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

FINAL REPORT FOR PRE-FEED STUDY

U. S. Department of Energy (DOE)

Contract No. 89243319CFE000025, Coal-Based Power Plants of the Future

By

Nexant, Inc

and

Bechtel Power and Infrastructure

April 30, 2020

Contents

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Volume I: Executive Summary & Business Case

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Section 1 Executive Summary

1.1 INTRODUCTION

The Department of Energy (DOE) Office of Fossil Energy (FE) and the National Energy Technology Laboratory (NETL), through its Coal FIRST (Flexible, Innovative, Resilient, Small, Transformative) initiative, seek to understand the configurations, equipment features, performance characteristics, and cost implications for a future commercial coal plant that incorporates attributes that include, among others, high overall plant efficiency, modular design, near-zero emissions, high ramp rates, minimized water consumption, integration with coal upgrading, and capable of natural gas co-firing.

Nexant and Bechtel performed a conceptual design of the **D**irect **I**njection **C**arbon **E**ngine-Gas Turbine (DICE) **C**ompound **R**eheat **C**ombined **C**ycle (CRCC) that demonstrated the aforementioned attributes of such a power plant. An option to complete a pre-defined design package (Pre-FEED study) was exercised to prove the technical and economic feasibility of the plant configuration. These efforts are documented in this report, which involves partnering and gathering input from equipment manufacturers and technology developers in determining component options for the this technology.

1.2 BUSINESS CASE

The business case covers a market scenario leading up to the commercialization of the DICE CRCC power plant. The main focus was on a commercial market driven scenario that is projected to be a candidate for the commercial implementation of DICE CRCC power plants. The business case addresses four main commercial factors covering market scenario, market applicability and advantage of concept, estimated cost of electricity, and commercialization pathway or roadmap for the DICE CRCC technology and power plant starting from a pilot plant to a NoaK commercial project.

Based on the current trends and outlook, the market scenario for coal based power generation varies widely on a regional basis both in the domestic U.S. and internationally. The commercial market dynamics are dependent upon key influencing drivers which may also serve as challenges and barriers which can potentially impact the commercial implementation of a DICE CRCC power project. These include energy supply, security, and independence, competing power sources, air emissions regulations, reducing carbon footprint, de-carbonization, and energy transition, and project financing. The market scenario leading up to the commercialization of the DICE CRCC power plant addresses the coal type, natural gas price along with a sensitivity analysis, CO_2 constraint of 90 percent and the current market price, and renewable energy penetration based on the EIA's Annual Energy Outlook 2020.

The market applicability in domestic U.S. is dependent upon key factors for the resurgence of new coal power projects which includes increase in price of LNG/natural gas, increasing value of CO_2 via regulation or carbon capture and utilization, and the impact of regulatory framework and policy. The market applicability internationally indicates countries with relatively lower cost coal but higher domestic natural gas prices (e.g. China, India, and Australia) which may also find the DICE CRCC power plants and configuration appealing. In the various countries and regions (e.g. Japan, South Korea, and Europe), smaller, modular, and efficient DICE CRCC power plants utilizing coal will most likely be attractive. The utilization of CO_2 for either EOR and/or enhanced gas recovery are also growing potential opportunities.

The market advantage of concept demonstrate that the DICE CRCC power plant is well suited for certain specific markets with unique attributes and features, such as those with smaller capacity utility grid(s) unable to accommodate large capacity power plants, modular design enabling "building block" methodology for incremental capital investment and capacity additions to match utility grid demand loads, higher efficiency and ability to operate at range of capacity factors, high natural gas price, the ability to use diesel fuel, high ambient temperature and humidity, and high altitude installations.

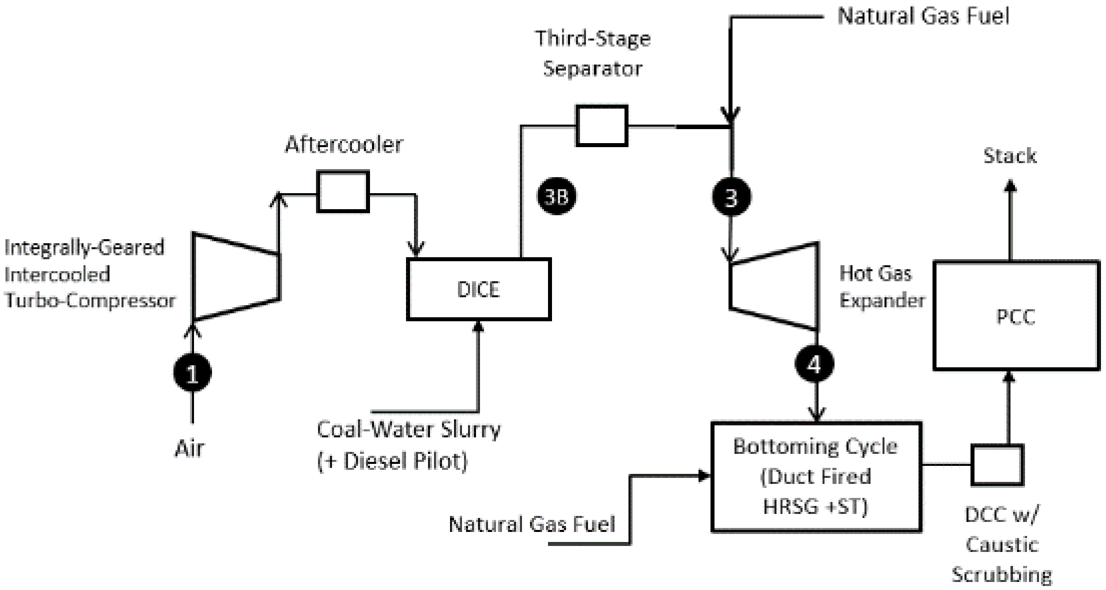
Based on the overall performance, total as-spent cost (TASC), and annual operating cost of the 100 MWe DICE CRCC plant, its LCOE was estimated to be $223.9/MWh. The LCOE of variant cases were also estimated with the DICE CRCC plant without PCC having an LCOE of $148.6/MWh, and the "ideal" DICE CRCC with PCC and centralization beneficiation having an LCOE of 145.7/MWh.

From a commercial project development and project financing perspective, the commercialization pathway for the DICE-GT CRCC power plant requires a two-phased approach and manner – ***initially with a pilot plant and later followed by a NoaK commercial plant***. The key funding and financing assumptions and drivers include TRL, funding via equity and grants for the pilot plant, funding via equity and limited recourse financing via debt for the first 1 to 3 NoaK plants (later followed by non-recourse financing), fiscal and financial incentives, and ***"bankable"*** transactional contracts.

1.3 TECHNOLOGY DESCRIPTION

The thermodynamic driver behind the DICE CRCC plant concept is described in detail in the papers and articles by Gülen. A simplified system diagram of the DICE 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



As shown in Figure 1-1, air compressed in the turbocompressor is sent to the DICE engine intake after being cooled in an aftercooler to a suitable temperature (~120 °F). Multiple DICEs, operating in parallel, burn MRC slurry to generate power. The DICE exhaust gas temperature is sent to the hot gas expander for power generation.

The bottoming cycle is a Rankine steam cycle comprising an HRSG and a steam turbine generator with the balance of plant (BOP) including a backpressure steam turbine, myriad pipes, valves, pumps and heat exchangers. The HRSG is a waste heat recovery boiler utilizing hot gas turbine exhaust gas to make steam. Duct firing of natural gas in the HRSG is required in order to generate enough steam to meet the demand of the PCC system.

The flue gas is desulfurized in a direct contact caustic scrubber to reduce the SOx content in the flue gas to less than 10 ppm and reduce amine losses in the downstream post combustion CO_2 capture (PCC) unit, while also cooling and condensing water from the flue gas, before it is sent to the amine-based PCC unit to remove 90 percent of its CO_2.

1.4 TECHNOLOGY GAPS

The DICE CRCC delivers the promised capabilities by combining mostly standardized, off-the-shelf, and commercially mature equipment with proven technology in a thermodynamically optimum manner. The combination of reheat with constant volume heat addition delivers the most efficient heat engine cycle, which can be implemented in the field with multi-equipment configurations for maximum modularity and flexibility with high efficiency at small ratings.

The DICE CRCC with post-combustion carbon capture (PCC) is a low emissions, coal-fired power plant comprising three “blocks” or “islands”:

- Coal beneficiation and coal-water slurry (CWS) fuel processing and production
- Modular electric power generation
- PCC

The PCC Block utilizes amine-based chemical absorption technology, which is currently available and is not considered a technology risk. The power generation system also comprises of commercially mature and proven technology *except for the DICE*. Thus, the main focus of the technology gap analysis is on:

- DICE R&D and development pathway
- CWS processing and production

1.4.1 DICE Technology Gaps and Risks

All of the major pieces of equipment for the DICE CRCC power system are standardized, off-the-shelf, and commercially mature products (i.e., representing TRL 9). The least-proven part of the cycle is DICE, which is a reciprocating internal combustion engine (RICE) fired with a coal-water slurry fuel, and which requires the following modifications and development:

- New fuel injector
- Cylinder/piston coating (with carbide)

The project team worked with the Commonwealth Scientific and Industrial Research Organisation (CSIRO) of Australia to address the developmental needs of DICE in these areas. The team also plans to continue partnering with CSIRO to further develop these modifications for the next phase of work.

1.4.1.1 R&D Requirements for DICE Commercialization

Table 1-1 suggests the component R&D program to commercialize the MRC-fired DICE component.

Table 1-1
Component R&D Program for DICE Commercialization

Component	4-stroke	2-stroke
Cylinder liners	Hard coating, optional provision of oil scrapper grooves to allow increased bore lubrication and flushing of solids to reduce filtration load on crankcase lubrication	Hard coating, optional provision of oil scrapper grooves to allow increased bore lubrication and flushing of solids above the scavenge ports
Piston	No change in short term, optimization of bowl shape for MRC rather than low NOx as required for fuel oil	
Rings	Hard coating, improved design to improve down scrape of contaminated bore oil	
Stuffing box	No change	Seal oil protection to eliminate the ingress of contaminated cylinder oil
Scavenge box drainage	No change	No change if scrapper grooves are used in the cylinder walls otherwise improved drainage
Crankcase oil filtration	200 percent increased filtration capacity; dual systems to allow on-line maintenance, separate centrifuge for cylinder scrape.	No change, but with separate centrifuge for reconditioning cylinder scrape
Fuel supply system	Dual system is required: One for MRC and one for a diesel/fuel oil which would be used for starting, idling and optional pilot injection (1-5% of heat rate, as is currently used for some gas engines).	
Injection system	Seal oil protected sliding surfaces including the pump plunger and needle valve. The seal oil should be maintained at 120% of the fuel supply pressure at all times.	
Pilot injection	Pilot injection is essential for engine conditions where ignition is less reliable - starting, idle and shutdown. Pilot injection is recommended for engine speed above 400 rpm, and at low load.	
Exhaust manifold (low speed 2-strokes)	Large horizontal exhaust gas ducting should also be provided with a positive grit removal system (e.g. auger).	
Exhaust turbine	No change for ash with aerodynamic diameter <10um. Possible use of coated metal for inlet guide vanes.	
Waste heat recovery	Conventional solid fuel boiler type for heat recovery	
Exhaust gas cleanup	The same as used for large land mounted 2-stroke engines using heavy fuel oils – ESP or fabric filtration, SCR and FGD	
Lubrication	Adjustment of crankcase oil to match sulfur content of the MRC and with increased detergency to keep char and ash in suspension.	

1.4.1.2 Staged Development of DICE

Previous R&D on DICE, while having provided promising findings on technical issues, can only provide a technology readiness level (TRL) of 4 for most technical aspects. DICE still needs considerable development and demonstration to match the technical development of current power generation technologies. However, this can be cost-effectively fast-tracked. Compared to the incumbent technologies, DICE has strong technical merit because of the ability to carry out a near-commercial scale demonstration at a relatively small size (e.g. 5 MW).

The 5 MW capacity engine-generator can be obtained in skid form, in a straight 6 configuration, giving a cylinder of approximately 400 mm bore and operating at 500 rpm. The simple in-line configuration and fewer cylinders ensure easier and faster incorporation of new components for testing - *essential to shortening development time*. This includes the option of only needing to make changes to one cylinder – which can also be swapped out as a complete power unit in a few hours to facilitate testing.

The data, information, and experience gained from this engine would be directly applicable to a larger semi-commercial demonstration (e.g. a V18 configuration producing 15 MW at 500 rpm). It is envisaged that successful demonstration at this scale would lead to larger commercial installations comprising multiple 15-20 MW engines, as is practiced for gas engine installations, without entailing any scale-up of DICE.

The cylinder size, rating and power output from a single engine unit for the proposed development steps to a full-size commercial engine are shown in Table 1-2.

Table 1-2
Proposed Engine Scale-Up

Development stage	Bore (cm)	Cylinder rating (kWe/cyl)	Cylinders Units	Plant Output (MWe)	Scale up
Small scale demonstration	46	1000	6	5-6	1
Demonstration plant	46	1000	18	20	1
First commercial	46	1000	18 5 units	100	1
Large commercial 4-stroke	63	2000	18 5 units	200	2x
Large commercial 2-stroke	94	5000	12 6 units	360	5x

The scale-up factor (based on cylinder area) between the development stages is at most 2-3x, which are relatively small scale-up steps compared to other technologies. It is envisaged that a staged development program could be established with an engine manufacturer and OEMs (e.g. suppliers of injection and turbocharging components) to quickly undertake the demonstration program to enable commercial deployment by 2030.

Following the successful demonstration, rapid commercialization is possible, and likely to be driven by a strong need for incremental coal generation capacity for:

- Replacing old, inefficient and uneconomic PC power plants (say units smaller than 300 MW and/or older than 30 years in plant economic life)
- New load-following capacity to secure a higher penetration of renewables, and in direct competition with gas open cycle plants with gas prices over $5/GJ
- Remote generation, especially for supplying large mines and surrounding regions
- New capacity with CO_2 capture and storage, as DICE has the potential for a 30 percent reduction in the cost of capture over PC coal plants. The cost reduction is due to a combination of higher thermal efficiency (fewer kg CO_2/MWh) and the ability to use 130°C coolant and exhaust heat for stripping
- Once an engine is adapted for DICE it will be capable of handling a wide range of other alternative fuels (i.e. difficult) fuels (for example coal-biochar or coal-ammonia blends, crude bio-oils) which would extend the facilities value past the proposed demonstration, and provide additional environmental incentives for the facility and commercialization of DICE.

  MRC, including higher ash products, could be used to replace fuel oil for boiler light-up and low load operation.

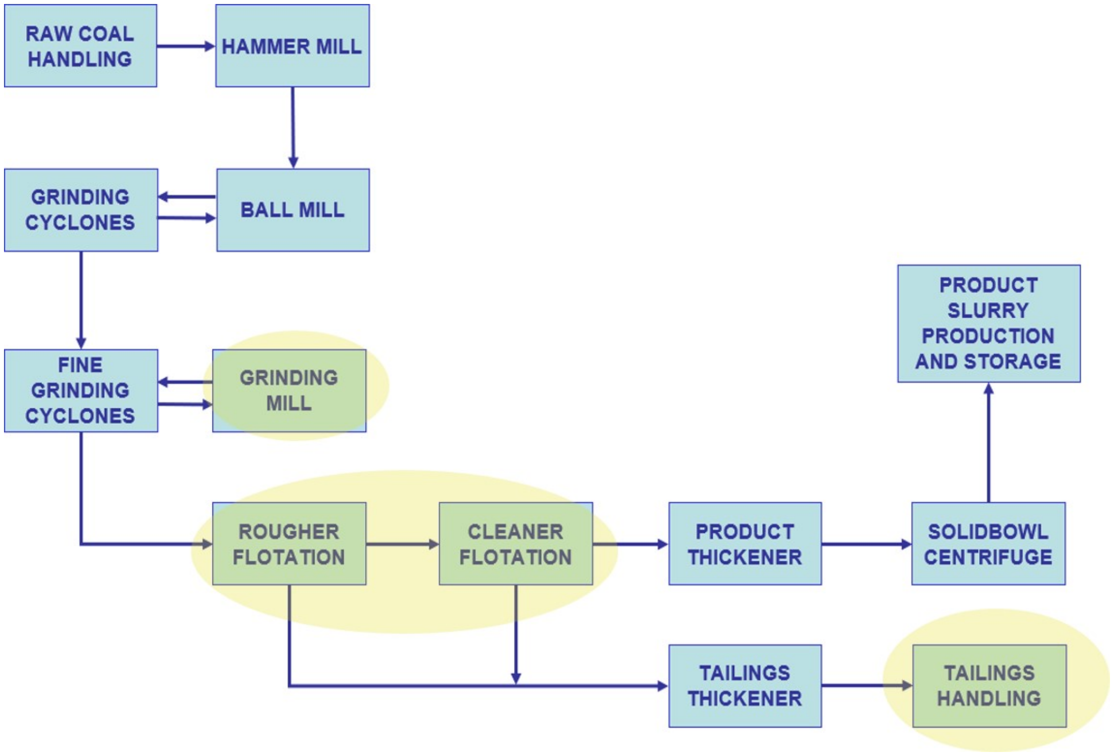
1.4.2 Fuel Production Technology Gaps and Risks

The project team worked with the Sedgman Inc to develop a flowsheet for the coal beneficiation and slurrying process and to address the developmental needs of the coal beneficiation plant. It is understood from Sedgman that for a typical commercial beneficiation process, there are currently no specific components, equipment, or systems which require undertaking traditional R&D nor having any technology gaps. However, as part of the overall beneficiation process, there are key commercially available plant unit operations whose end-use application is novel - when beneficiation is based on coal. As shown in Figure 1 2, these unit operations include fine grinding mill, ash removal (via rougher flotation and cleaner flotation), and tailings handling.

In this study's performance evaluation of the DICE CRCC, subbituminous PRB coal was used as the feedstock to the beneficiation plant. Due to the hydrophilic nature of the PRB coal, the overall product recovery yield was about 50 percent on both a mass and combustible value basis. A consequence of this low product yield is the large quantity of reject tailings that, while still containing significant heating value, is in slurry form, and has no commercial value. The unsaleable tailings thus has to be disposed of in ash ponds, which constitute an environmental risk.

While it is possible to process the reject slurry (via dewatering, briquetting, etc.) to a more functional form, this requires additional energy and cost input. It is therefore key to address the likely technology gap associated with disposing the otherwise unsaleable reject slurry tailings from coal beneficiation.

Figure 1-2
Key Coal Beneficiation Unit Operations



It is of utmost importance to increase the product recovery yield to way beyond the current 50 percent. Doing so would not only decrease the coal feed required by the beneficiation plant, but also minimize the quantity of reject tailings. It is understood that the hydrophilic nature of the subbituminous coal as-is makes it difficult to achieve a high recovery via the conventional flotation process for ash separation. Tests on various coal samples should therefore be undertaken to identify coal types that can achieve maximum product recovery

1.4.2.1 Development of Coal Processing Plant

From this study, items in proposed order of testing as discussed below, should be included in an ongoing work plan to further progress the development pathway of MRC as fuel for the DICE CRCC.

Feed Coal Analysis: One of the main drivers for the success of DICE CRCC is the feed coal selection. The PRB coal is shown to be not suitable in current pre-FEED study. Bench-scale tests are therefore needed on various coals to establish and select feed with best available yield, while meeting the heating value, ash content, and rheology specifications required by DICE. The selection of the preferred coal type is a critical component of any ongoing work as this will drive the downstream test work.

Coal Grain Analysis: Once a preferred coal source, or sources, are identified, detailed coal grain analysis on this coal is required to determine liberation requirements to reach the required product ash level.

Crushing and Grinding Test Work: Laboratory scale comminution tests (comminution is particle size reduction by breaking, crushing, or grinding of ore, rock, coal, or other materials) should be carried out on the selected coal to determine the energy inputs required for crushing and grinding.

Flotation Tests: Flotation tests should be performed on freshly ground coal samples to avoid oxidation of the particle surfaces which will adversely impact flotation performance. The results of the flotation test work may require an iteration of the grinding work to be done.

Thickening and Dewatering Tests: Both the product (concentrate) and tailings material from the flotation test work would need to be collected to perform thickening and dewatering testing. Thickener testing will help to determine thickener size, flocculant type and dosage rates. Dewatering test work will help to size the dewatering equipment and assist in selection of the final dewatering technology to use.

Rheology Characterization: To support the sizing and selection of agitators, pumps and piping a range of range of rheology characterization tests should be undertaken on the key intermediate and final product and tailings slurry streams.

Pilot Plant Operation: While the individual pieces of major equipment required for the coal beneficiation plant producing MRC slurry are commercially available, the overall process as applied to coal is novel. It is therefore recommended that following the completion of the above initial laboratory scale analysis, a pilot plant be constructed and operated to provide an indication of the expected continuous performance.

1.4.2.2 Centralized Beneficiation Plant

For a small, modular power plant such as the DICE CRCC (< 100 MW for this introductory variant), the performance and cost estimates presented in the report suggest that it makes no economic sense to install a coal beneficiation plant on-site at every DICE CRCC plant. This is analogous to building a crude oil refinery on-site at every gas station. For the modular DICE CRCC plant to be feasible, there must be multiples of such power plants, each receiving fuel from a centralized coal beneficiation plant, thereby taking advantage of the economies-of-scale benefits that the large central beneficiation plant possesses. Research and development efforts must therefore be geared towards a large centralized processing facility, and take into consideration the delivery aspects of the beneficiated coal (e.g. delivering the coal in dry, powdered form risks self-ignition, slurry form delivery incurs additional costs for shipping what is essentially just water)

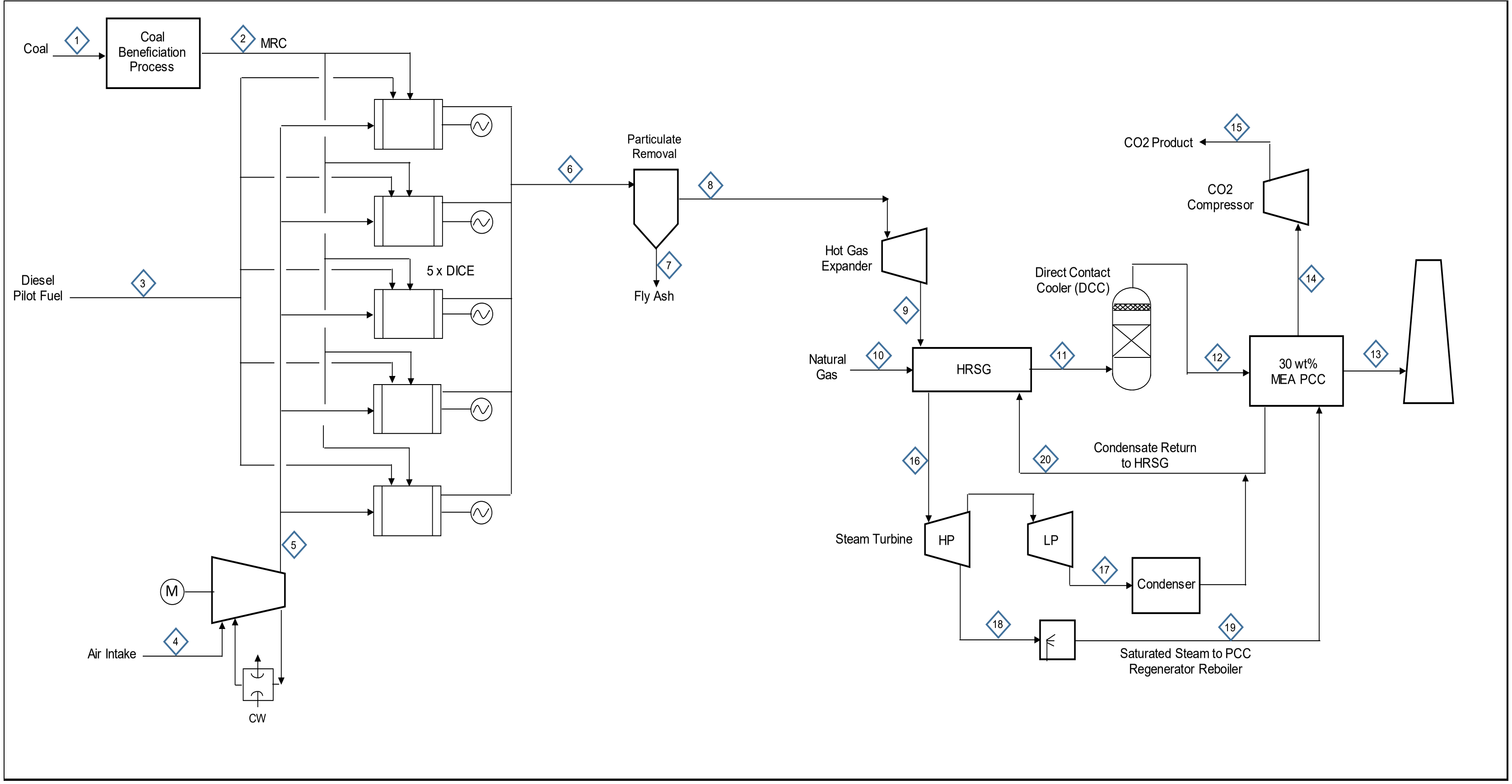
1.5 DICE CRCC PERFORMANCE RESULTS

1.5.1 Process Flow Diagram

The overall DICE CRCC power plant PFD is shown in Figure 1-3 and comprises the following:

- Coal beneficiation plant
- 5 DICE (nominally 20 MWe each)
- 1 main air compressor (MAC)
- 1 hot gas expander
- Bottoming cycle consisting of HRSG with natural gas duct firing and back pressure steam turbine
- 30 wt% MEA-based PCC unit capturing 90 percent of CO_2 in the flue gas

Figure 1-3
100 MWe Nominal DICE CRCC Process Flow Diagram



1.5.2 DICE CRCC Plant Net Efficiency

Table 1-3 summarizes the overall performance based on the design of the nominal 100 MWe DICE CRCC power plant. Overall fuel mix to the plant consists of 71.5 percent coal, 3.5 percent diesel fuel and 25.0 percent natural gas, on an LHV basis. The net efficiency of the plant is 30.8 percent on an LHV basis (29.1 percent HHV). As the rejected PRB coal tailings from the beneficiation process do not participate in the combustion reactions, the heating value associated with these rejects is not included in the efficiency calculation.

Table 1-3
Power Summary and Net Efficiency

Power Summary	
POWER GENERATION, kWe	
5 x DICE	78,730
Turboexpander	31,787
Steam Turbine	14,676
Total Power Generation	**125,192**
AUXILIARY LOAD SUMMARY, kWe	
MRC Fuel Prep	5,472
Main Air Compressor	26,301
SCR	88
Fabric Filter	69
Boiler Feed Water Pump	261
Economizer Recirculation Pump	5
Steam Turbine Auxiliaries	31
DCC Circulating Pump	400
CO_2 Capture	2,549
CO_2 Compression	7,838
Circulating Water Pumps	2,407
Makeup Water Pumps	70
Cooling Tower Fans	977
Wastewater Pumps	14
Miscellaneous Auxiliaries	135
Transformer Losses	626
Total Auxiliaries, kWe	**47,242**
Net Power, kWe	**77,950**
As-Received PRB Coal Feed, lb/hr	148,818
Beneficiated Coal Slurry Fuel Feed, lb/hr	91,934
Diesel Fuel Feed, lb/hr	1,651
Natural Gas Feed Flow, lb/hr	10,640
Coal LHV Thermal Input, MMBtu/hr	619
Diesel LHV Thermal Input, MMBtu/hr	30
Gas LHV Thermal Input, MMBtu/hr	216
Total LHV Thermal Input, MMBtu/hr	**865**
LHV Efficiency, %	**30.8%**
Coal HHV Thermal Input, MMBtu/hr	643
Diesel HHV Thermal Input, MMBtu/hr	32
Gas HHV Thermal Input, MMBtu/hr	239
Total HHV Thermal Input, MMBtu/hr	**914**
HHV Efficiency, %	**29.1%**

1.5.3 Plant Emissions

Table 1-4 summarizes the various DICE CRCC plant emissions and control measures undertaken to achieve these emissions.

Table 1-4
Plant Emissions Summary

Pollutant	lb/MWh-gross	Control Technology
SOx	Trace (0.000)	Direct Contact Cooler (DCC) with caustic scrubbing + MEA reaction with residual SOx in flue gas to effectively reduce to zero
NOx	1.2	Selective Catalytic Reduction + MEA reaction with NO_2 to effective scrub out all NO_2, reducing NOx content by 10% (assume 90:10 NO/NO_2 ratio in flue gas) while all NO passes through
PM	Trace (0.000)	DCC water wash in PCC plant further scrubs out residual PM in flue gas
Hg	3×10^{6} (estimated)	Third Stage Separator (TSS) + SCR + DCC. If mercury is still an issue, activated carbon injection (ACI) can be utilized at a location with appropriate temperature before the cyclone.
HCl	0.06 (unabated) 0.000 (SOx surrogate)	Uses SOx as surrogate, per DOE Bituminous Baseline Report
	lb/MWh-net	
CO_2	221	30 wt% MEA
Volatile Organic Compounds (VOC)	1 ppm	Water wash at the top of the PCC absorber is expected to remove VOC in flue gas before venting to atmosphere

1.5.4 Potential Variants

Two variants of the DICE CRCC system were considered and their performances were evaluated as part of this study. One scenario considered eliminating PCC of the DICE CRCC system flue gas. In this case, exhaust steam from the main steam turbine that would have been diverted to the PCC is sent to a condensing turbine to produce more power, resulting in greater power generation from the steam cycle.

The second scenario evaluated was that for a modular DICE CRCC plant that, instead of having an on-site, similarly modular coal beneficiation plant, receives coal from a centralized beneficiation facility, thereby taking advantage of the economies-of-scale benefits that a large central beneficiation plant possesses.

Table 1-5 summarizes the plant performances of these variations, along with the base case.

Table 1-5
Performance Comparison of Base Case DICE CRCC and Variants

Description	DICE CRCC with PCC (On-site coal beneficiation)	DICE CRCC No PCC	DICE CRCC with PCC (Centralized coal beneficiation)
POWER GENERATION			
DICE	78,730	78,730	78,730
Turboexpander	31,787	31,900	31,787
Steam Turbine	14,676	31,299	14,676
Total Power Generation, kWe	**125,192**	**141,929**	**125,192**
AUXILIARY LOAD SUMMARY, kWe			
Coal Processing	5,472	5,472	500
Power Cycle Auxiliaries	27155	27476	27155
CO2 Capture and Compression	10387	0	10387
Balance of Plant	4,229	3,891	4,240
Total Auxiliaries, kWe	47,243	36,840	42,282
Net Power, kWe	**77,949**	**105,089**	**82,910**
Coal HHV Thermal Input, MMBtu/hr	643	649	643
Diesel HHV Thermal Input, MMBtu/hr	32	33	32
Gas HHV Thermal Input, MMBtu/hr	239	270	239
Total HHV Thermal Input, MMBtu/hr	**914**	**952**	**914**
HHV Efficiency, %	**29.1%**	**37.7%**	**31.0%**
LHV Efficiency, %	**30.8%**	**39.9%**	**32.7%**

1.6 DICE CRCC COST RESULTS

1.6.1 Cost Estimation Methodology

Capital costs for the 100 MWe DICE CRCC plant were derived based on the following methodology:

- Capital costs for the coal beneficiation system were estimated by Sedgman and presented as a turnkey subcontract cost in this report. The capital cost estimate is reflective of the facility fully designed, supplied, fabricated and delivered to site, constructed and commissioned in accordance with the coal beneficiation plant scope of work detailed in the pre-FEED performance results study. .
- The costs for certain specialized, commercial equipment associated with the DICE CRCC plant, such as the air compressor, hot gas combustor, hot gas expander and the various generator equipment, were estimated and verified with budgetary quotes from equipment vendors. These were then 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.
- Post combustion capture (PCC) plant cost was determined via a bottoms-up cost estimate based on major equipment sizing and using past quotes from equipment vendors or cost curves derived from commercial cost estimate software
- DICE CRCC balance of plant (BOP) systems were estimated via a bottoms-up cost estimate based on major equipment sizing and developed to total plant cost level using historical factors. The exception is the ash handling system, which was scaled via capacity factor, using appropriate scaling parameters and capacity factoring exponents stated in NETL's Quality Guidelines for Energy System Studies (QGESS) Cost Scaling Report

1.6.2 Capital Cost Estimate

Table 1-6 provides a summary of the DICE CRCC total plant cost (TPC), total overnight cost (TOC), and total as-spent cost (TASC), in 2018 dollars.

The estimated TPC for the small, modular (nominal 100 MW "block") DICE CRCC plant is $422.4 million (MM), or $5,419/kW-net. Its TOC is $524.7MM, or $6,732/kW-net, and its TASC is $575.5MM, or $7,358/kW-net.

Table 1-6
Capital Cost Summary for DICE CRCC Plant

Plant	**DICE CRCC**
Size	**78 MWe**
Total Plant Cost (2018 $/kW)	**5,419**
Total Plant Cost (2018 $MM)	**422.4**
Bare Erected Cost	*323.5*
Home Office Expenses	*38.6*
Project Contingency	*17.7*
Process Contingency	49.9
Total Overnight Cost (2018 $/kW)	**6,732**
Total Overnight Cost (2018 $MM)	**524.7**
Owner's Costs	*102.3*
Total As-Spent Cost (2018 $/kW)	**7.358**
Total As-Spent Cost (2018 $MM)	**573.5**

1.6.3 Operating Cost Estimate

Table 1-7 presents a breakdown of the nominal 100 MWe DICE CRCC fixed and variable operating costs.

It is notable that the low recovery of beneficiated product from processing PRB coal, at less than 50 percent, results in a large consumption of the PRB coal feed. Additionally, it generates a significant quantity of coal tailings slurry that needs to be disposed of. A $38/ton disposal cost was used in the cost estimate, as referenced from the DOE Bituminous Baseline Report, resulting in a very high annual waste disposal cost of $24.4MM, by far the most significant contributor to the non-fuel O&M costs.

This disposal cost is considered conservative, since the tailings contain significant heating value, as much as the product itself, albeit with higher ash content and in the form of a slurry. Its quality can be comparable to that of lignite coals found in the Gulf Coast region, which have heating values as low as 4,000 Btu/lb, and moisture contents as high as 55 percent). It could therefore be potentially useful as a fuel for slurry-based gasification or for combustion after suitable processing (e.g. briquetting).

Table 1-7
100 MWe Nominal DICE CRCC Annual Operating Cost Breakdown

Plant	**DICE CRCC**
Size	**78 MWe**
Capacity Factor (CF)	**85%**
Fixed Operating Costs, 2018 $MM/yr	**20.8**
Annual Operating Labor Cost	*7.3*
Maintenance Labor Cost	*2.6*
Administration & Support Labor	*2.5*
Property Taxes and Insurance	*8.5*
Variable Operating Costs, 2018 $MM/yr	**39.4**
DICE CRCC Plant Maintenance Material	*4.0*
Coal Beneficiation Plant Maintenance Material	*2.0*
Water	*0.5*
Chemicals	*8.4*
Waste Disposal	*24.4*
Fuel, 2018 $MM/yr	**29.2**
PRB Coal	*21.2*
Diesel	*0.2*
Natural Gas	*7.9*
Total Annual O&M Costs 2018 $MM/yr	**89.4**

1.6.4 Design Levelized Cost of Electricity (LCOE)

Based on the overall performance, TOC, and annual operating cost of the 100 MWe DICE CRCC plant, its levelized cost of electricity (LCOE) was estimated to be $223.9/MWh.

Table 1-8
LCOE Parameters and Cost Breakdown

Plant	**DICE CRCC**
Size	**78 MWe**
Capacity Factor (CF)	**85%**
Years of Construction	**3**
Total As-Spent Cost/Total Overnight Cost Ratio	**1.093**
Fixed Charge Rate (FCR)	**0.0707**
Total As-Spent Cost (TASC), $MM	574
Fixed Operating Cost, $MM/yr	20.8
Variable Operating Cost @ 100% CF, $MM/yr	46.3
Fuel Cost @ 100% CF, $MM/yr	34.4
Annual 1000 MWh (100% CF)	683
LCOE (excl. CO_2 T&S), $/MWh	**223.9**
LCOE Breakdown, $/MWh	
Fuel (incl. coal beneficiation)	50.4
Variable O&M	67.8
Fixed O&M	35.9
Capital Charges	69.9
Total LCOE, $/MWh	**223.9**

Note: 3 year construction for DICE CRCC is consistent with NGCC construction period assumption as used by NETL in its reference reports. TASC/TOC ratio used for LCOE evaluation for such 3-year capital projects is 0.0707

1.6.5 LCOE Estimates of Variant Cases

Table 1-9 presents the summary comparison of the capital costs, operating costs, and LCOE breakdown of the DICE CRCC plant with and without PCC, and the envisioned "ideal" DICE plant that receives coal feed from a centralized coal beneficiation plant.

The DICE CRCC plant without PCC has an LCOE of $148.6/MWh, or 66 percent of the same plant with PCC. Essentially, adding the PCC plant to capture 90 percent of the CO_2 in the DICE CRCC flue gas increases its cost of electricity by 50 percent.

The ideal DICE CRCC plant using coal received from a centralized beneficiation plant, assumed to be at $4.3/MMBtu based on CSIRO's research on the cost of coal beneficiation. Including 90 percent CO_2 capture, the LCOE of this plant is reasonable at $145.7/MWh, or about 65 percent of the base case plant with on-site beneficiation.

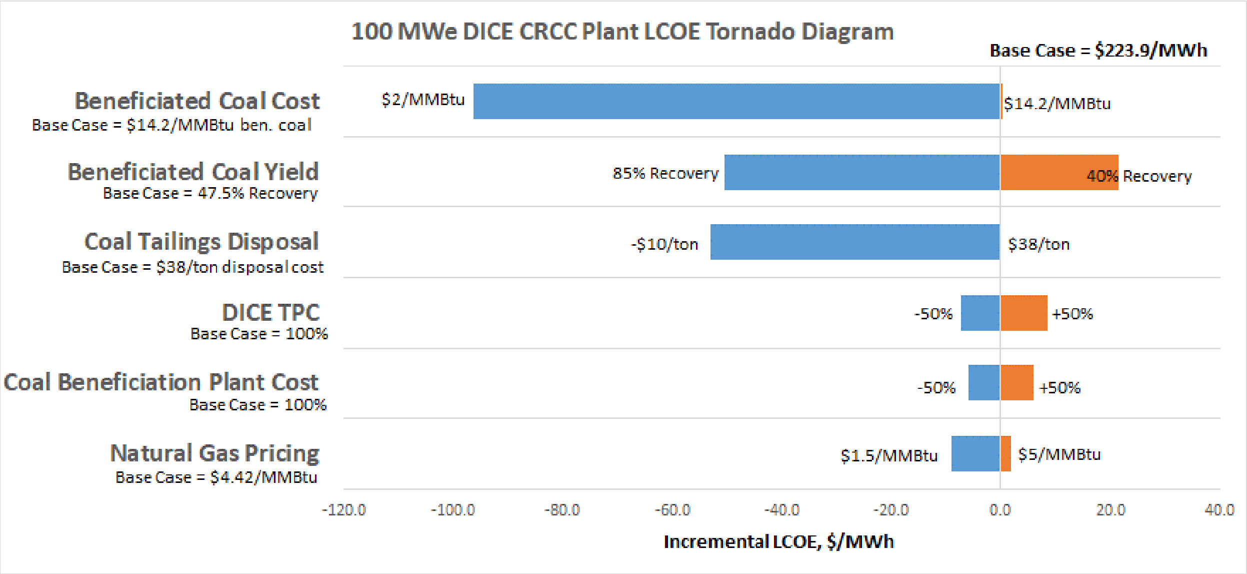
Table 1-9
Performance and LCOE Summary Comparison for DICE CRCC Variants

Plant	DICE CRCC No PCC	DICE CRCC with PCC (on-site beneficiation)	Ideal DICE CRCC with PCC (centralized beneficiation)
Size	**105 MWe**	**78 MWe**	**83 MWe**
Plant Efficiency, LHV	**39.9%**	**30.8%**	**32.7%**
Plant Efficiency, HHV	**37.7%**	**29.1%**	**31.0%**
Capacity Factor (CF)	**85%**	**85%**	**85%**
Total As-Spent Cost (TASC), $MM	474	573	492
Fixed Operating Cost, $MM/yr	17.6	20.8	15.2
Variable Operating Cost @ 100% CF, $MM/yr	40.8	46.3	13.4
Fuel Cost @ 100% CF, $MM/yr	35.8	34.4	33.7
Annual 1000 MWh (100% CF)	921	683	726
LCOE (excl. CO_2 T&S), $/MWh	**148.6**	**223.9**	**145.7**
LCOE Breakdown, $/MWh			
Fuel (incl. coal beneficiation)	38.9	50.4	46.4
Variable O&M	44.4	67.8	18.4
Fixed O&M	22.5	35.9	24.6
Capital Charges	42.8	69.9	56.4
Total LCOE, $/MWh	**148.6**	**223.9**	**145.7**

1.6.6 Sensitivity Analysis

Figure 1-4 depicts the tornado chart that provides both a ranking and measure of magnitude of the impact that the listed parameters have on the DICE CRCC plant LCOE. It is clear from this figure that the LCOE is most sensitive to the performance and cost of the coal beneficiation plant. It would therefore be most beneficial to the DICE CRCC technology if there was a centralized coal beneficiation plant with maximum economy-of-scale that also maximizes the yield of the beneficiation process (which simultaneously minimizes the tailings to be disposed of), thus reducing the beneficiated coal cost to be delivered to the modular DICE CRCC plant.

Figure 1-4
LCOE Tornado Chart



Section 2 Business Case

2.1 OBJECTIVE

The objective of this section is to evaluate a business case which demonstrates a market scenario leading up to the commercialization of Direct Injection Carbon Engine (DICE) Compound Reheat Combined Cycle (CRCC) technology and power plants. Accordingly, the main focus is on a commercial market driven scenario that is projected to be a candidate for the commercial implementation of DICE CRCC power plants.

2.2 INTRODUCTION

2.2.1 Overview

The power plant for this Pre-FEED study is configured as a 5x1x1x1 DICE CRCC facility generating a 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 is as follows:

1. Five (5) DICE (nominal 20 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 wt percent MEA plant capturing 90 percent of the total CO_2 in the flue gas

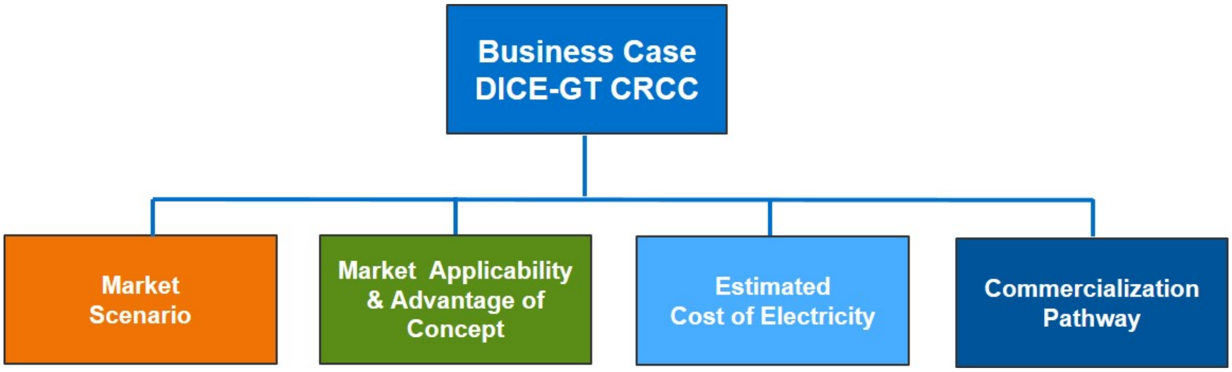
Subject to the design basis set forth in the contract, the design for the DICE CRCC power plant is to be developed as a greenfield project with a U.S. Midwestern or Gulf Coast location.

This section describes the key commercial circumstances which establish the business case for the DICE CRCC power plant while addressing:

- Current coal power generation marketplace
- Competing conventional power generation sources
- Drive towards reducing carbon footprint, de-carbonization, and ongoing energy transition
- How the proposed technology will most likely respond to varying power market scenarios

Accordingly, the business case presented includes four main commercial factors as shown in Figure 2-1:

Figure 2-1
Main Commercial Factors



In accordance with the scope criteria set forth in the contract, the business case addresses the main tasks starting with market scenario, market applicability and advantage of concept, and estimated cost of electricity. In addition, a commercialization pathway or roadmap is provided for the DICE technology and power plant starting from a pilot plant to a next-of-a-kind (NoaK) commercial project.

2.3 MARKET SCENARIO

2.3.1 Key Influencing Drivers

Based on the current trends and outlook, the market scenario for coal based power generation varies widely on a regional basis both in the domestic U.S. and internationally. The commercial market dynamics are dependent upon key influencing drivers which may also serve as challenges and barriers which can potentially impact the commercial implementation of a DICE CRCC power project. Table 2-1 provides a listing of the key influencing drivers:

Table 2-1
Key Influencing Drivers

Key Drivers	**Commentary**
Energy Supply, Security, and Independence	In the domestic U.S. and internationally, various coal types are available as an abundant natural resource and on a regional basis. Coal provides highly reliable energy supply, independence, and security wherein the dependency on imported fuels and feedstocks is reduced – *key emphasis is on cleaner and efficient utilization of coal*.
Competing Power Sources	There is potential competition for coal based power generation versus other conventional energy sources such as natural gas. In some regions, coal based power plants remain the lower cost sources of electricity. In other regions, based on the availability of oil and gas resources, natural gas fueled power generation via gas turbine combined cycle (GTCC) is typically more viable due to the availability of lower cost natural gas.
Air Emissions Regulations	Air emissions from coal power plants includes CO, CO_2, NOx, SOx, mercury, particulate matter, and other hazardous air pollutants. Based on the prevailing stricter domestic U.S. and international emissions/environmental regulations, permitting of coal power plants is much more difficult than competing conventional energy sources such as natural gas.
Reducing Carbon Footprint and Energy Transition	There is a global drive towards reducing carbon footprint, de-carbonization, and energy transition through sustainable forms of energy. Accordingly, based on signatories to the Paris Accord, nearly 179 countries have stated their goal to reduce greenhouse gas (GHG) emissions. Countries pledged to reduce CO_2 emissions in the range of 20 to 40 percent from their respective 2012 levels. Currently, the U.S. is not a signatory to the Paris Accord, however, there are multiple states which have enacted state-level energy policies and initiatives toward reducing carbon footprint, de-carbonization, and energy transition. In some states, there are commitments of up to 80 percent reductions by 2040. In these states, coal based power generation is a primary target with respect to reduction carbon footprint and de-carbonization (e.g. coal based power produces nearly double the CO_2 per MWh as compared to natural gas power generation). . In addition, sustainable power sources such as intermittent utility-scale renewable energy (e.g. solar PV and wind) is integrated with large-scale energy storage and increasingly benefitting from state-level government mandates and policy support along with attracting major capital investment.
Project Financing	Initially, for the NoaK commercial DICE CRCC plants, financing will most likely be on a limited recourse basis versus project financing (on a non-recourse basis) - in order to meet lenders “bankability” requirements as well as mitigating technical and commercial risks. Currently, project financing of coal based power plants is more challenging due to the future power market

	which has significant uncertainties (e.g. de-carbonization, stricter air emissions regulations, competing power sources, and power system wide penetration of renewable energy). In addition, larger output coal power plants are currently facing major challenges in securing financing from commercial lenders. Smaller and modular DICE CRCC plants may provide a lower risk profile since they require lower capital investment along with incremental capacity additions to meet baseload demand - *hence have a better opportunity for attracting financing*.

The market scenario leading up to the commercialization of the DICE CRCC power plant addresses the coal type, natural gas price, CO_2 constraint and price, and renewable energy penetration.

