concept and design criteria. The global economic assumptions for the COE calculation are based on the criteria set forth in the September 2019 version of NETL's QGESS Cost Estimation Methodology for NETL Assessments of Power Plant Performance (NETL-PUB-22580) summarized in Table 2-7.

Table 2-5
Global Economic Assumptions

Parameter	Value
Taxes	
Income Tax Rates	21 percent federal, 6 percent state (Effective tax rate of 25.74 percent)
Capital Depreciation	20 years, 150 percent declining balance method (DBM)

Investment Tax Credit	0 percent
Tax Holiday	0 years
Contracting and Financing Terms	
Contracting Strategy	Engineering, Procurement, Construction, and Management (owner assumes project risks for performance, schedule, and cost)
Type of Debt Financing	Project finance/non-recourse basis (collateral that secures debt is limited to the real assets of the project)
Repayment Term of Debt	Equal to operational period in formula method
Grace Period on Debt Repayment	0 years
Debt Reserve Fund	None
Analysis Time Period	
Capital Expenditure Period	3 years
Operational Period	30 years
Economic Analysis Period	33 years (capital expenditure plus operational period)
Treatment of Capital Costs	
Capital Cost Escalation during Capital Expenditure Period	0 percent
Distribution of Total Overnight Capital Cost over the Capital Expenditure	10 percent, 60 percent, 30 percent
Working Capital	Zero
Percentage of Total Overnight Capital that is Depreciated	100 percent
Escalation of Operating Cost and Revenues	
Escalation of COE and O&M costs	0 percent real (3 percent nominal)
Levelized Fuel Costs	$38.21/ton for PRB coal and $4.420/MMBtu for natural gas delivered to U.S. Midwest, per NETL QGESS Fuel Prices for Selected Feedstocks in NETL Studies (January 2019 update)
Finance Structures	
Debt Percentage of Total	55 percent
Equity Percentage of Total	45 percent

Real Current Dollar Cost	2.94 percent
Real Return on Equity	7.84 percent

The figure-of-merit used in the evaluation of coal and gas-fired power plants in the most recent version of the Bituminous Baseline Report (rev 4) is the ***real levelized cost of electricity (LCOE)***. Similarly, this pre-FEED study will determine the DICE GT-CRCC plant's performance based on the real LCOE. From the QGESS Cost Estimation Methodology for NETL Assessments of Power Plant Performance document, the pertinent factors used in determining the real LCOE as calculated based on the global economic assumptions shown in Table 2-7 are shown in Table 2-8.

Table 2-6
Inputs for LCOE Calculation

Parameter	Value
Total As Spent Capital/Total Overnight Cost factor ($TASC/TOC_{real}$)	1.093
Fixed charge rate (FCR)	0.0707
Capital recovery factor (CRF)	0.0630
Effective tax rate (ETR)	25.74 percent
Nominal after tax weighted average cost of capital ($ATWACC_r$)	4.73 percent

2.6.2 LCOE Calculation

Per the QGESS Cost Estimation Methodology for NETL Assessments of Power Plant Performance document, the following methodology is used to calculate the ***real*** LCOE, the figure-of-merit used in the Bituminous in this pre-FEED study, expressed in dollars per MWh.

1) Calculate the levelized capital cost (LCC) using the fixed charge rate and capital recovery factor (CRF) formulas as follows for a real (r) approach:

$$LCC_r = TASC_r * FCR_r$$

where: $$FCR_r = \frac{CRF_r}{1-ETR} - \frac{ETR*D_q}{1-ETR}$$

and $$CRF_r = \frac{ATWACC_r*(1+ATWACC_r)^y}{(1+ATWACC_r)^y-1}$$

and $$D_q = CRF_r * \sum_{n=1}^{z} \frac{d_n}{(1+ATWACC_r)^n}$$

where:

TASC = total as spent costs

FCR = Fixed charge rate

CRF = Capital recovery factor

ETR = effective tax rate

$ATWACC_r$ = real after tax weighted average cost of capital

D_q = Present value of tax depreciation expense

d_n = the tax depreciation fraction in year n

z = number of years of depreciation (21 for 20-year, 150 percent DBMpercent)

y = number of operating years

Based on the inputs given in Table 2-6, it is verified that FCR_r = 0.0707 per Table 2-7.

2) Calculate levelized (and annual) O&M expenses (AOM) per MWh using the following formula:

$$LOM = AOM * \frac{ATWACC*(1+ATWACC)^y}{(1+ATWACC)^y-1} * \frac{1-\left[\frac{(1+i)}{(1+ATWACC)}\right]^y}{ATWACC-i}$$

where:

y = number of operating years

i = assumed annual (real) escalation rate for O&M

ATWACC = after tax weighted average cost of capital

ETR = effective tax rate

Based on the inputs given in Table 2-6 where real escalation is specified as zero, the levelized value equals the annual value, LOM_{real} = AOM.

3) Calculate levelized annual fuel (LFP) expenses per MWh using the price forecast for fuel costs for a 2023 to 2053 (30 years) operating period.

$$LFP = PV_{fuel\ price} * \frac{ATWACC*(1+ATWACC)^y}{(1+ATWACC)^y-1}$$

where: $$PV_{fuel\ price} = \sum_{n=1}^{y} \frac{P_n}{(1+ATWACC_r)^n}$$

where:

n = the year of operation

y = number of operating years

P_n = real price of fuel in year n

ATWACC = after tax weighted average cost of capital

Per the QGESS Cost Estimation Methodology for NETL Assessments of Power Plant Performance document, the levelized fuel price for PRB coal delivered to the U.S. Midwest is $38.21/ton and the levelized fuel price for natural gas is $4.42/MMBtu on an HHV basis.

All factors in the COE equation are expressed in dollars for the on-line year, which is 2023 for the reference NETL Baseline Study. The equation used is:

$$COE = \frac{\begin{matrix} first\ year \\ capital\ charge \end{matrix} + \begin{matrix} first\ year \\ fixed\ operating \\ costs \end{matrix} + \begin{matrix} first\ year \\ variable\ operating \\ costs \end{matrix}}{\begin{matrix} annual\ net\ megawatt\ hours \\ of\ power\ generated \end{matrix}}$$

$$COE = \frac{(FCR)(TASC) + OC_{FIX} + (CF)(OC_{VAR})}{(CF)(MWH)}$$

where:

COE = revenue required to be received by the generator ($/MWh, equivalent to mills/kWh) during the power plant's first year of operation in order to satisfy the finance structure assumptions

FCR = fixed charge rate taken based on CRF values from that matches the finance structure and capital expenditure period. The interest rate used in the formula must by necessity be the ATWACC

TASC = total as spent capital (see TOC discussion below), expressed in on-line year cost

OC_{FIX} = the sum of all first-year-of-operation fixed annual operating costs

OC_{VAR} = the sum of all first-year-of-operation variable annual operating costs at 100 percent capacity factor, including fuel and other feedstock costs and (offset by) any byproduct revenues

CF = plant capacity factor, assumed to be constant (or levelized) over the operational period; expressed as a fraction of the total electricity that would be generated if the plant operated at full load without interruption

MWH = annual net megawatt-hours of electricity generated at 100 percent capacity factor