2.3.2 **Coal Pricing**

2.3.2.1 Design Fuel

The design fuel for the DICE CRCC power plant is a low-sulfur sub-bituminous Montana Rosebud Powder River Basin (PRB) coal, with an as-received heating value of 8,564 Btu/lb (HHV) or 8,252 Btu/lb (LHV). The coal has an ash content of 11.03 percent by weight (wt%) on a dry basis, and needs to be micronized and de-ashed to an appropriate level in order to protect the moving parts of the DICE unit that are exposed to either the micronized coal-water fuel (which is abrasive), or the solid particulate products of combustion which contain both ash and traces of unburned coal.

2.3.2.2 Physical Beneficiation

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

2.3.2.3 Cost of MRC Fuel

For this study, the design of a modular, on-site coal beneficiation plant for each 100 MW DICE CRCC plant was investigated. However, for such a small, modular power plant such as the DICE CRCC, it makes no economic sense to install a coal beneficiation plant on-site. This is analogous to building a crude oil refinery on-site at every gas station. For the modular DICE CRCC plant to be feasible, there must be multiples of such power plants, each receiving fuel from a centralized coal beneficiation plant, thereby taking advantage of the economies-of-scale benefits that the large central beneficiation plant possesses.

For this study, the equivalent beneficiated coal cost for PRB coal, calculated on a “net-back” basis, was \$14.2 per MMBtu, representing a more than 6-fold increase in coal cost due to the modular, economically disadvantaged coal beneficiation plant. However, based on CSIRO’s research involving Australian coals, it has been suggested that the cost of beneficiated coal is about AUD 6/GJ (USD 4.3/MMBtu). Additionally, coal beneficiation process and component developers have stated aspirational targets at less than \$1.50/MMBtu, based on using waste Eastern coal fines as feedstock, available at virtually no cost.

For the successful commercialization of DICE CRCC, it is of utmost importance that the beneficiated coal price be as low as possible. A market scenario which meets or exceeds CSIRO's $4.3/MMBtu target, and closer to the aspirational targets of $1.50/MMBtu would be imperative for this.

2.3.3 Natural Gas Price

For this Pre-FEED study, a levelized natural gas price of $4.19/GJ or $4.42/MMBtu (HHV) for delivery to the Midwest (reported in 2018 U.S. dollars) was used in the operating cost analysis, which is consistent with that used in the most recent DOE Bituminous Baseline Report (Revision 4, 2019). However, it is noted that current Henry Hub natural gas prices are only about $1.9/MMBtu. Since natural gas is a co-fired feedstock to the DICE CRCC plant, a market scenario leading to successful commercialization of DICE CRCC would be one with low natural gas pricing, along the lines of current Henry Hub prices.

2.3.4 CO_2 Constraint and Price

2.3.4.1 Post-Combustion CO_2 Capture

The DICE CRCC power plant is fully integrated with a post-combustion CO_2 capture (PCC) unit using 30 wt% MEA that ***captures 90 percent*** of the CO_2 in the flue gas. The captured CO_2 meets the purity specifications set forth by DOE for pipeline delivery to saline aquifer sequestration, at a pressure of 2,200 psig at the plant battery limit for delivery to the storage site at 1,200 psig.

When the PCC is in operation, the DICE CRCC power plant has a CO_2 emission rate of 221 lb/MWh-net, far lower than natural gas technologies (~800 lb/MWh-net) without capture. Additionally, it is designed for maximum power generation when the PCC is offline with the addition of a low-pressure (LP) condensing turbine generating an additional 17 MW from steam that is normally routed to the PCC when it is in operation, and the elimination of PCC-associated auxiliary loads of about 10 MW, resulting in a total of 27 MW more power available for export.

2.3.4.2 CO_2 Price and 45Q Tax Credit

Based on the current CO_2 pricing and trends, the U.S. energy-related CO_2 emissions should have decreased by an anticipated 2.0 percent in 2019 and forecast to decrease by 0.9 percent in 2020. Carbon taxes have been suggested to help achieve this reduction. No credit for CO_2 has been taken for the purposes of cost comparisons in this Pre-FEED Study. The Bipartisan Budget Act of 2018 included in the FUTURE Act (**F**urthering carbon capture, **U**tilization, **T**echnology, **U**nderground storage, and **R**educed **E**missions) was intended to extend and reform the 45Q tax credit. Key provisions included an increase in the CO_2 credit value incrementally over ten years from $10 to $35 per metric ton (MT) of CO_2 stored geologically through enhanced oil recovery (EOR), and from $20 to $50 per MT for saline and other forms of geologic storage. In addition, 45Q tax credit provides a $35 per MT for CO_2 captured and put to beneficial uses beyond EOR that reduce lifecycle emissions. Accordingly, the DICE CRCC power plant produces a captured CO_2 product at a purity greater than 95 percent, which currently can be sold in the U.S. market for in the range of $15 to $40 per MT CO_2.

2.3.5 **Renewables Penetration**

2.3.5.1 Major Energy Transition

As highlighted, the domestic U.S. and international commercial power market is undergoing a major energy transition towards more sustainable forms of energy. With emphasis on reducing carbon footprint and de-carbonization, there is increased interest and capital investment in commercialized renewable power technologies (e.g. utility-scale grid interconnected solar photovoltaics (PV), solar thermal, and onshore/offshore wind energy) that are at the center stage. As part of the definitive pathways towards de-carbonization, investors, lenders, market players such as project developers and sponsors, and policymakers are increasingly becoming aware of the need for flexibility in the energy value and supply chain.

2.3.5.2 Market Projections

The Annual Energy Outlook (AEO) 2020 presents an assessment by the U.S. Energy Information Administration (EIA) of the outlook for energy markets through 2050. Based on a high-level overview, the main highlights specifically with respect to electric power generation based on the Reference Case include:

- Power generation mix continues to experience a rapid rate of change with ***penetration of renewables being the fastest-growing source*** of electricity generation
- U.S. electricity load demand grows modestly with primary drivers for new capacity being:
    - Retirements of older and less-efficient conventional energy plants
    - Near-term availability of federal renewable energy tax credits and higher state-level renewables targets
    - Continued decline in the Capex of renewable energy sources, especially solar PV
    - Low natural gas prices and favorable costs for renewables result in natural gas and renewables as the primary sources of new generation capacity through 2050
    - Future generation mix is sensitive to the price of natural gas and growth in electricity demand
- U.S. ***coal*** and commercial nuclear power generation with ***most of the decline occurring by the mid-2020s as a result of plant retirements***

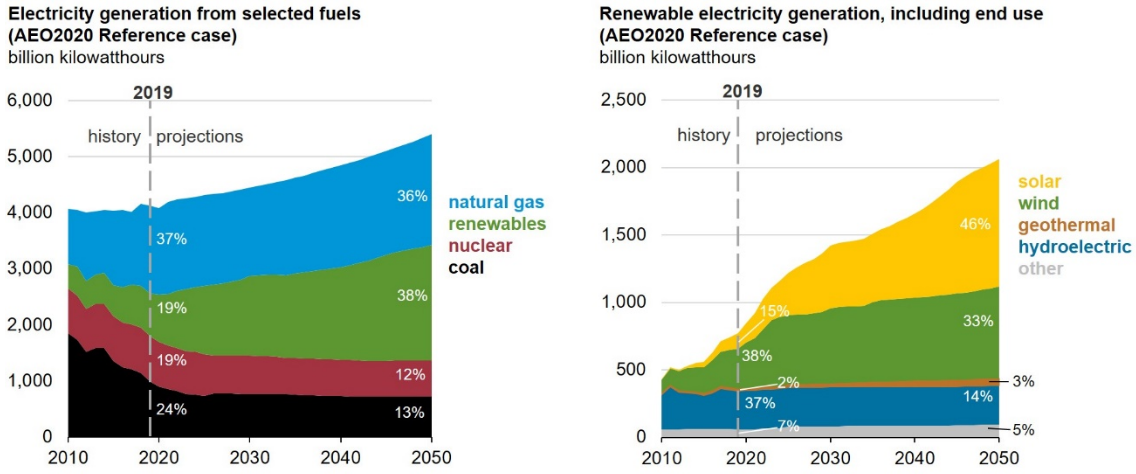
As shown in Figure 2-2, the AEO 2020 projects renewable energy growth from 19 percent (in 2019) to 38 percent (in 2050) of the total installed power generation. Of the total renewable energy growth, solar PV and wind energy market share is 53 percent (in 2019) increasing to 79 percent (in 2050).

Specifically, the share of solar PV is 15 percent (in 2019) increasing to 46 percent (in 2050). Wind energy with 38 percent (in 2019) with slight decrease to 33 percent (in 2050) since new wind capacity additions are at much lower levels after production tax credits (PTCs) expire in the early 2020s.

Installed power generation via coal with 24 percent (in 2019) declining to 13 percent (in 2050). Natural gas power generation is the marginal fuel source to fulfill incremental demand and increases in the later projection years, averaging 0.8 percent growth per year through 2050.

Figure 2-2
Electricity Share from 2019 to 2050

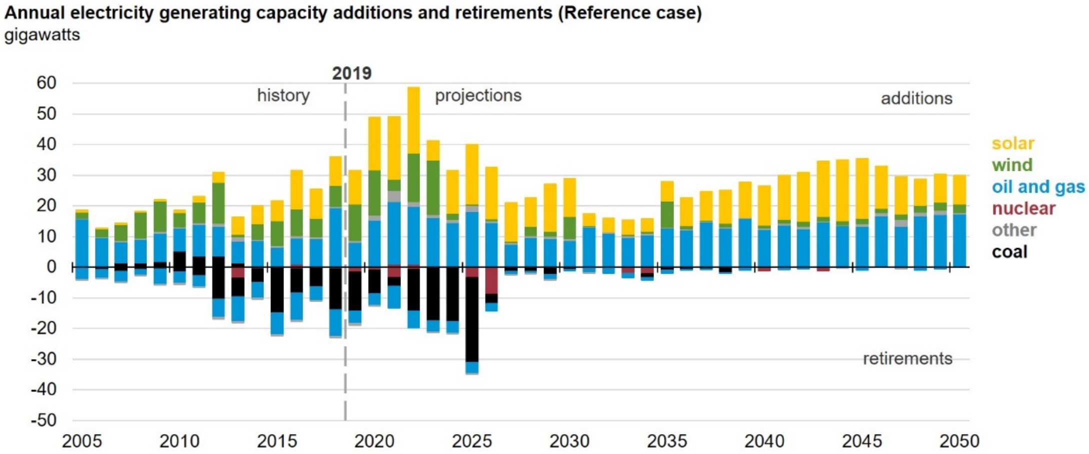
Source: EIA Annual Energy Outlook 2020



As projected in Figure 2-3, the expected requirements for new power generating capacity will be met by both renewable energy sources and natural gas. Coal and commercial nuclear power generation stabilizes over the longer term as the more economically viable plants remain in service.

Figure 2-3
Projections of Expected Retirements and Additions from 2019 to 2050

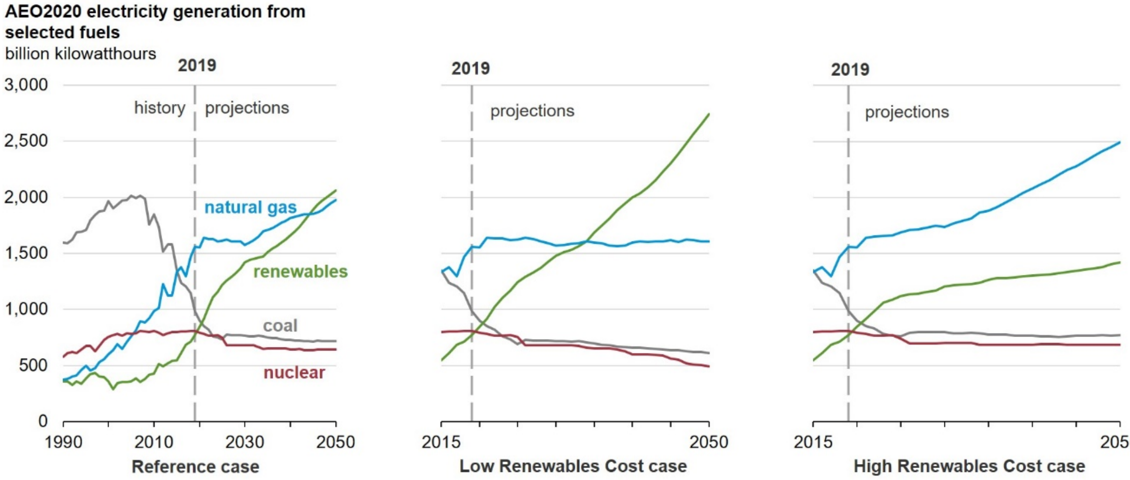
Source: EIA Annual Energy Outlook 2020



As highlighted, power generation from renewable energy and natural gas increases, respectively, as a result of the declining costs of solar PV and wind renewable capacity and lower natural gas prices and, making these power generation sources increasingly competitive. As illustrated in Figure 2-4, the high renewables cost and low renewables cost Sensitivity Cases assume different rates of cost reduction for renewable energy technologies compared with the Reference Case wherein the non-renewables assume the same rates. Changes in cost assumptions for new wind and solar PV projects result in significantly different projected fuel mixes for power generation.

Figure 2-4
Projections of High and Low Renewables Cost Sensitivity Cases from 2019 to 2050

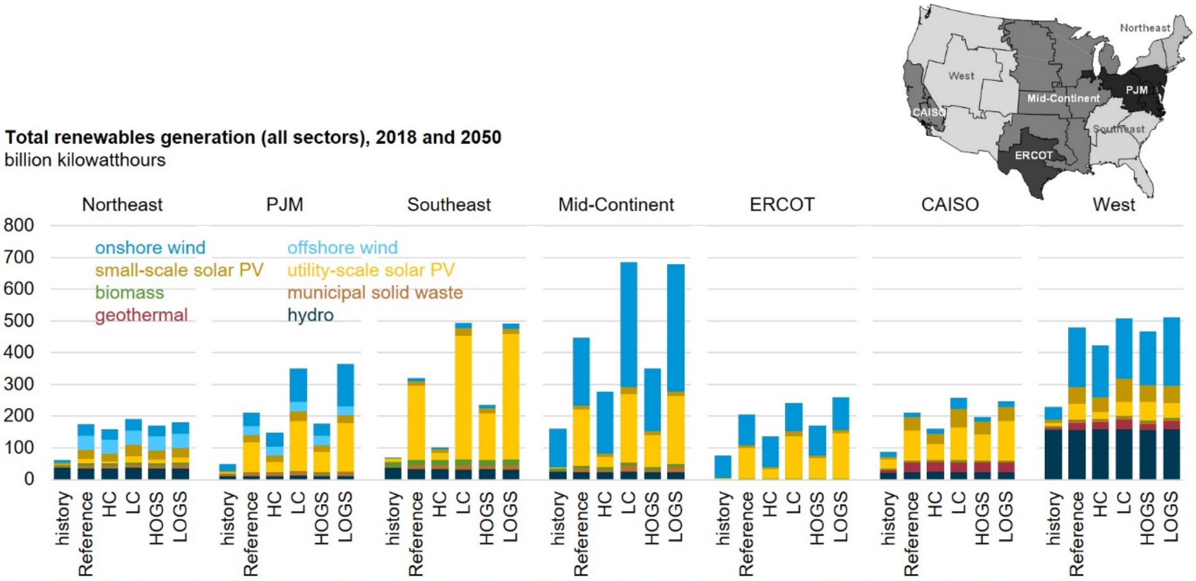
Source: EIA Annual Energy Outlook 2020



As depicted in Figure 2-5, the AEO 2020 shows that in all Reference and Sensitivity Cases, solar PV and wind energy lead the market share and growth in renewable power generation in most regions.

Figure 2-5
Share of Solar PV and Wind Energy in Renewable Energy Growth from 2019 to 2050

Source: EIA Annual Energy Outlook 2020



Note: HC = High Renewables Cost, LC = Low Renewables Cost, HOGS = High Oil and Gas Supply, LOGS = Low Oil and Gas Supply, PV= photovoltaic

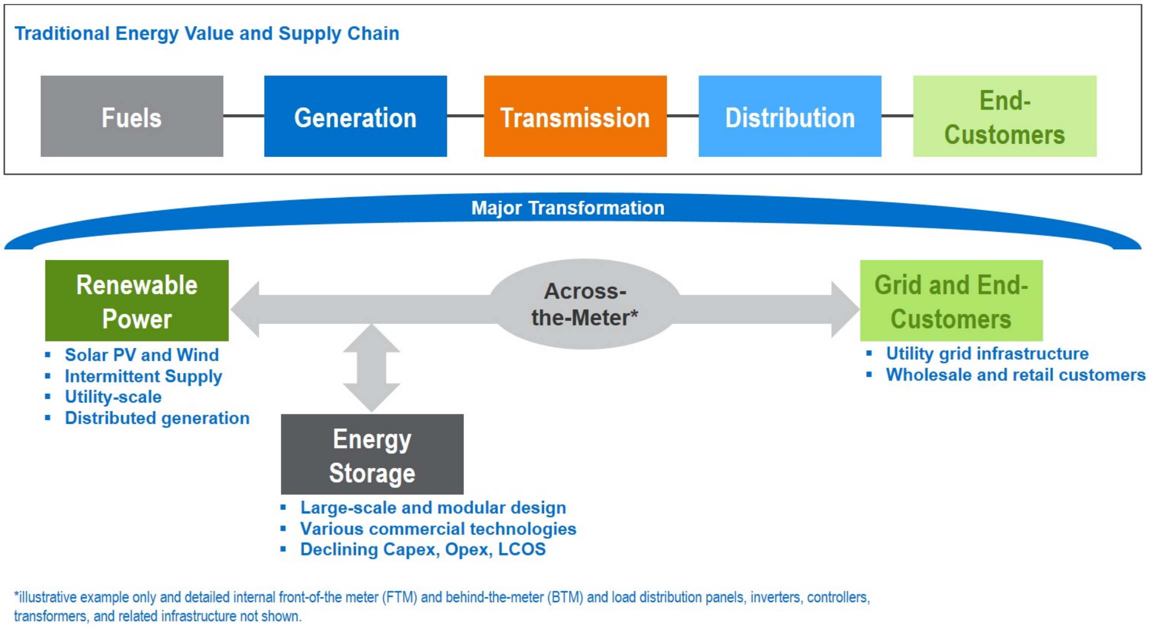
As more renewable energy resources are added, there will ***most likely*** be an additional need for novel, efficient, higher utilization capacity, and viable combustion power generation resources such as the DICE CRCC. A key market driver for DICE CRCC power plants includes providing grid reliability, availability, and maintainability (RAM). In addition, another market driver is ensuring grid resilience when the output of power generation via renewable energy sources is drastically reduced, curtailed, or insufficient.

2.3.5.3 Impact of Intermittency

An important commercial market impact and consideration is the intermittency of the various renewable energy sources and its consequential impact on front-of-the-meter (FTM) applications such as the utility grid. Integration of large-scale energy storage may most likely become the key enabler to the entire renewable power generation value and supply chain – especially solar PV power generation.

As illustrated in Figure 2-6, major electrochemical or battery energy storage system (BESS) capacity additions are expected to be integrated grid system wide with intermittent renewable energy sources in order to increase the dispatchability of utility-scale renewable power sources - *especially in FTM applications*.

Figure 2-6
Intermittent Renewable Energy Integrated with Energy Storage



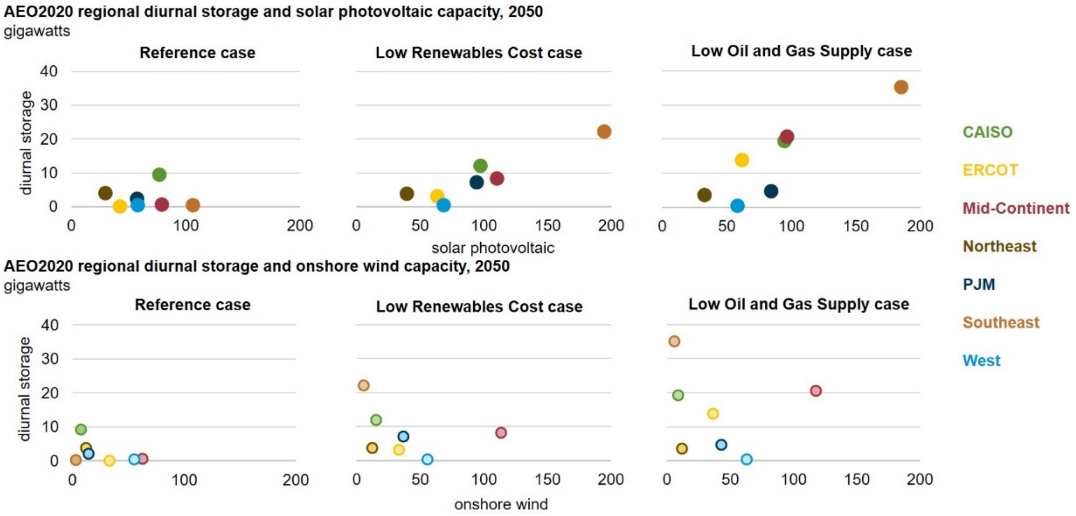
Based on technological innovation and increased commercial market share, large-scale BESS systems' Capex, Opex, and levelized cost of storage (LCOS) continue to decline. Commercial installations have tripled in less than three years, mainly using lithium-ion (Li-Ion) batteries that are primarily aimed at providing short-term energy storage, which presently accounts for nearly 80 percent of all BESS capacity. Besides Li-Ion, current BESS technologies include lead acid, sodium sulfur, sodium nickel chloride, and flow batteries (e.g. vanadium redox, iron, and zinc bromide).

As depicted in Figure 2-7, the AEO 2020 shows that the growth in utility-scale BESS follows the growth in solar PV in most regions in high renewable penetration scenarios.

Figure 2-7

Growth of BESS Follows Solar PV Growth from 2019 to 2050

Source: EIA Annual Energy Outlook 2020



Another important market driver related to the intermittency of renewable energy sources is the mandatory requirement proper utility grid protection which is currently being provided by various dispatchable sources - ***largely comes from conventional or traditional energy sources and corresponding value and supply chains***. In the U.S., some coal power plants, commercial nuclear power, and natural gas GTCC are providing such baseload grid support, requiring them to operate more flexibly in terms of modes of service and duty than they were originally designed for, which is potentially adverse to performance:

- Continuous duty
- Baseload
- Other modes (cycling, peaking, and standby)

Such an operating profile and characteristics may most likely also occur in other regions as the penetration of renewable energy sources grows, thereby impacting the need for baseload fossil power, while putting extra importance on their ability to provide RAM as well as ensuring grid resilience.

The direct impact of commercial renewable sources on the DICE CRCC power plant will most likely be felt in terms of potential fluctuations in power prices and resulting dispatch of the plant. This high-level review does not attempt to predict future power prices, the commercial power market structure, and regulatory framework and policy. However and instead, this review seeks to address the price competitiveness of the DICE CRCC power plant to other dispatchable power plants as discussed in the subsequent section related to estimated cost of electricity. If the DICE CRCC power plant is the lowest marginal cost option for dispatchable power, ***it will be competitive***.

2.3.5.4 Impact of Power Offtake

Power offtake is another commercial market impact and consideration. Most utility-scale renewable power projects operate with offtake under a power purchase agreement (PPA) with the local utility. These PPA contracts, typically on a take-or-pay terms and conditions, are based on competitive market price for the electricity. The LCOE of a given project is the present ***intrinsic*** value of that project's costs, levelized on an annual basis. For most solar PV and wind energy facilities, a project's LCOE closely tracks with the competitive PPA price.

Most project developers have good understanding of the prevailing PPA price in a given commercial market and at the project development stage seek out incentives, concessions from various suppliers, lenders, and local authority to match their baseline LCOE to the prevailing PPA prices. The project's LCOE is the "first order approximation" for that specific project's competitive PPA price. In order to increase the profit margin of the renewable energy facility, project developers always seek alternative methods of increasing revenue streams from power sales by assessing:

- Possible revenue streams based on a straight competitive PPA, versus
- Selling part of the power offtake from the renewable energy project under an ***avoided cost*** basis during winter and summer seasons and during respective peak periods via a levelized avoided cost of electricity (LACE)
- Resulting impact on project financing and rate of return on the capital investment

One most likely avenue available for a renewable project is selling power as a qualifying facility (QF) to the local utility as stipulated under the Public Utility Regulatory Policies Act (PURPA) regulations which was enacted in 1978. Current guidelines from the U.S. Federal Energy Regulatory Commission (FERC) indicate that renewable energy projects can be classified as a QF and sell power to the local grid under an avoided cost of generation basis.

If the DICE CRCC power plant, via its lower marginal LCOE and executed PPA, can demonstrate its price competitiveness to other dispatchable power plants, it can potentially be classified as a viable QF status.

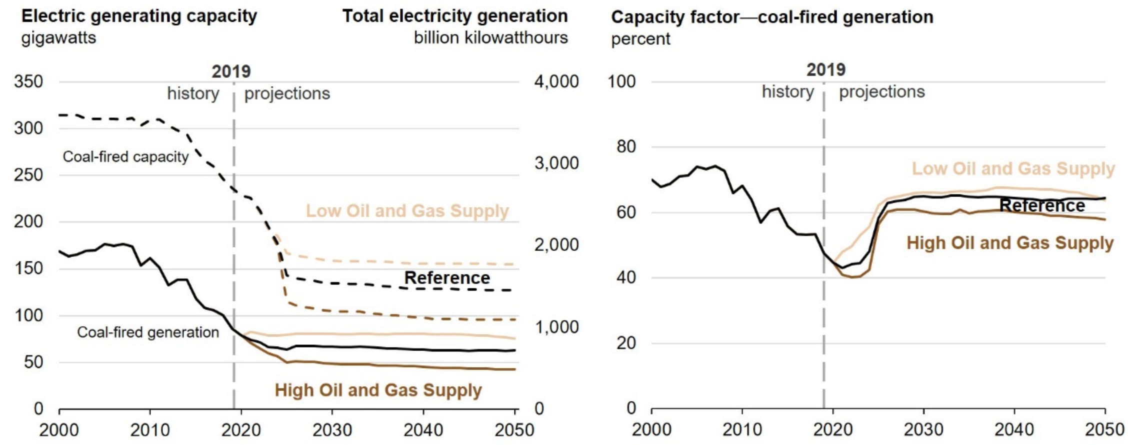
2.3.5.5 Impact of Capacity Retirement and Improved Capacity Factor

As highlighted in the EIA's AEO 2020, coal power generation capacity retires at a faster pace as capacity factors increase for the more efficient coal power plants that remain in service as projected in Figure 2-8. In addition to decreases in installed capacity as a result of competitively priced natural gas and increasing renewables generation, coal power generating capacity decreases by 109 GW (or 46 percent) between 2019 and 2025 to comply with the Affordable Clean Energy (ACE) rule before leveling off near 127 GW by 2050 in the Reference Case.

Figure 2-8

Coal Capacity Retirement and Improved Capacity Factor from 2019 to 2050

Source: EIA Annual Energy Outlook 2020



The average capacity factors for coal power plants improve over time as less-efficient power plants are retired, as heat rates in the remaining coal power generation fleet improve to comply with the ACE rule, and as natural gas prices increase. Between 2019 and 2025, coal power generation decreases by 26 percent in the Reference Case while natural gas prices increase. By 2030, the plant utilization rate of the remaining coal power generation capacity returns to 65 percent, which is slightly less than in the early 2000s. In the high oil and gas supply Sensitivity Case, coal power generation decreases by 42 percent between 2019 and 2025, and lower natural gas prices limit the plant utilization rate of the coal fleet to a capacity factor of about 60 percent in 2030.

In addition, higher natural gas prices in the low oil and gas supply Sensitivity Case slow the pace of coal power plant retirements by about 23 GW through 2025 compared with the Reference Case. The low oil and gas supply Sensitivity Case has 155 GW of coal power generation capacity still in service in 2050. Conversely, lower natural gas prices in the high oil and gas supply Sensitivity Case increase coal power plant retirements by 28 GW in 2025, and 96 GW of remaining coal power plant capacity remains by 2050.

In order to reasonably compare the design of the DICE CRCC power plant with the benchmark DOE reference coal plant, this unit cost of electricity (COE) evaluation assumes a similar baseload plant with an ***overall capacity factor of 85 percent***. The part load operation with the penetration of renewable energy sources is addressed in detail in the Performance Results Report Volume of this report. As highlighted, the DICE CRCC power plant ***will be competitive*** if it is the lowest marginal cost option for dispatchable power.

2.4 MARKET APPLICABILITY & ADVANTAGE OF CONCEPT

2.4.1 Domestic U.S.

In recent years, new coal power generation capacity additions have been drastically stagnating in the U.S. where coal is often non-competitive with offshore and onshore conventional as well as unconventional (shale) natural gas. In addition, coal power generation presents significant emissions, health, and related environmental risks. There are very few known greenfield coal power projects which are advancing in the U.S. and some major energy utilities have definitively pledged to eliminate coal power plants from their entire portfolio of power generation assets under operations and management.

However, based on this Pre-FEED study, it is believed that the DICE CRCC power plants can have a higher degree of success in the domestic U.S. market due to the modularity of the DICE CRCC technology, lower capital investment capital required as compared to large coal plants, incremental capacity additions to meet power market demand, relative abundance of coal in some regions and coupled with lower natural gas prices, thus minimizing its feedstock costs. Table 2-2 provides a high-level overview of the main market factors required for a significant resurgence in new coal power projects.

Table 2-2
Factors for Resurgence in U.S. of New Coal Power Projects

Factors	Commentary
Increase in price of LNG/natural gas	While the increase in the price of natural gas as compared to coal has not been forecasted, there is a potential especially as the international demand for LNG/natural gas grows.
Increasing value of CO_2 via regulation or carbon capture and utilization	Subject to the development of a major domestic U.S. market for CO_2, this scenario could potentially drive new coal power projects with carbon capture and storage (CCS). Also, EOR continues to be the primary form of utilization and targeting this market can most likely be a necessity for any new coal power projects along with CCS in the short-term. Major governmental sponsored programs such as 45Q tax credits can also provide a value for captured CO_2, which in turn benefits the overall project economics. As an incentive, the value of capturing CO_2 must be greater than the commodity cost, which is not the case in most circumstances. Accordingly, the value of CO_2 must increase (e.g. via regulation or utilization) and/or the cost must decrease for coal power projects with CCS to be economically viable.
Impact of Regulatory Framework and Policy	There is considerable uncertainty in future regulatory framework and policy which increases the risk profile of undertaking the project development and project financing of coal power plants - power generators, equity investors, lenders along with insurers are highly risk adverse to develop and execute such projects. Recent revisions to the Clean Air Act section 111(b) have been proposed to alter the definition of best system of emissions reduction for new coal power plants to the most efficient demonstrated steam cycle in combination with best operating practices, instead of requiring partial CCS as was the case in the previous version of the Clean Air Act. Enactment of effective regulatory framework, policy, and directives favoring coal power plants is key to providing both developer's, investors, lenders, and insurers comfort and adding certainty around the low-carbon future - *which is important for growth in coal power.*

2.4.2 International

There are countries with relatively lower cost coal but higher domestic natural gas prices (e.g. China, India, and Australia) which may also find the DICE CRCC power plants and configuration appealing as the bulk of the fuel consumed is the lower cost coal, while the higher efficiency of the system offsets the cost of co-firing more expensive natural gas. Given the fuel flexibility of the DICE unit and its ability to use diesel as a feedstock, it is also applicable in the international market where crude oil prices are lower, such as in the Middle East.

In the various countries and regions, smaller, modular, and efficient DICE CRCC power plants utilizing coal will most likely be attractive for undertaking project development, execution, and operations. The utilization of CO_2 for either EOR and/or enhanced gas recovery are also growing potential opportunities. The market demand for coal power plants internationally varies by both country and region. Table 2-3 provides a high-level overview of the potential for international coal power projects.

Table 2-3
Potential for International Coal Power Projects

Country or Region	Commentary
China	China continues to be the largest coal producer as well as the largest consumer in the world. Coal accounts for nearly 70 percent of its total energy consumption. China forecasts coal capacity growth of approximately 19 percent over the next five years, during this timeframe there is a potential for declining electricity demand. Thus, many coal power plants have been operating at reduced capacity factors. Based on declining demand and growing emissions, health, and environmental concerns, the Chinese government has announced it may likely postpone building some coal power plants that have received prior approval and curtail construction of other projects. There are large coal supply resources in China and there is continuing demand for greenfield power plant capacity primarily in western China.
India	India has very large domestic coal reserves. The ash content of Indian coal produced is in the range of 25 to 45 percent whereas average ash content of imported coal varies from 10 to 20 percent. Indian coal has comparatively higher ash content than imported coal due to drift theory of formation of coal deposits in India. In recent years, India had the largest growth in coal utilization of any country. India's draft National Electricity Plan forecasts that the 50 GW of coal power generation capacity in construction is sufficient to meet the domestic power demand for the next decade, but there is a potential for new coal power plant capacity additions. Most new coal power plants proposed are state-of-the-art pulverized coal (PC) or circulating fluidized-bed (CFB) supercritical units as India has imposed a carbon tax on coal, which is about $6.25 per MT of CO_2 which requires efficiency as a key parameter in the region. India continues to seek and locate viable reservoirs for CCS.
Japan	Japan had over 44 GW of coal power plants in operation in 2018, with more than 6 GW additional capacity either permitted or in construction. Japan's climate change pledge is to reduce GHG emissions by 26 percent from 2013 levels by 2030. Accordingly, improving efficiency and potentially performing CCS are important market drivers in Japan. In addition, Japan

	is keen on promoting novel coal power cycles which have a smaller physical footprint due to space limitation.
South Korea	Coal power generation market share is more than 40 percent of South Korea's power mix. South Korea continues to have plans for additional coal power generation, despite having a climate change pledge of nearly 30 percent reduction in GHG emissions by 2030. South Korea's 8th Basic Plan for Electricity Supply and Demand (8th BPE) has a target of 35 percent of coal power in the generation mix before 2030. Regardless, South Korea is planning to add a net 5GW of new coal power generation capacity by 2022. There is also strong interest in oxy-combustion, and the country is investing in several technologies, including pressurized oxy-combustion (South Korea has previously invested in the DOE's STEP program).
Europe	Based on the Paris Accord, in the region of western Europe, there are several countries which announced plans to end coal power generation within their borders or establish emissions reductions targets that would effectively require an end to coal power generation without CCS. Countries include France by 2023, United Kingdom and Austria by 2025, Netherlands by 2030, and Germany by 2050. This makes new coal power generation very difficult to operate in the region. In eastern Europe, there is a higher potential for new coal power generation as "brown" coal resources are abundant and lower cost. Efficiency and cleanliness will be key market drivers in this region. CCS may be a challenge, however, as underground storage is not popular, although Norway is developing a potential sink for CO_2 in the North Sea.
Others	There is increased utilization of coal in some regions in Africa (e.g., Kenya and Zimbabwe) and Southeast Asia (e.g., Indonesia and Vietnam), which presents major growth opportunities, although low-cost coal power generation will be critical in these areas. Smaller-scale plants will be a definite market advantage.

2.4.3 Advantage of Concept

As discussed in the market scenario, traditional coal power plants were typically designed for baseload mode of service and duty, and always-on or "must-run" operation. However, in the past decade, the penetration of utility-scale renewable energy sources has increased due declining costs, federal tax credits, state-level mandates. In addition, natural gas power generation has displaced coal power plants while providing greater flexibility in different modes of service and duty ranging from baseload, peaking, cycling, and standby.

As the commercial market matures in domestic U.S. and/or internationally, intermittent renewable energy sources may be less reliable, available, and maintainable than combustion based DICE CRCC power plants. As renewables become more cost-effective and a larger part of the generation mix, as previously highlighted, additional cycling requirements are being imposed on historically baseload coal power units and natural gas power generation - ***this was not originally anticipated when the coal power plants were designed and built***. Energy utilities currently meet the expected grid load demand by using a "day-ahead" projections of electrical load demand to develop a power generation resource stack. The resource stacks start with the lowest marginal cost option for dispatchable power and add brownfield and greenfield power generation resources until the demand is properly met. As more, non-dispatchable renewables are added to the total power generation portfolio, energy utilities must respond by adjusting the commitments to combustion based power generating resources. This key requirement requires coal power plants such as DICE CRCC to effectively transition from baseload operation to frequent cycling at certain times of the year. The DICE CRCC power plant is well suited for certain specific markets with unique attributes and features, such as those with:

- Smaller capacity utility grid(s) unable to accommodate large capacity power plants
- Modular design enabling "building block" methodology for incremental capital investment and capacity additions to match utility grid demand loads – baseload, peaking, and cycling duty and service
- Utilization of standard "off-the-shelf" components, equipment, and systems – minimizing requirements for basic and advanced R&D as well as demonstration
- Requirement for fast ramp rates and ability to operate at capacity factors as low as 30 percent
- High natural gas price (more than $10 to $12 per million BTU)
- Ability to use diesel fuel (places where gas supply is subject to uncertainty)
- High ambient temperature and humidity
- High-altitude installations
- Various combinations of the above

2.5 COMMERCIALIZATION PATHWAY

2.5.1 Overview

Coal based power generation technologies, existing assets, and greenfield projects ***face a challenging future*** given the uncertainty in the regulatory framework and policy area as well as environmental constraints (emissions and carbon capture), low natural gas prices, and declining cost of renewable energy resources. Given these ***commercial market realities***, the most applicable, relevant, cost effective, and commercially viable application for the DICE CRCC power plants will most likely be:

- Smaller, modular, and efficient design providing incremental capacity additions to meet displaced coal power capacity due to the retirement of existing coal power generation facilities

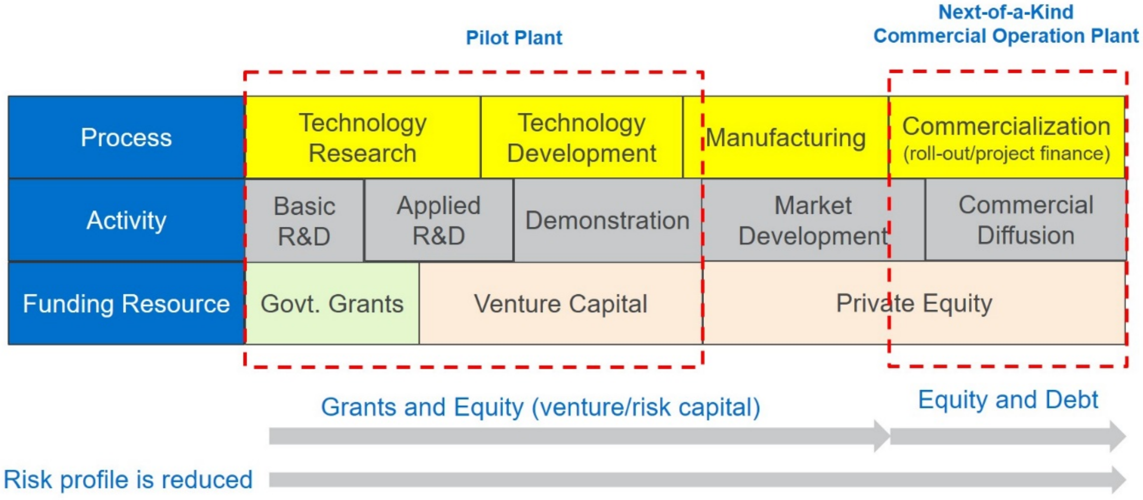
- Providing grid stability and resilience by operating at various capacity factors in baseload, peaking, and cycling service and duty

2.5.2 Two-Phased Approach

From the commercial project development and project financing perspective, it is most likely that an energy utility or a project developer would initiate the development, execution, and operations of the DICE CRCC power plant at a greenfield site in a two-phased approach and manner – ***initially with a pilot plant and later followed by a NoaK commercial plant***

For the pilot phase for the DICE CRCC power plant, the key technology investing stages and funding gaps cover basic R&D, applied R&D, and demonstration activities. In addition, for the NoaK phase for the commercial operation plant, key stages include market development and commercial diffusion which are directed towards roll-out and project financing. The traditional funding and investment stages of progression of energy technology and investments includes the development processes, various activities, and funding resources as shown in Figure 2-9.

Figure 2-9
Process, Activity, and Funding of Pilot Plant and NoaK Plant

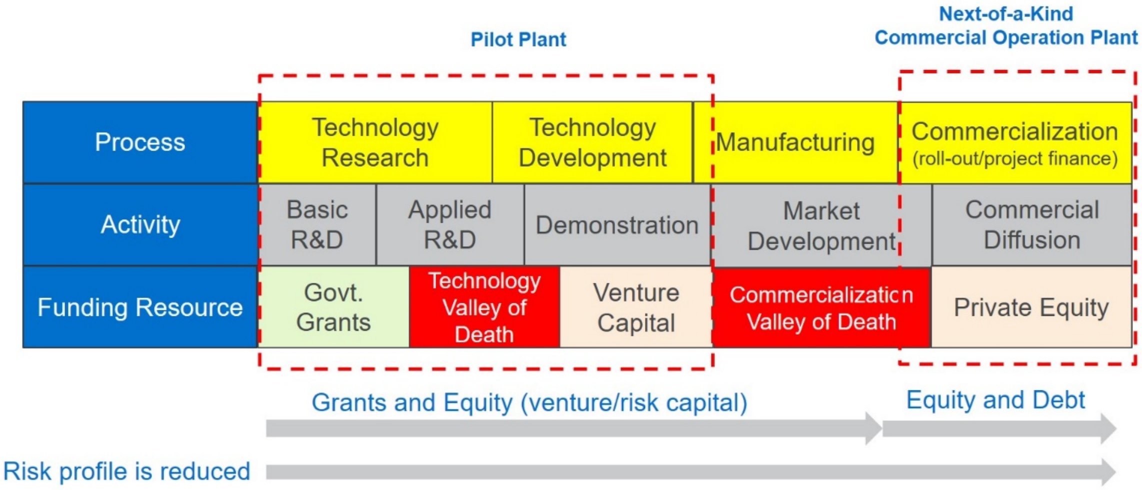


The key funding and financing assumptions and drivers for the DICE CRCC power plant (pilot plant and NoaK commercial plant) include TRL, funding via equity and grants, financing via debt, fiscal and financial incentives, and transactional contracts:

- TRL of 5 to 6 assumes the pilot project will be in a pre-demonstration phase and beyond bench-scale unit. TRL of 9 for NoaK plant assumes advanced commercialization of the technology and market ready for commercial deployment
- Pilot plant will attract grants and equity only. The grants (e.g. R&D grants and project grants) will be required for the pilot plant since the DICE CRCC technology is assumed to be in a pre-commercial stage (from the viewpoint of equity investors and commercial lenders)
- NoaK plant is funded by equity and financed by debt. Grants are not applicable for the NoaK plant which is an advanced commercialized stage
- With respect to fiscal and financial incentives, at the federal and/or state level as applicable, the pilot plant can attract subsidies via additional grants, income tax credits (ITCs), accelerated depreciation, and carbon credits for CO_2
- NoaK plant can attract at the federal and/or state level, as applicable, loan guarantees, income tax credits (ITCs), accelerated depreciation, and carbon credits for CO_2
- The requirement of transactional contracts for the pilot plant includes, but not limited to, technology license agreement (if required), and EPC and O&M contract. In addition, to provide comfort to equity investors and grantors, the EPC contract must consider a “wrap” to cover warranties and guarantees
- The requirement for transactional contracts for the NoaK plant are discussed in the subsequent subsection entitled “Structuring Financing for NoaK Plant”

As shown in Figure 2-10, as part of the effective implementation of the two-phased approach, any technology investing and funding gaps must be avoided for the pilot phase as well as the pre-commercialization stages in order for success of the DICE CRCC power plant.

Figure 2-10
Avoiding Technology Investing and Funding Gaps

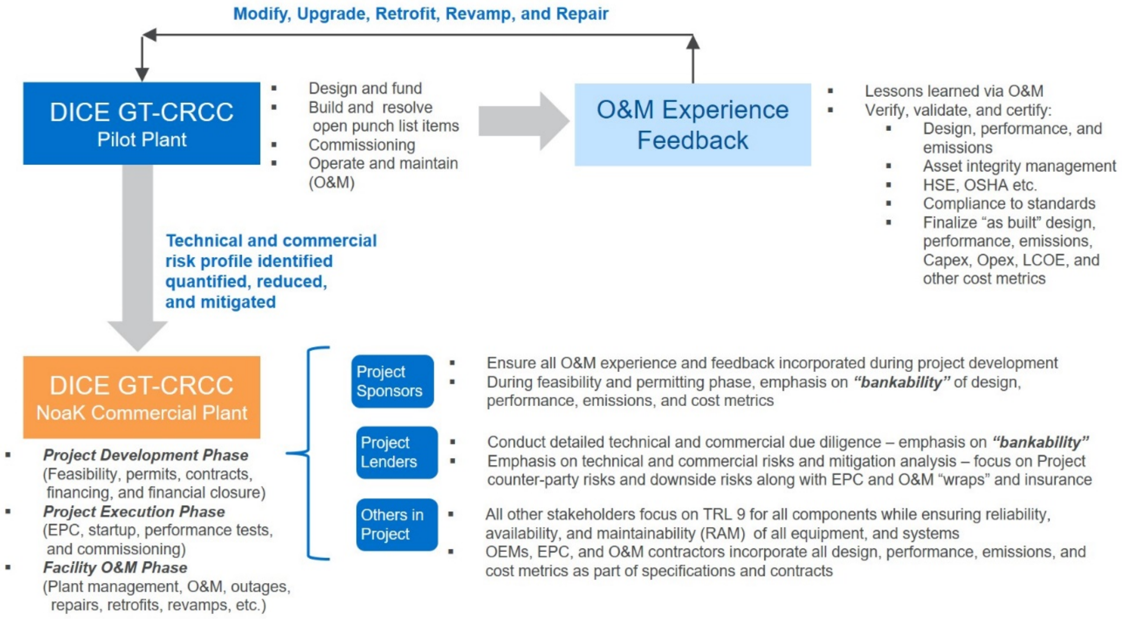


It is important to overcome any potential funding gaps which may arise for the pilot phase during the applied R&D phase and post-demonstration phase (prior to advanced commercialization). Typically, the "debt-equity gap" for capital requirements for commercializing energy technologies is beyond the risk tolerance and timelines of most existing debt and equity markets.

2.5.3 Transitioning between Two Phases

Once the pilot plant has been developed, executed, and in operations, definitive O&M experience feedback from the pilot phase for the DICE CRCC power plant can identify, quantify, and mitigate risks for implementing the NoAK commercial plant. As depicted in Figure 2-11, with lessons learned from O&M experience, the required modifications, upgrades, retrofits, revamps, and repairs can be undertaken to ensure the definitive transitioning from the pilot plant to the NoaK commercial operation plant.

Figure 2-11
Transitioning from Pilot Plant to NoaK Plant



- Design and fund
- Build and resolve open punch list items
- Commissioning
- Operate and maintain (O&M)

- Lessons learned via O&M
- Verify, validate, and certify:
  - Design, performance, and emissions
  - Asset integrity management
  - HSE, OSHA etc.
  - Compliance to standards
  - Finalize "as built" design, performance, emissions, Capex, Opex, LCOE, and other cost metrics

- ***Project Development Phase*** (Feasibility, permits, contracts, financing, and financial closure)
- ***Project Execution Phase*** (EPC, startup, performance tests, and commissioning)
- ***Facility O&M Phase*** (Plant management, O&M, outages, repairs, retrofits, revamps, etc.)

- Ensure all O&M experience and feedback incorporated during project development
- During feasibility and permitting phase, emphasis on ***"bankability"*** of design, performance, emissions, and cost metrics

- Conduct detailed technical and commercial due diligence – emphasis on ***"bankability"***
- Emphasis on technical and commercial risks and mitigation analysis – focus on Project counter-party risks and downside risks along with EPC and O&M "wraps" and insurance

- All other stakeholders focus on TRL 9 for all components while ensuring reliability, availability, and maintainability (RAM) of all equipment, and systems
- OEMs, EPC, and O&M contractors incorporate all design, performance, emissions, and cost metrics as part of specifications and contracts

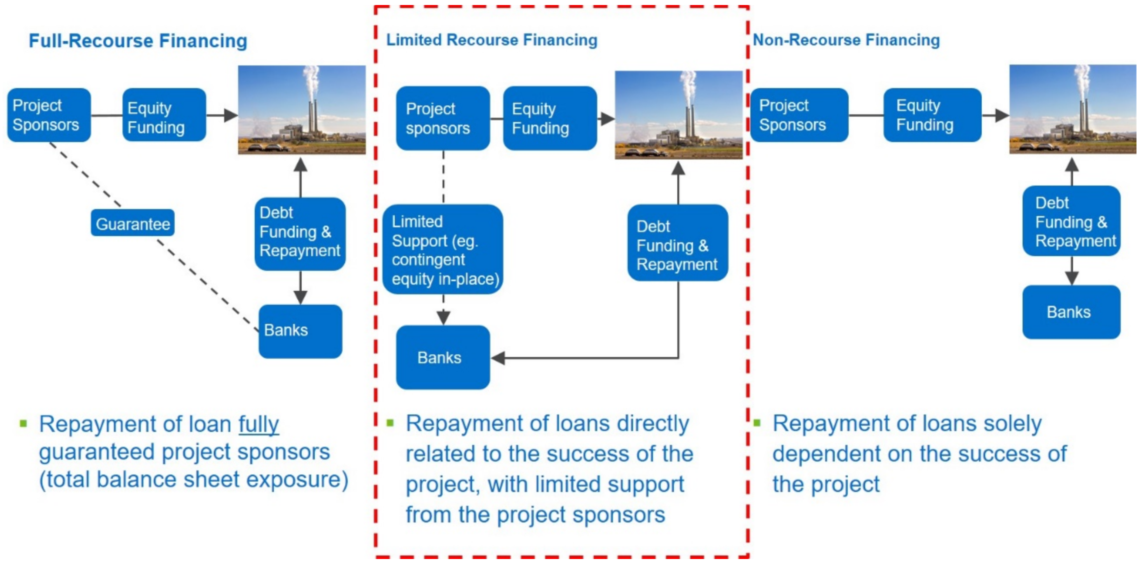
During the transitioning, the technical and commercial risk profile is identified, quantified, reduced, and mitigated. In addition, with the main emphasis on ***"bankability"***, key inputs are provided by the project sponsors, lenders, and other stakeholders in the DICE CRCC power plant project.

2.5.4 Structuring Financing for NoaK Plant

Typically, there are three (3) types of commercial financing available, namely, full-recourse, limited recourse, and non-recourse as shown in Figure 2-12. The structuring of the NoaK commercial operation plant would most likely attract limited recourse financing initially for the first 1 to 3 plants. For fully syndicating the limited recourse debt, lenders will most likely require the NoaK project assets be mortgaged, hypothecated, or collateralized. Thereafter, based on lenders' comfort, the next generation of DICE CRCC power plants can attract non-recourse financing wherein the project's earnings before interest, taxes, depreciation, and amortization (EBITDA) along with cash flows provide the required debt service coverage (DSC) over entire duration of repayment of loans while supported by ***"bankable"*** offtake agreements.

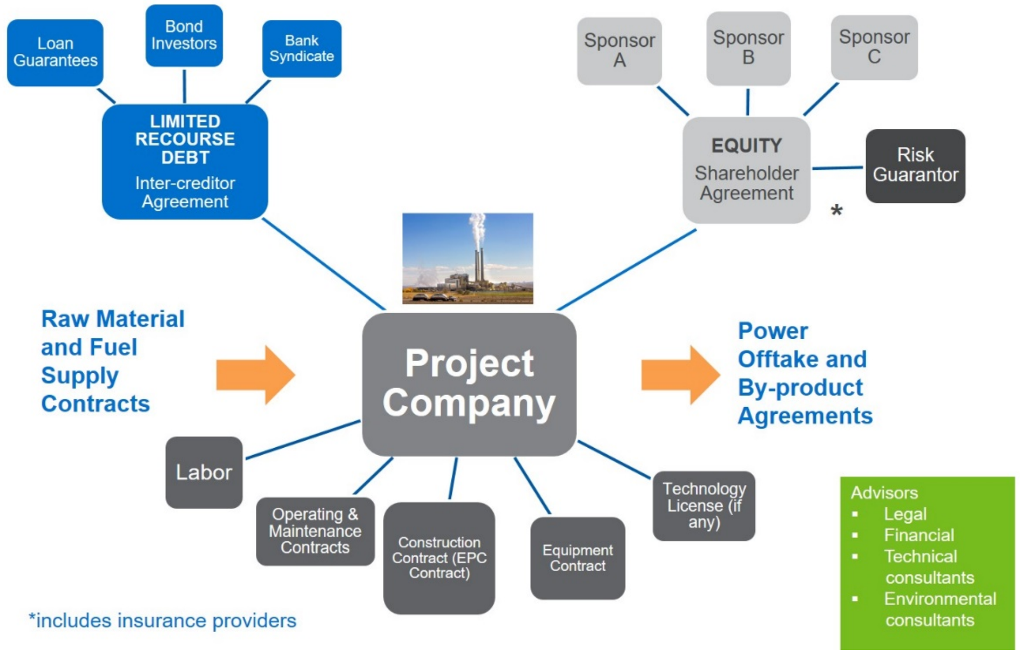
The typical Debt-to-Equity Ratio (DER) for the NoaK plant can typically range from 60:40 (or 1.5:1) to 70:30 (or 2.33:1). The lower DER is for first 1 to 3 plants and may vary depending on lenders risk profile and appetite.

Figure 2-12
Most Likely Scenario via Limited Recourse Financing



As illustrated in Figure 2-13, the limited recourse financing structure for the NoaK commercial operation plant will consist of a special purpose project company (SPPC) with key stakeholders covering debt, equity, insurance companies, risk guarantors, EPC and O&M contractors along with execution of ***"bankable"*** transactional contracts.

Figure 2-13
Limited Recourse Financing of Project Company



The limited recourse financing structure requires that the equity investment is made, possibly via escrow accounts, into the SPPC specifically set-up for the project development, execution, and operations of the DICE CRCC power plant project. The equity funding sources will execute shareholder agreements with the SPPC. The lenders for senior debt, subordinated debt, and working capital will execute respective loan agreements with the SPPC and debt drawl will occur, possibly via escrow accounts, in to the SPPC.

For subscribing equity and syndicating debt, both equity investors and lenders, respectively, will require detailed economic modeling and financial proforma analysis which can include, but not limited to, determining Capex, Opex, Total Installed Cost, LCOE, power tariffs for executing PPA, electricity merit-order dispatch scenarios, LACE for a securing a QF status, lifecycle assessment (LCA), insurance costs, and working capital margin. In addition, all financial projections over the economic life along with financial profitability indicators such payback period, internal rate of return (IRR), rate of return on equity (RROE), net present value (NPV), and debt service coverage ratio (DSCR). Based on the lenders debt financing norms, a sensitivity and scenario analysis must be conducted with respect to potential schedule delays, cost overruns, and changes in interest rates – *results showing variants and impact on IRR, RROE, DSCR, and payback period*.

The requirements for transactional contracts include, but not limited to, the DICE CRCC technology license agreement (if required), EPC and O&M contracts, fuel supply agreement (FSA), PPA, and agreement for purchase of carbon credits for CO_2. For the first 1 to 3 plants, the EPC contract must consider a "wrap" to cover warranties and guarantees. The O&M contact must consider a long-term service agreement (LTSA). In addition, all transactional contracts and agreements must be ***"bankable"*** with provisions for back-to-back arrangements to mitigate counterparty risks and downside risks.

2.5.5 Capital Structure

To illustrate the most likely structuring of the required financing for the NoaK commercial operation plant, a high-level example of a capital structure is provided in Table 2-4.

Table 2-4
Example of Capital Structure for NoaK Plant

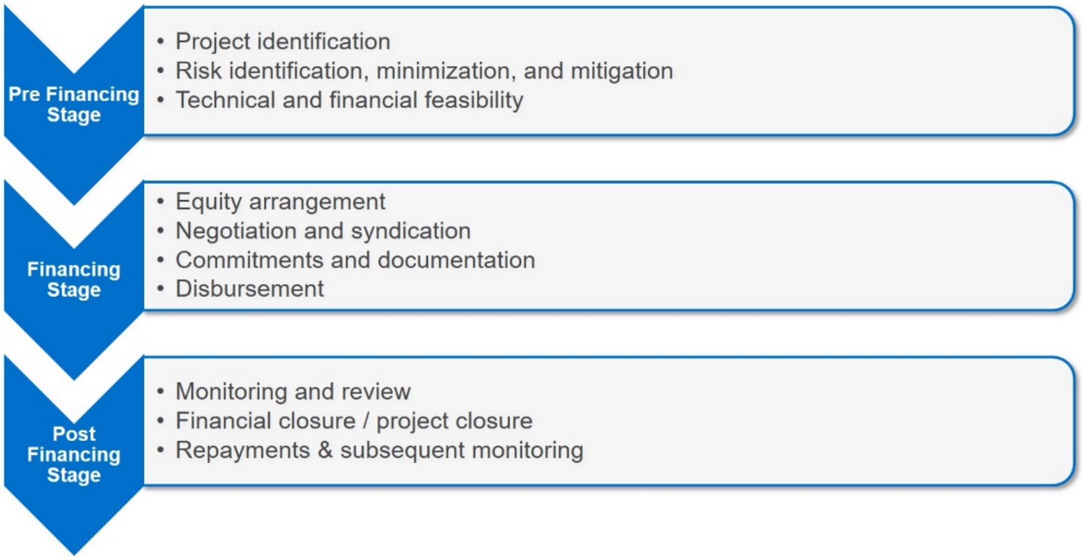
Key Metric	Data and Information
Basis of Key Assumptions	Cost Report dated February 15, 2020
Project Capacity	78 MW
Total Overnight Cost (TOC)	$525 million
Debt to Equity Ratio	60:40 or 1.5:1
Debt	▪ $315 million ▪ Senior, subordinated debt, and working capital ▪ Sources include U.S. Government loan guarantee and lenders (financial institutions, investment banks, and commercial banks)
Equity	▪ $210 million ▪ Common, preferred stock, and possible convertible debt along with warrants and options

	▪ Sources include project sponsors, developers, private equity (PE) firms, OEMs, EPC and O&M contractors
Grants	None assumed since NoaK is a commercial operation plant

2.5.6 Financing Stages

Based on the current financing norms, the three main stages for the NoaK plant covers pre-financing, financing, and post-financing including and up to financial closure. Figure 2-14 provides an overview.

Figure 2-14
Three Main Stages of Financing



2.5.7 Categories of Risks

As part of equity investors' and lenders' technical and commercial due diligence during the three stages of financing, a key emphasis is to identify, minimize, and mitigate project risks, external risks, and financing risks.

The potential risks associated with the financing of the DICE CRCC power plant can be divided into 3 key categories which must be evaluated during the aforementioned 3 main financing stages in order to satisfy and meet both equity investors' and lenders' comfort. Figure 2-14 provides a summary and highlights the 3 key categories of risks.

Figure 2-15
Three Key Categories of Risks

Project Risks

- Site Selection
- Permitting
- Construction and Completion
- Cost Overruns
- Technology
- Operating
- Sponsor/Developer

External Risks

- Environmental
- Infrastructure
- Political and Regulatory Framework, Policy, and Directives
- Inflation
- Demand and Market

Financing Risks

- Floating Interest Rates (currently very low)
- FX Rate on imported technology and equipment

2.5.8 Other Pre-Financing and Regulatory Requirements

2.5.8.1 Overview

As highlighted in Section 2.3.5.3, 2.3.5.4, and 2.3.5.5, the modular and higher efficiency DICE CRCC, via a NoaK commercial operation power plant, has the potential to meet growing electricity market demand for continuous duty, baseload, cycling, and other modes of service due to:

- Retiring of existing (older and inefficient) coal power plant capacity
- Intermittency of renewable resources
- Meeting mandatory requirement of proper baseload utility grid protection and support
- Providing critically required RAM while ensuring grid resilience

Typically, as part of either limited recourse financing or non-recourse/project financing, lenders and underwriters will require an independent electricity market assessment from the project sponsors and owners which includes a "merit order" dispatch ranking and priority analysis. In principle, the purpose of a merit order dispatch ranking and priority is to enable the lowest net cost electricity power generator to be dispatched first thus minimizing overall electricity system costs to wholesale and retail end-customers.

2.5.8.2 Continuous Duty and Baseload

In general practice, for all continuous duty and baseload power plants in a particular utility grid region which have executed a PPA and/or received a QF status, the approach and methodology utilized includes:

- Determining total power tariff (on two-part basis) via variable/energy cost ***plus*** fixed/capacity cost ***minus*** fiscal incentives (e.g. CO_2 credits)

- Ranking of all power plants solely on the basis of variable/energy cost ***minus*** fiscal incentives

- Based on the prevailing regulatory criteria, guidelines and directives of the State Public Utility Commissions (PUCs) and subject to the utility system grid demand response (DR) scenario, the power plant with the lowest variable/energy cost (***minus*** fiscal incentives) dispatches first, followed by the next highest, the next highest, and so on as part of the permitting and licensing process

Accordingly, the independent electricity market assessment verifies and validates the ***dispatchability*** of the NoaK DICE-GT CRCC commercial operation power plant (in continuous duty and baseload mode) while meeting the State PUCs regulations as well as lenders and underwriters financing requirements.

2.5.8.3 Peaking and Other Modes

For meeting peaking load demand and other grid duty and service, a similar merit order dispatch ranking and priority assessment is required to be carried out for power plants which have executed a PPA and/or received a QF status, and the approach and methodology utilized includes:

- Conventional power generation (e.g. DICE-GT CRCC, commercial nuclear, natural gas GTCC, etc.) on the basis of determining total power tariff (on two-part basis) via variable/energy cost ***plus*** fixed/capacity cost ***minus*** fiscal incentives (e.g. CO_2 credits)

- Intermittent renewable power generation (e.g. solar PV) on the basis of total power tariff (on two-part basis) ***minus*** fiscal incentives (e.g. CO_2 credits) ***plus*** Levelized Cost of Storage (LCOS) for integrated battery energy storage as applicable

- Based on each State's Clean Energy Plan, various PUCs have their own specific prevailing regulatory criteria, guidelines and directives which are subject to the utility system grid demand response (DR) scenario, energy efficiency, and demand side management (DSM)

- Depending on the specific State PUC, a merit order dispatch ranking and priority has to be determined and met as part of the permitting and licensing process

Accordingly, the independent electricity market assessment verifies and validates the ***dispatchability*** of the NoaK DICE CRCC commercial operation power plant (in peaking and other modes) while meeting the State PUCs regulations as well as lenders and underwriters financing requirements.

2.6 CONCLUSIONS

The business case covers a market scenario leading up to the commercialization of the DICE CRCC power plant. The main focus was on a commercial market driven scenario that is projected to be a candidate for the commercial implementation of DICE CRCC power plants. The business case addresses four main commercial factors covering market scenario, market applicability and advantage of concept, estimated cost of electricity, and commercialization pathway or roadmap for the DICE CRCC technology and power plant starting from a pilot plant to a NoaK commercial project.

Based on the current trends and outlook, the market scenario for coal based power generation varies widely on a regional basis both in the domestic U.S. and internationally. The commercial market dynamics are dependent upon key influencing drivers which may also serve as challenges and barriers which can potentially impact the commercial implementation of a DICE CRCC power project. These include energy supply, security, and independence, competing power sources, air emissions regulations, reducing carbon footprint, de-carbonization, and energy transition, and project financing. The market scenario leading up to the commercialization of the DICE CRCC power plant addresses the coal type, natural gas price along with a sensitivity analysis, CO_2 constraint of 90 percent and the current market price, and renewable energy penetration based on the EIA's Annual Energy Outlook 2020.

The market applicability in domestic U.S. is dependent upon key factors for the resurgence of new coal power projects which includes increase in price of LNG/natural gas, increasing value of CO_2 via regulation or carbon capture and utilization, and the impact of regulatory framework and policy. The market applicability internationally indicates countries with relatively lower cost coal but higher domestic natural gas prices (e.g. China, India, and Australia) which may also find the DICE CRCC power plants and configuration appealing. In the various countries and regions (e.g. Japan, South Korea, and Europe), smaller, modular, and efficient DICE CRCC power plants utilizing coal will most likely be attractive. The utilization of CO_2 for either EOR and/or enhanced gas recovery are also growing potential opportunities.

The market advantage of concept demonstrate that the DICE CRCC power plant is well suited for certain specific markets with unique attributes and features, such as those with smaller capacity utility grid(s) unable to accommodate large capacity power plants, modular design enabling "building block" methodology for incremental capital investment and capacity additions to match utility grid demand loads, higher efficiency and ability to operate at range of capacity factors, high natural gas price, the ability to use diesel fuel, high ambient temperature and humidity, and high altitude installations.

Based on the overall performance, total as-spent capital cost (TPC), and annual operating cost of the 100 MWe DICE CRCC plant, its LCOE was estimated to be \$223.9/MWh. The LCOE of variant cases were also estimated with the DICE CRCC plant without PCC having an LCOE of \$148.6/MWh, and the "ideal" DICE CRCC with PCC and centralization beneficiation having an LCOE of 145.7/MWh.

From a commercial project development and project financing perspective, the commercialization pathway for the DICE CRCC power plant requires a two-phased approach and manner – ***initially***

with a pilot plant and later followed by a NoaK commercial plant. The key funding and financing assumptions and drivers include TRL, funding via equity and grants for the pilot plant, funding via equity and limited recourse financing via debt for the first 1 to 3 NoaK plants (later followed by non-recourse financing), fiscal and financial incentives, and ***"bankable"*** transactional contracts.

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

VOLUME II: DESIGN BASIS REPORT

U. S. Department of Energy (DOE)

Contract No. 89243319CFE000025, Coal-Based Power Plants of the Future

By

Nexant, Inc

and

Bechtel Power and Infrastructure

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Section 1 Pre-FEED Study Design Basis

1.1 POWER PLANT DESIGN CRITERIA

1.1.1 General

Similar to the plant in the recently completed conceptual design, the DICE 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.

1.1.2 Site-Related Conditions

The DICE 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)

1.1.3 Meteorological Data

The design ambient conditions for the material balances, thermal efficiencies, system design, and equipment sizing are shown in the following and in Table 1-1.:

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

Table 1-1
Design Air Composition

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

1.1.4 Coal Feed Characteristics

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

Table 1-2
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

1.1.5 Coal Beneficiation Characteristics

The DICE 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 1-3. 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 1-3
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

1.1.6 Natural Gas Characteristics

Natural gas is the co-fired fuel in the DICE 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 1-4.

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.

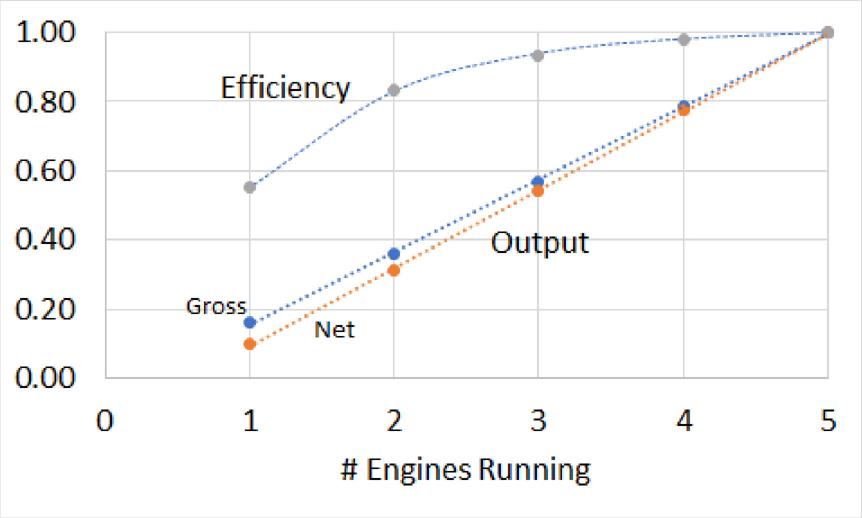
Table 1-4
Natural Gas Properties

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	5.75×10^{-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, °F	80	

1.1.7 Flexible Plant Performance Targets

The DICE 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 1-1, 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 1-1
DICE CRCC Part Load Performance



Other flexible performance plant targets include those set out in the contract as follow:

- Greater than or equal to 4% ramp rate
- Cold/Warm start in less than 2 hours
- 5:1 turndown with full environmental compliance

1.1.8 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.

1.1.9 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.

1.1.10 Plant and Instrument Air Supply

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

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

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

Nominal Temperature, °F	100
Maximum Temperature, °F	120

Nominal Pressure, psig	100
Maximum/Minimum Pressure, psig	150 / 80

1.1.11 Environmental/Emissions Requirements

Design emissions requirements and limits for the DICE 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

1.1.12 Major Equipment Performance Assumptions

The assumptions used in the design of the following major equipment of the DICE 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

1.2 PCC DESIGN CRITERIA

Guidelines for the PCC plant design include the following:

1.2.1 General

The PCC plant is designed as an integral part of the DICE 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.

1.2.2 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 CRCC plant is completed.

1.2.3 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 1-5, per the 2019 version of the DOE QGESS CO_2 Impurity Design Parameters (NETL-PUB-22529).

Table 1-5
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

1.2.4 **Utility Commodity Specifications**

Low Pressure Steam

Low pressure (LP) steam for the PCC stripper reboiler is the DICE 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, ºF	60
Return Temperature, ºF	100
Nominal Pressure, psia	As Required

1.3 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.

1.4 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 CRCC plant be broken down into these same categories.

1.4.1 Coal Beneficiation and DICE CRCC Power Island

For the pre-FEED design, additional cost details will be provided for the pertinent systems associated with the DICE CRCC plant. In particular, the Capex for the coal beneficiation and DICE 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 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.

1.4.2 PCC Plant

The Capex for the 30wt% MEA-based PCC for the DICE 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.

1.4.3 Balance of Plant

Cost estimates for the DICE CRCC balance of plant (BOP) systems, will be based on major equipment factored costs, wherever possible. For potential DICE 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.

1.5 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 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.

1.5.1 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

1.5.2 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.

1.6 FINANCIAL MODELING BASIS

1.6.1 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 1-6.

Table 1-6
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 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 1-6 are shown in Table 1-7.

Table 1-7
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

1.6.2 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

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

VOLUME III: TECHNOLOGY GAP ANALYSIS REPORT

U. S. Department of Energy (DOE)

Contract No. 89243319CFE000025, Coal-Based Power Plants of the Future

By

Nexant, Inc

And

Bechtel Power and Infrastructure

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Section 1 Introduction

1.1 CURRENT STATE-OF-THE-ART POWER PLANT

The current state-of-the-art in coal-fired power generation comprises supercritical (SC) and ultra-supercritical (USC) pulverized coal (PC) boiler-steam turbine generator (i.e., Rankine steam cycle) technology. Due to the nature of the main prime mover plant equipment and auxiliaries used and the underlying thermodynamic cycle (and the working fluid), the technology is cost-effective only at very large, utility-scale (almost gigawatt) installations. Even then, the strict environmental regulations governing criteria pollutants and other harmful emissions resulting from coal combustion impose very expensive coal treatment/preparation and flue gas treatment equipment, which negatively impacts plant cost and performance. On top of those challenges faced by conventional coal-fired power generation technologies, such mega-facilities are not amenable to fast and flexible operation requirements imposed by the rapidly changing nature of power generation portfolio with increasing penetration by renewables. Especially vexing is the clash between advanced alloys which are requisite to facilitate USC steam conditions for high efficiency (i.e., austenitic steels), which are less resistant to thermal stresses imposed by rapid load ramps and plant starts and shutdowns. A further challenge is faced during construction because of the need for skilled welders to handle pipes and valves made from such exotic (and expensive) alloys.

Even when all the practical challenges associated with advanced USC steam technology are ignored, the proverbial *"pot of gold at the end of the rainbow"* is more like copper – i.e., net lower heating value (LHV) efficiency that can be hoped for is worse than that of an E-class gas turbine combined cycle (GTCC).

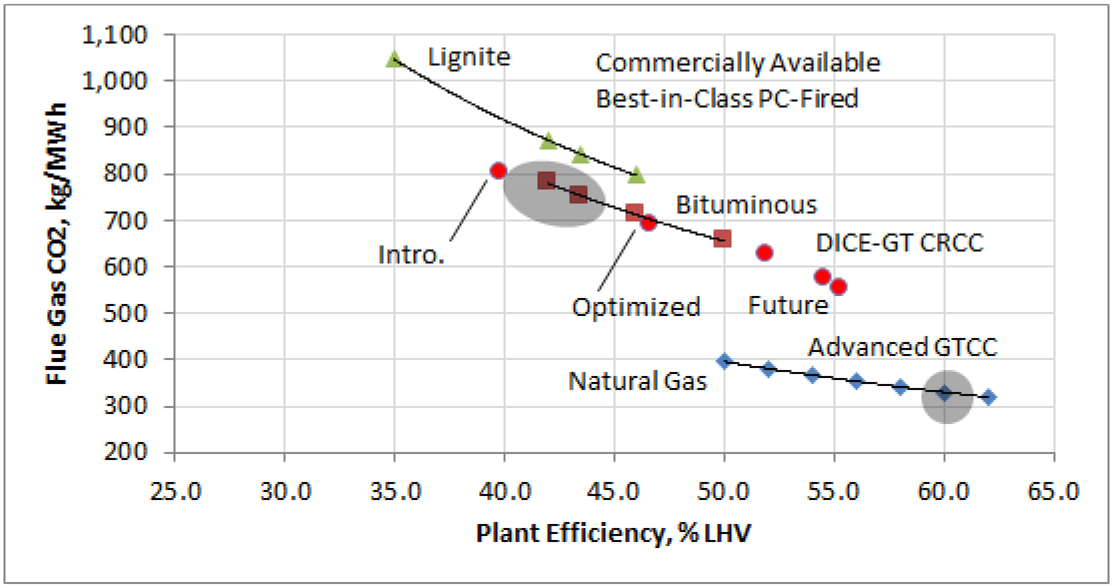
1.2 PROPOSED CONCEPT

The proposed concept, the **Direct Injection Carbon Engine Compound Reheat Combined Cycle** (DICE CRCC) delivers the predicted and achievable efficiency by the most advanced USC technology while being:

- Modular
- Flexible
- Small (120 MW base, about 80 MW with post-combustion capture, PCC)

This is clearly highlighted and illustrated by the chart in Figure 1-1, which shows the CO_2 emissions and plant efficiency of PC, GTCC and DICE CRCC (without PCC and including their best embodiments) technologies.

Figure 1-1
Efficiency-CO_2 Emission Comparison of Fossil Fuel-Fired Technologies



The DICE CRCC delivers the promised capabilities by combining mostly standardized, off-the-shelf, and commercially mature equipment with proven technology in a thermodynamically optimum manner. The combination of reheat with constant volume heat addition delivers the most efficient heat engine cycle, which can be implemented in the field with multi-equipment configurations for maximum modularity and flexibility with high efficiency at small ratings. The DICE CRCC with post-combustion carbon capture (PCC) is a low emissions, coal-fired power plant comprising three "blocks" or "islands":

- Coal beneficiation and coal-water slurry (CWS) fuel processing and production
- Modular electric power generation
- PCC

The basic operating principles and overview of the DICE CRCC can be found in Section 1 of the **Performance Results Report**.

1.3 TECHNOLOGY GAP ANALYSIS – THE PHILOSOPHY

The PCC Block utilizes amine-based chemical absorption technology, which is currently available and is not considered for technology gap/risk analysis. Detailed description of the PCC Block is provided in Section 4.8 of the **Performance Results Report**.

The Power Block also comprises of commercially mature and proven technology *except for the DICE*. Thus, the main focus of the technology gap analysis presented herein is on:

- DICE R&D and development pathway
- CWS processing and production.

The approach and methodology for the technology gap analysis presented herein is guided by the USDOE definition of **Technology Readiness Level** (TRL) is outlined in Appendix B. There are **three** areas of focus in the analysis:

- Technology Gap
- Technology Risk
- Development Pathway

The "gap" is determined by the TRL of a particular technology. *If the technology in question is at TRL 9, there is no gap*. If the technology is at, say, TRL 5, the technology gap is defined by the difference between TRL 9 and TRL 5.

As far as the distinction between technology "gap" and technology "risk" is concerned, in a nutshell:

- The "gap" is associated with the question "can we do it?"
- The "risk" is associated with the question "can we do it safely and economically?"

The "development pathway" is the key driving **stratagem** to be followed to bring the technology in question from TRL X < 9 to TRL 9 in the shortest time possible while mitigating the risks identified along the way.

The term "technology" can refer to a single system or a subsystem of a system. For example, the **Power Block** of DICE CRCC comprises the following "technologies" (not a *comprehensive* list):

- Reciprocating Internal Combustion Engine (RICE)
- Gas Turbine
    - Gas Compression
    - Combustion
    - Gas Expansion
- Waste Heat Recovery
- Steam Turbine
- Alternating Current Synchronous Machine
    - Motor
    - Generator

It should be highlighted that there is interchangeability between the terms "technology" and the "equipment" representing a particular technology. *All technologies enumerated above are at TRL 9 when used with a conventional liquid or gaseous fuel*.

From a subsystem perspective, the technology gap is inherent in RICE when burning an *unconventional* fuel (i.e., coal-water slurry in this case). In this particular case, the technology is referred to as *Direct Injection Carbon Engine* (DICE). Even then, note that DICE comprises various "subsystems", which are "technologies" in their own right, i.e.

- "Stock" engine comprising
  - Engine block/cylinders
  - Pistons
  - Crankshaft
  - Camshaft
  - Fuel injectors
- Turbocharger
- Synchronous alternating current (AC) generator
- Lubrication system
- Engine cooling system
- Charge air cooling system

The vast majority of all "subsystem technologies" in DICE are at TRL 9. The exception is the fuel (MRC) preparation and fuel injection system, which is discussed in detail below.

For N subsystems in a system with N – 1 subsystems at TRL 9 and one system at, say, TRL 4, can one take the average (it can even be a somehow "weighted" average) and state that the system is at, say, TRL 8.2? This may not always be the case because a system is like a chain, *it is as strong as its weakest link*.

The other key vexing question is this: If the subsystem in question is developed from TRL $X < 9$ to TRL 9, can it be introduced into *any existing system framework* (with all other subsystems at TRL 9) so that the new system will be at TRL 9? Specifically:

- If the fuel injection system is brought to TRL 9 by using a RICE platform from OEM[1] X, can one say that any RICE (from OEM Y or Z) can be transformed to DICE at TRL 9?
- If DICE is brought to TRL 9, can one say that DICE CRCC can be deemed to be at TRL 9?

The answer to the second question is ***NO***, because, while individual subsystems are at TRL 9, their seamless integration into a fully functional system may ***NOT*** *work and may require system modifications*. Due to the modular nature of DICE CRCC, however, moving from TRL 6 (pilot plant) to TRL 9 should be relatively straightforward. The focus is primarily on the interaction between the DICE and the expander in turbocompound configuration. There is field experience

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[1] Original Equipment Manufacturer (OEM)

in very similar applications (see Appendix A). The development path is more of a “risk elimination” exercise rather than closing a “technology gap”

The answer to the first question is ***NO*** as well due to the other “risks” (not “gaps” *per se*) involved in the DICE (enumerated and discussed in detail in section 1.3), i.e.:

- Combustion, specifically, ignition characteristics of the CWS fuel
- Wear and tear of components (cylinder walls, rings, pistons) due to ash particles
- Fouling of components

Finally, production of the CWS fuel itself is a technology, which is not at TRL 9 either. This is discussed in detail in Section 1.5. In this case, additional technology risks are present due to the variances in reliability among the different coal feedstock (i.e., bituminous, subbituminous or lignite with differences in quality and composition from mine to mine in each category).

1.4 DICE CRCC (POWER BLOCK) TECHNOLOGY GAPS AND RISKS

A partial list of the technology OEMs for major equipment including standard, off-the-shelf equipment, and commercially mature in the power generation block (DICE CRCC) are listed below.

- Major equipment needed:
  - Reciprocating internal combustion engines (RICE)
    - Medium-speed, large-bore
    - MAN, Wärtsila
  - Hot gas expander (HGE)
    - Baker Hughes
  - Main air compressor
    - Integrally-geared, centrifugal process compressor with intercooling
    - Kobelco, Dresser-Rand
  - Heat recovery steam generator (HRSG)
    - Single-pressure, non-reheat with duct burner and SCR/CO catalyst
    - NEM, Nooter Eriksen, Vogt
  - Steam turbine generator
    - Back-pressure (non-condensing)
    - GE, Siemens (Dresser-Rand), Elliott
  - Particle removal equipment
    - Third Stage Separator (TSS) used in FCC applications
    - Honeywell UOP
    - Shell

All of the major pieces of equipment are off-the-shelf and commercially mature products (i.e., representing TRL 9) *except* the RICE, which requires the following modifications to DICE:

- New fuel injector
- Cylinder/piston coating (with carbide)

The project team is planning to cooperate with CSIRO to further the development of these modifications in the next phase of work (CoalFIRST Critical Components Development).

The definitive associated technology gaps and risks as well as the development pathways are discussed in depth in Section 2 and Section 3.

It is also highlighted that:

- Bechtel has worked with all of the major OEMs of major equipment used in power generation and process
- Bechtel has access to data and information on the equipment included in the proposed concept

Section 2 DICE Technology Gaps and Risks

Prima facie, technology gaps and risks associated with the DICE CRCC concept are not overwhelmingly large. The least-proven part of the cycle is DICE, which is a *reciprocating internal combustion engine* (RICE) fired with a coal-water slurry fuel (roughly 45 weight percent (wt %) water). Even DICE has ample R&D and field operation history behind it (e.g., please refer to Nicol [1] and the extensive bibliography therein). One prominent example is medium-speed, large-bore RICE by Wärtsila, which has been successfully operated with Orimulsion in Finland [2].

2.1 LIMITATIONS AND ADAPTATIONS OF CURRENT ENGINES FOR DICE

While atomized MRC burns well in diesel engines, the engines require several essential modifications, and the engine also need to be low-medium speed (preferrably <500 rpm) to allow for longer combustion time and to reduce the fineness of atomization required to achieve efficient combustion.

To some extent these modifications are already used for commercial engines using Orimulsion and MSAR (bitumen-water emulsions – a close proxy for coal-based slurry in terms of combustion), high pressure gas, liquefied gases and alcohols. However, additional essential modifications are required for DICE. While most of these modifications involve straightforward engineering, several critical components will require redesign. The limitations and adaption of current engines for DICE is discussed for the following aspects:

- Cylinder size and speed
- Wear coatings
- Piston
- Ring shape
- Dual injection
- Injector
- Exhaust ducting
- Cylinder drains
- Turbocharger

2.1.1 Size and Speed

For coal, the cylinder size should be as large as possible and the engine speed as low as possible – larger and slower, respectively, than economically optimal for comparable installations using fuel oils and gas. Although low-speed engines cost proportionally more per MW, the benefits for coal are a reduction in cylinder wear and an increase in wear tolerance due to larger component sizes. In addition to increased wear tolerance, large bore and low speed mean that fineness of MRC atomization is less critical, and this allows both larger orifices (resulting in longer fuel jets) in the atomizer nozzle and lower injection pressure. Both are essential to reducing nozzle wear. A larger bore also increases the space available for the injector, which for MRC will likely be larger to accommodate ceramic components.

2.1.2 Fuel Supply System

Conventional fuel supply systems are unsuitable for MRC and will require redesign to avoid clogging and wear issues. The MRC supply system should provide a small, controlled circulation flow around the fuel rail and through the injectors to enable rapid flushing of the system and to eliminate clogging of the fuel system when the engine is not in operation. This circulating flow should be down through the injectors suction valve to the seat of the needle valve and be controlled either electronically or from the same oil that actuates the fuel pump plunger. The spring-loaded inertial valves often used with HFO are not recommended desirable due to the variable flow properties of MRC (shear thinning) and seat wear.

It is recommended that a twin pump low-pressure fuel system is used, with one pump controlling the pressure in the circulating flow, and the other used to control the return flow – as described in more detail in Section 3.1 of the Performance Results Report.

2.1.3 Injectors

Conventional injection equipment, including pump-line-nozzle, hydraulically actuated electronically controlled unit injectors (HEUI), mechanically actuated electronic controlled unit injectors (MEUI) and common rail injectors are completely unsuitable for MRC due to instantaneous jamming of sliding parts with coal particles, clogging of fuel galleries, and rapid wear due to erosion/cavitation. Required modifications are summarized as follow:

Jamming of any sliding surfaces wetted by the fuel -- This is especially the case for the fuel pump plunger and the cut-off needle valve spindle, which will jam solid within several injection cycles unless protected by a higher-pressure seal oil. This also precludes the use of a conventional jerk pump with spill ports to control injection rate.

Clogging of fuel ways if the fuel is allowed to remain stagnant – This will occur especially if the engine is hot and the fuel has been repeatedly pressurized to injection pressure (which can destabilize the fuel). This means that flushing of the fuel system is necessary either before or immediately after stopping of the engine.

Erosive wear of fuel system components – This occurs not just to the atomizer orifices, but also for the non-return valve seat and the needle valve seat. The size of fuel galleries must also be increased to reduce fuel velocities to below 10 m/s if possible. Velocities over 20 m/s will cause galleries to wear. Erosive wear is further accelerated by corrosion-erosion mechanism if materials subjected to high-velocity fuel are not sufficiently hard and corrosion-resistant.

Cavitation wear is increased with MRC due to the higher vapor pressure of the fuel’s continuous phase (water), and also due to its higher viscosity. Other fuel properties may contribute to cavitation, including the high particulates loading and the strongly shear-thinning nature of MRC, which tends to channel flow.

2.1.3.1 Piston

The piston bowls of modern engines are shallow and wide for less intense fuel-air mixing to reduce peak combustion temperatures and NOx formation: NOx should not be an issue due to the cooling effect of the fuel water – but requires full scale demonstration. Although the optimum shape for MRC has not been identified, it is probable that the older-style, deeper bowl, higher squish piston will give better results by providing faster and more complete fuel air mixing, which effectively increases the combustion time and allows the use of lower excess combustion air. The latter will also result in a higher charge temperature at the start of injection, further improving both ignition and combustion. Fuel-air mixing for DICE is also likely to be enhanced by the need for additional nozzle orifices to pass the higher fuel volume of MRC. A deeper bowl piston is also expected to reduce fuel contamination of the upper cylinder bore.

2.1.3.2 Piston Rings

There has been little published R&D on ring design for MRC. Conventional ring designs with hard coatings have given reasonable performance with MRC – but tests appear to have been of short duration (a maximum of 200 hours continuous). It is speculated that an optimized ring design will be necessary to minimize wear via 1) additional cylinder lubrication to carry away char and ash contamination of the cylinder wear surface, 2) avoiding Brinnelling by hard ash particles means that pressure equalisation across the ring pack will be more important which also increases the minimum oil film thickness, 3) ring porting/draining needs to be increased to allow for a step increase in particulates (ash and char) in the lubricant film, 4) ring shape may need to be changed to increase down scrap of contaminated lubricant to collection points. Piston ring rotation would also assist in evacuating contaminated oil grunge from behind the rings.

2.1.3.3 Materials

In general, the materials used for the critical components in the fuel system, piston rings and cylinder liner in conventional diesel engines are unsuitable for MRC. High hardness is essential to avoid abrasive wear from coal ash. Although ceramic coatings are available for piston rings and liners, conventional hard coatings are generally too thin to prevent the Brinelling effect of large hard fly ash particles – i.e. indenting through the hard coating into the softer substrate. Thicker, more monolithic coatings will be necessary with binders that are resistant to corrosion and grain plucking. The injector nozzle is particularly challenging. Although conventional polycrystalline diamond compacts have been shown to be effective in managing nozzle abrasive and cavitation wear of nozzles, the newer nanoparticle compacts of polycrystalline diamond or cubic boron nitride are expected to give an even better performance – and are tougher. These materials should also be used for fuel system valve seats and needles/poppets. A redesign of the injector is required to utilize these ceramics, in particular, as the ceramic components require an increase in component cross-section to compensate for lower tensile strength.

MRC can be handled using conventional steels (as for coal water fuels); however, it is recommended that components downstream of the fuel strainer are constructed from stainless steel – especially the engine fuel delivery system and high-pressure injection system. This is to reduce scaling and erosion-corrosion. For pump and injector bodies, steels recently developed for biofuel should be considered (e.g. Duval TN15 or similar).

2.1.3.4 Exhaust Ducting

Conventional horizontal ducting between the turbocharger turbine outlet and emissions control equipment will likely result in ash deposits on the lower surfaces of ducting – especially from shed ash deposits. Minimizing horizontal runs, live bottom ducts (e.g. equipped with drag chains), dropout boxes, soot blowers, and other measures will need to be used to prevent deposition from becoming an issue.

2.1.3.5 Dual Injection

A dual injection system will be necessary to allow the engine to start and warm-up on diesel or lighter fuel oil, and to enable pilot injection to control ignition (depending on the MRC quality). For some engines, the fuel oil side of the existing dual-fuel system may be used - possibly downsized to match only starting and pilot rating.

2.1.3.6 Cylinder Lubricant Drains

To accommodate increased particulates contamination of the cylinder lubricant film, increased cylinder lubrication is required, with provision to collect contaminated down scrap of lubricant (e.g. using a spiral/circumferential oil collection groove(s) near the bottom of the stroke). This arrangement will enable dirty lubricant to be routed out of the engine for separate deep cleaning using a centrifuge, thereby reducing the filtration load on the crankcase lubricant system.

2.1.3.7 Turbocharger

Coarse particulate matter in the engine exhaust will cause inlet vane and turbine erosion, especially for particles larger than (say) 10µm. While the bulk of the flyash is likely to be finer than this value (larger cenospheres are unlikely to be an issue as they are spherical and being hollow have a small equivalent aerodynamic diameter), ash deposits shedding from inside the engine and exhaust ducting will be larger. For this reason, turbines and inlet vanes will require hard facing – as used for large low-speed 2-stroke marine engines using heavy and residual fuel oils.

2.2 DICE TECHNOLOGY GAPS

While it is believed that there are no technical limitations concerning adapting an engine for DICE (this is an engineering issue only), there are a number of technology gaps that continue to hamper development. As these involve both the fuel and the engine, these gaps are discussed under that of a new fuel cycle involving the production of new fuel, for adapted engines for new coal generation markets

- For the fuel, this includes producing a suitable slurry fuel from coal that is exclusively used in boilers, and for which no experience with DICE exists
- Measurement of parameters requisite to predict coal suitability
- For the engine these involve items critical to producing a commercial engine with acceptable longevity and RAM[2] requirements
- Overall, there is a lack of logistics/infrastructure for a DICE fuel cycle
- Emissions prediction, especially, particulate matter (PM) 2.5, NOx and CO, requires significant field experience and system tuning

While all of the issues were considered to some extent in the comprehensive USDOE program from 1978-92 (which focused on bituminous coal replacing diesel fuel), this data is only partially relevant to the present initiative which is for a sub-bituminous coal particle size distribution, new abrasion-resistant materials, manufacturing techniques, and larger capacity stationary generation. Also, there has been a range of new technologies and business drivers over the last 25 years, for example, more efficient mills, new abrasion-resistant materials, manufacturing methods, electronic control, the rise of the reciprocating engine for both decentralized and baseload generation.

What is lacking is an understanding of the trade-offs between fuel quality and engine modifications, and this balance should be reassessed in the context of developments in ultra-hard materials and manufacturing techniques introduced over the last 25 years.

Table 2-1 summarizes the currently known technology gaps. .

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[2] Reliability, Availability, and Maintainability (RAM)

Table 2-1
Perceived DICE Technology Gaps

Technology gap	Description	Importance
Processing and formulation of subbituminous coal	• De-ashing by flotation or selective agglomeration may result in a higher product ash • Lower rank coals can make excellent MRC if the surface properties are altered and any porosity reduced (e.g. by hydrothermal treatment or low temperature carbonization) • Cost effective additive packs to provide optimal solids content and rheology	High (trade-off between fuel cost and engine cost)
Fuel logistics	• Fuel quality standards including suitable performance tests need to be established • Pulverized coal and fuel oil standards do not apply for DICE • CSIRO has a number of DICE fuel tests which could be used	High
Fuel-engine interactions	• Very little data for subbituminous coals • The occurrence of mineral matter in the processed coal will have a big influence on the required engine adaptations (armoring) and repairs and maintenance (R&M) costs • However, expect only a small increase in engine capital cost due to special componentry (for the Nth engine)	High
Engine design	• Current designs and materials of construction assume clean fuel. This limitation applies to the fuel supply system, the injection system, cylinder components, exhaust valve seats, exhaust system, turbocharger turbine, and heat recovery systems.	High

Technology gap	Description	Importance
	• Engine maker philosophy – the fuel needs to match the engine	High – potential large new markets using lower cost fuel needs to be valued
Next generation DICE fuel systems	• Atomization and atomizer longevity is the absolute essential requirement/obstacle to DICE • The existing practice of pressure atomization is a quick fix – it works, but not for very long • Air blast atomization can solve this problem but requires more adaptation to the engine systems • A change in engine philosophy is required: new air blast could be much better than that of the 1920's, the benefits of DICE warrant extra effort on the engine, MRC is a different fuel that requires a different engine	Medium in the short term, but could eliminate the atomizer problem and result in relaxed fuel quality requirements High Engine manufacturers currently adopt the view that the fuel must match the engine. The opposite could be optimal for DICE
New coal philosophy – life-cycle analysis (LCA) based	• DICE is a higher value market for coal. A new philosophy around quality and optimizing the overall coal fuel cycle is required. For example higher ash MRC could be used as a boiler low load or light-up fuel, creating operations for MRC with higher ash fractions to PC boilers, mining of tailings dams, other higher value end-uses for MRC quality coals • The highly flexible nature of DICE could directly underpin a high penetration of intermittent renewables	High Potential to reinvigorate the industry High New system boundaries need to be established – with coal and DICE

2.3 TECHNICAL RISKS AND ISSUES

The key technical risks and issues associated with developing DICE – based on recent CSIRO experiences, are as follows, in decreasing order of importance:

2.3.1 **Commitment**

Ensuring commitment of both the engine manufacture and fuel supplier/fuel chain as this involves producing and using a fuel that is new to the world – this requires industry backing and commitment to not only undertake the engineering RD&D, but also to establish new logistics (including tests for quality, OH&S, public perceptions). If a holistic development approach is not taken, development could stall due to a chicken-and-egg situation between fuel supply and availability of suitable engines.

2.3.2 **Tradeoffs**

Establishing at the outset nominal trade-offs between fuel quality and engine modifications. The engine manufacturer will likely insist that the fuel is produced to suit the engine and the fuel supplier that the engine is adapted to suit the fuel. Although a full-scale demonstration is required to quantify the optimum quality-engine adaptations, an early decision should be made on fuel quality targets to give an acceptable overall generation cost. Other changes are also required: For the coal supplier, MRC must be regarded as a premium fuel and prepared and handled accordingly; for the engine manufacturer it should be accepted that MRC is not a fuel oil, and that DICE will require substantial changes to engine manufacturers to incorporate new materials and changes to the base engine (e.g. a new fuel system, revised cylinder heads to accommodate a larger injector, increased crankcase lubricant cleaning, revised exhaust ducting and turbine materials etc)..

2.3.3 **Development Philosophy**

Ensuring that both the engine manufacturer and fuel supply parties agree with the engine development program. There are two diametrically opposite pathways to achieving a commercial engine: 1) develop and test what is considered to be key components prior to undertaking the engine tests/demonstration, or 2) undertake engine tests early with adapted components to identify and prioritize component development needs and learn by doing. This single issue was the cause for termination of the recent CSIRO project with an engine manufacturer and the Australian coal industry: The coal industry disagreed with OEM's approach (which was a 3-5 year program based on early engine trials prior to component development) to develop a commercial engine for DICE. It is emphasized that the program was not terminated on technical grounds – only conflicting philosophies on how development should proceed.

2.3.4 **Supporting R&D**

Including a parallel program to develop and establish fuel cycle logistics. This should include identifying/developing suitable tests for the fuel – which will likely involve a hybrid of fuel oil and coal type tests. It is recommended that a high degree of importance is placed on understanding how the inorganics in the as mined coal report to the MRC fuel, the exhaust gases, and the wear implications – especially for the injector nozzles and cylinder components. For example, depending on the coal and the cleaning methods used, around one-third of the ash content (in, say a 2% ash coal) could be derived from organically bound or finely disseminated mineral matter which will have different wear implications that coarser extraneous quartz particles. Another key area is MRC rheology: If this is correct the relatively high viscosity fuel will inject as well as fuel oil and will be safe to store without agitation. If not, fuel system and injector nozzle blockages will result, and fuel tanks settle to form a compacted sludge.

2.3.5 Engine-ready MRC

Developing a cost effective, engine ready fuel. For bituminous coals fully commercial technologies are available to do this. For lower rank coals such as Powder River Basin coal, some development is required to ensure sufficiently low mineral content and to allow an MRC with over 50% coal to be produced with acceptable rheology.

2.3.6 Engine Modification

The minimum modifications to enable an engine trial, for example, to obtain combustion and heat release data, and to identify other issues, is a seal oil protected injector and fuel pump. Using a standard tool steel nozzle should enable 5-10 hours of consistent operation to gain early engine performance data and to refine the component development program.

2.4 KEY R&D REQUIREMENTS FOR DEVELOPMENT

The technical R&D requirements are discussed below in the context of developing an overall fuel cycle that is ready for commercialization by 2030:

- Fuel development (elaborated in detail in Section 3.1)
- Engine component development
- Logistics.

2.4.1 Engine Component R&D

Engine component R&D is mostly for fuel delivery and injection systems, including materials selection. Key areas include:

- Wear coatings for the piston rings and cylinder walls
- Piston bowl shape
- Ring shape
- An MRC injection system with seal oil protected sliding surfaces and ceramic valves and atomizer nozzle.
- Exhaust ducting - reengineered to manage ash dropout
- Cylinder lubricant drains to remove contaminated oil
- Turbocharger armoring
- Reengineered fuel delivery system

These are described in more detail under development imperatives and the development pathway below.

2.4.2 Logistics R&D

DICE is a potential new market for both coal and reciprocating engines that requires the establishment of new fuel cycle logistics, especially fuel quality standards, and fuel supply logistics. These are described in more detail under development imperatives and the development pathway below

Section 3 Fuel Production Technology Gaps And Risks

The fuel burned in DICE is in the form of a "slurry", which is defined as a "semi-liquid mixture, typically of fine particles of solids *[in our case, coal]* suspended in water". The *coal-water slurry* (CWS) fuel has to be prepared before being used in DICE. This process can take one of the two forms:

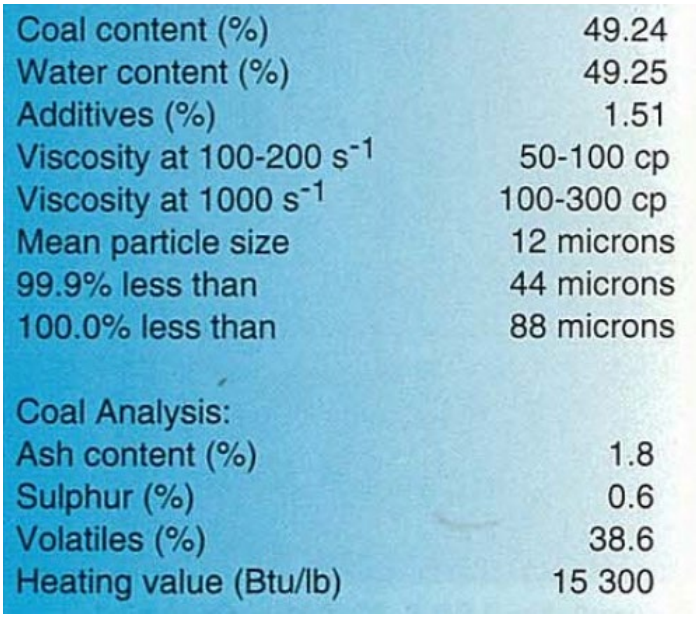
- A central fuel processing plant (analogous to a petroleum refinery producing gasoline and diesel fuel among other products) serving many CWS-fired power plants
- A dedicated fuel processing plant serving each CWS-fired power plant

The CWS fuel processing power plant has two major functions:

- Creating "coal powder" to be mixed with water
- "Cleaning" the coal powder (commonly referred to as "beneficiation") to reduce sulfur and ash

In the literature, cleaned, pulverized (or "powderized") coal is also referred to as *micronized refined coal* (MRC) because of the size of the fine coal particles (mean size of the order of 10 to 15 *microns*). Typical, CWS is a mixture of MRC and water in roughly equal amounts by weight and has a consistency similar to that of paint. As an example, CWS properties from the USDOE's *Clean Coal Technology* program in 1994 are provided in Table 3-1 [3]. (Additives such as xanthan gum and surfactants are used to control slurry viscosity; dispersants are added to prevent agglomeration.)

Table 3-1
CWS Properties



Coal content (%)	49.24
Water content (%)	49.25
Additives (%)	1.51
Viscosity at 100-200 s^{-1}	50-100 cp
Viscosity at 1000 s^{-1}	100-300 cp
Mean particle size	12 microns
99.9% less than	44 microns
100.0% less than	88 microns
Coal Analysis:	
Ash content (%)	1.8
Sulphur (%)	0.6
Volatiles (%)	38.6
Heating value (Btu/lb)	15 300

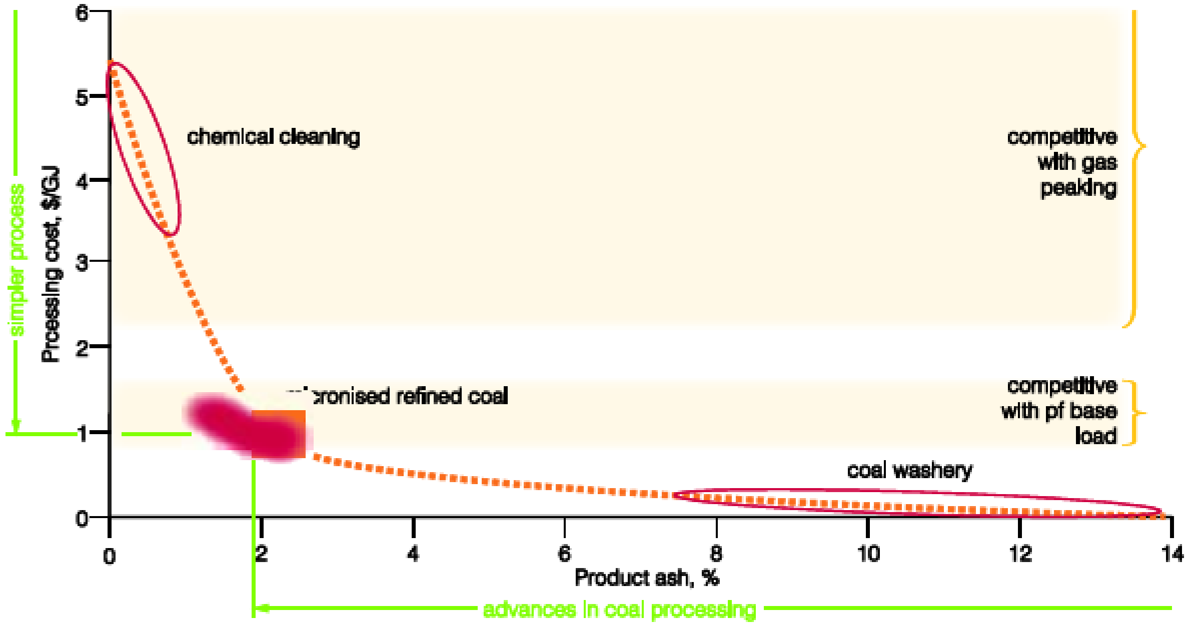
Ideal MRC properties for *black* ("high rank" or bituminous) and *brown* ("low rank", subbituminous or lignite) coals are provided in Table 3-2 [4].

Table 3-2
MRC Properties

Property		Black	Brown
HHV (MJ/L)		21-25	16-19
Mineral ash (wt% dry) Total ash (wt% dry)		1-2 1-2	0.2-1 2-3
Viscosity (apparent, mPa.s) @100/s (pumping) @100,000/s (injection)		 200-500 100-300	 400-700 200-400
Unstirred settling rates(stagnant) mm/month		1-5	1-5
Particle size	d50 μm d95 μm	10-15 50	10-15 70
Cost including coal ($/GJ)		$4-6	$2-3

Neither coal pulverization nor coal cleaning/beneficiation requires "invention" of new technologies. Currently available physical and chemical cleaning technologies can readily eliminate ash (including mineral sulfur) but there is a cost-performance trade-off as illustrated in Figure 3-1 [1]. Reducing the MRC specification from 2 wt% to 1 wt% can easily triple the coal processing cost.

Figure 3-1
Coal Beneficiation Cost (in Australian Dollars)



3.1 FUEL DEVELOPMENT NEEDS

3.1.1 Fuel R&D

Cost-effective fuel processing to meet a specification that is suitable for DICE is essential. For most coals, this will require producing a finer and lower ash product than for existing markets – but without the usual moisture constraints. Three steps are involved, and all require R&D and testing to optimize the processing for the specified feed coal.

1. Demineralizing and densification
2. Micronizing and slurry production
3. Blending

The steps and nominal targets for both R&D and test work is described below, based on CSIRO's experience with 48 coals.

3.1.1.1 Demineralizing and Densification

The first step is to produce feed coal with sufficiently low ash, and without coarse, hard minerals such as quartz, pyrites or rutile. It is important to recognize that this requires low temperature plasma ashing (LTA), followed by quantitative X-ray diffraction (XRD), to determine the mineral species. This complements a standard coal ash analysis. From recent experience, this step will be challenging for the sub-bituminous PRB coal proposed, as deep cleaning by a highly selective process, such as flotation or selective agglomeration, is likely to be less effective than for bituminous coals –resulting in both higher product ash and lower recovery. Ideally, cleaning would be undertaken on densified material – e.g. after pretreatment by hydrothermal treatment. Hydrothermal treatment is also known to reduce hydrophilic surface groups and oxygen content (slightly), which further assist in both cleaning and by increasing calorific value of the fuel slurry.

3.1.1.2 Micronizing and Slurry Production

The second step is to micronize the cleaned feed coal. Ideally, this is by higher efficiency wet milling with the required slurry water plus additives. For a 500 rpm engine, a conservative top size (d_{97}) is 65µm. The aim is to produce a size distribution that will have a good packing efficiency, which maximizes the coal loading and therefore calorific value of the fuel.

Unless a cleaning step follows micronizing (as would be the case for bituminous coal), micronizing should be undertaken with steel mill media, as ceramic media can chip and cause unacceptable contamination. If steel media is used, the fuel will pickup some Fe, but as discussed below, this iron pickup can improve fuel rheology.

3.1.1.3 Blending and Trimming

It is unlikely that a fuel freshly micronized and slurried in Step 2 will have acceptable rheology. A significant improvement in fuel rheology requires a combination of further blending and aging. Blending is most efficiently undertaken using a combination of a high shear mixer (eg Eirich-type paddle mixer) followed by a longer period of low-intensity mixing (*eg* a Visco-jet or similar). Experience has shown that the energy required for the high-intensity mixing stage can be as high as 30-50% of that of micronizing. The low shear mixing could also be provided by storage tank agitation. During the blending and trimming step, the rheology of the MRC should be measured for the shear rate range 0.1-3000/s (or higher) to ensure the shear thinning behavior of the MRC. Additional trim additions of a surfactant or thickening agent may be required to achieve these properties.

Examples of additions for Australian bituminous and lignite coals are shown in Table 3-3.

Table 3-3
Nominal Additives Used to Produce MRC

Purpose	Example	Range wt%[1]	Comment
Dispersant	Polystyrene sulfonate	0.1-0.5	Needs to be optimized for the coal. Other dispersants may be more economical
Stabiliser	Carboxymethylcellulose	0 0.1	Often not required, can interfer with the dispersant
Auxillary	Soluble Fe or Ca	0.01–0.1	Bridging agent. Most effective for bituminous coals. Not required for alkaline ash coals
Biocide	See proprietary biocides	0.0-0.1	Usually not required

1 active ingredient, dry coal basis

As a general comment, processed lignite and sub-bituminous coal usually produce excellent fuel slurries from a stability and shear thinning perspective; however, porosity and residual surface groups reduce the coal content and, therefore, the calorific value of the fuel for a given viscosity. The other factor that affects the coal content of the slurry is the particle size distribution, which determines the packing efficiency (can be calculated).

3.1.2 Further Research Studies

Suggestions for research studies that would assist in de-risking the fuel technology for bituminous and sub-bituminous coals are given below. It should be noted that not all of these studies may be required – as work progresses, the research will be amended to achieve the goal cost effectively

3.1.2.1 Mineral Matter

- Identify the mineral species in the coal (LTA plus XRD, and the size distribution of the various minerals by SEM - very useful in considering beneficiation issues and options.
- Optimize mineral removal from micronized coal(with and without hydrothermal treatment), using flotation or other physical separation procedures- how much of which mineral species is removed?. This study will include the effect of flotation aids/chemicals on slurry rheology.

Dewatering is required after flotation, which requires a dilute (~5%) slurry. Research is required to develop the most cost-effective dewatering technology and to optimize dewatering aids, prior to fuel slurry formulation.

3.1.2.2 Surface Groups

- For lower rank coals, the level of carboxylic acid/carboxylate surface groups should be measured (e.g. by a titration procedure).
- If insufficient surface groups are present to achieve stability and shear thinning studies will be undertaken to determine how can they be generated at minimal cost for bituminous and sub-bituminous coals (eg by increasing surface oxidation using chemicals or electrolysis).
- Additives such as calcium ions have a very beneficial effect on bituminous coal slurries, with small additions (<0.02%) changing slurries from shear thickening to shear thinning. Is this effective for the target coal, and what is the effect when combined with a dispersant?
- What is the effect of hydrothermal treatment (and perhaps other treatments such as compression, or low temperature pyrolysis) on the coal properties such as surface groups and porosity may need to be assessed, as coal characterization proceeds.

3.1.2.3 Milling/Micronization

- It may be possible to wet micronize the coal to achieve the final slurry coal. concentration. This would have the benefit of avoiding an additional trim dewatering step, especially if a dry beneficiation process was used

3.1.2.4 Slurry Generation

- Mixing conditions (time, intensity, dispersant, type of mixer) are known to affect the properties of the slurry, but this depends on the coal and additives used. Experimentation is required to optimize mixing for the particular coal

3.1.2.5 Fuel Stability

- Coal slurries can be adversely affected by bacteria and may need biocides to maintain stability. Work is required to determine if biocide, if required, and identify formulations that do not negatively affect slurry rheology. CSIRO has had a bacterial problem with only 2 coals to date (out of 48). However, other research groups have experienced significant bacterial issues.
- Stability tests - many of the tests in the literature are focussed on comparatively short term stability (days to weeks). There is a need for tests that are relevant to commercial operations associated with storage and transport (months)
- Stability tests – many of the tests in the literature are focused on comparatively short-term stability (days to weeks). There is a definitive need for tests that are relevant to commercial operations associated with storage and transport (months)

3.2 CWS PROCESSING PLANTS

CWS processing plants in pilot scale has been designed, built and operated in the past. Key examples are:

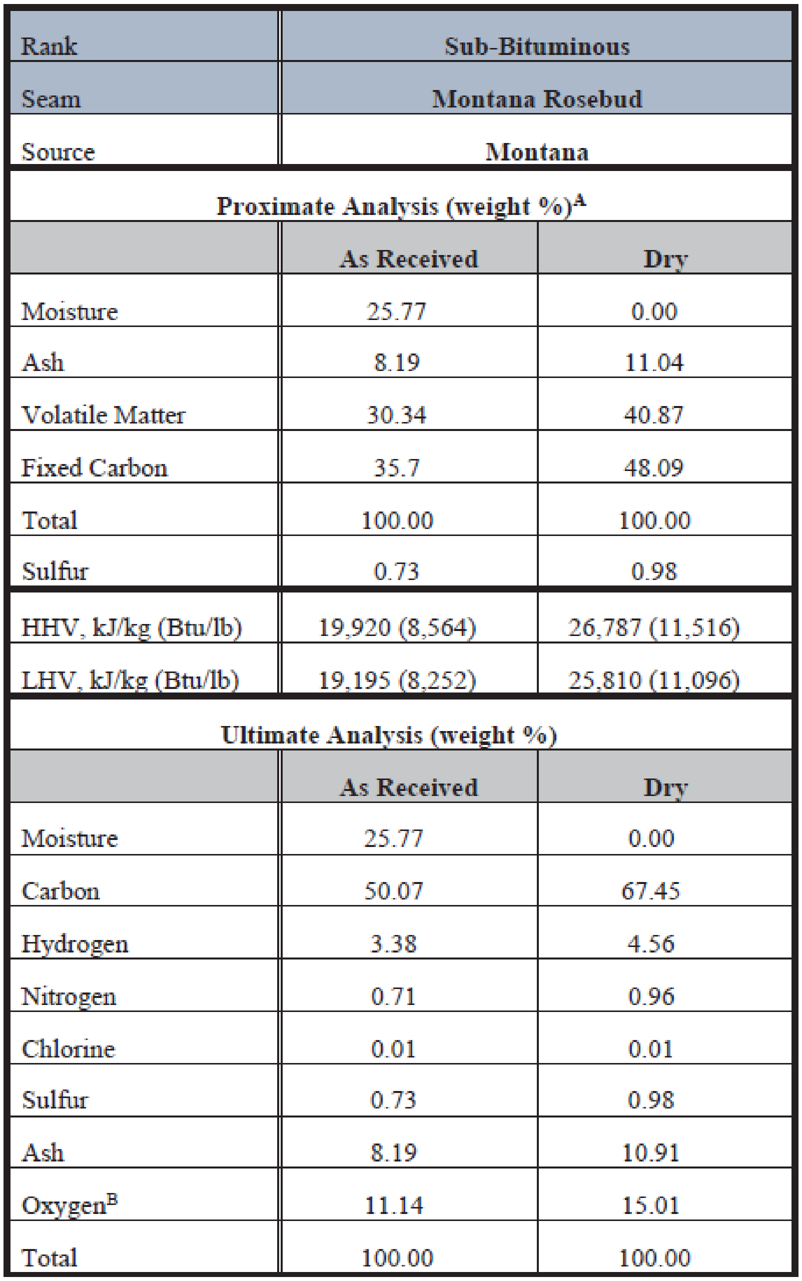
- University of North Dakota's Energy & Environmental Research Center (EERC) CWS production process with hot water drying (using Kentucky and Usibelli coals) [5,6]
- Jameson Flotation Cell (Glencore Technology) in Australia [7]

A comprehensive review can be found in Nicol [1]. However, so far, no commercial-scale CWS production facility which is commensurate with the stringent requirements of DICE application has been built. In order to have an idea about the "commercial scale", the DICE considered in this project (about 16 MWe generator output) consumes CWS at a rate of **18,750 lb/hr** (about **8.5 metric tons** per hour). The proposed power plant is based on five DICE units.

In order to design the appropriate CWS processing plant, properties of the coal feedstock should be analyzed in great depth. The first step is to obtain a small sample of the coal feedstock to determine if grinding to finer particle sizes liberates the ash. If grinding does not liberate the ash, some cleaning technologies may not be able to produce a low ash coal. Additional lab work would be required to determine the best approach to clean the coal. As discussed in detail, *this is not an easy task*:

The design basis coal for the present project is low-sulfur, subbituminous Power River Basin (PRB) coal (a low rank coal) with proximate and ultimate analysis summarized in Table 3-4. In his 1993 Master's Thesis, Kong identified a total of 25 mineral phases in the samples from the Big Sky and Absaloka mines in the Rosebud subbituminous coal seam [8]. (The Big Sky samples were taken from different layers of the seam.) Mineral concentrations ranged between 5 wt% and 15 wt% on a whole coal basis (see Table 3-5). Pyrite (FeS_2) was the only important sulfide mineral identified. In the B-I sample in Table 3-5, pyrite was 8.5 wt% on coal basis; in B-III sample, it accounted for 2.5 wt%. In the others, pyrite content changed between 0.15 wt% and 1.29 wt%. The data and information clearly illustrates the difficulty of predicting de-ashing effectiveness and MRC product quality from proximate or ultimate analysis.

Table 3-4
Design Basis Coal Analysis



Rank	Sub-Bituminous	
Seam	Montana Rosebud	
Source	Montana	
Proximate Analysis (weight %)[A]		
	As Received	**Dry**
Moisture	25.77	0.00
Ash	8.19	11.04
Volatile Matter	30.34	40.87
Fixed Carbon	35.7	48.09
Total	100.00	100.00
Sulfur	0.73	0.98
HHV, kJ/kg (Btu/lb)	19,920 (8,564)	26,787 (11,516)
LHV, kJ/kg (Btu/lb)	19,195 (8,252)	25,810 (11,096)
Ultimate Analysis (weight %)		
	As Received	**Dry**
Moisture	25.77	0.00
Carbon	50.07	67.45
Hydrogen	3.38	4.56
Nitrogen	0.71	0.96
Chlorine	0.01	0.01
Sulfur	0.73	0.98
Ash	8.19	10.91
Oxygen[B]	11.14	15.01
Total	100.00	100.00

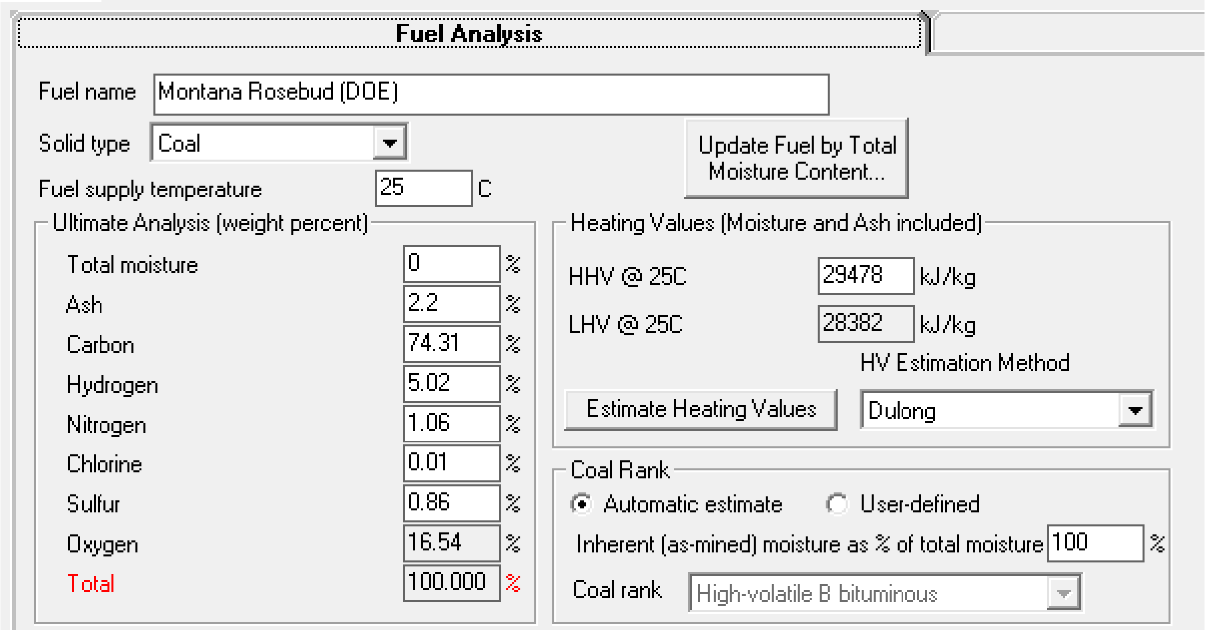
The average total mineral content of the five Big Sky mine samples (B-I through B-V) in Table 3-5 is 7.35 wt%. Ignoring the outlier B-I, the average is 5.84 wt%. Accounting for the sulfur in pyrite, non-sulfur mineral content average is 6.17 wt%; without the outlier B-I, the average is 5.33 wt%. At the risk of being somewhat optimistic, we have assumed that non-sulfur mineral content of the design basis coal is 6.7 wt% so that the cleaned coal ash content can be reduced to 1.5 wt%. As far as the sulfur is concerned, we decided to be less optimistic and have assumed that 20% of the sulfur in the "as-received" coal is inorganic and can be removed during beneficiation.

Beneficiated "clean" coal properties (dry basis) are shown in Figure 3-2. The improvement in heat content on a higher heating value (HHV) basis is 29,748 / 26,787 = 1.11 or 11 percent.

Table 3-5
Mineral Content of Rosebud Coal Seam Samples (percent by weight)

Mine	B-I	B-II	B-III	B-IV	B-V	A06	Average
Total Mineral	14.91	4.98	8.88	4.76	5.33	5.23	7.35
Pyrite	8.45	0.46	2.5	0.34	0.15	1.29	2.20
S (Pyrite)	4.52	0.25	1.34	0.18	0.08	0.69	1.18
Total - S	10.39	4.73	7.54	4.58	5.25	4.54	6.17

Figure 3-2
Beneficiated "Clean" Feedstock Properties



Fuel name: Montana Rosebud (DOE)
Solid type: Coal
Fuel supply temperature: 25 C

Ultimate Analysis (weight percent)

Total moisture	0	%
Ash	2.2	%
Carbon	74.31	%
Hydrogen	5.02	%
Nitrogen	1.06	%
Chlorine	0.01	%
Sulfur	0.86	%
Oxygen	16.54	%
Total	100.000	%

Heating Values (Moisture and Ash included)
HHV @ 25C: 29478 kJ/kg
LHV @ 25C: 28382 kJ/kg
HV Estimation Method: Dulong

Coal Rank
● Automatic estimate ○ User-defined
Inherent (as-mined) moisture as % of total moisture: 100 %
Coal rank: High-volatile B bituminous

This study assumes that the MRC composition is 45 wt% water and 55 wt% beneficiated and micronized coal. The resulting MRC fuel composition is listed in Table 3-6. The LHV of this fuel is 14,513 kJ/kg (HHV is 16,214 kJ/kg). It should be emphasized that, for an accurate determination of MRC composition, more detailed information about the feedstock (i.e., petrography data) is requisite. Depending on the actual coal microstructure, final MRC ash content can be 2 wt% or higher.

Table 3-6
Study MRC Composition

	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

It is noted that this MRC composition based on PRB coal as feedstock differs from that listed in the coal beneficiation study in Appendix B. The MRC composition for this pre-FEED study assumes 45 percent total moisture and 55 percent dry coal solids by weight. In the coal beneficiation study performed by Sedgman, the coal beneficiation process OEM, it is assumed that the MRC has a free moisture content of 45 percent by weight and that the 55 percent solids by weight in the product still contains the inherent moisture of the PRB coal.

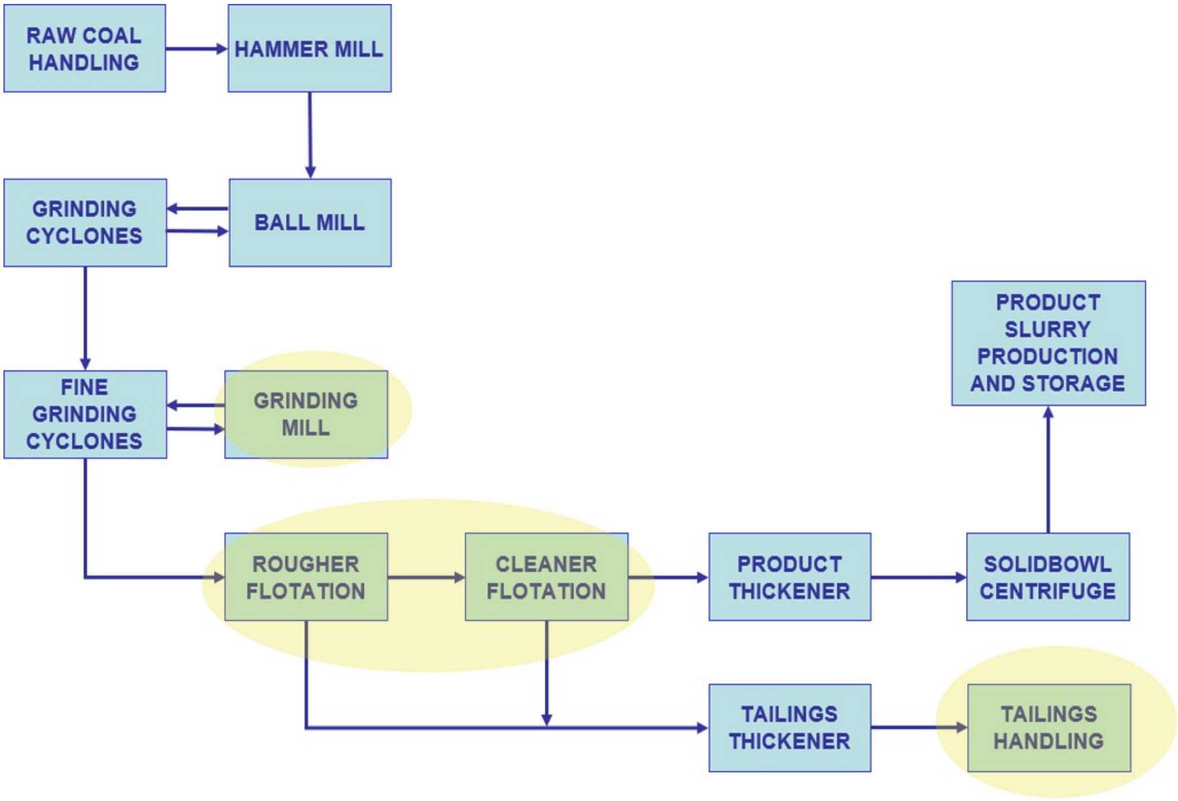
Due to the lower total moisture content of the MRC assumed in this study's design, the performance may be optimistic. The actual total moisture content of the MRC needs to be studied further and verified via testing on actual coals. These tests should establish the moisture content of the micronized coal and the minimum moisture content required for the slurried MRC to meet DICE rheology requirements.

3.3 TECHNOLOGY GAPS, RISKS, AND DEVELOPMENT PATHWAYS

3.3.1 Potential R&D Needs

For the typical commercial beneficiation process, there are *currently no specific components, equipment, or systems which require undertaking traditional R&D nor having any technology gaps*. However, as part of the overall beneficiation process, there are key commercially available plant unit operations whose end-use application is novel - ***when beneficiation is based on coal***. As shown in Figure 3-3, these unit operations include fine grinding mill, ash removal (via rougher flotation and cleaner flotation), and tailings handling.

Figure 3-3
Key Coal Beneficiation Unit Operations



Based on the findings from the Performance Results and Cost Results reports, while the various components for a conventional flotation-based coal beneficiation plant, as shown in Figure 3-3, are all commercially available, the low overall product yield and tailings handling are areas that need to be addressed in order for the process to be economically feasible.

In the DICE CRCC pre-FEED study that uses PRB coal as the feedstock to the beneficiation plant, the overall product recovery yield was about 50 percent on both a mass and combustible value basis. A consequence of this low product yield is the large quantity of reject tailings that, while still containing significant heating value, is in slurry form, and has no commercial value. The unsaleable tailings thus has to be disposed of in ash ponds, which constitute an environmental risk.

While it is possible to process the reject slurry (via dewatering, briquetting, etc.) to a more functional form, this requires additional energy and cost input. It is therefore key to address the likely technology gap associated with disposing the otherwise unsaleable reject slurry tailings from coal beneficiation.

It is of utmost importance to increase the product recovery yield to way beyond the current 50 percent. Doing so would not only decrease the coal feed required by the beneficiation plant, but also minimize the quantity of reject tailings. It is understood that the hydrophilic nature of the subbituminous coal as-is makes it difficult to achieve a high recovery via the conventional flotation process for ash separation. Tests on various coal samples should therefore be undertaken to identify coal types that can achieve maximum product recovery.

Virginia Tech has developed a process that can increase combustible recoveries of typically hydrophilic materials such as PRB coals, which involves using an additive to increase their hydrophobicity. Virginia Tech plans to investigate and develop this technology further under the USDOE CoalFIRST Critical Components development program. Besides performing tests on a variety of high- and low-rank coals, this technology can also be used to recover MRCs from waste coals that are currently being discarded in the eastern US coal fields. If it can be demonstrated that these waste coal fines can be successfully beneficiated to produce suitable CWF fuels for firing in DICE, this substantially reduce the coal cost and produce MRC-based CWFs at cost below $1.50/MMBtu. Supply of low-cost CWF fuels should expedite the commercialization of DICE technology and ensure a success of the CoalFirst program.

Additionally, Virginia Tech's process is understood to be able to reduce the inherent moisture of the coal particles in the MRC via a mechanism known as dewatering by displacement (DbD), described in US Patent 9,518,241. In this process, a hydrophobic liquid is introduced to displace the water trapped within the coal's pore structure and reduce its moisture. The resulting hydrophobic liquid phase contains coal particles free of surface moisture and entrained droplets of water stabilized by the coal particles, while the aqueous phase contains the mineral matter. By separating the entrained water droplets from the coal particles mechanically, a clean coal product of substantially reduced mineral matter and moisture contents is obtained. The spent hydrophobic liquid is separated from the clean coal product and recycled.

Another advantage of Virginia Tech's technology is that it processes the coal at a relatively coarse size, which allows the rejects to be easily disposed of without the need for expensive dewatering or environmentally hazardous ponds. Furthermore, the coarse product coal is dry yet does not catch fire spontaneously during shipping, which allows for the beneficiated product to be shipped to the DICE CRCC plant dry, where it is micronized and slurried on-site. This ability to ship a relatively coarse, dry product that avoids spontaneous combustion is believed to be able to reduce the overall fuel costs substantially.

3.3.2 Development Pathway via Testing

Since there is no requirement for undertaking traditional R&D, there is however a need for a commercial development pathway to definitively verify, validate, and confirm the key assumptions, design/concept impact, and end-use application of the highlighted beneficiation unit operations based on coal. Testing (e.g. combinations and permutations of laboratory based, independent/third-party, or any performance testing) is highly recommended and required to be undertaken. Currently, the beneficiation testing opportunities based on coal are limited since such applications are primarily market-driven. For commercial end-use application, further testing and development is required on specific coal types for optimal yield and efficiency for each of the key unit operations covering:

- **Fine Grinding Mill**: Available proven technologies include impact and attrition mills. Selection of most suitable grinding technology depends on various factors which include product size, feed size, and energy consumption
- **Ash Removal (via rougher/cleaner flotation)**: Different proven flotation technologies available with different energy and reagent input requirements. The low ash concentration in product coal (2 wt% db) is a potential challenge which need to be proven-out via testing
- **Tailings Disposal/Utilization**: There is no market value in slurry form. There is additional energy/cost to process (dewatering, briquetting). Disposal and utilization is a function of product yield (< 50% for PRB coal)

3.3.3 Testing Regime - Future Work Plan

From this study, items in proposed order of testing as discussed below, should be included in an ongoing work plan to further progress the development pathway of MRC as fuel for the DICE CRCC. As shown in Table 3-7, these tests will verify, validate, and confirm the key assumptions, design/concept impact, component and equipment selection and sizing.

The specific detailed testing regime will be dependent on the final coal type(s) selected, availability of sample, and the testing work budget and schedule.

Table 3-7
Testing Required to Confirm Key Assumptions, Design/Concept Impact

Key Assumptions	Design/Concept Impact	Testing Required to Confirm
Feed quality size independent – all feed processed	▪ Pre-sizing requirements ▪ Screening requirements ▪ Feed handling system (conveyors)	▪ Size/ash analysis of feed ▪ Coal Grain Analysis
Liberation of carbon requires grinding to 100% passing 50 micron	▪ Grinding technology and power requirement ▪ Downstream processing technology and size (flotation thickening, dewatering)	▪ Size/ash analysis ▪ Coal Grain Analysis ▪ Grinding characteristics testing
Deep froth and high wash water required for low ash product	▪ Flotation technology	▪ Flotation testing (tree flotation)
2 stage flotation required to reach required product ash	▪ Flotation plant layout and size ▪ Power and consumables requirement	▪ Flotation testing (tree flotation)
24 hour product storage	▪ Product slurry storage tank size and number	▪ Based on DICE CRCC pilot plant

Feed Coal Analysis: One of the main drivers for the success of DICE CRCC is the feed coal selection. The PRB coal is shown to be not ideal based on the current pre-FEED study. The low product yield results in a large quantity of as-received feed requirement, while generating similarly large quantities of tailings for disposal. Thus, bench-scale tests needed on various coals to establish and select feed with the best available yield. As part of the testing regime, analysis on a selection of possible feed coals should be carried out. A shortlist of possible feed coals with suitable properties (ash, sulfur content, and energy levels) could be selected based on known existing coal quality from different mine sites. The selection of the preferred coal type is a critical component of any ongoing work as this will drive the downstream test work, the results of which will determine equipment sizing and final project costs (e.g. capital and operating).

Coal Grain Analysis: Once a preferred coal source, or sources, are identified, the development team shall carry-out detailed coal grain analysis on this coal to determine liberation requirements to reach the required product ash level. The results of this analysis is critical to both the grinding and flotation equipment selection.

Crushing and Grinding Test Work: Laboratory scale comminution tests (comminution is particle size reduction by breaking, crushing, or grinding of ore, rock, coal, or other materials) should be carried out on the selected coal to determine the energy inputs required for crushing and grinding. These tests can be performed by a metallurgical testing laboratory or by sending samples to equipment suppliers. The following tests are recommended:

- Drop shatter
- Hargrove grindability

- Abrasion index testing
- Bond crushing work index or JK drop weight test
- Bond rod mill index
- Bond ball mill work index
- Signature plot and/or jar test

Flotation Tests: Flotation tests should be performed on freshly ground coal samples to avoid oxidation of the particle surfaces which will adversely impact flotation performance. These can be performed as part of a metallurgical laboratory suite of testing or samples can be sent to different suppliers/technology providers. These tests will assist in determining:

- Flotation behavior of ultrafine feed material
- Suitable flotation technology
- Suitable flotation circuit configuration to achieve required performance (ash and yield) - e.g. rougher-cleaner, rougher-scavenger, and rougher-cleaner-scavenger
- Reagent dosage required
- Froth carrying capacity
- Wash water requirements
- Froth depth requirements

The results of the flotation test work may require an iteration of the grinding work to be done.

The coal grain analysis will provide a target value for liberation size, however, the variability of coal feed and inefficiencies of the flotation process may necessitate a finer grind to be performed to realize the target ash. If this is the case then iterative tests may need to be performed.

Thickening and Dewatering Tests: Both the product (concentrate) and tailings material from the flotation test work would need to be collected to perform thickening and dewatering testing.

Thickener testing will help to determine thickener size, flocculant type and dosage rates. Dewatering test work will help to size the dewatering equipment and assist in selection of the final dewatering technology to use.

Rheology Characterization: To support the sizing and selection of agitators, pumps and piping a range of range of rheology characterization should be undertaken on the key intermediate and final product and tailings slurry streams. This testing will provide information on the deformation and flow behavior of the slurry compositions expected in the plant.

Pilot Plant Operation: The proposed flowsheet utilizes commercially available equipment however for most major equipment, as highlighted the commercial application to coal is novel. It is therefore recommended that following the completion of the above initial laboratory scale analysis, a pilot plant be constructed and operated to provide an indication of the expected continuous performance. A nominal throughput of 1 ton per hour should be considered as basis however the throughput will likely be based upon the size of the equipment commercially available. Often equipment can be leased from one or more laboratory testing companies or equipment suppliers. Evaluation of a suitable location for undertaking the test work should consider the proximity to the feed coal, the disposal method for the tailings/waste, and if the product will be tested/utilized in the same location, i.e. a DICE CRCC pilot plant included with the coal beneficiation pilot plant.

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Section 4 Development Coordination

4.1 OBJECTIVES

There is a need to work in close coordination with the DICE and coal beneficiation process developers. For example, the ash content, sulfur content, rheology, among other beneficiated MRC properties, need to be established between the DICE and coal beneficiation developers.

There must be an objective to develop this coordination under DOE CoalFIRST Critical Components development program. Accordingly, there are two competing “chicken or egg” factors that make a coordinated DICE development approach very difficult:

1. As clearly indicated by the findings of the pre-FEED study, a dedicated “fuel block” with each DICE is clearly not an economically viable proposition

2. Without a readily available fuel supply, DICE technology is a dead end

While the obvious solution to widespread DICE deployment is a centralized “coal-water slurry fuel factory” similar to a refinery producing gasoline or diesel fuel (after all, DICE CRCC is best suited to distributed generation), the question that remains is also obvious:

> *Who would make the investment into such a fuel factory without a readily available market for its product?*

The second obvious question is a corollary of the first:

> *Who would make the investment into DICE technology without a readily available fuel supply?*

Evidently, the two questions can be formed into a single one:

> *What is the market for DICE (or another technology for that matter) firing coal?*

The key problem to this is that unless there is a coordinated effort akin to a “Manhattan Project” to “impose” widespread deployment of a modular, flexible and efficient coal-burning technology such as DICE CRCC for distributed generation applications in a future generating portfolio with heavy contribution from solar and wind energy (and other non-fossil fuel technologies).

Addressing this problem is certainly out of the scope of the pre-FEED study. However, it is still necessary to come up with a coherent approach to develop the technology in a feasible manner to TRL 8 or 9. The key obstacle in this endeavor is still the same, i.e., cost, and ultimately a question of financing.

4.2 DICE DEVELOPMENT PATHWAY

A development pathway is proposed in the context of a revised positioning of the DICE fuel cycle, including:

- Energy security
- High thermal efficiency and lower CO_2/MWh at small unit size
- A new coal replacement for oil, coal and natural gas
- Nimble generation to support variable electricity demand
- Underpinning a high penetration of intermittent renewables (it is the CO_2 intensity of the overall system that is key – not that of the individual technologies)
- A first commercial DICE plant by 2030

Also, the program considers several development imperatives, de-risking by staged development and scale-up risk, discussed per the following:

4.2.1 Development Imperatives

Recent R&D has highlighted development imperatives, which have shaped the proposed development pathway:

1. Securing the commitment of an engine OEM and component manufacturer (e.g., fuel systems).
2. Development of a suitable large engine test facility (i.e. small-scale demonstration engine), which is capable of firing MRC at near commercial scale conditions; for example, an inline 6-cylinder variant of a larger V18 cylinder engine suitable for commercial generation.
3. Small demonstration-scale engine tests to obtain key performance data on combustion, using tonnage lots of consistent and high-quality MRC produced from larger fuel plants.
4. Detailed techno-economic assessment of DICE for different markets to assist with developing engine and fuel targets, and to increase the case for industry commitment.
5. Detailed risk and hazard review to further de-risk the new fuel cycle, identify key technology gaps/showstoppers, and to broaden stakeholder engagement.
6. Duration engine tests to investigate fouling. These tests could be performed using smaller engine tests and a range of adapted boiler test methods, to avoid the need for producing a larger tonnage amount of MRC and the costs of duration operation of the larger test engine.
7. R&D to obtain data for optimizing fuel handling logistics, and to enable engineered systems to be developed for a range of scenarios (local generation, distributed generation, export).
8. Developments in MRC standards, in particular, to account for the wide differences and trade-off in MRC properties between different coals.
9. Developing an outreach program to ensure correct positioning and avoid negativities from coal's past image.

4.2.2 De-risking with Staged Development

While the previous R&D has provided promising findings for a range of technical issues around coal-engine interactions, this work can only provide a *technology readiness level* (TRL) of 4 for most technical aspects. De-risking by increasing the TRL from 4 to 8 in order to justify (e.g. a 50 MWe) commercial demonstration project requires that appropriate small-scale demonstration tests are undertaken – taking full benefit of the many technical improvements over the last 25 years. DICE needs considerable development and demonstration to match the technical development of current power generation technologies. However, this can be cost-effectively fast-tracked. Compared to the incumbent technologies, DICE has strong technical merit because of the ability to carry out a near-commercial scale demonstration at a relatively small size (e.g. 5 MW).

The 5 MW capacity engine-generator can be obtained in skid form, in a straight 6 configuration, giving a cylinder of approximately 400 mm bore and operating at 500 rpm. The simple in-line configuration and fewer cylinders ensure easier and faster incorporation of new components for testing - *essential to shortening development time*. This includes the option of only needing to make changes to one cylinder – which can also be swapped out as a complete power unit in a few hours to facilitate testing.

The data, information, and experience gained from this engine would be directly applicable to a larger semi-commercial demonstration (e.g. a V18 configuration producing 15 MW at 500 rpm). It is envisaged that successful demonstration at this scale would lead to larger commercial installations comprising multiple 15-20 MW engines, as is practiced for gas engine installations. This would not entail any scale-up of DICE. Standard approach to reduce capital cost and to improve overall efficiency is a conventional combined cycle. For higher efficiency, DICE CRCC is the ideal solution.

4.2.3 Scale-Up Risk

The cylinder size, rating and power output from a single engine unit for the proposed development steps to a full-size commercial engine are shown in Table 4-1).

Table 4-1
Scale-Up Factors from Demonstration through to Large Comercial Installation

Development stage	Bore (cm)	Cylinder rating (kWe/cyl)	Cylinders Units	Plant output (MWe)	Scale up
Small scale demonstration	46	1000	6	5-6	1
Demonstration plant	46	1000	18	20	1
First commercial	46	1000	18 5 units	100	1
Large commercial 4-stroke	63	2000	18 5 units	200	2x
Large commercial 2-stroke	94	5000	12 6 units	360	5x

The scale-up factor (based on cylinder area) between the development stages is at most 2-5x, which are relatively small scale-up steps that have low technical risk:

- The scale-ups are considered very conservative by the engine manufacturers – especially if a National Test Facility is available to test the latest developments before deployment
- In contrast to many technologies, DICE has the advantage of being able to undertake near full-scale demonstration at small-scale.
- As cylinder size increases, many of the technical issues associated with firing MRC decrease (e.g., more time and space for combustion allows reduced atomization, and wear effects also decrease).

Overall, it is envisaged that a staged development program could be established with an engine manufacturer and OEMs (e.g. suppliers of injection and turbocharging components) to quickly undertake the demonstration program, to enable commercial deployment by 2030.

4.2.4 Staged Development Program

The recommended program involves 3 stages, which allows sequential de-risking and the development necessary to provide the experience and data required to develop the components to adapt an engine for a demonstration plant. In comparison to other new technologies, DICE has the advantage of being based entirely on relatively small adaptations of existing commercial technology, and at a small scale to drastically shorten the time required to progress from single-cylinder tests through to commercial deployment. The stages and timings are as follows:

Stage 1 (2020-22)	Single-cylinder engine tests - component development, single-cylinder engine tests, logistics and business cases
Stage 2 (2023-26)	DICE test facility and fuel plant (5 MW)
Stage 3 (2027-30)	Semi-commercial DICE plant (20 MW units)

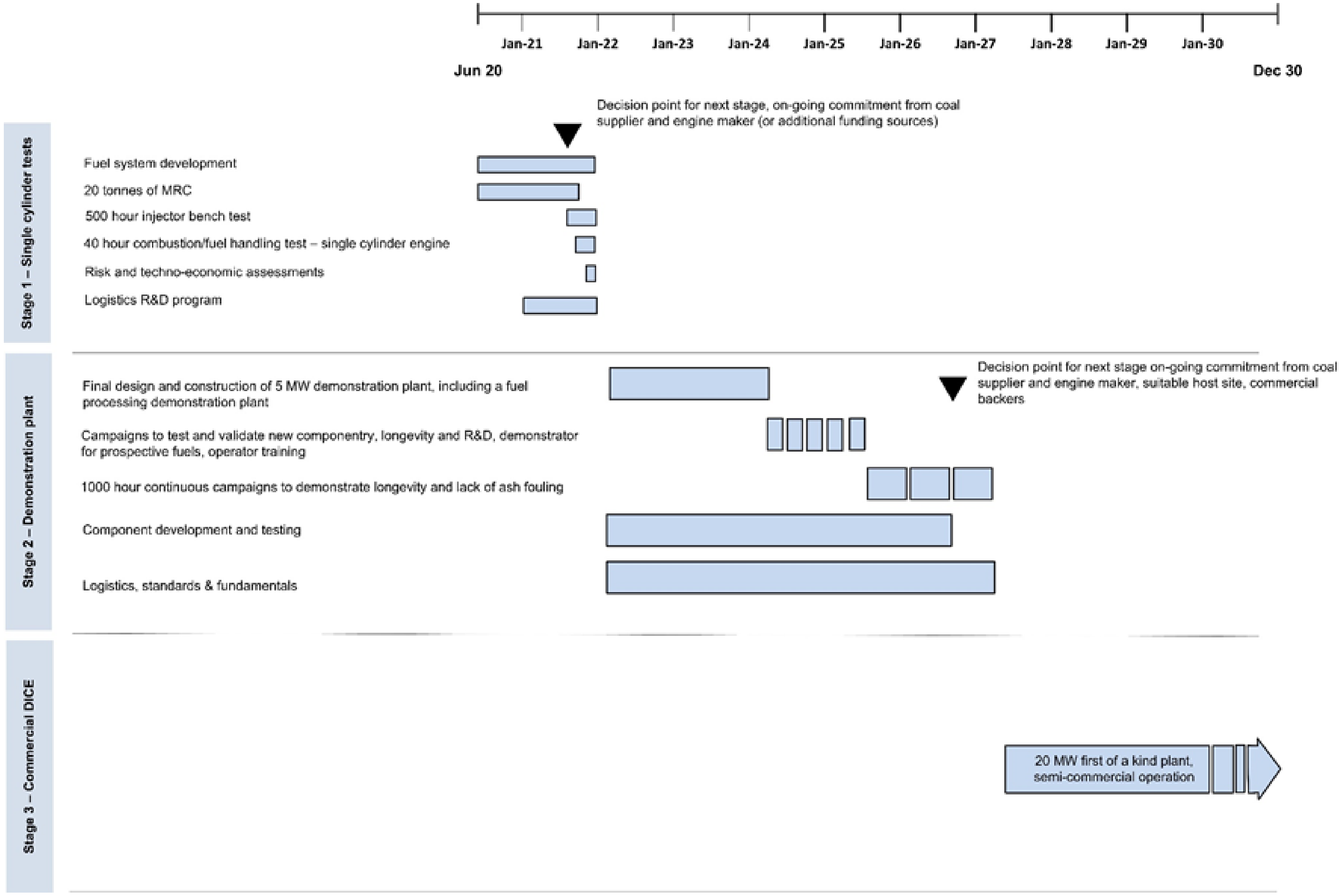
The program timeline is also shown in Figure 4-1, with additional details on the individual activities given below.

4.2.4.1 Stage 1 - Single-cylinder engine tests

These tests will provide both a focus and a framework for the entire fuel cycle, including:

- Processes and experience in the production of (say) 20 mt of suitable fuel
- Negotiation of a trade-off between fuel quality and engine modifications – both for short-term tests and future commercial operations.
- Hands-on experience with producing, handling and storage of bulk MRC fuel
- Fuel quality testing
- On-engine fuel handling experience, including both the low-pressure fuel supply system and the high-pressure injection system
- DICE operating strategy, including startup, operation at various load settings, and shut down with or without system flushing
- Optimizing pilot fueling
- Exhaust emissions
- Duration testing of a new injector
- Preliminary data on ash fouling
- Preliminary techno-economics and risk assessment
- Business case for DICE facility – a shared national facility or consortia owned
- Broadening stakeholder engagement with real data

Figure 4-1
Proposed 3-Stage Development Program



4.2.4.2 Stage 2 – DICE demonstration plant (5 MW)

Development of a suitable engine test facility (i.e., demonstration engine), capable of firing MRC under near commercial scale conditions is essential to development – of both the engine and fuel production.

While all manufacturers are capable of undertaking engine tests in dedicated test cells, to avoid competition for test cell access, it is recommended that either a dedicated test cell is obtained, or a new host site is used close to supporting engineers. Also, while a brake dynamometer is normally used for engine testing, a standard alternator load (i.e., as a genset) can be used with sufficiently accurate information of combustion and engine performance being obtained from cylinder indicator readings. The use of a generator also allows power exports to offset test costs (important for the longer duration tests).

An engine-generator producing around 5-6 MWe is recommended to increase the validity of the test results by demonstrating the technology with a cylinder size suitable for commercial operation – for example, a 6-cylinder variant of the 18V 48/60 engine by MAN.

An engine of this size will require around 6000 liters of fuel per day, equivalent to about 2 t/h of processed coal - which would also ensure MRC production at a reasonable scale.

Engine tests could determine the effects of the following on combustion/heat release, performance, thermal efficiency, lubricant contamination, wear, etc.:

- Engine load
- Cylinder air inlet temperature (by changing coolant flow to the aftercooler)
- MRC coal loading and rheology
- Pilot fuel timing and rate
- Development of operating strategies for starting, warmup, load changing, and shut down (short and long)
- Component durability tests – which could include using different materials and component designs for individual cylinders to provide a quicker and more cost-effective comparison of component performance than using individual test campaigns.
- Emissions as a function of load and fuel properties
- Engine ash fouling
- Turbine abrasion

Additional fuel supply tanks should be available to enable fuel batching to ensure consistent fuel quality for each series of tests.

It is also recommended that a parallel R&D and logistics program be undertaken, including:

- Detailed risk and hazard assessment, to further de-risk the new fuel cycle, identify key technology gaps/showstoppers, and to broaden stakeholder engagement. MRC slurry fuels and new coal combustion equipment will be required to demonstrate no surprises. For example, MRC is finely divided coal, but it is not classified as flammable. Spills can be readily cleaned up with a shovel once the fuel loses a few percent moisture. While MRC looks like oil, spills are less detrimental (see Figure 4-2), and different handling and storage procedures are required.

Figure 4-2
MRC Spill 24 Hours Later (From Hydrothermally Treated Lignite)

- Detailed techno-economic assessment of DICE for different markets to assist with developing engine and fuel targets, and to increase the case for industry commitment. This assessment should include using DICE as both incremental and old replacement capacity at existing coal-fired power plants, as well as for greenfield development.
- R&D to obtain data for optimizing fuel handling logistics, and to enable engineered systems to be developed for a range of scenarios (captive or mine-mouth generation, decentralized generation, centralized generation, export).
- Developing standards and certification to account for the very different properties of MRC compared to fuel oil.
- Developing a detailed business case for commercialization.
- Broadening engagement/outreach. DICE is a potential new (and large) market for both coal suppliers and engine manufacturers and their componentry. However, recent experience has shown that engine manufacturers are generally reluctant to consider DICE due to coal's high CO_2 intensity (at the burner tip) – on top of their business-as-usual competing commercial priorities. It is therefore essential at the outset to establish and clearly articulate both the economic and environmental benefits of DICE to all stakeholders, for example:
    - Nomination as clean coal is no longer enough.

  - DICE allows the novel use of coal to provide the backbone for a nimble, secure, ultra-low emissions power system by underpinning a high penetration of renewables - including the direct use of biomass and renewable ammonia. **It is the performance of the overall system that is key, <u>not</u> the individual technologies, as neither would likely exist without the other.**
  - Also, once DICE is installed it can utilize a wide range of alternative fuels including crude bio-oils, chars and other niche fuels etc – giving many other advantages (increased utilization, reduced processing costs and losses, and the use of bioenergy wastes). These should be quantified using life cycle analysis. Only a streamlined LCA will be required to show the overall benefits. The LCA should be supported by a corresponding techno-economic assessment of the integrated energy cycle.

4.2.4.3 Stage 3 First-of-a-Kind DICE plant – 20 MW

The smallest representative, first of a kind DICE power plant, is likely to be that of a single large 4-stroke engine (say) 20 MWe.

- An engine of this size can be broken down into manageable sections, to enable road transport to most locations.
- Although essentially a commercial operation, it is expected that only limited performance warranties would be provided by the engine manufacturer, but this would be offset via the initial pricing and by close supervision of operation and maintenance by the engine manufacturer (and other equipment suppliers).
- Suitable locations or host sites for the first of a kind DICE plant are envisaged as:
  - Alongside existing pf steam plants to enable sharing of coal supply, logistics, and transmission infrastructure – possibly with the long-term aim of progressively replacing older pf units. This could have an additional benefit of training future operators and maintenance personnel. The MRC plant could also be used to supply light up and low load fuel to the pf plant.
  - A mine-mouth power plant. This location would provide additional economic benefits for the coal miner and allow any lower quality MRC feed coals to be diverted to conventional markets.
  - Alongside a natural gas fired power plant with limited gas supply – with the possibility of switching out/retrofitting existing engines for MRC.

4.2.4.4 Commercialization Approach beyond Stage 3

Following the successful demonstration, rapid commercialization is possible, and likely to be driven by a strong need for incremental coal generation capacity for:

- Replacing old, inefficient and uneconomic PC power plants (say units smaller than 300 MW and/or older than 30 years in plant economic life)
- New load-following capacity to secure a higher penetration of renewables, and in direct competition with gas open cycle plants with gas prices over $5/GJ

- Remote generation, especially for supplying large mines and surrounding regions
- New capacity with CO_2 capture and storage, as DICE has the potential for a 30 percent reduction in the cost of capture over PC coal plants. The cost reduction is due to a combination of higher thermal efficiency (fewer kg CO_2/MWh) and the ability to use 130°C coolant and exhaust heat for stripping
- Once an engine is adapted for DICE it will be capable of handling a wide range of other alternative fuels (i.e. difficult) fuels (for example coal-biochar or coal-ammonia blends, crude bio-oils) which would extend the facilities value past the proposed demonstration, and provide additional environmental incentives for the facility and commercialization of DICE.
- MRC, including higher ash products, could be used to replace fuel oil for boiler light-up and low load operation.

Section 5 Emissions Control Technology

DICE CRCC is a fossil-fuel power plant burning two different types of fossil fuels: coal (in the form of a slurry) and natural gas. Let us address the second fuel first.

In DICE CRCC, natural gas is burned in the reheat combustor upstream of the hot gas expander and/or in the HRSG duct burners. In the introductory variant considered in the pre-FEED study, the reheat combustor is eliminated. Natural gas is the cleanest fossil fuel and is not a significant source of PM, VOC and SOx emissions. In the duct burners, flame temperatures are quite low so that no significant NOx emissions are expected either. Nevertheless, during the field operation, CO production due to flow and combustion instabilities can be a source of CO. In any event, minute amounts NOx and CO generated in the HRSG duct burner are going to be managed by the SCR (downstream in the HRSG). In conclusion, there is no technology gap associated with this fuel, from the perspective of equipment for NOx and CO removal.

5.1 SOX AND HG REMOVAL

PRB is a low-sulfur coal and the elemental sulfur is removed during the beneficiation process. SOx removal is accomplished in the direct contact cooler (DCC) with caustic injection (to cool the flue gas and remove the bulk of the SOx in the flue gas).

PRB coal typically contains less than 1 percent (wt) sulfur and less than 50 ppm chlorine, and the mercury (Hg) is primarily in the elemental form. Due to this reason, it is expected that the coal beneficiation process will remove some or most of the Hg in the coal feedstock. A feedstock sample analysis is requisite in order to provide a concrete estimate. For Hg remaining in micronized refined coal, post-combustion removal from the flue the gas is necessary to meet MATS requirements.

Activated carbon injection (ACI) is the standard method used for removal of Hg from the flue gas in coal-fired power plants. Activated carbon sorbents and high surface area unburned (loss on ignition, or LOI) carbon should be very effective for mercury capture when sufficient halogens (e.g., fluorine (F), chlorine (Cl) or bromine (Br)) or halides such as HCl are present in the flue gas[3].

Activated carbon catalyzes SO_2 to H_2SO_4 in flue gas. The overall mercury adsorption capacity is dependent on the formation of H_2SO_4 on the surface of the carbon. Thus, the capacity of activated carbon for mercury is higher in low SO_2 flue gas such as in DICE CRCC. However low content of chlorine or bromine in the flue gas can render ACI infeasible for application in DICE CRCC. Once again, sample analysis and combustion tests with flue gas chromatography are requisite to provide a concrete answer.

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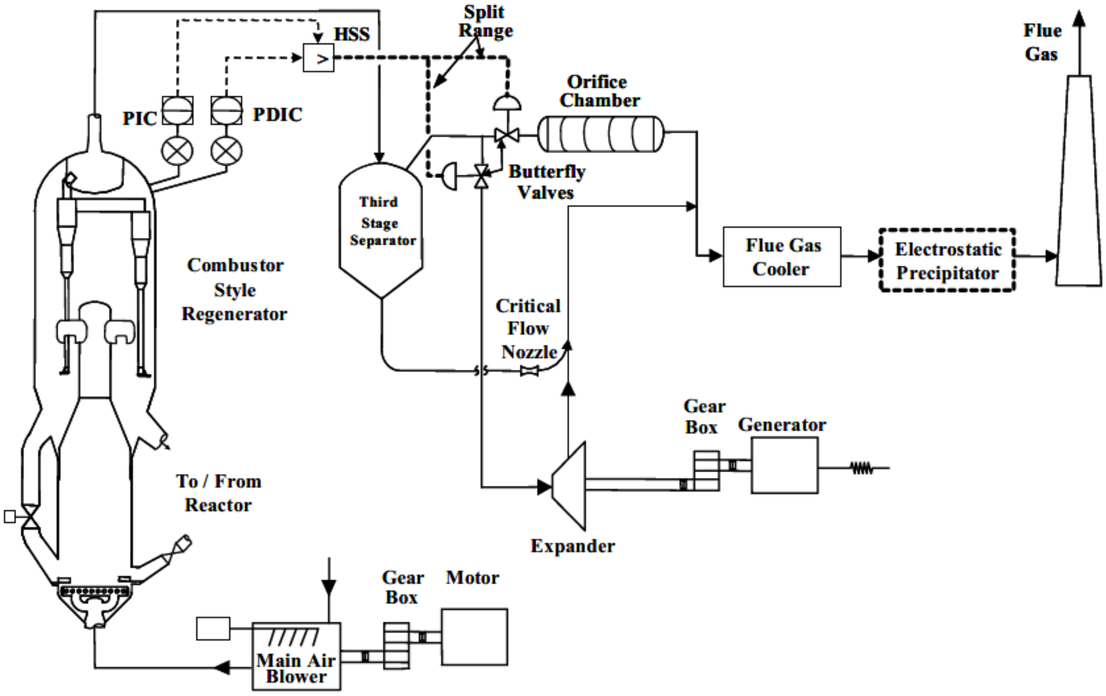
[3] HCl increases the mercury removal effectiveness of activated carbon and fly ash for mercury, particularly as the flue gas HCl concentration increases from 1 ppm to nominally 10 ppm.

In any event, the vanadium-based SCR catalyst used for NOx-control promotes the oxidation of elemental mercury Hg to Hg^{2+} in the flue gas. Hg^{2+} is water soluble and can effectively be captured in a wet scrubber or, in this case, in the DCC.

5.2 PARTICULATE MATTER REMOVAL

Coal burned in the DICE is “cleaned” during the fuel production process to contain low ash and sulfur, sources of PM and SOx emissions, respectively. DICE exhaust gas is scrubbed in a cyclone-type device to reduce PM content for protection of the downstream equipment, in particular, the hot gas expander. Similar devices have been widely used in fluidized catalytic cracking (FCC) of heavy hydrocarbon feeds for separating fine solids from vapor streams exactly for the same purpose, i.e., protection of the hot gas expander downstream (used for power recovery). A typical system is shown in Figure 5-1.

Figure 5-1
FCC Power Recovery System (UOP Honeywell)



It is worth noting that the hot gas expander shown in Figure 5-1 is the same piece of equipment used in DICE CRCC. The equipment used to clean up the particulate matter in the gas coming from the FCC reactor is the “third stage separator” (TSS). In order to understand the use of TSS and its suitability to application in DICE CRCC, an overview of the FCC process is provided.

In the FCC process, catalyst particles circulate between a cracking reactor and a catalyst regenerator. The cracking reaction deposits coke on the catalyst, thereby deactivating the catalyst. The catalyst regenerator burns coke from the catalyst with oxygen containing gas, usually air. Flue gas formed by burning coke in the regenerator is treated for removal of particulates (by the regenerator cyclones) and for conversion of carbon monoxide. Even so, the amount of solid particles in most FCC flue gas streams exiting the regenerator is enough to cause severe erosion of the power recovery turbine (i.e., the hot gas expander) blades. Unfortunately, the PM remaining at this point are exceedingly difficult to recover, having successfully avoided capture despite passing through (typically) two stages of highly efficient cyclones. These particles ("fines") are very small, essentially all of them are below 20 microns, and including significant amounts of submicron to under 5-micron sized material. Thus, a third stage of separation, which can capture these fines is necessary, i.e., the "third stage separator".

The TSS uses a large number of small diameter cyclones because they give much better fines collection than larger cyclones, for the same gas velocity and pressure drop[4]. A schematic diagram of UOP Honeywell TSS is shown in Figure 5-2. FCC regenerator flue gas enters the TSS at the top and passes through a number of small-diameter, high efficiency, cyclonic elements arranged in parallel and contained within the separator vessel. After the catalyst particulates are separated from the flue gas in the cyclones, the clean flue gas leaves the separator. A small stream of gas, called the underflow, exits the separator through the bottom of the separator vessel. In some applications with stringent emission limits, the underflow is directed to an additional separation (i.e., the "fourth stage separator") and collection stage before combining with the clean flue gas.

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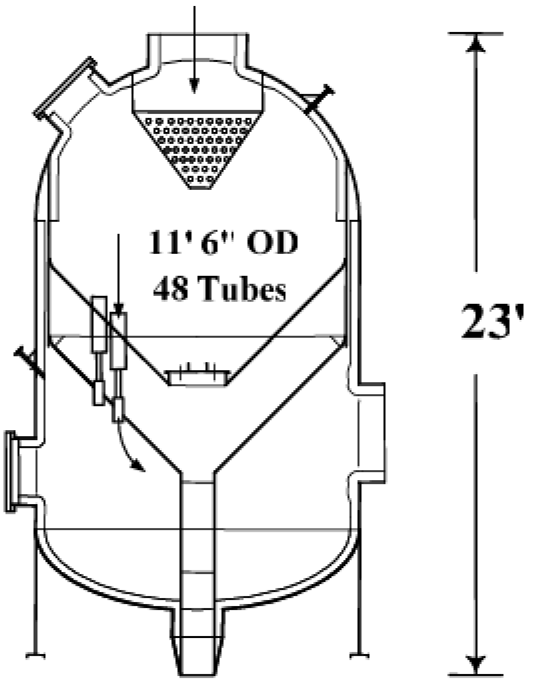
[4] For example, for a 5 to 20-micron dust mixture, dust collection improves significantly as cyclone diameter decreases, i.e., with collection efficiencies for 6, 9 and 24-inch cyclones being 90%, 83% and 70% respectively.

Figure 5-2
UOP Honeywell TSS



As highlighted earlier, the hot gas expander used in DICE CRCC (by Baker Hughes) is the same equipment used in FCC applications. Equipment specification by Baker Hughes regarding PM is shown below (the term "catalyst" refers to the catalyst fines discussed above):

"The warranty is valid subject to the following conditions, to be fulfilled by Purchaser during the four (4) years of continuous operation:

- The catalyst concentration in the flue gas to the expander shall be maintained at less than 100 ppm (by weight)
- The catalyst particle size distribution shall not exceed the values listed below:
    - 99.9 percent less than 12 microns
    - 98.5 percent less than 10 microns
    - 92.0 percent less than 5 microns
    - 75.0 percent less than 2 microns

Typical coal (MRC) water slurry used in DICE has the following ash characteristics:

- 0.2 to 1 percent (w) mineral
- 1.5 to 3 percent (w) total
- With P50 of 10-15 microns and P95 of 70 microns

DICE exhaust gas conditions are around 1,000 °F and 60 psia, which are well within the range typical of FCC applications. For the particular fuel used in pre-FEED performance calculations, particulate loading at the inlet of the TSS would be around 750 to 800 ppm (by weight). Consequently, in order to satisfy the expander requirements, the TSS should be capable of 90 percent reduction.

UOP Honeywell confirmed that the service is similar to the typical FCC application for protecting a hot gas expander. They also confirmed that the temperature and pressure is within our experience range. UOP Honeywell is confident that, even without doing any calculations, they typically can meet the expander PM requirements of 100 ppm and the removal of large particles (<10 micron). However, they also stated that they would need more detailed particle size distribution (PSD) and particle density in order to perform requisite calculations. UOP Honeywell also recommended a more detailed feasibility study to further optimize the TSS design, the turndown strategy, and to further refine the cost estimates. Depending on the scope and what other information is required, a high-level estimate for this study is estimated to be approximately $150,000.

In conclusion, equipment necessary for removal of PM from the DICE exhaust stream does not present itself as a technology gap as such. While the application of the existing equipment in DICE CRCC would be a first, it is clear that what is needed is requisite FEED to pinpoint the final design for the selected feedstock. This may require some testing as is the case with the design of the coal beneficiation system. Remaining fines (100 pm and P90 5 micron or less) will be washed away in the direct contact cooler upstream of the carbon capture block.

Section 6 References

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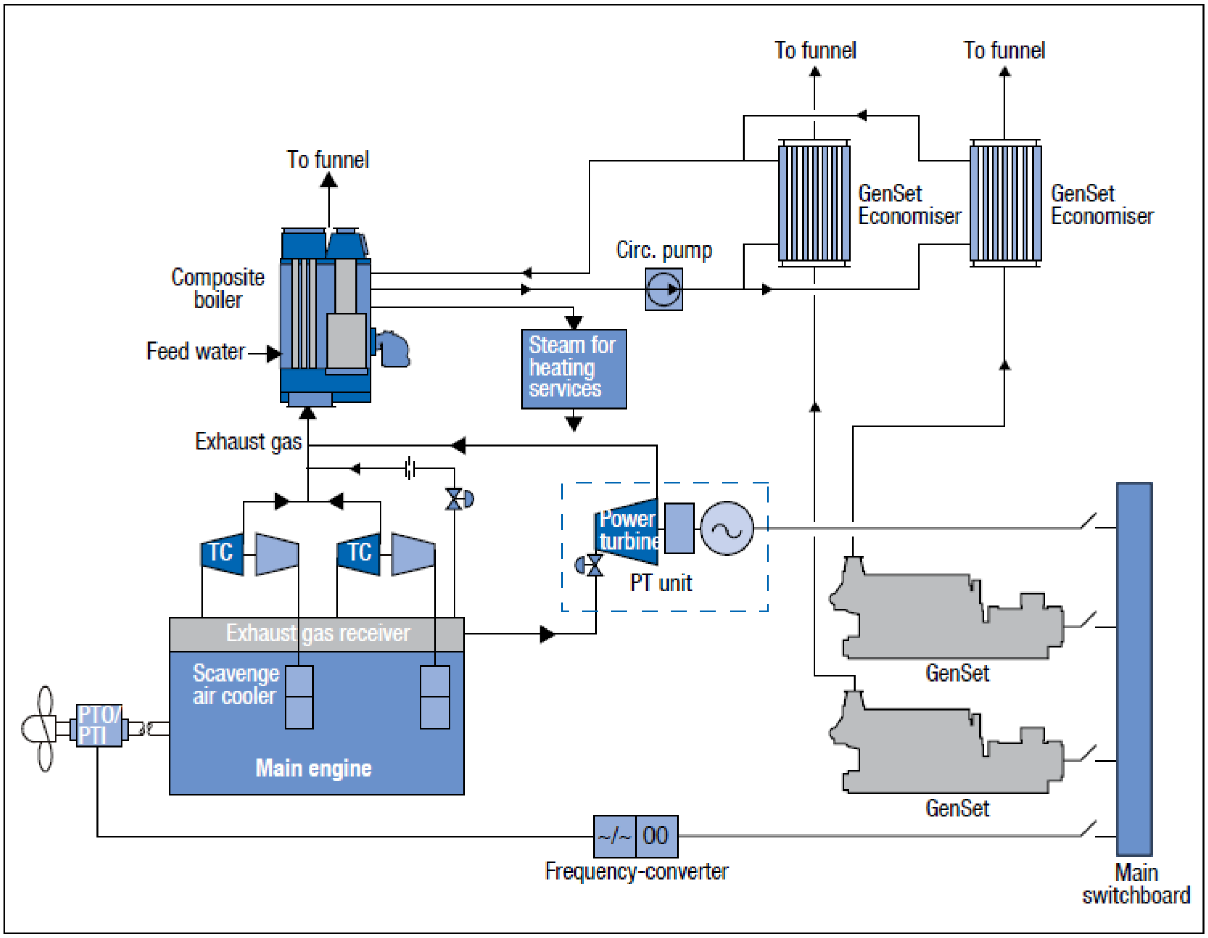
Turbocompounding has a long history going back to 1930s and 1940s for locomotive and aircraft propulsion. MAN Diesel & Turbo installed several turbocompound electric power generation systems about 20 years ago. MAN Diesel & Turbo also developed a turbocompound system for ship propulsion(e.g., see Figure A-1 for the system flow diagram). As shown in the diagram, the hot gas expander (the power turbine) is driven by part of the exhaust gas flow which bypasses the turbochargers. The power turbine produces extra output power for electric power production, which depends on the bypassed exhaust gas flow amount.

Figure A-1
Schematic Diagram of MAN D&T Turbocompound Ship Propulsion System



Appendix B Technology Readiness Levels (TRLs)

Table B-1 contains the detailed descriptions of the USDOE's TRLs.

Table B-1
Detailed Descriptions of USDOE's TRLs

Relative Level of Technology Development	Technology Readiness Level	TRL Definition	Description
System Operations	**TRL 9**	Actual system operated over the full range of expected mission conditions.	The technology is in its final form and operated under the full range of operating mission conditions. Examples include using the actual system with the full range of wastes in hot operations.
System Commissioning	**TRL 8**	Actual system completed and qualified through test and demonstration.	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental testing and evaluation of the system with actual waste in hot commissioning. Supporting information includes operational procedures that are virtually complete. An Operational Readiness Review (ORR) has been successfully completed prior to the start of hottesting.
	TRL 7	Full-scale, similar (prototypical) system demonstrated in relevant environment	This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Examples include testing full-scale prototype in the field with a range of simulants in cold commissioning (1). Supporting information includes results from the full-scale testing and analysis of the differences between the test environment, and analysis of what the experimental results mean for the eventual operating system/environment. Final design is virtually complete.

Technology Demonstration	**TRL 6**	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment	Engineering-scale models or prototypes are tested in a relevant environment. This represents a major step up in a technology's demonstrated readiness. Examples include testing an engineering scale prototypical system with a range of simulants (1). Supporting information includes results from the engineering scale testing and analysis of the differences between the engineering scale, prototypical system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. TRL 6 begins true engineering development of the technology as an operational system. The major difference between TRL 5 and 6 is the step up from laboratory scale to engineering scale and the determination of scaling factors that will enable design of the operating system. The prototype should be capable of performing all the functions that will be required of the operational system. The operating environment for the testing should closely represent the actual operating environment.
Technology Development	**TRL 5**	Laboratory scale, similar system validation in relevant environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Examples include testing a high-fidelity, laboratory scale system in a simulated environment with a range of simulants (1) and actual waste (2). Supporting information includes results from the laboratory scale testing, analysis of the differences between the laboratory and eventual operating system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. The major difference between TRL 4 and 5 is the increase in the fidelity of the system and environment to the actual application. The system tested is almost prototypical.
Technology Development	**TRL 4**	Component and/or system validation in laboratory environment	The basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of ad hoc hardware in a laboratory and testing with a range of simulants and small scale tests on actual waste (2). Supporting information includes the results of the integrated experiments and estimates of how the experimental components and experimental test results differ from the expected system performance goals. TRL 4-6 represent the bridge from scientific research to engineering. TRL 4 is the first step in determining whether the individual components will work together as a system. The laboratory system will probably be a mix of on hand equipment and a few special purpose components that may require special handling, calibration, or alignment to get them to function.

Relative Level of Technology Development	Technology Readiness Level	TRL Definition	Description
Research to Prove Feasibility	**TRL 3**	Analytical and experimental critical function and/or characteristic proof of concept	Active research and development (R&D) is initiated. This includes analytical studies and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative tested with simulants (1). Supporting information includes results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. At TRL 3 the work has moved beyond the paper phase to experimental work that verifies that the concept works as expected on simulants. Components of the technology are validated, but there is no attempt to integrate the components into a complete system. Modeling and simulation may be used to complement physical experiments.
Basic Technology Research	**TRL 2**	Technology concept and/or application formulated	Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytic studies. Supporting information includes publications or other references that outline the application being considered and that provide analysis to support the concept. The step up from TRL 1 to TRL 2 moves the ideas from pure to applied research. Most of the work is analytical or paper studies with the emphasis on understanding the science better. Experimental work is designed to corroborate the basic scientific observations made during TRL 1 work.
	TRL 1	Basic principles observed and reported	This is the lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Examples might include paper studies of a technology's basic properties or experimental work that consists mainly of observations of the physical world. Supporting Information includes published research or other references that identify the principles that underlie the technology.

[1] Simulants should match relevant chemical and physical properties.

[2] Testing with as wide a range of actual waste as practicable and consistent with waste availability, safety, ALARA, cost and project risk is highly desirable.

Source: U.S. Department of Energy, "Technology Readiness Assessment Guide". Office of Management. 2011.

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

VOLUME IV: PERFORMANCE RESULTS REPORT

U. S. Department of Energy (DOE)

Contract No. 89243319CFE000025, Coal-Based Power Plants of the Future

By

Nexant, Inc

and

Bechtel Power and Infrastructure

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Section 1 Technology Overview

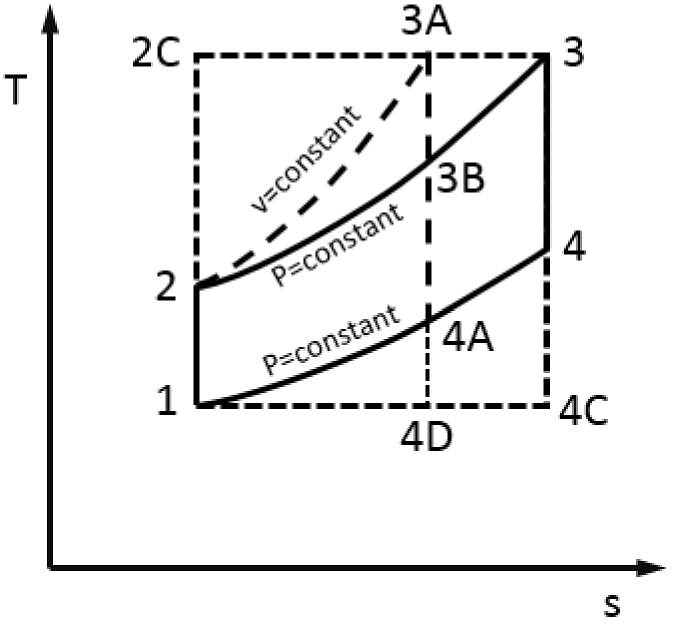
1.1 BASIC OPERATING PRINCIPLE

The fundamental thermodynamic basis behind the Direct Injection Carbon Engine (DICE) Gas Turbine Compound Reheat Combined Cycle (GT CRCC) plant concept is described in detail in the papers and articles by Gülen earlier, e.g., Refs.[1,2]. The thermodynamic cycle of the power plant is a seamless integration and mesh of Atkinson (internal combustion engine) and Brayton (gas turbine) cycles, which combines the two most effective heat engine cycle performance enhancers: constant volume heat addition and reheat. As illustrated in the temperature-entropy diagram in Figure 1-1, the resulting new cycle has six processes (instead of the typical four processes in Carnot, Brayton and Atkinson cycles):

1. Isentropic compression (1 to 2)
2. Constant volume heat addition (2 to 3A)
3. First isentropic expansion (3A to 3B)
4. Constant pressure heat addition (3B to 3)
5. Second isentropic expansion (3 to 4)
6. Constant pressure heat rejection (4 to 1)

This new ideal cycle {1-2-3A-3B-3-4-1} is the thermodynamic basis of the turbocompound-reheat gas turbine cycle. By adding a “bottoming cycle” into the lower triangular area {1-4-4C-1}, cycle waste heat, i.e., heat rejection from 4 to 1, can be utilized for additional work. Thus, one arrives at the *turbocompound-reheat gas turbine combined cycle*.

Figure 1-1
Comparison of CPC {1-2-3-4-1} and CVC {1-2-3A-4A-1} cycles



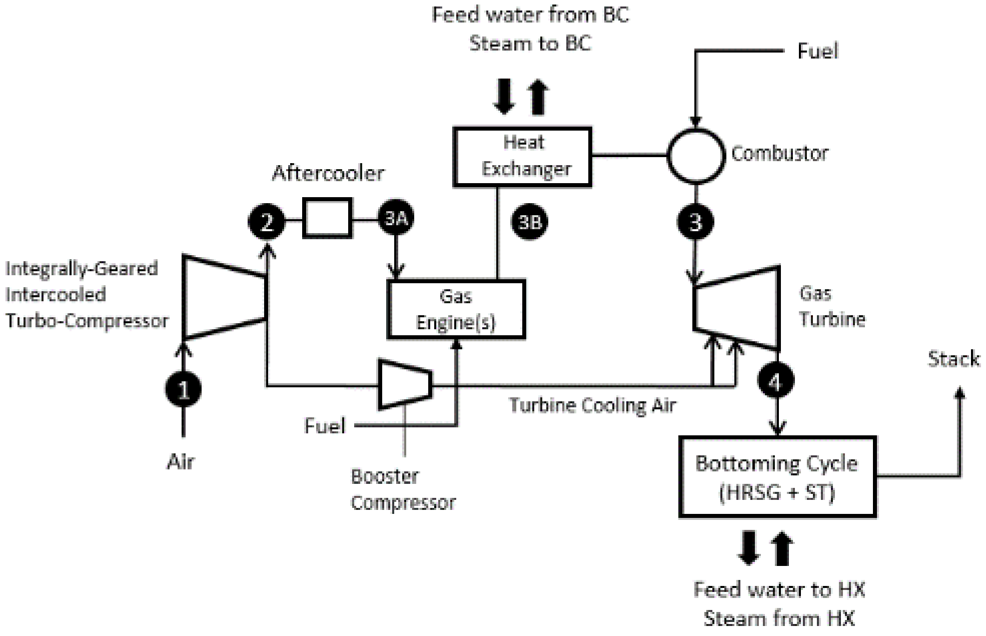
1.2 OVERVIEW OF DICE CRCC SYSTEM

1.2.1 Original Gas-Fired Turbocompound Reheat Embodiment

The original embodiment of the natural gas-fired turbocompound reheat (TC-RHT) gas turbine combined cycle (GTCC) is disclosed in the US Patent 9,249,723 (Gülen, February 2, 2016). It comprises three pieces of major equipment (a simplified system diagram is shown in Figure 1-2):

1. An intercooled, integrally geared centrifugal turbocompressor with an aftercooler
2. Advanced gas engine with the turbocharger removed
3. An industrial (heavy duty) gas turbine with the compressor section removed

Figure 1-2
Simplified Schematic Diagram of Original Embodiment of Turbocompound-Reheat GTCC



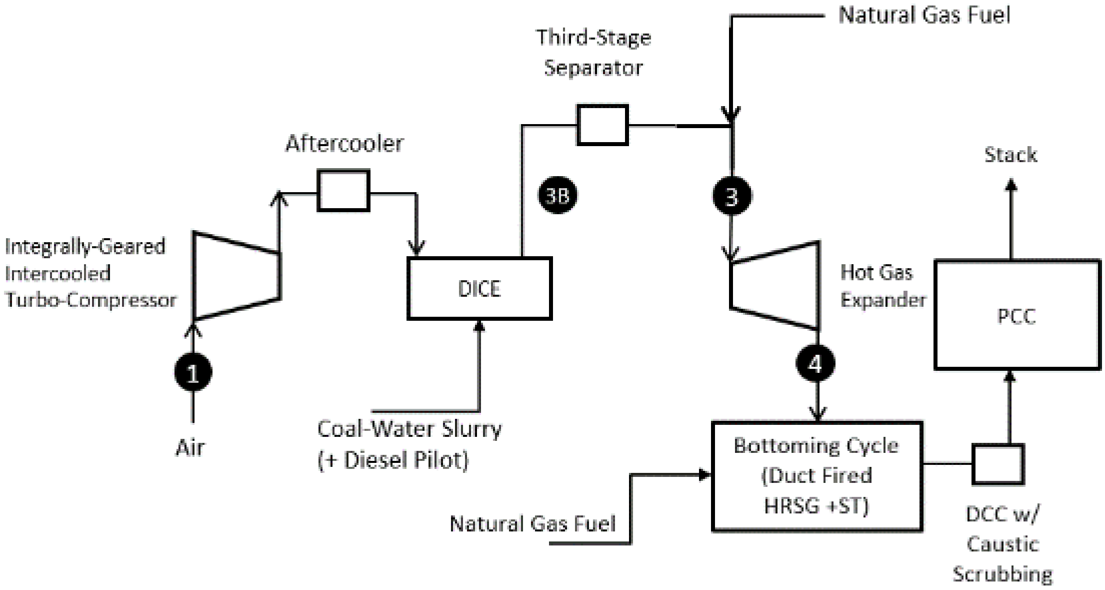
1.2.2 Current Coal-Fired Embodiment

For the pre-FEED design of the coal-water slurry-fired DICE-CRCC, a simplified version is considered for the following reasons:

- Minimum amount of equipment modification
- Shortest possible timeframe from concept to front-end engineering design (FEED) to pilot plant

A simplified system diagram is shown in Figure 1-3.

Figure 1-3
Simplified Schematic Diagram of Coal-Fired DICE CRCC with Hot Gas Expander and Duct-Fired HRSG



Compared to the original embodiment as shown in Figure 1-2, this system has the following differences:

- The heat exchanger between the DICE and the hot gas expander is eliminated
- The reheat combustor and gas turbine are replaced with a hot gas expander due to the following constraints:
  - Limited availability of oxygen in DICE exhaust gas (roughly 10 percent by volume)
  - Necessity for supplementary firing in the HRSG to generate sufficient steam to meet the demand of the stripper reboiler in the post-combustion capture (PCC) block, which required supplementary air to make up for oxygen spent in the reheat combustor
  - The cap put on non-coal fuel consumption (maximum 30 percent)
- Duct-firing heat recovery steam generator (HRSG) is utilized to meet steam demand of PCC system
  - In the presence of diesel pilot fuel in DICE (roughly 5 percent of DICE heat consumption), no supplementary air is supplied to the HRSG duct burner. This would otherwise have made satisfaction of less than 30 percent non-coal fuel consumption requirement impossible to meet with the reheat combustor. The resulting system is simpler and cheaper with very low impact on plant efficiency.
- Particulate matter (PM) removal is achieved with the presence of the "third-stage separator" (TSS) downstream of the DICE exhaust
- SOx scrubbing is achieved in a *direct contact caustic scrubber* with sodium hydroxide Na(OH) injection along with flue gas cooling to meet the CO_2 capture absorber requirements
- 90 percent of the CO_2 in the HRSG exhaust is captured using a standard 30 wt% MEA-based chemical absorption-desorption process

As shown in Figure 1-3, air compressed in the turbocompressor is sent to the DICE engine intake after being cooled in an aftercooler to a suitable temperature (~120 °F). Since the charge air is already compressed at the engine air intake, there is no need for the engine turbocharger.

Multiple DICEs, operating in parallel, burn MRC slurry to generate power. The DICE exhaust gas temperature, expected to be between 575 and 600 °C, is sent to the hot gas expander for power generation.

The bottoming cycle is a Rankine steam cycle comprising an HRSG and a steam turbine generator with the balance of plant (BOP) including a backpressure steam turbine, myriad pipes, valves, pumps and heat exchangers. The HRSG is a waste heat recovery boiler utilizing hot gas turbine exhaust gas to make steam. Duct firing of natural gas in the HRSG is required in order to generate enough steam to meet the demand of the PCC system.

Superheated steam generated in the duct-fired HRSG is first 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 to complete the cycle.

The flue gas leaving the HRSG contains about 300 ppm of SOx. If left untreated, this high level of SOx in the flue gas will cause unacceptable levels of amine degradation in the PCC unit. The flue gas therefore is desulfurized in a direct contact caustic scrubber, a packed bed column that uses caustic to reduce the SOx content in the flue gas to less than 10 ppm and reduce amine losses in the downstream PCC unit, while also cooling and condensing water from the flue gas.

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 leaves 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.

Section 2 Coal Beneficiation

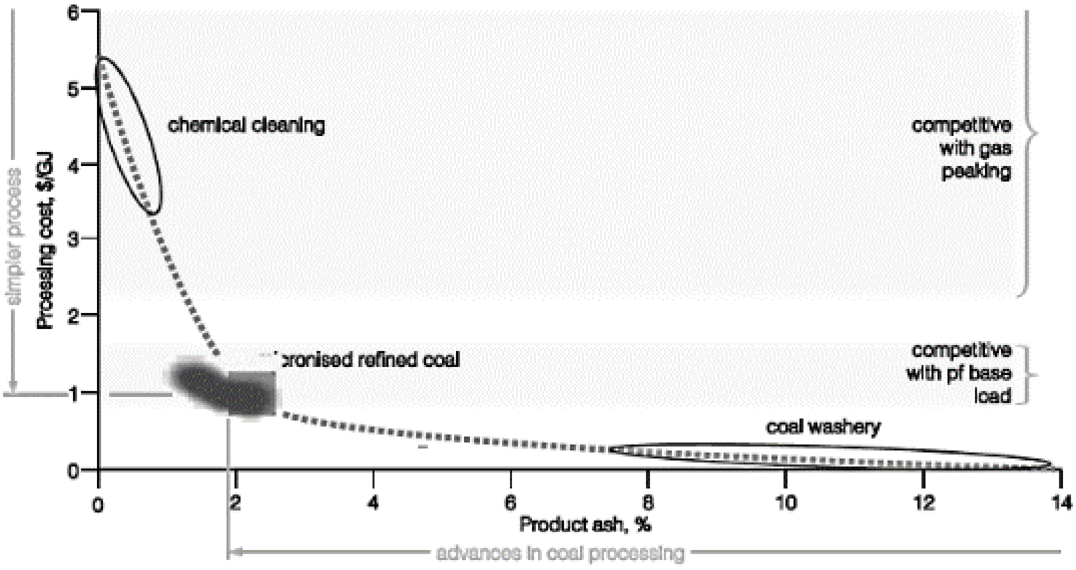
2.1 INTRODUCTION

The fundamental technical and operational challenge in modifying a standard reciprocating internal combustion engine (RICE) – designed for liquid fuel (e.g., heavy fuel oil, HFO) – for coal-fired operation is to protect the mechanical moving parts of the engine that are exposed to either the coal-water fuel (which is abrasive) or the solid particulate products of combustion, which contain both ash and traces of unburned coal. The objective is to ensure acceptable engine life as well as reliability, availability, and maintainability (RAM) without excessive operating and maintenance (O&M) costs.

Coal cleaning/washing, commonly referred to as “beneficiation”, can be “physical” (e.g., froth flotation, selective agglomeration and dense medium separation) or “chemical” (i.e., using solvents). The purpose of beneficiation is to reduce the ash content of the coal fuel to a level acceptable to the engine.

Earlier US DOE work (Clean Coal Diesel Demonstration Project) concluded that coal with 1 to 3 percent (by weight on a dry basis) ash was suitable for DICE [3]. Wibberley reports that, after collaborating with MAN in DICE development R&D in Australia (under the auspices of CSIRO), 1 to 2 percent was deemed acceptable as long as one could live with the trade-off between processing cost and engine and maintenance costs [4]. This is dramatically illustrated by the chart in Figure 2-1 (from [5], original work done by Wibberley in 2013).

Figure 2-1
Product Ash (Dry Basis) of Coal Beneficiation Techniques with Cost



Micronized Refined Coal (MRC) in Figure 2-1 refers to finely ground low ash carbons in a slurry, which is similar in consistency to acrylic paint. For effective atomization when injected into the DICE cylinder, MRC should have a maximum size of around 50 microns and a beneficiated coal solids concentration of at least 55 percent (i.e. 45 percent water). The average (P50) size is less than 20 microns.

There are a variety of MRC production processes, which are described in some detail in other reports [5]. In generic terms, for high rank coals, the process comprises (in the order listed) [6]:

- Washing
- Micronizing (fine grinding/milling)
- Froth floatation (deashing)
- Partial dewatering to 55 wt% coal MRC

(Micronizing before deashing instead of before injection avoids fuel contamination by the grinding media)

In order to fully understand the coal beneficiation process, as well as the associated technology gaps and risks involved in building a commercial-scale coal-water slurry (CWS) processing plant to serve the needs of the DICE CRCC, the project team has contracted a company with past experience in DICE technology, **Sedgman** (www.sedgman.com). Sedgman has been involved with the **DICEnet**[1] (www.dice-net.org) for a number of years and has previously investigated this process for the coal beneficiation facility in Australia.

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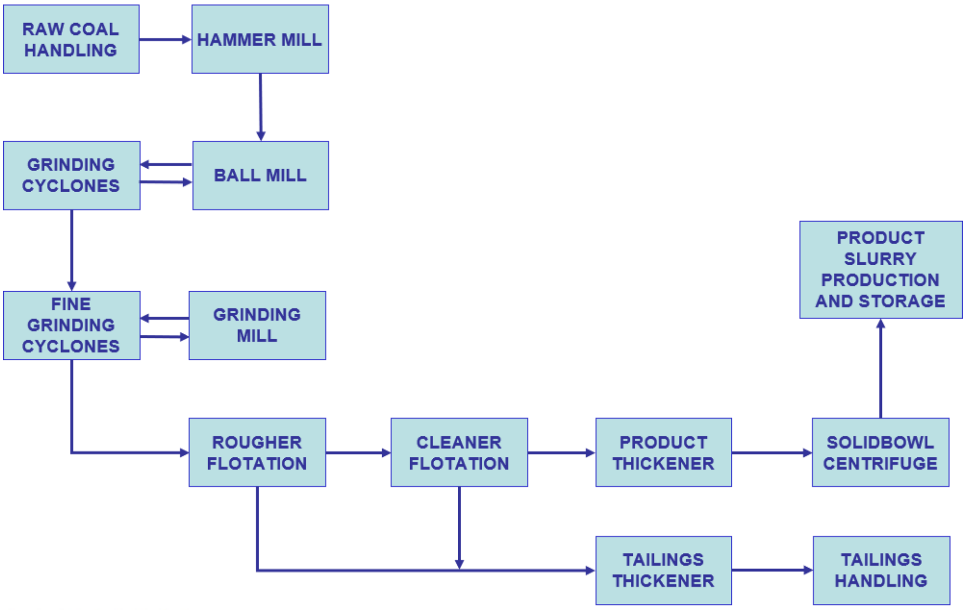
[1] DICEnet was established in March 2013 to support DICE development internationally, including pilot and demonstration projects with Generation 3 technology, and R&D for Generation 4

2.2 PROCESS DESCRIPTION

Sedgman utilized its experience in coal and mineral processing technology to investigate various options for design of the MRC plant. A simplified process block diagram of the coal preparation plant is shown in Figure 2-2.

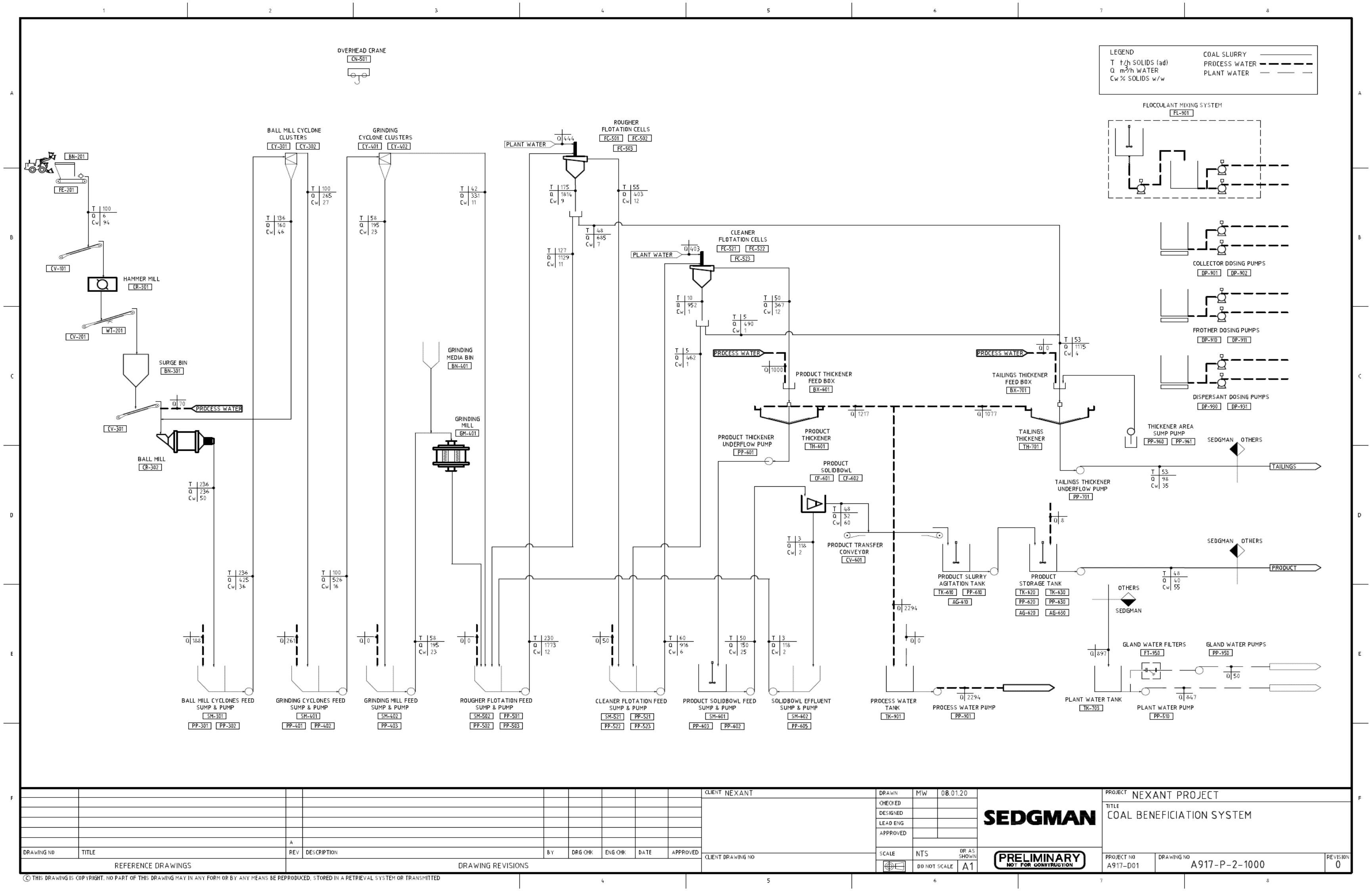
Figure 2-2
Coal Preparation Plant Simplified Block Flow Diagram



A more detailed process flowsheet is shown in Figure 2-3. This scheme was selected for the study as it was considered the most robust, given that it allows for full grinding of the plant feed and is suitable for processing a broad range of feed quality. It consists of the following processes:

- Feed coal receiving and handling
- Hammer mill first stage size reduction
- Ball mill second stage size reduction
Vertimill (tower mill) fine grinding
- Two-stage (rougher/ cleaner) flotation
- High-rate thickeners for both product and tailings
- Solid bowl centrifuge dewatering of product
- Baffled and agitated tanks for product slurry storage

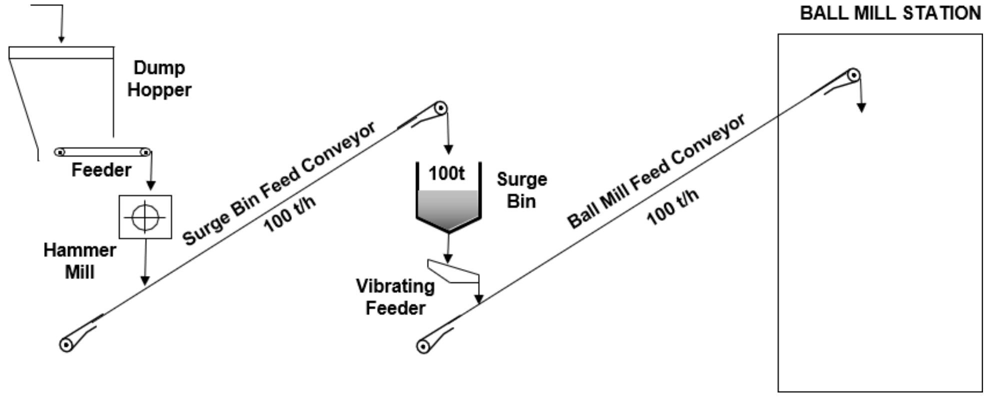
Figure 2-3
Coal Beneficiation Plant Process Flowsheet



2.2.1 Feed Coal Receiving and Handling

The feed coal receiving and handling arrangement is presented in Figure 2-4. The feed coal is loaded from the feed coal stockpile into the dump hopper by a front-end loader. Material in the hopper is drawn out of the hopper by a belt feeder and transferred to the hammer mill.

Figure 2-4
Raw Coal Handling Diagram



2.2.2 First Stage Size Reduction

Based on the feed coal size distribution and the possible reduction ratios of conventional size reduction equipment, two stage size reduction was deemed necessary. The recommended equipment for this application is to use a hammer mill as primary size reduction, followed by a ball mill to reduce the top size of the grinding mill feed material to a P80 of 93 µm. Hammer mills are proven technology which can produce the required primary size reduction down to a P80 of 13 mm at the required throughput with suppliers confirming that capability. A typical hammer mill is shown in Figure 2-5. Fines generation which is typically of concern in a coal washing plant are not an issue here and are encouraged to assist the grinding circuit.

Figure 2-5
Typical Hammer Mill Installation

2.2.3 Secondary Size Reduction

The hammer mill product top size is suited to a ball mill for secondary size reduction. Ball mills are a common method of impact grinding and have proven capability of producing the required discharge particle size distribution. A typical ball mill is show in Figure 2-6.

Figure 2-6
Typical Ball Mill Installation

2.2.4 Primary Grinding Classification

The ball mill will be required to operate in closed circuit with classifying cyclones. The cyclones are used for size separation and to ensure no oversize material is fed through to the regrind mill.

Ball mill product is pumped to the ball mill grinding cyclones. The cyclones will separate the coal slurry based on particle size at a cut-point of 93µm (P80). Undersize material will continue on to the regrind mill, while oversize material will be directed back to the ball mill feed for further size reduction.

2.2.5 Fine Grinding

The regrind mill will provide the final stage of size reduction, to the desired P100 of 50µm for ash flotation. Stirred mills are a method of wet grinding that are proven to be highly efficient when very fine grinds are required. For this application, a VXPmill will be suitable for achieving the desired level of grinding at the specified throughput. This mill is a medium intensity mill running at higher speed than a Vertimill but lower speeds than and IsaMill. A typical VXPmill is shown in Figure 2-7.

Figure 2-7
Typical VXPmill Installation

The selection of the most suitable fine grinding technology will depend on a number of factors/requirements including:

Required product size (P_{80})

For a given feed size, as the required product sizing gets finer, the energy requirements increase, with some technologies being more suited to ultrafine grinding than others. For the 50 µm product size requirement for this project, rod mills will not be suitable as they have difficulty generating product less than 1mm (1000 µm). Further, rod mills require in excess of 30 percent more power than ball mills performing the same duty. Suitable technologies for this product size include tube mills, stirred mills and tower mills.

Feed sizing (F_{80})

Different milling technologies have different maximum feed sizes that they can handle, depending on the required product size. Some tower mills require very fine feed size (1 mm or less) which typically would require multiple additional crushing and grinding stages to prepare the feed, adding to circuit complexity and maintenance requirements and capital cost.

Grinding efficiency

The amount of energy required to reduce particle size increases as the particle size decreases. The energy requirement to attain the desired PSD can vary depending on the method of grinding employed and ultimately the grinding efficiency. Two common methods are impact (e.g. Ball mill, Tube mill, SAG mill) and attrition (tower or stirred mills). Typically, impact mills are less efficient for very fine grinding as energy is lost through media impact, noise and the energy required to rotate the shell to lift the media compared to slower moving attrition mills.

Other factors that impact on grinding efficiency include: slurry flow rate, slurry density, and slurry rheology all of which can be controlled to a certain extent.

Operating Costs

Energy is by far the most significant operating cost of any mill, however, other items also contribute to the ongoing operating costs, including wear liners and grinding media. Typically, attrition mills will have reduced wear on liners as they do not operate by impact of media on the ore. The mill operating speed will impact the liner and media wear rate as well as its grinding efficiency and is dependent on the technology selected. Additional testing is recommended to show which technology provides the optimal balance for this application.

2.2.6 Fine Grinding Classification

For this application, the VXPmill will operate in an open circuit with classifying cyclones. Classifying cyclones are used for size separation to ensure limited oversize material is fed through to the flotation circuit. While this is not catastrophic, it will likely impact the final ash content.

Ball mill cyclone cluster overflow is pumped to the fine grinding cyclones. These cyclones separate the material based on particle size at a cut-point of 32µm (D95). Undersize material continues to the flotation circuit, while oversize material is recycled to the VXPmill for a final stage of grinding.

Whether the fine grinding cyclone must operate in closed or open circuit with the fine grinding mill is dependent on the technology selected and must be considered in any further technology trade-off.

2.2.7 Ash Removal

The most efficient method for ash removal from the feed material will be dependent on the optimal size requirement. For the purposes of this study, it is assumed that the feed material will need to be reduced to a liberation size that would require flotation as the only feasible conventional processing method.

Operation of the flotation cells have a number of variables that can be adjusted to obtain the required product quality. These include; reagent dosage, froth depth and wash water rate.

There are a number of different flotation technologies available which have different energy and reagent input requirements. Regardless of the technology chosen, flotation of such fine coal to such a low concentrate ash will have the following issues which must be addressed/determined:

Froth carrying capacity

Carrying capacity is the rate at which material can be removed from the cell (t/h/m^2 cell area). Ultrafine coal typically has a very low carrying capacity compared to ‘standard’ coal flotation (at most half the value). This will invariably lead to a larger number of cells required to process the material.

Froth washing

To achieve the low concentrate ash, froth washing will be required. High ash slimes will invariably be present in the concentrate with such a fine feed after being liberated in the grinding circuit as it is carried with water into the froth. The best method of removing this material is to wash the froth with clean water. This involves running the cell with a relatively deep froth at depth of 1 to 1.5 m (3 to 5 ft).

Multiple stages

Even with froth washing, it will be necessary to have multiple stages of flotation to achieve the desired ultra-low ash content in the product coal. This will be a cleaner stage which would re-float the concentrate from the first stage (roughers) to allow additional ash removal. The requirement for this would depend on the quality of the feed. A low ash fines feed may not require a second cleaning stage.

Note that if a relatively coarse sizing (e.g. 250-500 micron) is possible to achieve the required ash content, then cheaper processing technologies e.g. spirals, reflux classifiers, could be employed. These technologies do not require any additional reagents and typically require less circulating water volumes and pumping requirements, resulting in operating cost savings.

2.2.8 **Dewatering**

The use of flotation as the main processing technology for this material results in a slurry product of relatively low solids concentration (approximately 12 wt%) whereas the solids concentration in the final coal water slurry product is 55 wt%. Dewatering of the flotation product is therefore required to reach the desired final slurry concentration.

The philosophy to dewater the MRC product to a higher solids concentration than required in the final slurry to allow a controlled addition of water (and dispersant) to be added back in so that the target solids concentration can be obtained.

Fortunately, due to the low ash content of the product (and given the relatively good quality feed to the system, medium level ash of the tailings), dewatering behavior of the material is not expected to be impacted by excessive slimes or clays, which are detrimental to dewatering performance. However, given the ultrafine size of the material in the plant, dewatering is still a relatively high intensity process to achieve the required moisture.

At this size, the most common dewatering methods are plate and frame filters, belt press filters, screen bowl centrifuges and solid bowl centrifuges. Sedgman evaluated each of these ultrafine dewatering systems on a qualitative basis and provided a high-level comparison of these technologies as shown in Table 2-1.

Table 2-1
Dewatering Technology Comparison

	Assessment Criteria*							
Technology	Product Moisture	Fines Loss	Flocculant Dosage	Continuous Production	Footprint	Maintenance	Circuit Complexity	Total
Solid bowl Centrifuge	3	3	3	1	1	1	1	**13**
Screen bowl Centrifuge	2	4	2	1	1	2	2	**14**
Plate and Frame	1	1	1	4	1	4	4	**16**
Belt Press Filter	4	2	4	1	4	3	3	**21**

*1 = best, 4 = worst

From the comparison table, the solid bowl centrifuge technology, as depicted in Figure 2-8, was deemed the most favorable. It should be noted that this evaluation was conducted in the absence of any test data, and that test work on the various dewatering processes, including items such as flocculant dosage and equipment footprint would need be carried out with the slurry product in order to verify this finding and indicate the specific capacity of the equipment.

Figure 2-8
Typical Solid Bowl Centrifuge Installation

All these technologies will require some form of pre-thickening of the feed to help improve dewatering efficiency and minimize the size of equipment required. Therefore, a high rate thickener needs to be installed upstream of the selected dewatering equipment. A typical thickener installation is shown in Figure 2-9.

Figure 2-9
Typical Thickener Installation

2.2.9 Slurry Preparation

Product material is discharged from the solid bowl centrifuges to a product transfer conveyor, which in turn deposits the material into the product slurry agitation tank. It is likely that a dispersant will be added to the slurry to keep the solids in suspension for extended periods before usage. Product slurry is then pumped into one of two product storage tanks.

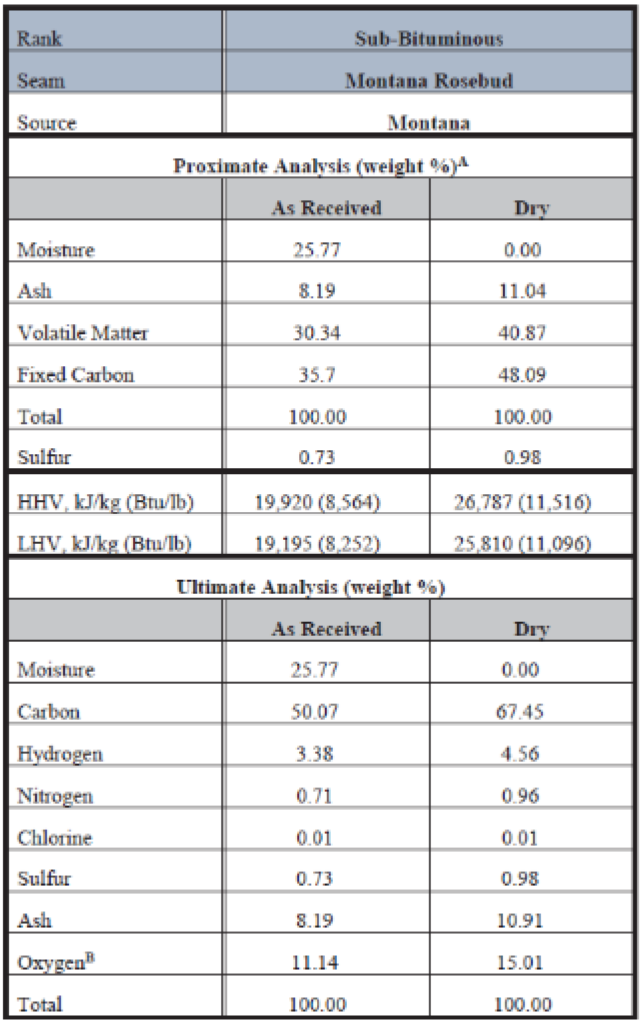
Once the slurry mixture has been created, moving this material to long term storage will require pumping, however, the high solids concentration of this material make the use of conventional centrifugal pumps unlikely to be viable. A progressive cavity or positive displacement pumping technology will likely be required. Viscosity testing of the final slurry material will be required to determine the best pumping technology for this material.

2.3 COAL BENEFICIATION PROCESS PERFORMANCE

2.3.1 Beneficiated Product Yield

The study coal is low-sulfur, subbituminous PRB coal (a low rank coal) with proximate and ultimate analysis as summarized in Table 2-2.

Table 2-2
Design Basis Coal Analysis



Rank	Sub-Bituminous	
Seam	Montana Rosebud	
Source	Montana	
Proximate Analysis (weight %)^A		
	As Received	**Dry**
Moisture	25.77	0.00
Ash	8.19	11.04
Volatile Matter	30.34	40.87
Fixed Carbon	35.7	48.09
Total	100.00	100.00
Sulfur	0.73	0.98
HHV, kJ/kg (Btu/lb)	19,920 (8,564)	26,787 (11,516)
LHV, kJ/kg (Btu/lb)	19,195 (8,252)	25,810 (11,096)
Ultimate Analysis (weight %)		
	As Received	**Dry**
Moisture	25.77	0.00
Carbon	50.07	67.45
Hydrogen	3.38	4.56
Nitrogen	0.71	0.96
Chlorine	0.01	0.01
Sulfur	0.73	0.98
Ash	8.19	10.91
Oxygen^B	11.14	15.01
Total	100.00	100.00

Sedgman made the following assumptions in estimating the composition of the beneficiated coal product and reject tailings based on the process described in Section 0. The estimation effort was based on Sedgman's work done during the DICEnet collaboration and from its overall experience in coal and mineral processing technology.

- The coal feed is sub-bituminous Montana Rosebud, as shown in Table 2-2
- The beneficiated coal product is upgraded to 2% ash on a dry basis (db) and its sulfur content is reduced by 20 percent
- For mass balance purposes, the remaining components related to the organic part of the coal including C, H, N, O and Moisture retain the same proportions in both the product and reject material as in the original feed

- Mass balance calculations from an open circuit mill show a 47.5 percent beneficiated product yield on an *as received* (ar) basis, or 45.8 percent yield on a dry basis
- Final MRC slurry composition is 55 percent dry coal solids and 45 percent moisture
- The calculation methodology entails the following steps:
  - Feed ultimate = Feed (ar) from Table 4-1
  - Feed adjusted to dry basis
  - Product ash set to 2 percent (db) and S set to 80 percent of Feed S percent (db)
  - Product adjusted to (ar) basis after feed moisture is adjusted for ash and S changes
  - Reject (ar) calculated for each component according to yield percent (ar)
  - Reject (db) calculated for each component according to yield percent (db)
  - Check calculation for Reject (db) from Reject (ar).

Table 2-3 shows the calculated Ultimate Analyses for the Feed, Product and Reject streams.

Table 2-3
Ultimate Analysis Calculations for Feed, Product, and Reject Streams

Component	Feed ar (%)	Feed Dry (%)	Prod Dry (%)	Prod ar (%)	Reject ar (%)	Reject Dry (%)
C	50.07	67.45	74.53	53.31	47.14	61.48
H	3.38	4.55	5.03	3.60	3.18	4.15
N	0.71	0.96	1.06	0.76	0.67	0.87
S	0.73	0.98	0.79	0.56	0.88	1.15
Cl	0.01	0.01	0.01	0.01	0.01	0.01
Ash	8.19	11.03	2.00	1.43	14.31	18.66
Moisture	25.77	0.00	0.00	28.47	23.32	0.00
Oxygen	11.14	15.01	16.58	11.86	10.49	13.68
Total	100	100	100	100	100	100

Table 2-4 shows the estimates of the beneficiated coal product and tailings reject energies on both a dry and an-as received basis. The combustible recovery rate is about 50.5 percent on an HHV basis. The beneficiated coal product in final slurry form consists of 55 wt% coal solids and 45 wt% moisture. The resulting MRC fuel composition is listed in Table 2-5.

Table 2-4
Energy Estimates of Beneficiated Coal Product and Reject

			Product	Reject
Dry basis	HHV	kJ/kg	29535	24409
		Btu/lb	12715	10509
Ar basis	HHV	kJ/kg	21125	18719
		Btu/lb	9094	8058
	LHV	kJ/kg	19673	17640
		Btu/lb	8470	7594

Table 2-5
Study MRC Composition

	Dry (wt%)	Slurry (wt%)
Moisture	0.00	45.00
Carbon	74.53	40.99
Hydrogen	5.03	2.77
Nitrogen	1.06	0.58
Chlorine	0.01	0.01
Sulfur	0.79	0.43
Ash	2.00	1.10
Oxygen	16.58	9.12
Total	100.00	100.00

For the 100 MWe DICE CRCC power plant, 642 MMBtu/hr (HHV) of MRC feed is required. This translates to about 92,000 lb/hr of MRC slurry at 55 wt% solids/45 wt% moisture. On a dry basis, this is about 50,600 lb/hr of beneficiated coal product. At the stated recovery rate of 45.8 percent (dry) or 47.5 percent (as-received), the coal beneficiation plant therefore has to process about 149,000 lb/hr of as-received PRB coal.

2.3.2 Beneficiation Plant Power Consumption

The estimated power demand for the coal beneficiation plant is shown in Table 2-6 and totals about 5.5 MWe. The power to the plant will be supplied by the DICE CRCC plant, thus reducing the net output of the plant.

Table 2-6
Coal Beneficiation Auxiliary Load Breakdown

COAL BENEFICIATION PLANT AUXILIARY LOADS	**kWe**
Hammer Mill	240
Ball Mill	800
Grinding Mill	2,800
Grinding Cyclones Feed Pumps	44
Flotation	288
Dewatering	529
Slurry Transfer and Storage	333
Miscellaneous	438
TOTAL AUX LOAD	**5,472**

Section 3 DICE System Design

3.1 CONCEPTUAL DICE PLANT BACKGROUND

The following section details the conceptual DICE power plant based on the current understanding of the technology, and how large 4-stroke medium speed diesel engines could be adapted for DICE.

3.1.1 Base Engine Choice

Although a wide range of engines has been used for MRC coal slurry fuels, including up to 1,900 rpm in the earlier US DOE program, it is generally accepted that the lower speed engines are most suitable:

- Low-speed two-stroke marine type engines (10-100 MW at 90-120 rpm), as depicted in Figure 3-1. Note that the latest super long-stroke versions of these engines (~60 rpm) are considered less likely to economic for land-based generation due to the cost of the alternator, extra weight and foundations required
- Large four-stroke medium-speed engines (20 MW at 400-500 rpm), as depicted in Figure 3-2

Figure 3-1
Low Speed Engine with Generator by MAN (55 MW, 120 rpm)

Figure 3-2
MAN Gas Engine Generators (20 MW, 500 rpm)

Low engine speed is recommended because this increases the time for ignition and combustion which reduces the requirement for fine atomization of the fuel (requiring lower viscosity fuel and higher nozzle velocity). While fine atomization of slurry fuels is technically possible, this comes at the cost of increased atomizer wear.

Low speed engines also have larger cylinder bores which have two important advantages for MRC fuels:

- Allows for longer fuel jets - important for difficult fuels as fuel jets must not impinge on the liner
- Larger cylinder heads/covers provide more space for a dual injection system

An additional benefit of the large, low-speed engines is their longevity and tolerance to lower quality fuels – for conventional diesel engines, this includes the use of residual fuel oils, which contain up to 0.2 wt% of highly abrasive corundum-like catalyst fines. For MRC, this includes increased tolerance to mineral ash content, coarser coal top size and, higher viscosity.

The choice of engine will also be site- and application-dependent. While the low-speed engine has slightly higher efficiency and lower maintenance costs, the cost of these engines is higher at nominally $1,300 k/MW compared to $750 k/MW for medium-speed engines. Overall, installed costs will be location, site, and project-specific.

3.1.2 Recent Developments on Coal-Slurry Fuels Adaptability

Despite being an extremely mature technology, reciprocating engines continue to undergo development that improves suitability for DICE. These developments should result in higher thermal efficiency, higher flexibility, and lower capital cost than for conventional coal-based generation plants. Developments include higher firing pressures (up to 300 bar), electronic control, more efficient turbochargers, new materials for highly stressed components (valve seats, cylinder liner coatings, ring coatings, valve seats/sealing for high-speed gas valves). To some extent, this has been driven by the use of alternative fuels such as biofuels (corrosive), LNG, and bitumen water fuels. For example, electronically controlled (eg MAN ME type) engines are implemented as "intelligent engines" with auto-tune ability for individual cylinders – highly beneficial for maximizing combustion efficiency for MRC.

3.1.3 **Manufacturers**

A range of manufacturers produce lower speed 4-stroke engines (say 500 rpm), which could include derating of 600 and 720 rpm engines.

For large marine-type 2-stroke engines, there are only 3 suppliers – MAN, WING&D and MHI. All of these 2-stroke engines are produced in SE Asia (China, Korea, and Japan) under license. Although MAN is presently the only supplier offering large 2-stroke engines for land-based power generation, other suppliers have expressed interest in producing large low-speed 2-stroke engines optimized for (constant speed) power generation given sufficient need.

While most manufacturers have had some previous negative experiences with coal fulling of engines, all acknowledge that the previous work was undertaken without a high level of commitment, and none of the programs were completed because the expected scenario of oil shortages did not materialize or funding ceased.

Future developments will benefit from recent experience with Orimulsion and MSAR (multiphase superfine atomized residue), previous experiences from the USDOE program for black coals, and more recently by CSIRO's R&D for both black and brown coals and chars.

3.1.4 **Bitumen-Water Fuels as Analogs for MRC**

The use of bitumen water emulsions and slurries in diesel engines provides a good analog for MRC.

Over the last 25 years, there have been several initiatives to produce bitumen water fuels to replace HFO in boilers, and these fuels have also been used in diesel engines. Fuels include Orimulsion produced from natural bitumen and MSAR produced from refinery residue (an extremely heavy tar) - developed as an Orimulsion replacement for diesel engines. While it is a problematic fuel, giving both poor ignition and highly abrasive catalyst fines, it is used as a marine fuel in adapted engines. Also, as the bitumen component of MSAR has a very high viscosity of >106 mPa.s at ambient temperature, it is essentially a slurry of solid bitumen in water and thus is analogous with MRC (especially from bituminous coals).

Wärtsilä has extensive experience with firing Orimulsion into medium-speed 4-stroke engines (including a 40 MW demonstration power plant at Vaasa, and a 150 MW power plant in Guatemala).

Suitable adaptations have been considered by two large engine manufacturers, and examples are shown below, noting that several of these have already been developed for bio-oils. A fuel testing program is underway between CSIRO and Chinese engine manufacturer Zibo Zichai New Energy Co., Ltd to develop fuel specifications and identify a suitable engine for a demonstration plant.

3.1.5 **Humidified Diesel Engines**

A summary of humidified diesel engines is given, as water in fuel is associated with poor thermal efficiency in steam plants, and is not normally associated with diesel engines.

Combustion of fuel-water emulsions is the oldest and easiest method of reducing NOx emissions in diesel engines. In this technology, water is added to the fuel and passed through an emulsifier immediately before injection into the combustion chamber as an effective way of reducing the flame temperature - thereby suppressing the formation of NOx. An efficiency penalty of ~2% (ie an increase of 4% in fuel consumption) is incurred for a water/fuel volume ratio of 0.87 (equivalent to ~50% water in fuel on a mass basis) – which is considerably less than if used in a steam plant.

3.1.6 **Direct Water Injection (DWI)**

Several direct water injection technologies have also been used: Wärtsilä has used this in medium-speed engines, and involves injecting water into the cylinder just before injection of the fuel. Injection rates of 0.4-0.7 kg water/kg of fuel are typically used. Special injectors, comprising separate water and fuel nozzles, are used. The advantage of this system is that the water penalty is substantially avoided as the water spray cools the compressed air charge, thereby reducing compression work.

Mitsubishi Heavy Industries has developed a more complicated version of water in fuel for NOx control. This system is called stratified fuel-water injection (SFWI), and it uses a single injector to inject slugs of fuel-water-fuel sequentially into the combustion chamber to maintain more extended control of peak combustion temperatures.

DWI and SFWI systems generally give a 70% reduction in NOx for a thermal efficiency penalty of 1 1.5% points (around 2-3% on a heat rate basis).

Scavenge air moisturization (SAM) is the most favored system for reducing NOx for the larger low-speed engines and involves humidifying the scavenge air immediately before entering the cylinder with warm seawater or freshwater injected and evaporated into the hot air from the turbocharger compressor to saturate the air to the cylinder (around 7-9 vol% water). Wärtsilä has a variant of this for large 4-stroke engines, with fogging nozzles introducing freshwater directly into the charge air stream after the turbocharger, resulting in combustion air with a humidity of around 60 g water/kg of air (10 vol %). This technique reduces NOx levels by over 70%.

MAN has achieved similar NOx reduction levels by increasing the humidity of the charge air with seawater. Compressed hot air from the turbocharger is passed through a humidification tower (a packed bed) that is fed with hot seawater heated by the engine's cooling system.

Overall developments in humidification have demonstrated that diesel engines can tolerate high levels of water ingestion (including seawater mist) without a significant impact on fuel consumption, thermal efficiency, or engine longevity. MDT claims an efficiency of 59% (LHV, flywheel) for a 12K98 engine with waste heat recovery using SAM (Jensen, 2009). For stationary power generation, this is equivalent to around 56% sent out basis.

3.2 ENGINE MODIFICATIONS NEEDED FOR MRC

3.2.1 Overall Modifications

Table 3-1 provides nominal engine component modifications for both 2- and 4-stroke engines. The most significant modifications are for the fuel supply (i.e. the low-pressure fuel supply from the service tank) and the high-pressure injection system.

Table 3-1
Nominal Engine Component Modifications for DICE

Component	4-stroke	2-stroke
Engine foundations	No change	
Engine frame, bed plate, crankcase	No change	
Crank shaft	No change	
Cylinder liners	Hard coating, optional provision of oil scrapper grooves to allow increased bore lubrication and flushing of solids to reduce filtration load on crankcase lubrication	Hard coating, optional provision of oil scrapper grooves to allow increased bore lubrication and flushing of solids above the scavenge ports
Piston	No change in short term, optimization of bowl shape for MRC rather than low NOx as required for fuel oil	
Rings	Hard coating, improved design to improve down scrape of contaminated bore oil	
Exhaust valves	No change	
Stuffing box	-	Seal oil protection to eliminate the ingress of contaminated cylinder oil
Scavenge box drainage	-	No change if scrapper grooves are used in the cylinder walls otherwise improved drainage
Crankcase oil filtration	200 percent increased filtration capacity; dual systems to allow on-line maintenance, separate centrifuge for cylinder scrape.	No change, but with separate centrifuge for reconditioning cylinder scrape
Fuel supply system	A dual system is required: One for MRC and one for a diesel/fuel oil used for starting, idling and optional pilot injection (1 5% of heat rate, as is currently used for some gas engines). The MRC system should provide a small, controlled circulation flow around the fuel rail and injectors to enable rapid flushing of the system and to eliminate clogging of the fuel system when the engine is not in operation. This circulating flow should be down through the injectors suction valve to the seat of the needle/cut off valve and should be controlled either electronically or from the same oil that actuates the fuel pump plunger. The spring-loaded inertial valves often used with HFO are not recommended due to the variable flow properties of MRC (shear thinning) and seat wear. It is recommended that a twin pump low-pressure fuel system is used, with one pump controlling the pressure in the circulating flow, and the other used to control the return flow.	
Injection system	Seal oil protected sliding surfaces, including the pump plunger and	

Component	4-stroke	2-stroke
	needle valve. For typical hydrocarbon seal oils, the seal oil should be maintained at around 120% of the fuel supply pressure at all times (critical during engine off), and to 120% of the high-pressure fuel pressure during injection. This strategy minimizes seal oil consumption and oil contamination of the fuel return flow (which, if excessive, can cause coal particles to agglomerate). A single high-pressure seal oil system can be used if a water-soluble seal fluid is used (eg a polyglycol such as UCON).	
Pilot injection	Pilot injection is essential for engine conditions where ignition is less reliable - starting, idle, and shutdown. The amount will depend on the MRC properties, engine speed, cylinder size, and whether Miller cycle is used (lowers compression temperatures). Pilot injection is recommended for engine speeds above 400 rpm, and at low load. The electronically controlled pilot injection is essential to allow fine-tuning of MRC combustion.	
Exhaust manifold (low speed 2-strokes)	While the fly ash produced from MRC combustion is likely to be very fine <10µm and to remain in suspension, the 20-40x increase in solids passing through the engine will inevitably cause ash deposits that will shed periodically as larger grit. A grit dropout before turbocharger is therefore recommended (as is sometimes used with residual fuels). Large horizontal exhaust gas ducting should be provided with a positive grit removal system (eg bottom auger, chain conveyer, blowers) – especially for the large main exhaust collector across the top of the engine.	
Exhaust turbine	No change for ash with aerodynamic diameter <10um. Possible use of coated metal for inlet guide vanes.	
Waste heat recovery	Conventional solid fuel boiler rather than finned heat exchangers common for cleaner fuels. A vertical fire tube or horizontal water tube is preferred to reduce ash clogging. Until experience is gained to prove otherwise (given the different fuel chemistry and combustion conditions) access is required for manual soot blowing with compressed air or steam.	
Exhaust gas cleanup	The same as used for large land mounted 2-stroke engines using heavy fuel oils – ESP or fabric filtration, SCR and FGD	
Lubrication	Adjustment of crankcase oil base number to match sulfur content of the MRC and with increased detergency to keep char and ash in suspension. Base number should take into account any sulfur reporting to the ash.	Adjustment of cylinder lubricant base number to match sulfur content of the MRC. Base number should take into account any sulfur reporting to the ash.

3.2.2 **Fuel Supply System**

There have been several fuel supply systems proposed for DICE, which all involve some method of agitating the fuel in storage, plus a valving system to enable system flushing of the pump and lines to the injectors. A better system includes a screening system before the main fuel supply pump and controllable return flow. This system is shown schematically in Figure 3-3 and operates as follows:

- Fuel is stored in a 12,000 m^3 service tank sufficient for ten days supply for a 100 MWe plant. This tank is equipped with either a live bottom or a very slow speed rake-type agitator (say 1 revolution per hour). Note, that, conventional high-speed tank mixers are ineffective, giving localised agitation only due to the shear thinning behavior of MRC, and are energy intensive.

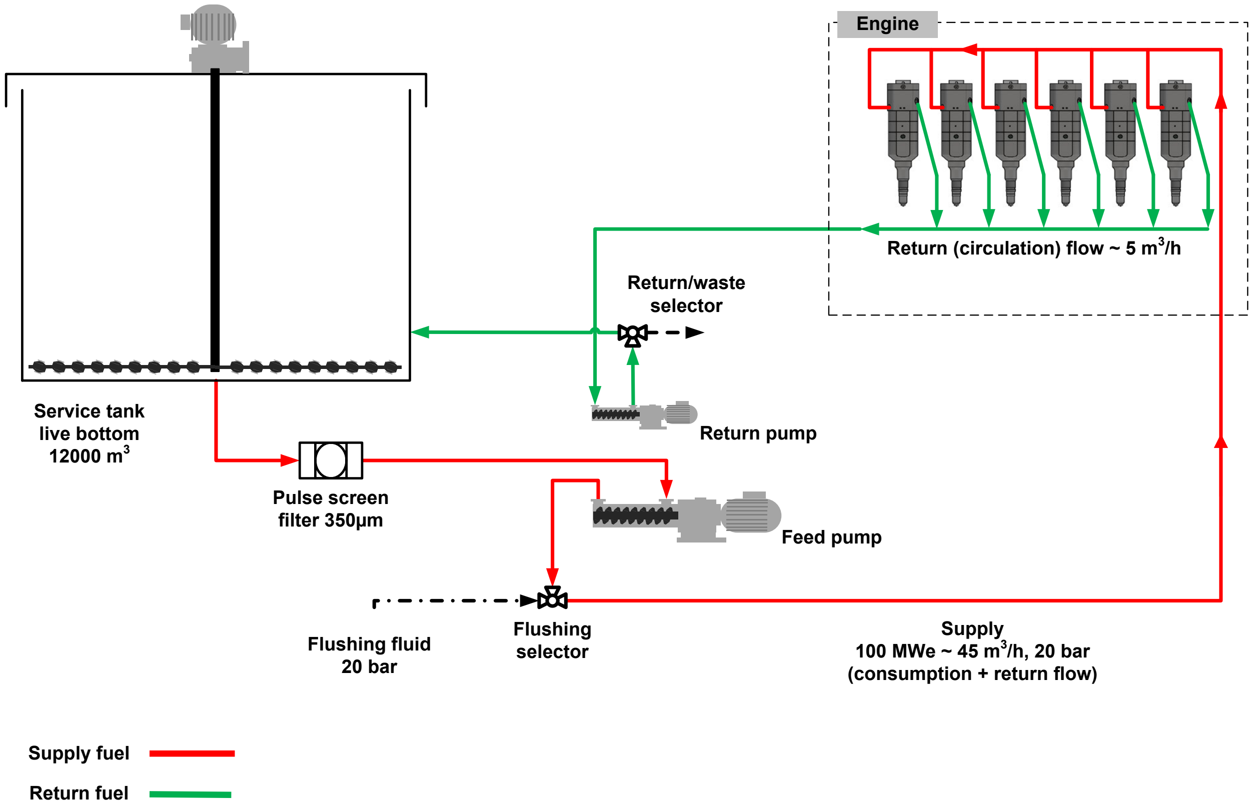
- Fuel passes through a pulse screen filtration device before a positive displacement supply pump. The speed of the supply pump is controlled to maintain the supply rail pressure. A screen aperture of 350μm would be suitable for an engine with injector orifices of 600-800μm. Various screening devices can be used. However, MRC rapidly clogs filters with apertures finer than 10-15x the maximum particle size unless pulsed. The purpose of screening is to allow the bulk of the fuel to pass but trap major oversize particles and contamination such as flakes of rust, paint etc.

- The fuel supply pump is a positive displacement pump (progressive cavity type) which supplies the fuel supply rail. The speed of the supply pump is controlled to maintain the supply rail pressure.

- Electronically controlled unit injectors are preferred for the MRC (eg HEUI or MEUI type) to allow closer control of injection timing. The injectors should preferably incorporate fuel circulation valves, which allow controlled flow of fuel down through the injector's pump and preferably down the body of the injector to the needle/cut off valve seat, and back out to a return rail.

- A positive displacement (progressive cavity type) return pump operating in reverse is advantageous to control the total return flow to the service tank, or in the case of flushing, to a dump tank. The letdown pump need only be ~10% of the capacity of the supply pump – which would enable complete flushing of the system within (say) 30 seconds. The speed of the return pump is controllable to set the return flow. Operating the return pump in reverse reduces shaft seal wear. Controllers should be tuned to allow dead-heading without damaging the pumps.

Figure 3-3
Suggested Fuel Supply System



3.2.3 Fuel Injection System

A range of high-pressure injection systems have been used for MRC, including:

1. Conventional jerk pump (200 bar) - line - media separator (shuttle piston or diaphragm) – nozzle (GE and Cooper Bessemer during the earlier USDOE programs).
2. Hydraulic actuated pump (600 bar) – media separator (diaphragm) – nozzle (CSIRO)
3. Unit injector: Common rail hydraulics (700 bar) – seal oil protected media separator – nozzle (WING&D/Maersk)
4. Unit injector: Hydraulic ram (150-300 bar) – seal oil protected plunger – nozzle (CSIRO/MAN)

Although all options have been made to work with MRC, the unit injector-types 3 & 4 have the advantage of compactness and controllability. Desirable features include:

1) Modular body construction (to facilitate maintenance and component development), comprising a:

   - servo oil valve module containing a high-speed solenoid valve
   - hydraulic actuator module
   - pump module,
   - fuel ring module containing a non-return valve for the fuel inlet
   - lower flanged body which contains the usual spring, push rod, nozzle body and cut-off needle valve.

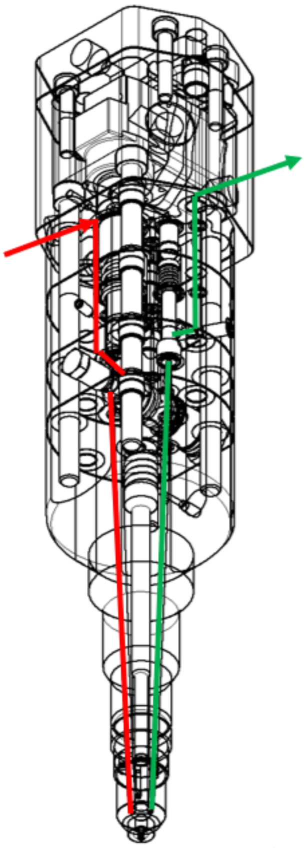
2) An automatically (this could also be electronically actuated) operated return valve to provide positive fuel flushing around the injector between injection events and whilst the engine is standing. This ensures continuous movement of the fuel, which dramatically reduces the chance of clogging, enables rapid fuel switching, or system flushing – either during engine operation or when stopped. Figure 3-4 shows the circulating flow around the injector required to ensure high reliability. This injector shown is an enlarged version of an injector for a 4L single-cylinder laboratory engine at CSIRO.

3) All fuel wetted surfaces are provided with seal oil continuously (this can be hydraulic or motor oil) at a slightly higher pressure than the fuel (say 25 bar).

4) The fuel pump and needle spindle are provided with high-pressure seal oil during the actual injection event. The seal oil pressure can be provided by an integral intensifier pump within the injector's hydraulic ring, or from an external supply. In the case of the latter, a two pressure system should be used to reduce seal oil pressure when the engine is standing, to avoid unnecessary seal oil contamination of the return fuel.

5) Although MRC has a much higher viscosity than diesel fuel, CSIRO has found that only a slightly larger orifice size is required (say 10% larger diameter) due to the strongly shear-thinning behavior of MRC fuels (if correctly prepared). Shear-thinning results in marked wall slip, which increases the volumetric flow of a nozzle. Experience has shown that a nozzle size of 500-750µm will provide a balance between atomization and jet penetration for cylinder bores up to (say) 50 cm.

Figure 3-4
CSIRO Injector Showing Fuel Return Circulating Flow through the Injector



3.3 DICE FUEL SPECIFICATIONS

This section discusses the specifications of MRC required for combustion in DICE. An overall summary of fuel specifications is followed by additional discussion for each of the critical properties.

Fuel for DICE has significantly different quality requirements than for conventional coal slurry fuels used in boilers. This difference is because engines have short combustion times (say 30 ms in engines, versus 1-2 s in boilers), which requires more intense atomisation than for a boiler. Also, in engines, unburnt char and ash particles will cause chronic engine wear, piston ring jamming, and even turbocharger erosion. Also, the exhaust system of engines is not designed to pass significant ash – which for DICE could be 30x that of even the lowest quality residual fuel oil.

In DICE, it is paramount that the fuel 1) gives a high degree of atomization during injection (which ensures rapid ignition, combustion, and complete burnout), 2) forms minimal abrasive ash particles, 3) has the highest coal solids loading. These requirements will be strongly interdependent, and also be strongly influenced by the size of the cylinders, engine speed, and the extent of engine armoring. Overall properties include:

- Low abrasive mineral content – to minimize injector nozzle and cylinder/ring wear especially
- Coal particle size distribution with a d50 of <15µm and a d90 <60µm to ensure burnout
- High coal content to minimize latent heat losses in the engine – subject to meeting the viscosity specifications
- High stability of formulated fuel to prevent settling in the fuel handling equipment, as well as ease of transportation and storage
- Strongly shear thinning behavior to allow injection and effective atomization – essential for controlled heat release and to minimize unburnt char
- Resistance to microbial action – some slurry fuels degrade rapidly, which can affect both stability and shear thinning behavior – in addition to increasing occupational, health, and safety (OH&S) concerns

Nominal target specifications, based on both literature and recent engine experiences are as follows (formulated MRC slurry basis):

- Ash content < 2% (dry basis)
- Residual mineral size <15µm and preferably <5µm
- Coal particle distribution giving a d50 of < 15µm and d98 < 50µm
- Coal content of the fuel should be as high as attainable, while still meeting the following nominal rheology targets:
  - >10,000 mPa-s @ 0.1/s
  - <400 mPa-s @ 100/s
  - <100 mPa-s @ 10,000/s and be shear thinning at higher shear rates
- Heating value > 18 MJ/liter
- pH of 3.5-8.5

- Stable – say exhibiting no settling (coherent cake on the bottom surface) over 90 days when stored in a sealed 500 mL measuring cylinder at (constant) ambient temperature. After 90 days, all MRC should drain from the upturned measuring cylinder

Experience has shown that, while individual properties can be readily met, achieving a balance between all properties is more difficult. For example, a high SE fuel can be produced by increasing the solids content, which will have the advantage of also increasing fuel stability. However, this will also increase the viscosity and may cause shear thickening behavior, which will make the fuel very difficult (even impossible) to inject, resulting in poor atomization. The resulting large fuel droplets (containing many smaller coal particles) will likely dry to form a single large coal agglomerate, resulting in slower ignition and incomplete combustion. This will invariably lead to chronic ring jamming by char. The resulting flash from poor atomization is also likely to be larger due to the interaction and fusing of fine mineral grains and organically bound ash forming components within the coal. These interactions are discussed in more detail below.

3.3.1 Coal Loading

Coal loading has two main effects, 1) strongly affects fuel viscosity – especially at higher coal loadings (say >55 wt%), and 2) water reduces the calorific value of the fuel and increases the latent heat penalty.

It is important to note that while the effect of coal loading on calorific value is linear, the effect on viscosity is exponential at higher coal loadings (say 57wt% for bituminous coals, and above 53% for sub-bituminous coals – depending on the shape of the size distribution). This rapid increase in viscosity means that the maximum coal loading is usually dictated by the highest viscosity - which ensures satisfactory atomization..

3.3.2 Coal Particle Size

As a guide, at 500 rpm, around 30 ms is available for combustion, and practical experience suggests that a coal top size of 50-60μm will give satisfactory combustion with minimal unburnt char in the exhaust – providing atomization is sufficient. Sub-bituminous coals (higher oxygen content, more reactive chars) and lower speed engines are likely to allow a coarser tail in the size distribution.

However, there are several other factors that need to be considered, as the particle size distribution of the coal in the MRC strongly affects the fuel's rheology for a given coal loading, and therefore its atomization, ignition, and combustion. The particle size distribution also affects the degree of mineral liberation during fuel preparation and the size distribution of liberated minerals in the final fuel. In general:

- A wide size distribution allows a higher particle packing efficiency, and therefore coal loading (this can be calculated), which improves thermal efficiency and fuel stability, and reduces fuel transport costs.
- An optimum coal loading and wide particle size distribution should give a high low shear viscosity (essential for fuel stability in storage) and shear thinning behavior, which enables injection and atomization. Coal loadings above the optimum rapidly cause shear-thickening fuel, which causes fuel system clogging and poor atomization.
- Both the quality of atomization and the coal top size affect the effective size of the coal at the time of ignition - which in turn determines the time for combustion. Finer grinds may not be better: For example, overly fine grinds can increase fuel viscosity and result in poor

atomization. Subsequent agglomeration of the coal during heating, and before combustion, results in a coarser effective coal particle size distribution than that of dispersed particles.

In general, the slower the engine, the larger the allowable top size; however, this also depends on the devolatilization behavior of the coal under the extremely rapid heating and intense combustion intensity in an engine. Combustion intensity can exceed 5 GW/m3 – around two orders greater than for pf combustion –some coals are likely to exhibit a large enhancement in volatiles yield, which gives faster ignition and combustion. Overall, combustion data for coal in engines is lacking, and existing data for pulverized coal firing is likely to be misleading for DICE.

3.3.3 **Coal Volatiles**

Although there is no literature information on the effect of coal volatile content, with previous engine experience using only medium to high volatile coals (28-40%), higher volatile coals are expected to give improved ignition and combustion. However, the standard method of determination of coal volatiles (the Proximate analysis) will underestimate the effective volatiles content under the extremely rapid heating rates of atomized MRC and the high pressures in diesel engines (which can exceed 150 bar at the start of injection). The morphology of the resulting char is also likely to be very different than that for conventional pulverized coal combustion in boilers, and more akin to that in slurry fed gasification.

The effects of volatiles on ignition and combustion are also affected by the oxygen content of the coal. For example, CSIRO has found that low volatile chars (carbonized at 850°C and containing around 5% volatiles) require 40°C higher charge temperature to achieve the same ignition performance as a 30% VM bituminous coal, and hydrothermally treated Victorian brown coal (45% VM and with 25-27% O) giving an ignition temperature 60°C lower. Note that with these low rank coals, a significant proportion of the volatiles content is CO_2 and H_2O).

3.3.4 **Ash content**

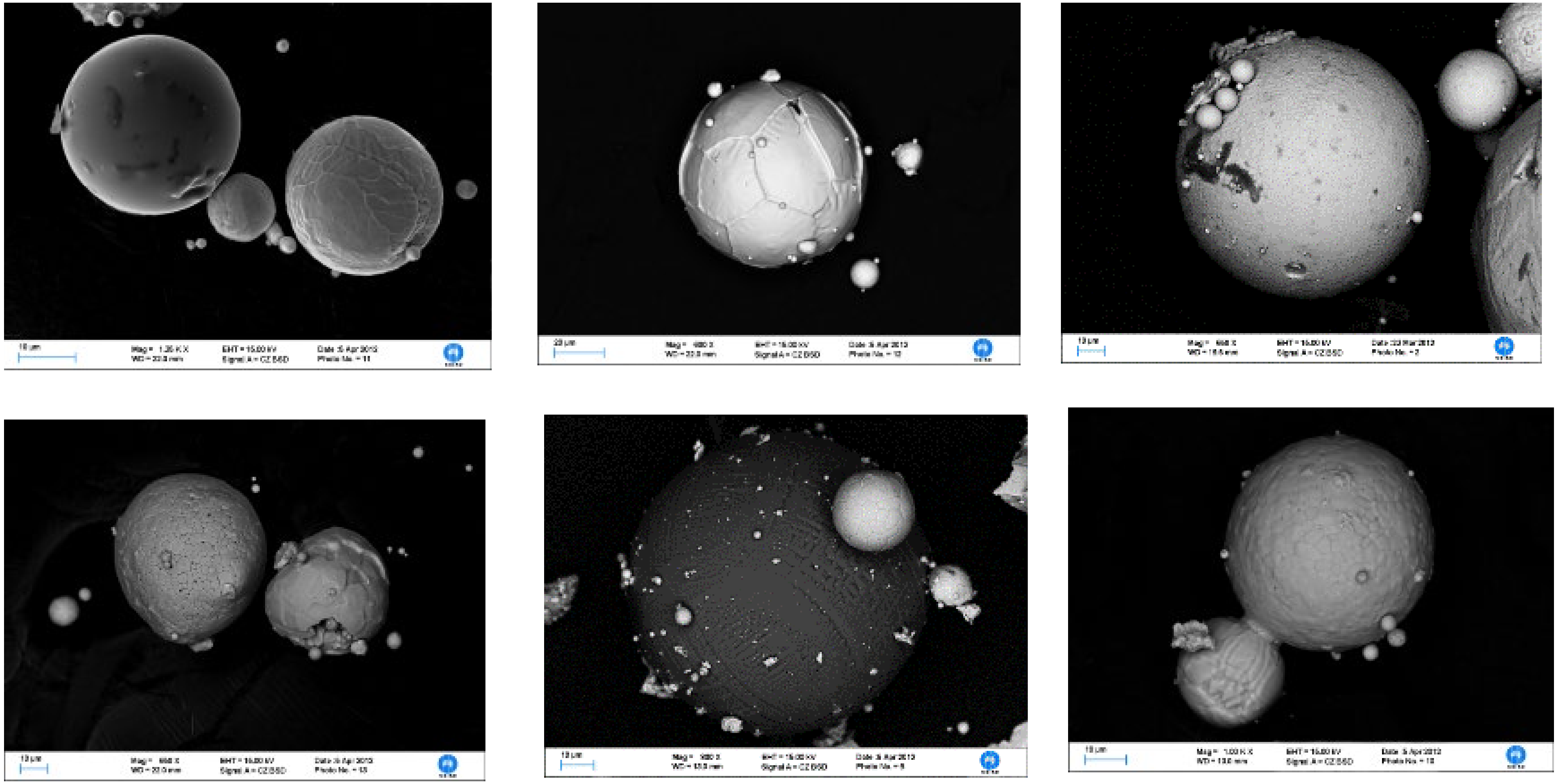
Ash is the residue after complete combustion, and comprises altered mineral particles from the extraneous ash components, plus finer particles from condensed, oxidized and sulfated compounds formed from the fine, organically bound and mineral particles contained within the coal particles. As the latter interact during burnout of the char, these particles are usually a complex mixture of aluminosilicates and sulfates depending on the coal.

After combustion in a diesel engine, all mineral particles below 10µm size are spheroidized, including quartz. However, even highly fused ash particles have the potential to cause cylinder wear unless the diameter is less than the minimum oil film thickness (1-2µm). Larger sand particles will be most problematic.

For low rank coals and wood chars, the ash also comprises ultra-fine micron size particles formed from the volatilized ash components. Cenospheres have also been observed (see Figure 3-5). Neither the submicron fume nor the cenospheres are likely to cause abrasive wear.

The wear implications of ash require that a detailed investigation of the occurrence of the ash forming constituents of the target coal is undertaken to understand the ramifications for engine wear. This also requires collecting fly ash from either an engine or an appropriate high-pressure spray combustion chamber.

Figure 3-5
SEM Images of Cenospheres from DICE using a Hydrothermally Treated Victorian Coal



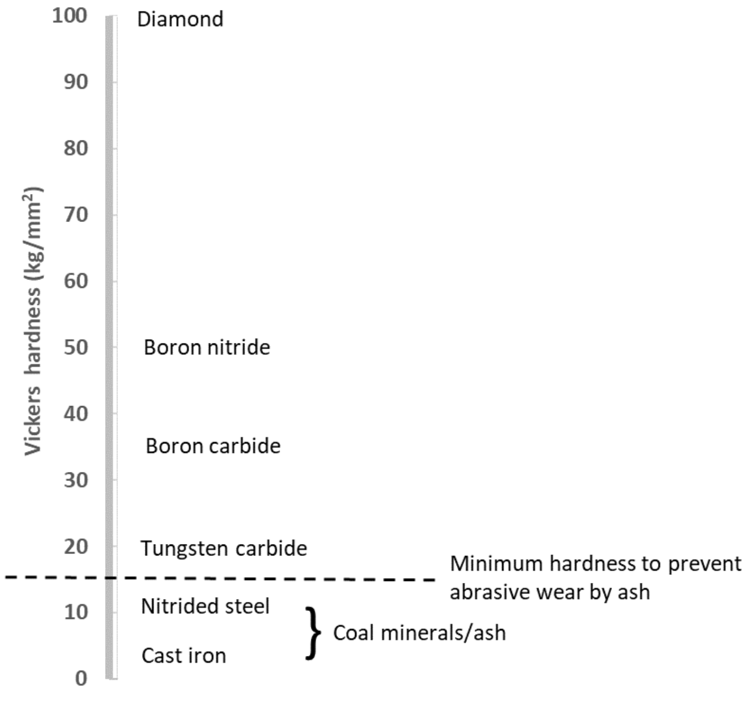
The present understanding of ash-engine interactions is that:

- Coarse (say, >5μm) and hard minerals (quartz, pyrites, rutile) in the fuel will increase abrasive wear of the atomizer nozzles, rings, cylinder wear, exhaust valve seat, and the turbocharger turbine inlet vanes and rotor.
- Ash residues can also deposit in the oil film on the cylinder wall and be scrapped by ring action to pack in the piston ring grooves behind the ring – a potentially serious condition leading to catastrophic scuffing.

Although these issues could theoretically be eliminated by using harder material and changing the design of engine componentry, all previous DICE projects have been on the basis that DICE requires cost-effective production of ultra-low ash coals - the cleaner, the better.

However, coal specifications for commercial deployment of large diesel engines remain to be established, and in particular, there is a lack of data linking engine wear to ash content and the morphology of the mineral content. Also, there is no information on the trade-off between processing cost, fuel ash, and engine component and maintenance costs. For example, abrasive wear can only occur if the abrading particle is 30% (approximately) harder than the underlying material. For coal ash, the dominant hard material is usually quartz with a hardness (Vickers) of around 11 kgf/mm^2, showing that a wide range of commercially available ceramics could be used to prevent abrasive wear (Figure 3-6) – provided that they can be incorporated into an engine.

Figure 3-6
Hardness of Materials Relative to Coal Ash



The earlier USDOE work generally concluded that coal with 2-3% ash would likely be suitable, thereby enabling the use of physically cleaned coals (as distinct from more costly chemical cleaning). In recent studies with MAN and WING&D/Maersk, the target ash was <1.5% with a maximum of 2%, noting that this limit was set by available fuel quality and the use of unarmored engines, rather than based on a sound techno-economic basis. Also, these targets were set with little consideration of the type and morphology of the starting mineral matter – mostly due to limited capacity to produce tonnage fuel required for the large engine tests involved. The morphology is very significant, as recent wear tests (using a modified HFRR test) by CSIRO has shown that oils contaminated with fine ash from lower rank coals decreases wear of hardened steel by up to 30%. For tungsten carbide HFRR components, there was a negligible difference between clean and contaminated oils regardless of the mineral type.

Overall, the lack of data has caused a divergence of philosophies between the engine manufactures and the coal industry, which has hampered DICE development. To generalize, the engine manufactures have required that the fuel should be made to match the (current) engine componentry, whilst the coal suppliers have pressed for armored engine componentry to allow higher ash MRC. This dilemma requires that a full-size DICE facility (including fuel preparation plant) are established to allow longer-duration engine trials with armored engine componentry, and for a range of MRC quality. Quantifying the effect of ash on engine componentry costs, durability, and other R&M issues would result in a scientifically based coal quality value model needed to progress the technology.

3.3.5 **Sulfur**

Large diesel engines designed to operate with heavy fuel oil can tolerate relatively high sulfur fuels (2 percent) providing cylinder lubrication uses the appropriate lubricant (i.e. base number) to avoid acid attack of the cylinder walls. As MRC will require deep cleaning of coal, sulfur levels of PRB coals will not be a problem – even if S containing dispersants are used for fuel formulation (e.g., NaPSS – sodium polystyrene sulfonate).

3.3.6 **Alkalis**

While alkalis are a significant issue for coal-fired boilers (nominally, for $Na_2O:SiO_2$ ratios >0.04, or in the presence of high S and Cl), to date, there is no evidence that alkalis are an issue for DICE. Recent CSIRO experience with a chemically cleaned coal (a caustic ash removal process) with a high $Na:SiO_2$ ratio showed negligible ash deposits after 40 hours at full load of a 4-liter single-cylinder test engine – see Figure 3-7. Other indirect evidence is from marine engines, which show no cylinder fouling despite ingesting salt spray (from humidification or aftercooler leaks).

It is surmised that the lack of ash fouling is a result of the large pressure swings (> 100 bar) for each engine cycle, which regularly mechanically sheds the porous particulate ash deposits (ie deposit panting).

Figure 3-7
Head Valves after 40 hours of Full-Load Operation Using MRC Produced from Yancoal UCC

3.3.7 Viscosity/Rheology

Fuel rheology has been largely overlooked in previous RD&D programs to use coal for diesel engines, other than to ensure the fuel's viscosity was sufficiently low to enable injection without nozzle clogging. However, in the recent CSIRO studies, fuel rheology was a major focus due to other important interrelated effects - ignition, burnout, and both injector and cylinder wear.

In general, the coal content must be maximized (at least 50%, and preferably >55%) to reduce latent heat penalty - but also while meeting the following rheological targets:

- High viscosity at low shear rates (say 10,000 mPa.s @ 0.1/s) is essential for good stability
- Rheology that is strongly shear thinning
- Viscosity of <400 mPa.s @ 500/s to ensure good injectibility and atomization.

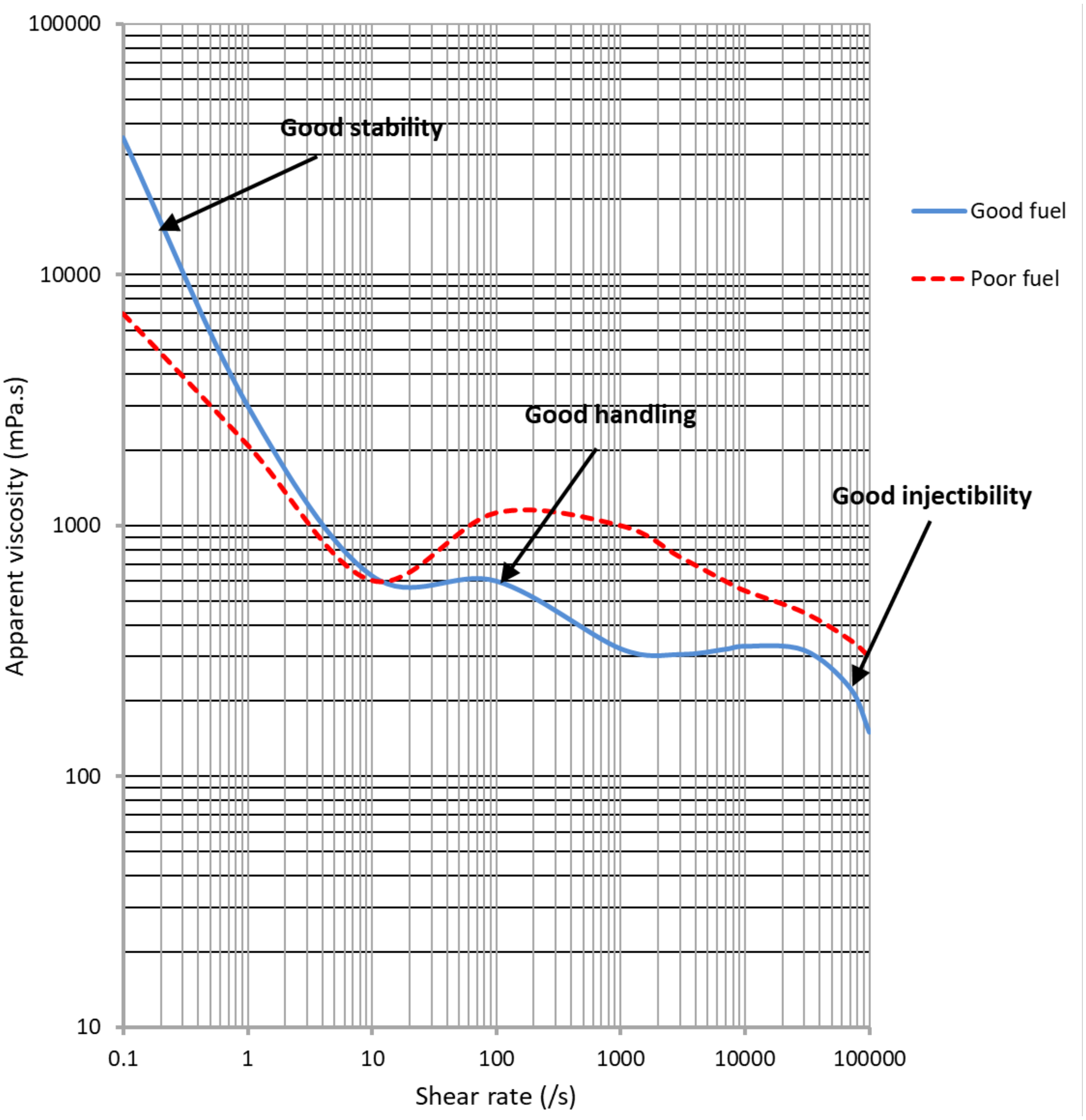
These specifications are very different to that of coal water slurries for boilers, which have a higher coal loading and much higher viscosity at higher shear rates (including being shear-thickening rather than thinning). This difference in rheology is clearly apparent when the different fuels are poured from a beaker, as shown in Figure 3-8.

The first two requirements above – stability and shear thinnng - are the most important attributes, as fuel stability is essential to producing a fuel with the correct rheological properties for DICE: Stable and shear thinning fuel (providing the califie value is high enough) will always makes a good engine fuel – which can be thinned if necessary prior to injection with trim water additions. However, the reverse is not always the case: Highly injectable fuels will not automatically exhibit good stability. Strongly shear thinning fuel (correlates with good stability, handling, injectability, atomization - and ultimately good combustion and reduced wear issues from unburnt char packing behind piston rings.

Figure 3-8
Fuel Rheology: Left, Coal Water Fuel for a boiler by JGC; right, MRC for DICE

Unstable fuel is particularly problematic, regardless of how well it injects, due to the formation of deposits in fuel handling equipment, which, at worse will clog fuel injector nozzles, or at least increase the effective particle size of the fuel entering the combustion chamber leading to poor combustion and char issues. Once MRC forms a hard pack deposit due to poor stability, mechanical means are required for its removal. Figure 3-9 shows nominal rheology plots for good, and poor MRC fuels.

Figure 3-9
Nominal MRC Rheology for a Good and Poor Fuel



3.3.8 Stability

Fuel stability, or lack of build-up of sediment in fuel containers with storage, is essential to avoid serious operational issues from blockages, plus secondary effects described in the rheology section above. An unstable fuel is unacceptable for DICE.

Most established stability tests only require stability over relatively short periods (say) 1 week – this is too short. CSIRO work is aimed at 100% stability for >1 month, and preferably >6 months. This testing period is much longer than specified by most stability tests for coal water fuels for boilers. It is noted that some bulk slurries produced to this specification have been completely stable with negligible sediment for more than 2 years. In general, lower rank coals will provide more stable fuels.

3.3.9 Control of Microbial Activity

Microbial activity in the fuel has the potential to destabilise the slurry, in addition to causing safety concerns. However, CSIRO experience with MRC fuels from 48 coals from Australia, Venezuela, Indonesia, and Germany have shown no evidence of microbial activity – except for a single NSW coal slurry prepared by others. Microbial activity has however, been observed with MRC produced from low-temperature chars – see Figure 3-10.

Figure 3-10
Microbial Activity on Pine Char Slurry after 205 Days

3.4 DICE PERFORMANCE

3.4.1 DICE Performance Modeling

Engine:

- Stock engine is based on Wärtsila 18V46, but with estimation of many key parameters
- Thermal efficiency loss using MRC slurry is estimated approximately 1.8 percentage points
- Output reduction is estimated as 9 percent (based on Orimulsion experience)

Fuel:

- PRB coal, analysis as supplied, normalized to 2 percent ash dry basis, as specified by the coal beneficiation process
- MRC slurry assumes 55 wt% coal.
- Temperature on injection 90 °C.
- Pilot fuel is diesel at 5 percent of the total heat rate

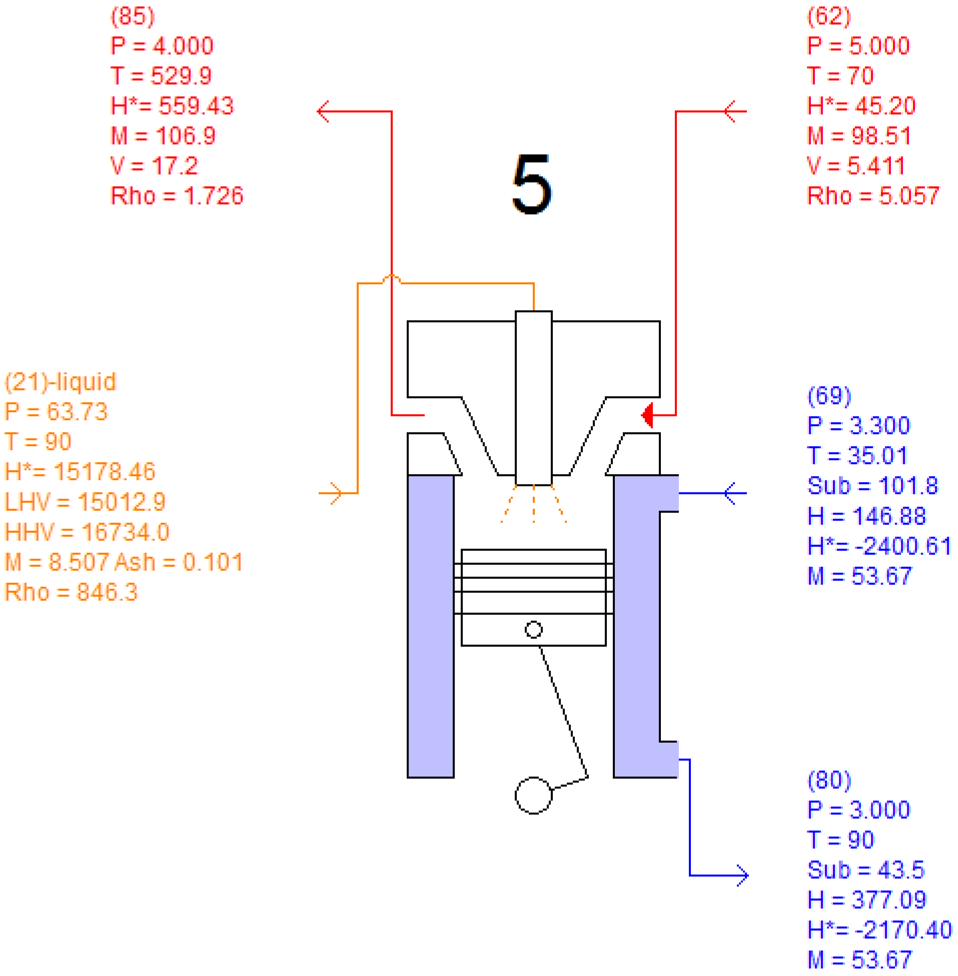
Stock engine heat and mass balance data fired with HFO and MRC slurry is presented in Table 3-2.

Table 3-2
Stock Engine Heat and Mass Balance

		Stock Engine (HFO Fuel)	MRC Slurry	MRC Slurry (Fuel preheat)
Heat Consumption	kWth	37,480	36,578	35,491
Fuel Heating	kWth			389
Charge Air Cooler Heat Rejection	kWth	5,082	5,082	5,082
Lube Oil	kWth	2,294	2,294	2,294
Jacket Water	kWth	1,694	1,694	1,694
Surface heat	kWth	519	519	519
Exhaust	kWth	10,289	10,740	10,042
Mechanical Losses	kW		231	231
Shaft Output	kW	17,602	16,018	16,018
		47.0%	43.8%	45.1%
Heat Balance Error	kW	0	0	0
HB Error / Heat Consumption		0.00%	0.00%	0.00%
Generator Output	kWe	17,303	15,746	15,746
Generator Efficiency		98.30%	98.30%	98.30%
Overall Efficiency		46.17%	43.05%	44.37%
Exhaust Flow	kg/h	106,920	106,920	106,920
	kg/s	29.70	29.70	29.70
Exhaust Temp	ºC	342.0	369.0	327.2

With the turbocharger removed, engine charge air is supplied at 5 bar and 70 ºC by the MAC with the aftercooler. Exhaust gas is at 4 bar and 530°C. Engine heat and mass balance in the Thermoflex model is shown in Figure 3-11.

Figure 3-11
Thermoflex "User-Defined" Reciprocating Engine DICE Model



3.4.2 **Performance Validation**

The DICE performance model development was described in great detail in Section 2.2.3 of the Conceptual Design Final Report (submitted on August 13, 2019) and will not be repeated herein. In brief, it was an amalgamation of several sources of data and information, including

- OEM's specs (tested for heat and mass balance consistency)
- Detailed engine simulation by Czero, Inc (including combustion modeling)
- Published DICE performance reports
- Field experience with Orimulsion

At this point, there is no opportunity to validate the predicted performance in the field or in the laboratory. The only available option was to ask a third party to conduct a rigorous engine simulation study and compare the results with what we have. Consequently, CSIRO, who has done extensive studies on DICE, was contracted to undertake this study as part of their contract.

Due to their unique position of being the most experienced organization in DICE (and their extensive past collaboration with MAN in fuel injector development and testing), CSIRO is in the best position to provide valuable feedback on DICE performance predictions.

Nevertheless, it is important to realize that this type of simulation can only provide a guide to engine performance until detailed information is available on the combustion characteristics of the chosen PRB coal, and engine adaptations are proven with full-scale operational experience. For example, the engine maker may require the derating of the peak firing pressure due to ring wear concerns or may reduce the allowable pressure limit to account for the increase in power (and therefore stresses on other parts of the engine) that is possible with MRC firing.

The CSIRO DICE engine modeling/simulation study is described in detail below and in Appendix C of the overall pre-FEED study package.

An engine model was used to predict the thermal efficiency and exhaust gas of a MAN 18V48/60TS engine using MRC from a Powder River Basin coal (2wt% ash, but otherwise using an as-mined coal composition). This data is required for the assessment of heat recovery/integration options by others.

The engine model used is a 1-dimensional thermodynamic model, using thermodynamic data from the NASA thermo-build system, and free energy minimization from the NASA CEA program. In-cylinder processes assume a homogeneous mixture of air and combustion products, ideal gas behavior and that the system is at thermodynamic equilibrium.

3.4.2.1 Cylinder heat loss

The heat transfer co-efficient is calculated using the Woschini equation[2]. With this equation three stages in an engine cycle considered:

- gas exchange period (between exhaust valve open and inlet valve close)
- compression
- combustion and expansion period

$$h_c = \frac{3.26}{1000} D^{-0.2} P^{0.8} T^{-0.53} w^{0.8}$$

where:

h_c = heat transfer coefficient (kW/m^2.K)

D = cylinder bore (m)

P = cylinder pressure (kPa)

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[2] Woschni, G., "A Universally Applicable Equation for the Instantaneous Heat Transfer Coefficient in the Internal Combustion Engine," SAE Transactions, Vol. 76, p. 3065, 1967

T = cylinder temperature (K)

w = average cylinder gas velocity (m/s)

$$w = C_1 S_{\text{MeanPiston}} + C_2 \frac{V_{displacement} T_0}{p_0 V_0} (p - p_m)$$

where:

C_1 = constant (6.18 for period 1; 2.28 for periods 2 and 3)

$S_{\text{MeanPiston}}$ = mean piston speed (m/s)

C_2 = constant (0 for periods 1 and 2; 3.24×10^{-3} for period 3)

$V_{displacement}$ = cylinder displaced volume (m^3)

T_0, p_0, V_0 = temperature, pressure and volume

3.4.2.2 Equilibrium Products

Additionally, during combustion, the equilibrium composition is calculated using free energy minimization. A limited number of species are modeled, Ar, CO, CO_2, H, H_2, H_2O, N, N_2, NO, NO_2, N_2O, O, O_2, OH, SO_2. These species are the only ones that will occur at any significant concentrations and were included mostly to account for dissociation at higher temperatures, rather than the amounts of minor species. SO_2 levels in the exhaust gas assumed that there is no partitioning of S to fly ash components. While the latter does occur in boiler off-gases (especially for coals with high alkali/alkaline ash), the extent is unknown for DICE with much shorter residence times below 1000°C.

3.4.2.3 Friction Calculations

The model uses the Chen-Flynn friction model[3] which has the form:

FMEP = $C_{FMEP} + (C_{PCP} * P_{Peak}) + (C_{MPS} * S_{MeanPision}) + (C_{MPSS} * V_{MeanPistion}^2)$

where:

FMEP = friction mean effective pressure (bar)

C_{FMEP} = constant for FMEP

C_{PCP} = constant factor for peak cylinder pressure

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[3] Chen, S.K., and Flynn, P.F., "Development of a Single Cylinder Compression Ignition Research Engine," SAE Paper 650733

P_{Peak} = peak Cylinder Pressure (bar)

C_{MPS} = constant factor for mean cylinder velocity

$S_{MeanPiston}$ = mean piston velocity (m/s)

C_{MPSS} = constant factor for mean cylinder velocity squared

3.4.2.4 Heat Release Rate

The most important aspect of the combustion phase is the calculation of the rate at which the fuel will combust, generally referred to as the heat release rate (HRR). The model using a three term Weibe heat release model[4] fitted with actual heat release rate data from a hydrothermally treated Victorian lignite, which imposes a non-predictive burn rate based on crank angle.

Its single term form is

$$C_A = \left(\frac{D_A}{2.302^{-(1+E_A)} - 0.105^{-(1+E_A)}}\right)^{-(1+E_A)}$$

where:

C_A = Weibe constant for part of the combustion

D_A = duration of that part of the combustion (°)

E_A = exponent for that part of the combustion

In the three-term form used in the model, the combustion profile is separated into three section, a premix phase, a main diffusive phase and a tail diffusive phase. With these three phases an overall expression for the fraction of fuel consumed is as follows:

$$F_t = 1 - (F_P + F_d)$$

$$\begin{aligned}\mathcal{F}_{Fuel}(\theta) = {} & F_P(1 - e^{-C_p(\theta - \mathcal{T}_{SOI} - \mathcal{T}_{IgnD})^{(E_p+1)}} + \\ & F_d(1 - e^{-C_d(\theta - \mathcal{T}_{SOI} - \mathcal{T}_{IgnD})^{(E_d+1)}} + \\ & F_t(1 - e^{-C_t(\theta - \mathcal{T}_{SOI} - \mathcal{T}_{IgnD})^{(E_t+1)}}\end{aligned}$$

where:

$\mathcal{F}_{Fuel}(\theta)$ = Fraction of fuel burnt at crank angle θ

---

[4] Wiebe I., Halbempirishe Formel dur die Verbrennungsgeschwindigkeit, in Krafstoffaufbereitung und Verbrennung bei Dieselmotoren, ed. G Sitkei, pp. 156-159, Springer-Verlag, Berlin, 1964

F_P = Fraction of fuel burnt in premix phase

F_d = Fraction of fuel burnt in diffusive phase

F_t = Fraction of fuel burnt in tail phase

The values of the constants can be varied to match actual heat release data from experimental data. In the model this has been done with the data for coal, while recommended values have been used for diesel.

During the exhaust phase the cylinder contents discharge to an exhaust chamber, which is assumed to remain at a constant pressure.

To calculate the exhaust mass flow, compressible flow through the exhaust valve in both choked and un-choked conditions must be modeled – based on the criteria of Streeter and Wiley.

The effective area for the exhaust port is calculated as the annular area created between the actual exhaust port and the exhaust valve as it is opened multiplied by a discharge coefficient. The lift profile is modeled initially with a sinusoidal function based on a specified lift rate. The area is then unchanging until the valve closes again based on the same lift rate. The shape of the curve can be varied by changing the value of the lift rate as well as the opening and closing positions.

3.4.2.5 Base Engine Parameters

The model was based on engine parameters obtained from MAN Energy Solutions, and missing parameters (some key information are proprietary) estimated from best available literature data – e.g., valve timing. The procedure was to:

- Obtain a reasonable fit with published data using diesel fuel, and using the same parameters repeat for PRB coal assuming 50 and 55wt% coal in the fuel (Cases PRB-1 and PRB-2 respectively).
- Repeat the calculations for two different firing strategies: PRB-3--fixed heat input rate and PRB 4--fixed peak combustion pressure. These cases were included to simulate likely operating extremes using MRC (because the water content and heat release rate are significantly different from diesel fuel oil, resulting in lower combustion pressure).

The ignition delay for fuel oil was 2.5 ms, and for MRC 5 ms was used (experimentally determined for hydrothermally treated Victorian brown coal).

3.4.2.6 Results

The full set of modeling results are presented in CSIRO DICE Study Report in Appendix C. The modeling results for the four combinations described above show that Cases PRB-1 and PRB-2 (with the same heat input as for diesel fuel oil) give the closest match in engine performance, with:

- Thermal efficiency of 45.1-45.8% LHV.
- A 40 bar (15%) reduction in the peak combustion pressure.
- A decrease in power output of 6-8%.

  - An increase in coal loading from 50 to 55%, giving an increase in thermal efficiency of 0.7% points, or a decrease in the heat rate of 1.6%.

These findings fully confirmed the findings from the conceptual design study. **Consequently, it was decided to continue the pre-FEED study with the DICE engine performance used in the conceptual design study.**

The modeling results with the same peak pressure as for diesel fuel oil, Cases PRB-3 and PRB-4, gave a radical change in engine output and exhaust conditions. If practical (at this point not deemed to be likely), this method of firing would

- Increase power output by around 68%.
- Increase exhaust temperature significantly and reduce the oxygen content to 6-7 mol% (and thereby increase CO content).
- Reduce engine thermal efficiency by 4.5% points compared to diesel fuel.
- Overall, this option would be best suited for plants additional heat integration – including with waste heat recovery by turbo compounding and/or steam plant, or post-combustion capture of CO_2.

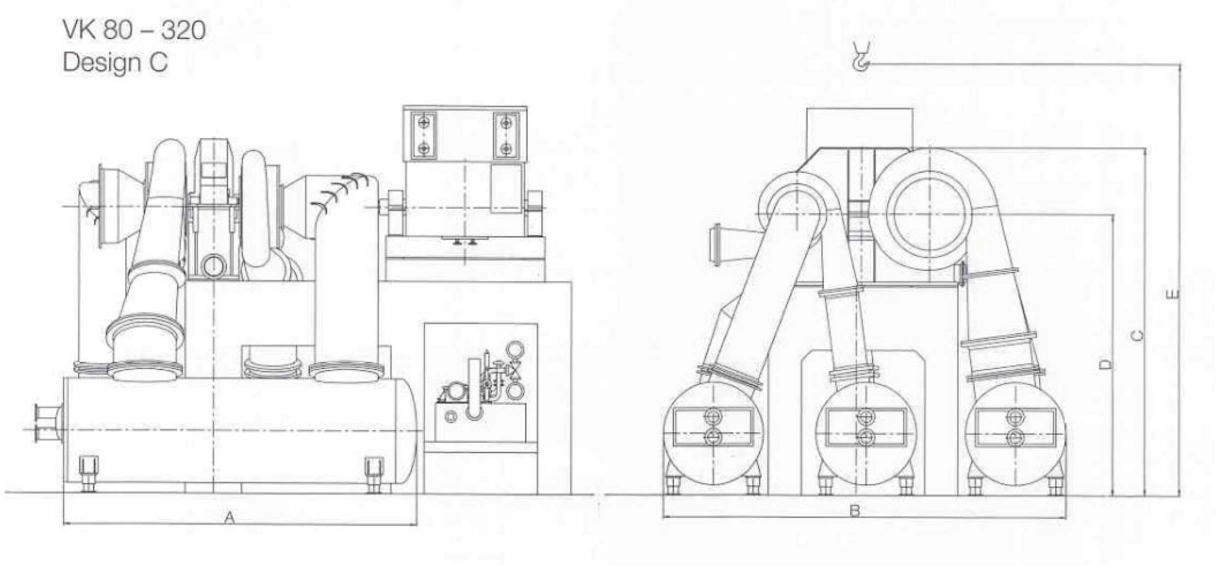
Section 4 DICE CRCC Other Major Plant Components

The remaining major plant system components were previously described in the Phase 1 Conceptual Design Report and reported here for completeness and clarity. These system components are standard off-the-shelf equipment that are commercially available and do not need further development.

4.1 MAIN AIR COMPRESSOR

The main air compressor (MAC) is an integrally-geared, intercooled centrifugal process compressor, which supplies the charge air to the DICE. For the present plant concept, Siemens Turbocompressor STC-GV (200-3) is considered. The compressor package includes the main driver (electric motor), air inlet filter, auxiliary support systems and the control system. The compressor has three stages with a 78 in. first stage impeller. Power consumption is about 110 hp (about 85 kW) per lb/s of airflow. The unit can be turned down to 50 percent flow with cooled bypass.

Figure 4-1
Main Air Compressor (MAC) Plane View (Siemens)



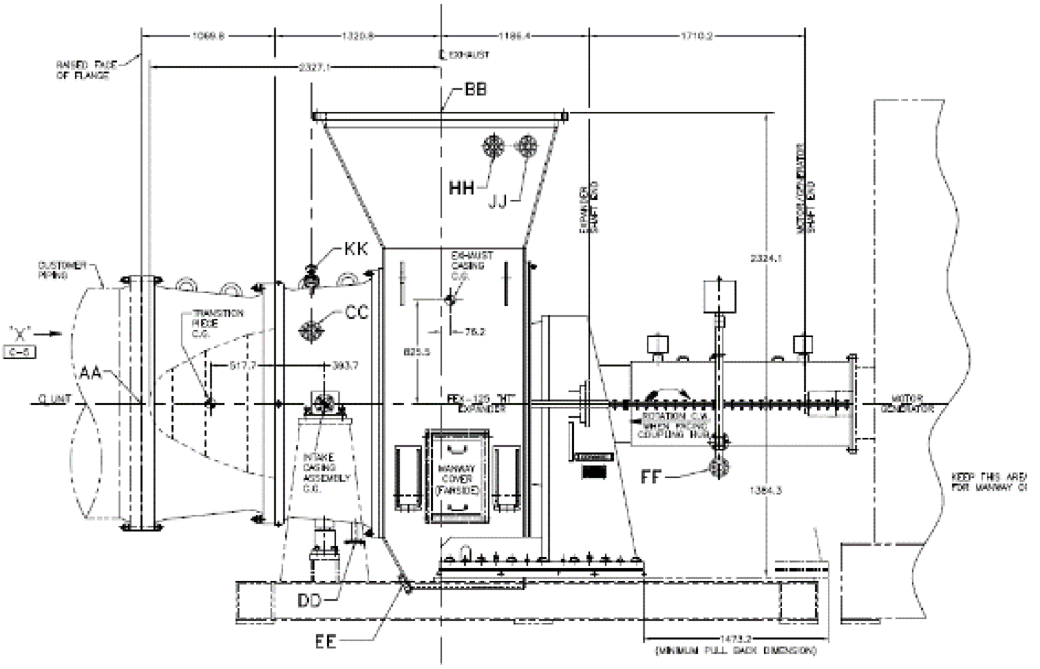
A: 8,490 mm (overall length), B: 10,400 mm (width), C: 8,500 mm (overall height), D: 6,900 mm (shaft centerline height), E: 9,500 mm (crane hook height)

4.2 HOT GAS EXPANDER

The hot gas expander (HGE) is a product of Baker Hughes (BHGE, formerly Nuovo Pignone of General Electric). BHGE had previously designed and commissioned several units of the same frame size proposed for this application (up to a pressure ratio of 4 and inlet temperature of 1,400 °F). An elevation view of the HGE is shown in Figure 4-2. The machine has four major parts: Intake casing and nose cone, rotor assembly, inner exhaust casing and exhaust casing. The rotor assembly comprises the following parts: shaft, rotor disc (from austenitic nickel-based superalloy), seal ring, tie bolt and rotor blades. At 4 bara and 760 °C inlet conditions, the unit can generate about 140 kW per lb/s of gas flow. At the introductory pre-FEED conditions, i.e., pressure ratio of about 3.6 and inlet temperature of about 980°F, the specific power output is about 95 kW per lb/s.

Hot gas turbo-expanders are widely employed in *Fluid Catalytic Cracking* (FCC) industry for conversion of flue gas pressure into useful shaft power. For reliable operation and long blade life (up to four years before replacement), catalytic fines in the flue gas must be removed prior to entry into the expander[5]. Otherwise, extremely abrasive particles can catastrophically damage the blades and casing walls within a few hundreds of hours of operation.

Figure 4-2
Baker Hughes Hot Gas Expander (HGE) Elevation View



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[5] Catalytic (or catalyst) fines, cat fines in short, are hard aluminum and silicon oxide particles that are normally present in heavy fuel oil. For refineries relying on catalytic cracking, cat fines are added to the crude oil to enhance low temperature fuel cracking.

4.3 THIRD-STAGE SEPARATOR

For the hot gas expander, BHGE requires that the abrasive particle concentration in the flue gas to the expander shall be maintained at less than 100 ppm. Furthermore, abrasive particle size distribution should not exceed 12 microns with D75 of two microns. In FCC applications, cat fines are removed in large-diameter primary/secondary cyclones in the FCC regenerator and in the "third-stage separator" (TSS) prior to entry into the HGE.

In refineries, typically, 2 to 8 primary and 2 to 8 secondary cyclones are utilized in FCC regenerators because of mechanical constraints and pressure drop concerns. These cyclones have a fairly large diameter, which restricts the amount of centrifugal acceleration which can be achieved. These cyclones let particles below 15 to 20 micron range pass through. Thus, a Third-Stage Separator (TSS) is installed upstream of the turbo-expander to reduce the catalyst fine loading and protect the blades. In essence, TSS is a containment vessel with a multitude of small-diameter cyclones inside. They are designed to withstand very abrasive service at a temperature of 1,450 °F. As such, TSS is the ideal choice for particle removal equipment in DICE CRCC.

4.4 HRSG

The HRSG is single-pressure with no-reheat and includes the SCR and CO catalyst sections. It is equipped with a duct burner upstream of the HP superheater section. The scope of supply of the HRSG vendor is complete from the combustion turbine outlet flange through the exhaust stack including all of the required pressure parts necessary to generate the desired HP steam production, LP system for generation of deaerating steam (either to an integral deaerator supplied by the vendor or a remote deaerator supplied by others), interconnecting ASME Section I Code piping local to the boiler, ASME boiler trim including feedwater control valve stations and water and steam flow measurement devices, recirculation system to elevate the temperature of the incoming condensate to 60 °C (140 °F), exhaust stack with CEMS ports, ladders, platforms and stair-tower.

During the study, several design modifications are adopted:

- The LP section is omitted; condensate return from the PCC stripper reboiler at a high pressure (i.e., above 50 psia), operating the deaerator at a high pressure (say, 45 to 50 psia) and venting steam is sufficient to maintain the dissolved O_2 limit (typically, 7 ppb).
- When the PCC block is off-line, steam extracted from the HP section is utilized to heat the condensate coming from the steam turbine condenser for deaeration.

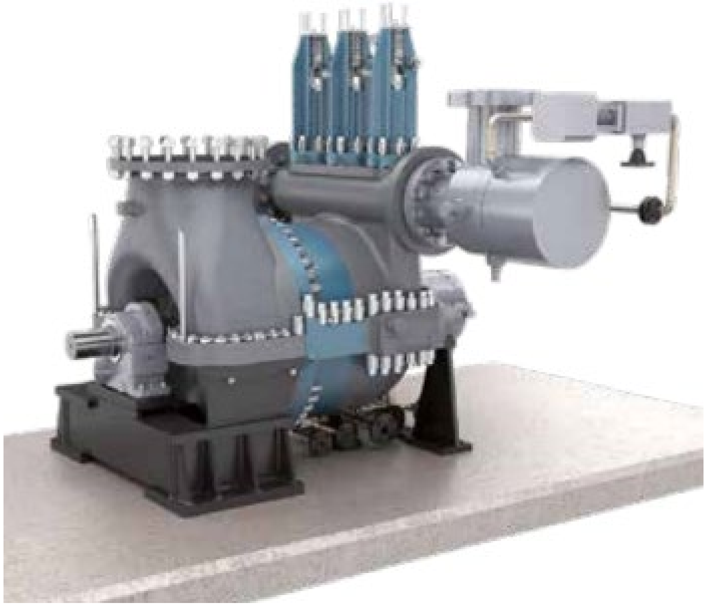
Sulfuric acid dew point is calculated as 291 °F (144 °C). Condensate temperature at the economizer inlet is 283 °F (139 °C) (247 °F [119 °C] when PCC block is offline). In order to ensure minimum tube surface temperature to prevent sulfuric acid condensation on the economizer tubes, the feedwater is recirculated from the economizer discharge to economizer inlet to maintain 150 °C (302 °F) tube temperature.

The HRSG is supplementary (or "duct") fired with natural gas to produce the requisite amount of steam for the MEA stripper reboiler in the PCC plant.

4.5 BACK-PRESSURE STEAM TURBINE (BPST)

The study concept incorporates PCC with amine-based chemical absorption technology. The main purpose of the bottoming cycle is to supply 60 psia nominally saturated steam to the PCC stripper's kettle reboiler. This precludes the utilization of an efficient bottoming cycle design with a condensing steam turbine. The steam turbine in the plant is a backpressure, non-condensing unit, nominally rated at 20,000 hp, which can be supplied off-the-shelf by a multitude of OEMs, e.g., Siemens' Dresser-Rand (D-R) subsidiary. The specific unit that fits the requirements of the application is D-R R/RS standard multi-stage steam turbine, as shown in Figure 4-3. This machine can handle steam inlet conditions up to 915 psia and 900°F. It is designed in compliance with API 611/612 standards with impulse-type blading. The steam turbine rating can be up to 33,500 hp and turbine speed is 15,000 rpm (or less depending on the rating). In this conceptual design, steam conditions are set to 650 psia and 750°F. The turbine is connected to the generator via a gearbox.

Figure 4-3
Dresser-Rand DR R/RS Type Steam Turbine



4.6 LP CONDENSING TURBINE AND SURFACE CONDENSER

Additionally, the DICE CRCC plant is designed for maximum power generation with the addition of a low-pressure (LP) condensing turbine for use exclusively when the PCC is offline. The turbine generates additional power from the steam that is normally routed to the PCC when it is in operation.

The LP turbine is connected to the generator via a SSS ("triple S") clutch. The clutch separates the LP turbine from the generator when the PCC is online. When the PCC is offline, steam from the backpressure is routed to the LP turbine, which starts spinning and the SSS clutch automatically engages for additional power generation. The condenser pressure during LP turbine operation is set to 2.5 in Hg. Condenser cooling water system forms a closed loop with the plant cooling tower.

4.7 DIRECT CONTACT CAUSTIC SCRUBBER/COOLER

For the 100 MWe DICE CRCC plant, a direct contact cooler (DCC) with caustic injection is used to cool the flue gas and remove the bulk of the SOx in the flue gas. This is a packed bed absorber with circulating water to condense out most of the moisture in the flue gas feed. In the DCC, water is directed downward through a packing media to counter the upward flow of the flue gas and to cool it to the required temperature. It also removes acid gases down to around 10 ppm SO_2 equivalent, using caustic injection as determined by pH control.

4.8 POST-COMBUSTION CO_2 CAPTURE (PCC) PLANT

A single-train MEA-based PCC plant treats the flue gas leaving the HRSG to recover 90 percent of the CO_2. The PCC plant consists of two sections: a CO_2 Capture Plant to extract the CO_2 from the flue gas; and a CO_2 Compression Plant to pressurize the CO_2 product for delivery to final sequestration. The CO_2 Capture Plant will be designed with state-of-the-art generic 30 wt% MEA technology. All equipment in the CO_2 Capture Plant is constructed of stainless steel to minimize corrosion effects associated with 30 wt% MEA.

4.8.1 CO_2 Capture Plant

The CO_2 capture plant process scheme consists of flue gas CO_2 absorption and amine solution regeneration.

A flue gas blower located between the scrubber and absorber boosts the pressure of the flue gas in order to overcome the pressure drop associated with the CO_2 absorber. The boosted flue gas with enters the bottom of the absorber column and is scrubbed counter-currently by lean 30 wt% MEA solution to remove 90 percent of its CO_2 content. The CO_2-depleted flue gas continues to travel upwards to the water wash section of the tower, where it is contacted counter-currently with wash water to remove any amine and volatile organic compounds (VOCs) present in the gas, before it is routed to the stack for venting to atmosphere.

The CO_2-rich MEA solvent is collected at the bottom of the absorber and pumped to the stripper column for CO_2 regeneration. Heat is recovered in a rich/lean amine heat exchanger to recover some of the energy in the hot lean amine to minimize steam consumption in the stripper reboiler.

The heated rich solution is then stripped of CO_2 in a reboiled amine stripper to regenerate the lean MEA solution. Overhead vapor from the stripper is cooled with cooling water in an overhead condenser and sent to a reflux drum. The vapor leaving the drum is the recovered CO_2 and needs to be compressed in the CO_2 compression plant before it can be delivered to the battery limit.

The stripper reboiler, a kettle-type heat exchanger, is heated with 60 psia saturated steam leaving the BPST to generate the vapor used to strip the CO_2 from the MEA solution. The steam is condensed in the reboiler and is pumped back to the HRSG to be heated by the hot flue gas again.

4.8.2 **CO_2 Compression Plant**

The CO_2 from the CO_2 capture plant needs to be delivered to the battery limit at 2215 psia. This is accomplished first by compressing the CO_2 vapor to 1,315 psia in a 3-stage centrifugal CO_2 compressor with inter-stage cooling. Each stage has an average compression ratio of approximately 4. The cooled supercritical CO_2 at 1,315 psia is then pumped to the final delivery pressure of 2,215 psia (152 bara).

In order to meet the 50 ppm water specification for the CO_2 product, the CO_2 is dried in a heatless dehydration unit after the second stage of compression at approximately 365 psia. This unit is a pressure swing absorption system that utilizes molecular sieve adsorbents to remove water. It consists of two tanks storing the adsorbents and alternating with each other in drying the inlet gas. About 7 percent of the inlet gas volume is purged in a stream containing the adsorbed moisture. This purge stream is recycled back to the first stage of CO_2 compression where the moisture is removed in the first stage knockout. The net condensate collected from the CO_2 compression section is sent back to the amine stripper for recovery.

Section 5 DICE CRCC Plant Performance

5.1 PROCESS FLOW DIAGRAM

The overall DICE CRCC power plant PFD is shown in Figure 5-1 and comprises the following:

- Coal beneficiation plant
- 5 DICE (nominally 20 MWe each)
- 1 main air compressor (MAC)
- 1 hot gas expander
- Bottoming cycle consisting of HRSG with natural gas duct firing and back pressure steam turbine
- 30 wt% MEA-based PCC unit capturing 90 percent of CO_2 in the flue gas

The overall cycle is described as follows:

- Charge air for the DICE is supplied by the MAC (an integrally geared and intercooled process compressor)
- Exhaust gas from the DICE generates additional power in a hot gas expander
- Gas turbine exhaust is utilized in a natural gas duct fired HRSG to produce enough steam for CO_2 capture
- Superheated steam produced in the HRSG is expanded in a backpressure steam turbine (BPST) to generate additional power
- BPST exhaust steam is desuperheated and sent to the PCC amine stripper reboiler, where its latent heat of condensation is used to regenerate the lean MEA solution
- The hot condensate leaving the stripper reboiler is routed back to the HRSG to be heated and make steam

Additional process flow diagrams depicting in more detail, the CO_2 capture plant, and CO_2 compression plant, are shown in Figure 5-2 and Figure 5-3 respectively. The coal beneficiation plant simplified block flow diagram and detailed process flowsheet have previously been shown in Figure 2-2 and Figure 2-3 respectively.

5.2 HEAT AND MATERIAL BALANCE

The corresponding heat and material balance details of the major streams shown in Figure 5-1 are presented in Table 5-1.

Figure 5-1
100 MWe Nominal DICE CRCC Process Flow Diagram

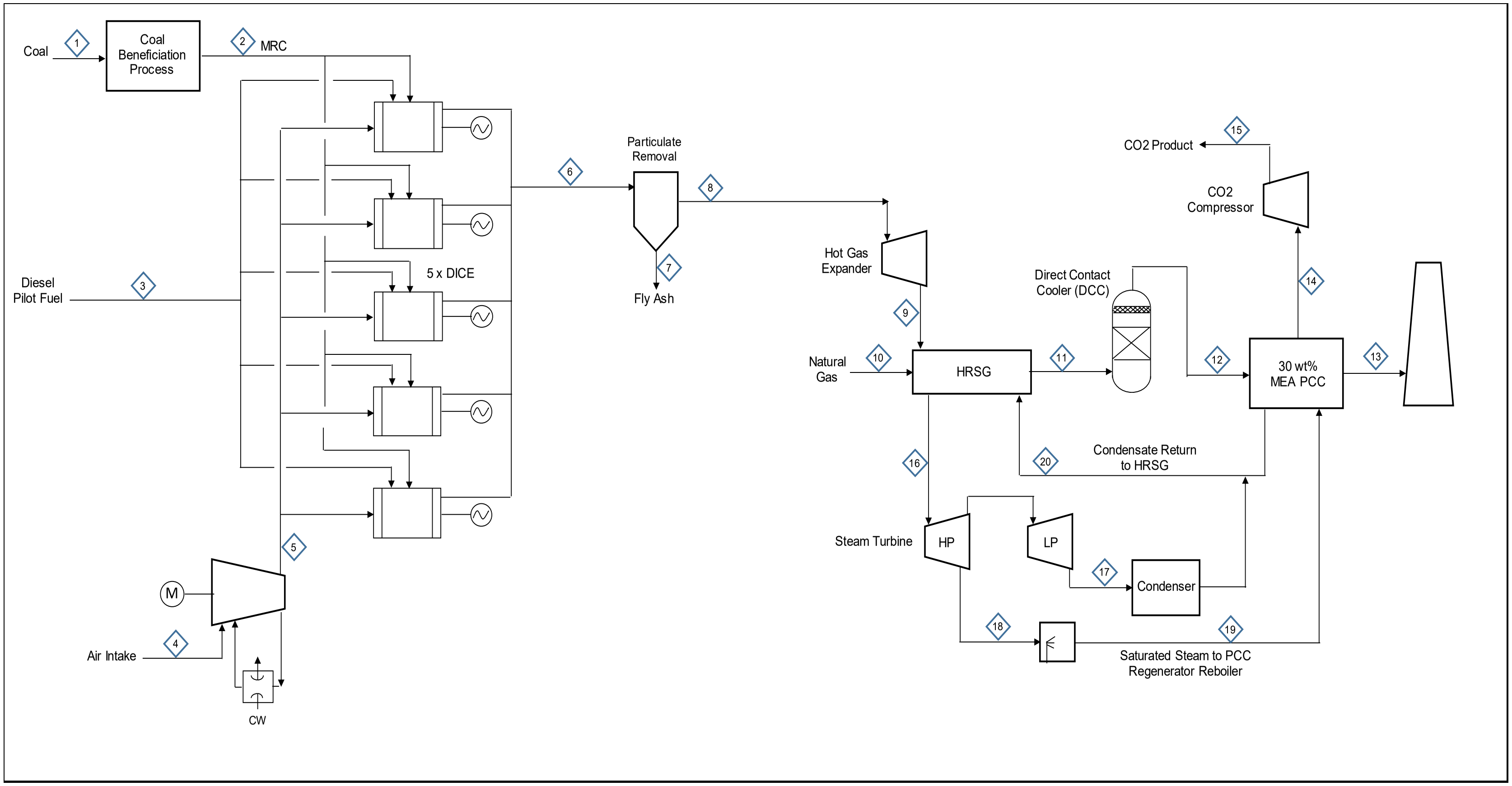


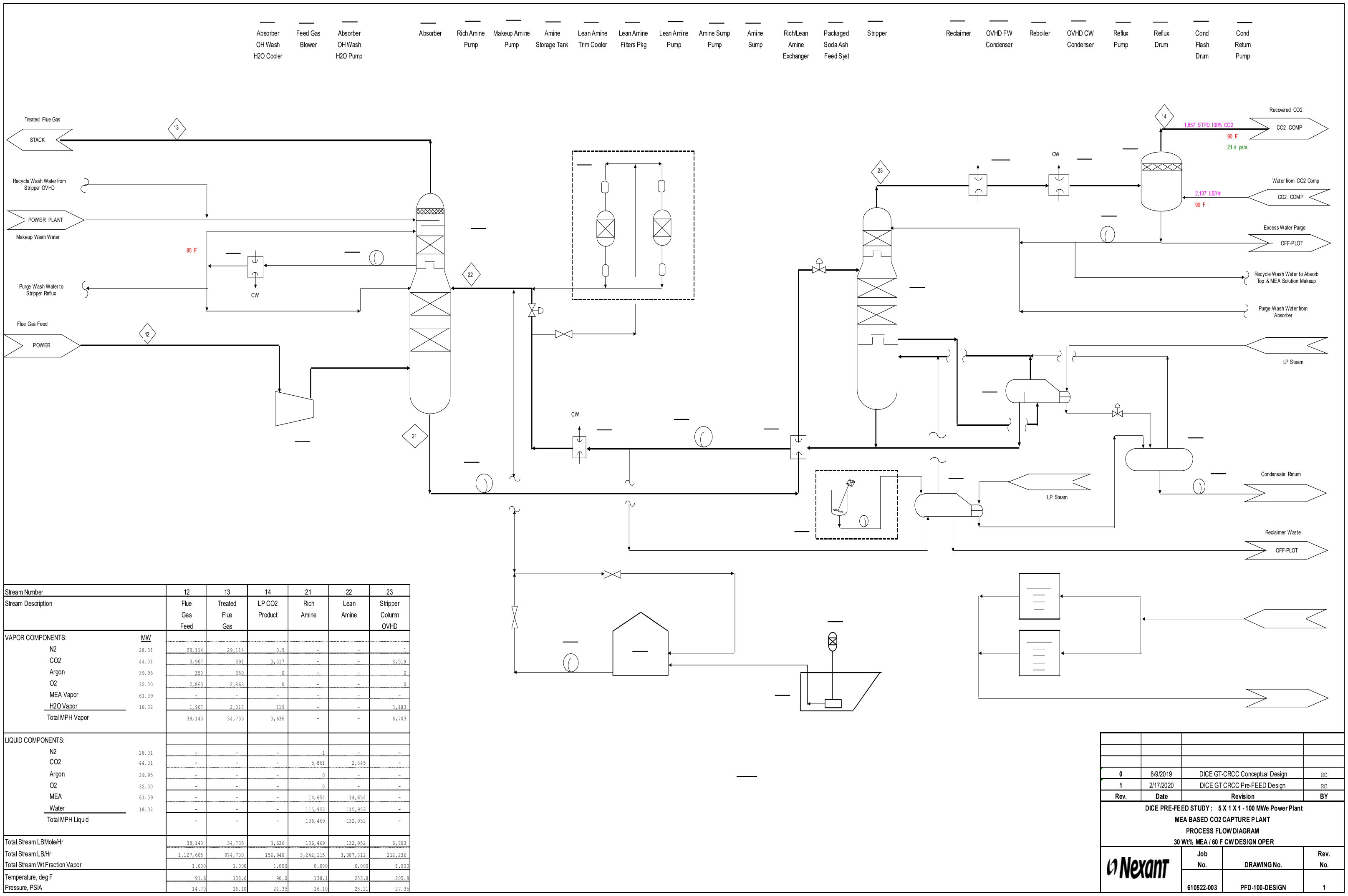
Table 5-1
100 MWe Nominal DICE CRCC Stream Table

V-L Mole Fraction	1	2	3	4	5	6	7	8	9	10
N2	0.0000	0.0000	0.0000	0.7729	0.7729	0.7116	0.0000	0.7116	0.7116	0.0000
O2	0.0000	0.0000	0.0000	0.2074	0.2074	0.1006	0.0000	0.1006	0.1006	0.0000
H2O	0.0000	0.0000	0.0000	0.0101	0.0101	0.0990	0.0000	0.0990	0.0990	0.0000
CO2	0.0000	0.0000	0.0000	0.0003	0.0003	0.0799	0.0000	0.0799	0.0799	0.0000
Ar	0.0000	0.0000	0.0000	0.0093	0.0093	0.0086	0.0000	0.0086	0.0086	0.0000
SO2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0003	0.0000	0.0003	0.0003	0.0000
SO3 (ppmvd)	0.0000	0.0000	0.0000	0.0000	0.0000	17	0.0000	17	17	0.0000
Total	**0.0000**	**0.0000**	**0.0000**	**1.0000**	**1.0000**	**1.0000**	**0.0000**	**1.0000**	**1.0000**	**0.0000**
Natural Gas Flowrate, klb/hr	0	0	0	0	0	0	0	0	0	10.6
V-L Flowrate, klb/hr	0	0	0	1085.9	1085.9	1178.6	0	1178.6	1178.6	10.6
V-L Flowrate, lbmol/hr	0	0	0	37631	37631	40936	0	40936	40897	614
Coal Flowrate, klb/hr	148.8	0	0	0	0	0	0	0	0	0
Diesel Flowrate, klb/hr	0	0	1.7	0	0	0	0	0	0	0
Slurry Flowrate, klb/hr	0	91.9	0	0	0	0	0	0	0	0
Ash, klb/hr	0	0	0	0	0	1.1	1.1	0	0	0
Pressure, psia	--	--	--	14.7	72.5	56.3	--	56.3	15.3	430
Temperature, °F	--	--	--	59.0	158.0	985.8	--	985.8	642.2	80

Table 5-1 (continued)
100 MWe Nominal DICE CRCC Stream Table

V-L Mole Fraction	11	12	13	14	15	16	17	18	19	20
N2	0.7011	0.7633	0.8382	0.0002	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000
O2	0.0689	0.0751	0.0824	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
H2O	0.1271	0.0500	0.0581	0.0326	0.0000	1.0000	1.0000	1.0000	1.0000	1.0000
CO2	0.0941	0.1024	0.0112	0.9670	0.9997	0.0000	0.0000	0.0000	0.0000	0.0000
Ar	0.0084	0.0092	0.0101	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SO2	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
SO3 (ppmvd)	46	0	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	**1.0000**	**1.0000**	**1.0000**	**1.0000**	**1.0000**	**1.0000**	**1.0000**	**1.0000**	**1.0000**	**1.0000**
Natural Gas Flowrate, klb/hr	0	0	0	0	0	0	0	0	0	0
V-L Flowrate, klb/hr	1189.2	1127.6	974.7	156.9	154.8	263.5	0	263.4	263.6	263.6
V-L Flowrate, lbmol/hr	41529	38143	34735	3636	3518	14625	0	14620	14632	14632
Coal Flowrate, klb/hr	0	0	0	0	0	0	0	0	0	0
Diesel Flowrate, klb/hr	0	0	0	0	0	0	0	0	0	0
Slurry Flowrate, klb/hr	0	0	0	0	0	0	0	0	0	0
Ash, klb/hr	0	0	0	0	0	0	0	0	0	0
Pressure, psia	14.85	14.70	16.1	21.4	2215	671.4	--	63.0	60.0	54.1
Temperature, °F	345.4	91.6	108.6	90.0	90.0	753.5	--	296.6	293.7	286.1

Figure 5-2
MEA-Based CO_2 Capture Plant Process Flow Diagram



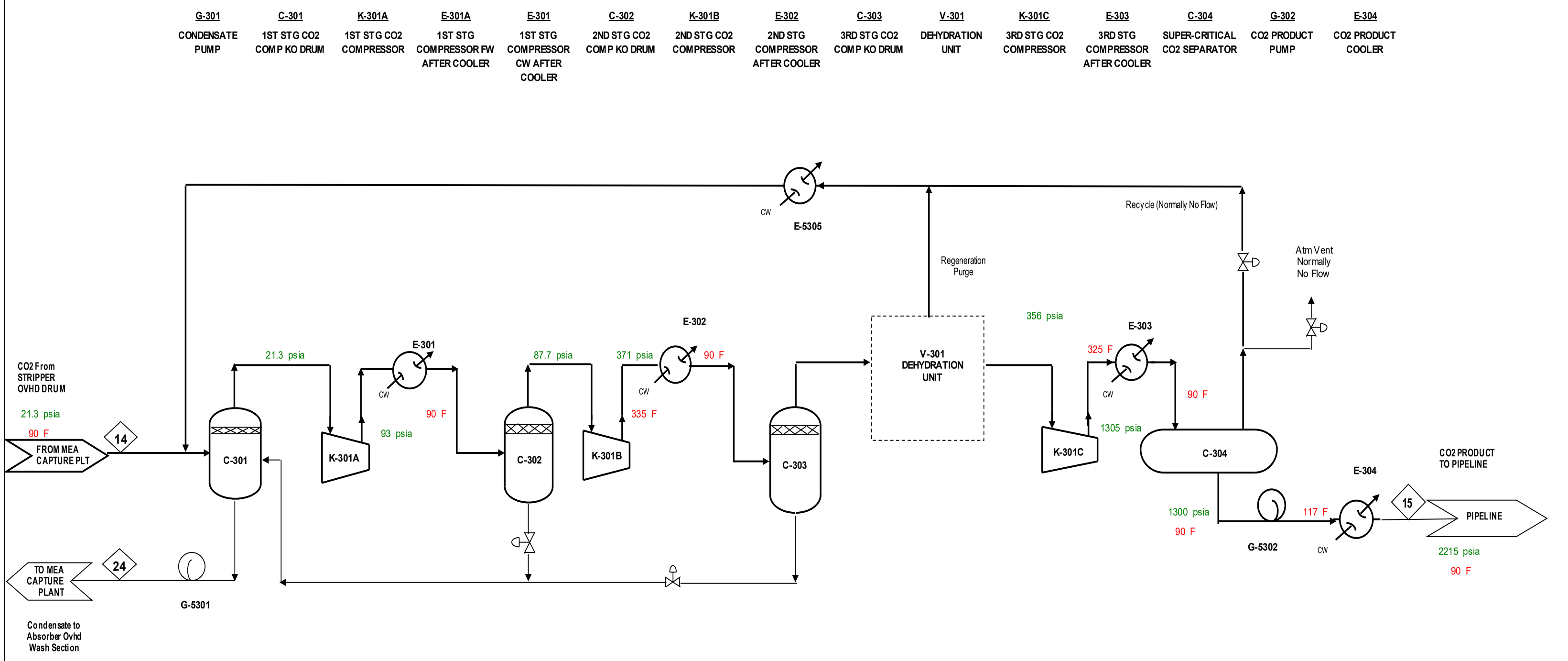
Stream Number	MW	12	13	14	21	22	23
Stream Description		Flue Gas Feed	Treated Flue Gas	LP CO2 Product	Rich Amine	Lean Amine	Stripper Column OVHD
VAPOR COMPONENTS:	MW						
N2	28.01	29,114	29,114	0.9	-	-	1
CO2	44.01	3,907	391	3,517	-	-	3,519
Argon	39.95	350	350	0	-	-	0
O2	32.00	2,863	2,863	0	-	-	0
MEA Vapor	61.09	-	-	-	-	-	-
H2O Vapor	18.02	1,907	2,017	119	-	-	3,183
Total MPH Vapor		38,143	34,735	3,636	-	-	6,703
LIQUID COMPONENTS:							
N2	28.01	-	-	-	1	-	-
CO2	44.01	-	-	-	5,861	2,345	-
Argon	39.95	-	-	-	0	-	-
O2	32.00	-	-	-	0	-	-
MEA	61.09	-	-	-	14,654	14,654	-
Water	18.02	-	-	-	115,953	115,953	-
Total MPH Liquid		-	-	-	136,469	132,952	-
Total Stream LBMole/Hr		38,143	34,735	3,636	136,469	132,952	6,703
Total Stream LB/Hr		1,127,605	974,700	156,940	3,242,115	3,087,312	212,236
Total Stream Wt Fraction Vapor		1.000	1.000	1.000	0.000	0.000	1.000
Temperature, deg F		91.6	108.6	90.0	138.1	253.8	205.8
Pressure, PSIA		14.70	16.10	21.35	16.10	28.21	27.35

Rev.	Date	Revision	BY
0	8/9/2019	DICE GT-CRCC Conceptual Design	RC
1	2/17/2020	DICE GT CRCC Pre-FEED Design	RC

DICE PRE-FEED STUDY : 5 X 1 X 1 - 100 MWe Power Plant
MEA BASED CO2 CAPTURE PLANT
PROCESS FLOW DIAGRAM
30 Wt% MEA / 60 F CW DESIGN OPER

Job No.	DRAWING No.	Rev. No.
610522-003	PFD-100-DESIGN	1

Figure 5-3
CO_2 Compression Plant Process Flow Diagram



Stream No.		14	24	15
Stream Name		LP CO2 Product	Condensate	CO2 Product
Component	MW	lbmol/hr	lbmol/hr	lbmol/hr
N2/Ar	28.15	0.9	0	0.9
O2	32	TRACE	0	TRACE
CO2	44.011	3516.6	0.1	3516.6
H2O	18.016	118.6	118.6	0.0
MEA	61.08	TRACE	TRACE	0
Total	lbmol/hr	3636.2	118.7	3517.5
	lb/hr	156933	2141	154793
Actual Flow	GPM	-	4.3	379
Vapor Flow	MMSCFD	33.1	-	-
Temp	°F	90	88	90
Pressure	psia	21	21	2215

Notes
=========

1) All information show n on this diagram or data sheet represent estimatons for given operations and are provided for pre-feasibility evaluation purposes based on Nexant's in-house data from similar applications. The information show n represent projected best achievable performance for generic inhibited MEA processes. While useful for studies, Nexant does not guarantee the accuracy and completeness of the information show n. Actual performance and design specifications and guarantees are the responsibilities of the selected technology licensors.

2) All rates show n are for 1 train. One identical trains are required for DICE.

3) Normal consumptions for given operation are listed in the utlities summary data sheet. Equipment design sizes are show n under the major equipment listing data sheet.

Rev No.	Date	Revision	Engineer	Checked	Approval
0	8/9/2019	DICE GT CRCC Conceptual Des	RC		
1	2/17/2020	DICE GT CRCC Pre-FEED	RC		

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San Francisco, CA

DICE GT-CRCC PRE-FEED DESIGN : 5 X 1 X 1

Process Flow Diagram
CO2 COMPRESSION/ 60 F CW DES OPERATION

Job No.	Drawing No.	Revision No.
610522-003	DS-PFD-1300-DESIGN	1

5.3 DICE CRCC PLANT NET EFFICIENCY

Table 5-2 summarizes the overall performance based on the design of the nominal 100 MWe DICE CRCC power plant. Overall fuel mix to the plant consists of 71.5 percent coal, 3.5 percent diesel fuel and 25.0 percent natural gas, on an LHV basis. The net efficiency of the plant is 30.8 percent on an LHV basis (29.1 percent HHV), not including the heating value associated with the rejects as these do not participate in the combustion reactions. With the heating value of the rejects included i.e. efficiency is calculated based on total heating value from the raw PRB coal, the overall efficiency is 18.0 percent LHV (17.2 percent HHV).

Table 5-2
Power Summary and Net Efficiency

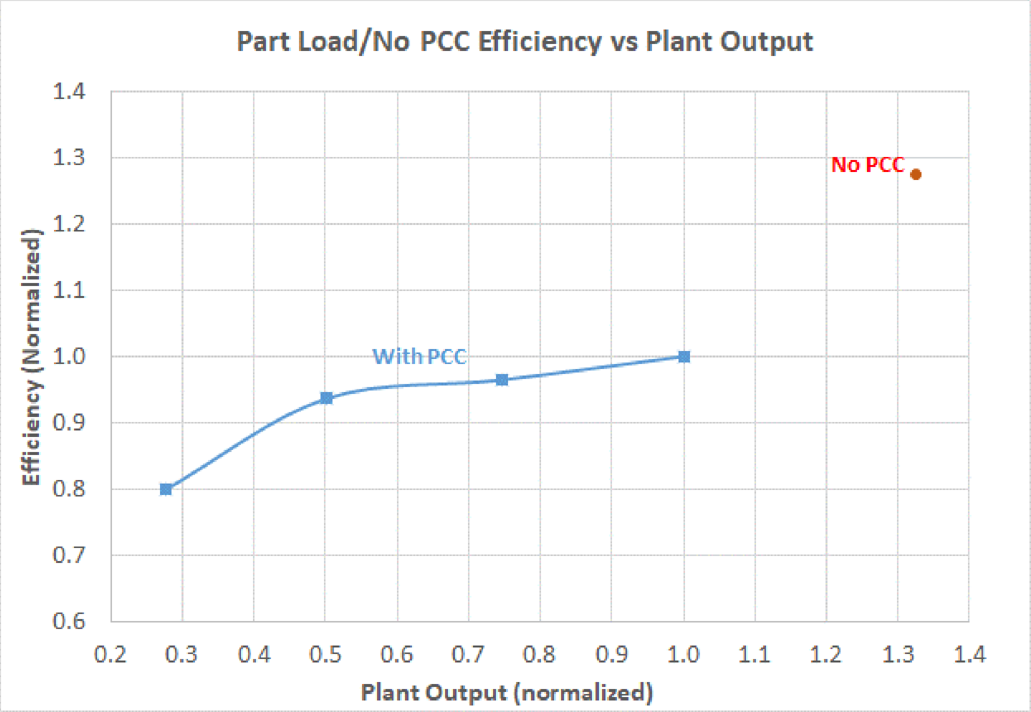
Power Summary	
POWER GENERATION, kWe	
5 x DICE	78,730
Turboexpander	31,787
Steam Turbine	14,676
Total Power Generation	**125,192**
AUXILIARY LOAD SUMMARY, kWe	
MRC Fuel Prep	5,472
Main Air Compressor	26,301
SCR	88
Fabric Filter	69
Boiler Feed Water Pump	261
Economizer Recirculation Pump	5
Steam Turbine Auxiliaries	31
DCC Circulating Pump	400
CO_2 Capture	2,549
CO_2 Compression	7,838
Circulating Water Pumps	2,407
Makeup Water Pumps	70
Cooling Tower Fans	977
Wastewater Pumps	14
Miscellaneous Auxiliaries	135
Transformer Losses	626
Total Auxiliaries, kWe	**47,242**
Net Power, kWe	**77,950**
As-Received PRB Coal Feed, lb/hr	148,818
Beneficiated Coal Slurry Fuel Feed, lb/hr	91,934
Diesel Fuel Feed, lb/hr	1,651
Natural Gas Feed Flow, lb/hr	10,640
Coal LHV Thermal Input, MMBtu/hr	619
Diesel LHV Thermal Input, MMBtu/hr	30
Gas LHV Thermal Input, MMBtu/hr	216
Total LHV Thermal Input, MMBtu/hr	**865**
LHV Efficiency %, based on beneficiated coal feed	**30.8%**
%, based on as-received PRB coal feed	**18.0%**

Coal HHV Thermal Input, MMBtu/hr Diesel HHV Thermal Input, MMBtu/hr Gas HHV Thermal Input, MMBtu/hr	643 32 239
Total HHV Thermal Input, MMBtu/hr	**914**
HHV Efficiency %, based on beneficiated coal feed	**29.1%**
HHV Efficiency %, based on as-received PRB coal feed	**17.2%**

Plant part load performance (normalized) is summarized in Figure 5-4. The horizontal axis indicates the part load net output expressed as a fraction of the full load (5 DICE, with PCC) net output, and is based on an operational range of two DICE through the maximum of all five DICE. The right-most point on the graph shows the net efficiency of the plant when the PCC is not in service and steam is routed to a condensing turbine to generate additional power instead of the PCC reboiler.

The coal beneficiation plant is expected to operate in batch mode and will run intermittently at full capacity to fill up the beneficiated coal slurry buffer tank when its levels are low. The auxiliary load consumed by the coal beneficiation plant is hence not included in the part load performance plot.

Figure 5-4
DICE CRCC Part Load Performance



5.4 OVERALL UTILITIES BALANCE

The overall utilities balance that summarizes the DICE CRCC plant's various utilities consumption and generation, including power, steam, water, water-cooled and air-cooled duties, are shown in Table 5-3.

5.5 DICE CRCC WATER BALANCE

Water demand represents the total amount of water required for a particular process. Some water is recovered within the process and is re-used as internal recycle. The difference between demand and recycle is raw water withdrawal. Raw water withdrawal is defined as the water removed from the ground or diverted from a POTW for use in the plant and was assumed to be provided 50 percent by a POTW and 50 percent from groundwater. Raw water withdrawal can be represented by the water metered from a raw water source and used in the plant processes for all purposes, such as DCC makeup, BFW makeup, and cooling tower makeup. The difference between water withdrawal and process water discharge is defined as water consumption and can be represented by the portion of the raw water withdrawn that is evaporated, transpired, incorporated into products or otherwise not returned to the water source from which it was withdrawn. Water consumption represents the net impact of the plant process on the water source balance.

Table 5-4 summarizes the water balance for the 100 MWe DICE CRCC power plant.

Raw water demand is minimized by reusing the condensate (125 gpm) from the flue gas DCC column in the PCC plant as cooling tower makeup water. Additionally, cooling tower blowdown water (228 gpm) is used for slurrying both the tailings and beneficiated coal to be fed to the DICE, thereby minimizing the raw water needed for the overall operation of the plant.

Table 5-3
100 MWe Nominal DICE CRCC Overall Utilities Balance

Item Name	DICE GT-CRCC Elect. Power	Steam				PCC Condensate	Desuperht Condensate	Demin Makeup	Treated Water	Makeup Water		Internal Recycle	Wastewater			Cooling Water		Air Cooling	
		1000 Lbs/Hr																	
	KW	671 psia/ 754 F	HP Exh: 63 psia/ 318 F	'60 psia / 298 F	Deaerator Vent	54 psia/ 286 F				Ground Water	Municipal Water	Recycle	Internal Recycle	Sewage Water	Process Wastewater	CW, MMbtu/hr	C.W. circ. GPM	MMbtu/hr Absorbed	Remarks
DICE-GT CRCC POWER ISLAND																			
COAL BENEFICIATION																			
COAL HANDLING & CONVEYING:	incl																		
COAL BENEFICIATION & SLURRYING:																			
COAL BENEFICIATION	5,472								0.0				114.3		0.0				
DICE																			
DICE MAIN AIR COMPRESSOR	26,301																		
MAIN AIR COMPRESSOR FIN FAN COOLER																120.0	11,984		
DICE #1	(15,746)																		
DICE #2	(15,746)																		
DICE #3	(15,746)																		
DICE #4	(15,746)																		
DICE #5	(15,746)																		
FABRIC FILTER	69																		
TURBOEXPANDER:																			
HOT GAS TURBOEXPANDER	(31,787)																		
STEAM CYCLE:																			
SCR	88																		
HRSG		263.5			(14.4)	(263)	(0.2)	11.8							2.6				
HP STEAM TURBINE	(14,676)	(263.5)	263.5																
DESUPERHEATER			(263.5)	263			0.2												
BFW PUMPS	261																		
ECONOMIZER RECIRCULATION PUMP	5																		
STEAM TURBINE AUXILIARY LOAD	31																		
PCC ISLAND																			
CO2 CAPTURE:																			
DCC												(62.4)							
DCC CIRC COOLER																133.7	13,357		
DCC CIRC COOLER PUMP	400																		
FLUE GAS BLOWER	1,547																		
MEA ABSORBER												(0.7)			(1.1)				
MEA STORAGE MAKEUP TANK												0.7							
WASH WATER COOLER																16.3	1,625		
WASH WATER PUMP	89																		
RICH AMINE PUMP	464																		
MEA STRIPPER REBOILER				(263.3)		263.3													
CONDENSATE RETURN PUMP	65																		
STRIPPER CONDENSER																64.4	6,435		
STRIPPER OVERHEAD RECEIVER												2.1							
STRIPPER REFLUX PUMP	8																		
LEAN AMINE PUMP	376																		
LEAN AMINE COOLER																167.5	16,734		
CO2 COMPRESSION:																			
1ST STAGE CO2 COMPRESSOR	2,820																		
1ST CO2 COMPRESSOR INTERCOOLER																11	1,093		
1ST STAGE CO2 FEED KO DRUM												(2.1)							
2ND STAGE CO2 COMPRESSOR	2,638																		
2ND CO2 COMPRESSOR INTERCOOLER																10	1,030		
3RD STAGE CO2 COMPRESSOR	2,060																		
3RD CO2 COMPRESSOR INTERCOOLER																19	1,944		
SUPERCRITICAL CO2 PUMP	320																		
SUPERCRITICAL CO2 AFTERCOOLER																3	290		
ELECTRICAL AND MISCELLANEOUS																			
MISCELLANEOUS																			
TRANSFORMER LOSSES	626																		
MISCELLANEOUS AUXILIARIES	135																		
SUBTOTAL DICE/PCC ISLAND	**(81,417)**	**0**	**0**	**0**	**(14)**	**0**	**0**	**12**	**0**	**0**	**0**	**(62)**	**114**	**0**	**1**	**545**	**54,492**		
COOLING WATER , COOLING TOWER AND WATER TREATMENT																			
COOLING TOWER:																			
COOLING WATER PRODUCTION									505.1			62.4	(114.3)		(27.6)	(545)	(54,492)		
CIRCULATING WATER PUMP	2,407																		
COOLING TOWER FANS	977																		
DEMINERALIZER																			
DEMIN SYSTEM								(11.8)			15.4				(3.6)				
MU WATER SUPPLY & TREATMENT																			
MU WATER PUMP	70																		
MU WATER FILTER PACKAGE									(505.1)	297.1	297.1				(89.1)				
POTABLE WATER																			
POTABLE WATER TREATMENT											1.1			(1.1)					
WASTEWATER TREATMENT																			
WASTEWATER PUMPS	14																		
SUBTOTAL CW & CT	**3,467**	**0**	**0**	**0**	**0**	**0**	**0**	**(12)**	**0**	**297**	**314**	**62**	**(114)**	**(1)**	**(120)**	**(545)**	**(54,492)**		
OVERALL DICE-CT CRCC	**(77,950)**	**0**	**0**	**0**	**(14)**	**0**	**0**	**0**	**0**	**297**	**314**	**(0)**	**0**	**(1)**	**(119)**	**0**	**0**		

DICE GT-CRCC PRE-FEED UTILITIES SUMMARY
REVISIONS

JOB NUMBER	610522.003.01	
	Drawing No.	REV.
	DS-UTIL-001	A

Table 5-4
100 MWe DICE CRCC Water Balance

Water Use	Water Demand	Internal Recycle	Raw Water Withdrawal	Process Water Discharge	Raw Water Consumption
	gpm	**gpm**	**gpm**	**gpm**	**gpm**
MRC Slurrying	228	228	0	--	--
Demin Water Makeup	31	--	31	--	31
Demin System Discharge	--	--	--	7	-7
Steam Cycle Blowdown	--	--	--	5	-5
Deaerator Vent	--	--	--	18	-18
DCC Discharge Water	--	-125	--	--	--
MEA Absorber Discharge		-1	--	2	-2
MEA Storage Tank Makeup	1	1	0	--	0
MEA Regenerator Ovhd Makeup	4	4	0	--	--
CO_2 Compression KO Water	--	-4	--	--	--
Cooling Tower Makeup	1,134	125	1,009	--	1,009
Cooling Tower Blowdown	--	-228	--	55	-55
Makeup Water Treatment Net Demand	178	--	178	--	178
Potable Water Demand	2	--	2	--	2
Makeup Water Treatment Discharge	--	--	--	178	-178
Discharge to Sewage	--	--	--	2	-2
Total	**1,579**	**--**	**1,220**	**268**	**952**

5.6 PLANT EMISSIONS

Table 5-5 summarizes the various DICE CRCC plant emissions and control measures undertaken to achieve these emissions. For this report, given the low chloride content (0.01 wt%) in the PRB coal, HCl emissions are estimated to be 0.06 lb/MWh-gross in a worst-case, unabated scenario. However, in the DOE Bituminous Baseline report, SO_2 emissions were utilized as a surrogate for HCl emissions, and HCl was not reported. Similarly, assuming HCl control follows SO_2 emissions control technology per the Bituminous Baseline Report, the HCl emissions for the DICE CRCC plant would be at trace level.

Mercury levels for PRB coal is estimated to be 0.056 ppm on a dry basis. It has been shown in literature than conventional beneficiation methods using cyclones and froth flotation can remove up to 62 percent of the mercury in the coal[6]. Assuming no other mercury control method in the power plant, the mercury emissions as a result of using flotation in the coal beneficiation process is 9×10^{6} lb/MWh-gross. However, in the presence of emissions control equipment such as the TSS and SCR, whose vanadium-based catalyst promotes the oxidation of elemental mercury Hg to water-soluble Hg^{2+} in the flue gas, which can then be captured in the DCC, the mercury emissions for the DICE CRCC is expected to meet the emissions limits of 3×10^{6} lb/MWh-gross. If mercury emissions are shown to exceed, the limits, the industry-standard activated carbon injection (ACI) can be utilized to further reduce these emissions. The DOE Bituminous Baseline Report states that a combination of ACI with the above-mentioned control technology can reduce mercury emissions by upwards of 97 percent of mercury, which will easily meet the 3×10^{6} lb/MWh-gross target.

Table 5-5
Plant Emissions Summary

Pollutant	Env. Target	Est. Emissions	Control Technology
	lb/MWh-gross		
SOx	1.00	Trace (0.000)	DCC + MEA reaction with residual SOx in flue gas to effectively reduce to zero
NOx	0.7	0.7 (estimated)	SCR + MEA reaction with NO_2 to effective scrub out all NO_2, reducing NOx content by 10% (assume 90:10 NO/NO_2 ratio in flue gas) while all NO passes through. While NOx emissions are hard to predict, it has been found that DICE emits half the NOx as engines running on diesel at the same load. Based on CSIRO's experience, DICE exhaust is likely to achieve 350 ppmv NOx or lower, given the longer ignition delay, better mixing of fuel and air, and progressive burn of MRC. At < 350 ppmv NOx in the exhaust, the resulting NOx emissions at the stack will meet the 0.07 lb/MWh-gross emissions limit

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[6] Emissions Control Strategies for Power Plant, Bruce G. Miller, Clean Coal Engineering Technology pp 375-481, 2011

PM	0.09	Trace (0.000)	DCC water wash in PCC plant further scrubs out residual PM in flue gas
Hg	3 x 10^{-6}	3 x 10^{6} (estimated)	TSS + SCR + DCC. If mercury is still an issue, activated carbon injection (ACI) can be utilized at a location with appropriate temperature before the cyclone.
HCl	0.010	0.000 (SOx surrogate)	Per Bituminous Baseline Report, SO_2 emissions are used as a surrogate for HCl. Provided the SO_2 emissions limit is not exceeded, it can be assumed per the MATS regulation that the HCL emissions limit is also satisfied as the caustic scrubber and MEA absorber operations are able to remove the HCl.
CO_2	90 percent removal	90 percent removal (221 lb/MWh-net)	30 wt% MEA
VOC	N/A	1 ppm	Water wash at the top of the PCC absorber is expected to remove VOC in flue gas before venting to atmosphere

5.7 POTENTIAL VARIANTS

5.7.1 No Post-Combustion Capture

Implementing post-combustion capture (PCC) to the DICE CRCC system imposes a significant penalty on its efficiency, capital cost, and operating cost, thereby resulting in a high LCOE. A parametric scenario without PCC was evaluated to quantify the performance and cost impact. For this case, exhaust steam from the main steam turbine that would have been diverted to the PCC is sent to a condensing turbine to produce more power, resulting in greater power generation from the steam cycle. Additionally, auxiliary power consumed by the PCC is eliminated, resulting in a 35 percent increase in net power generation. The calculated efficiency of this case is 39.9 percent on an LHV basis (37.7 percent HHV).

Table 5-6 presents a side-by-side comparison of the performance breakdown between the DICE CRCC plant with and without PCC.

Table 5-6
Performance Comparison for DICE CRCC with and without PCC

Description	DICE CRCC with PCC (On-site coal beneficiation)	DICE CRCC No PCC
POWER GENERATION		
DICE	78,730	78,730
Turboexpander	31,787	31,900
Steam Turbine	14,676	31,299
Total Power Generation, kWe	**125,192**	**141,929**
AUXILIARY LOAD SUMMARY, kWe		
Coal Beneficiation	5,472	5,472
Main Air Compressor	26,301	26,277
SCR	88	88
Fabric Filter	69	69
Boiler Feed Water Pump	261	302
Economizer Recirculation Pump	5	310
Steam Turbine Auxiliaries	31	31
DCC Circulating Pump	400	400
CO2 Capture	2,549	0
CO2 Compression	7,838	0
Circulating Water Pumps	2,407	2,117
Makeup Water Pumps	70	60
Cooling Tower Fans	977	859
Wastewater Pumps	15	11
Miscellaneous Auxiliaries	135	135
Transformer Losses	626	710
Total Auxiliaries, kWe	47,243	36,840
Net Power, kWe	**77,949**	**105,089**
As-Received PRB Coal Feed, lb/hr	148818	150435
Coal Slurry Fuel Feed, lb/hr	91934	92932
Diesel Fuel Feed, lb/hr	1651	1669
Natural Gas Feed Flow, lb/hr	10640	12000
Coal LHV Thermal Input, MMBtu/hr	619	625
Diesel LHV Thermal Input, MMBtu/hr	30	31
Gas LHV Thermal Input, MMBtu/hr	216	244
Total LHV Thermal Input, MMBtu/hr	865	899
LHV Efficiency, %	30.8%	39.9%
Coal HHV Thermal Input, MMBtu/hr	643	649
Diesel HHV Thermal Input, MMBtu/hr	32	33
Gas HHV Thermal Input, MMBtu/hr	239	270
Total HHV Thermal Input, MMBtu/hr	**914**	**952**
HHV Efficiency, %	29.1%	37.7%

5.7.2 **Centralized Coal Beneficiation Plant**

For a small, modular power plant such as the DICE CRCC (< 100 MW for this introductory variant), the performance and cost estimates presented in previous reports suggest that it makes no economic sense to install a coal beneficiation plant on-site, analogous to building a crude oil refinery on-site at every gas station. For the modular DICE CRCC plant to be feasible, there must be multiples of such power plants, each receiving fuel from a centralized coal beneficiation plant, thereby taking advantage of the economies-of-scale benefits that the large central beneficiation plant possesses. The performance and impact of such a scenario is quantified in Table 5-7.

Table 5-7
Performance Comparison for DICE CRCC with On-site and Centralized Coal Beneficiation Plant

Description	DICE CRCC with PCC (On-site coal beneficiation)	DICE CRCC with PCC (Centralized coal beneficiation)
POWER GENERATION		
DICE	78,730	78,730
Turboexpander	31,787	31,787
Steam Turbine	14,676	14,676
Total Power Generation, kWe	**125,192**	**125,192**
AUXILIARY LOAD SUMMARY, kWe		
Coal Beneficiation	5,472	0
Slurry Pumping	incl w/ beneficiation	500
Main Air Compressor	26,301	26,301
SCR	88	88
Fabric Filter	69	69
Boiler Feed Water Pump	261	261
Economizer Recirculation Pump	5	5
Steam Turbine Auxiliaries	31	31
DCC Circulating Pump	400	400
CO2 Capture	2,549	2,549
CO2 Compression	7,838	7,838
Circulating Water Pumps	2,407	2,407
Makeup Water Pumps	70	70
Cooling Tower Fans	977	977
Wastewater Pumps	15	26
Miscellaneous Auxiliaries	135	135
Transformer Losses	626	626
Total Auxiliaries, kWe	47,243	42,282
Net Power, kWe	**77,949**	**82,910**
Coal Slurry Fuel Feed, lb/hr	91934	91934
Diesel Fuel Feed, lb/hr	1651	1651
Natural Gas Feed Flow, lb/hr	10640	10640
Coal LHV Thermal Input, MMBtu/hr	619	619
Diesel LHV Thermal Input, MMBtu/hr	30	30
Gas LHV Thermal Input, MMBtu/hr	216	216
Total LHV Thermal Input, MMBtu/hr	865	865
LHV Efficiency, %	30.8%	32.7%
Coal HHV Thermal Input, MMBtu/hr	643	643
Diesel HHV Thermal Input, MMBtu/hr	32	32
Gas HHV Thermal Input, MMBtu/hr	239	239
Total HHV Thermal Input, MMBtu/hr	**914**	**914**
HHV Efficiency, %	29.1%	31.0%

5.8 ENERGY STORAGE CAPABILITY

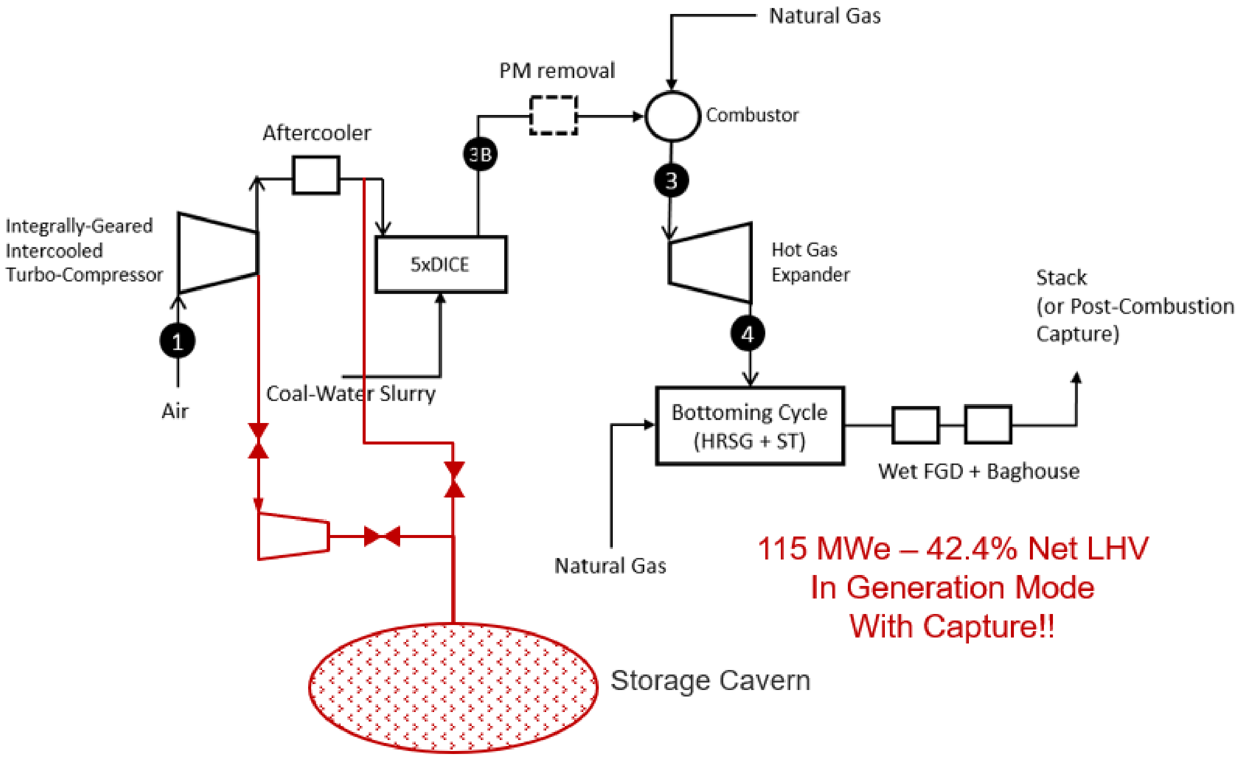
One unique feature of the DICE CRCC concept with separate air compressor and gas turbine/expander trains is its amenability to **compressed air energy storage** (CAES) with *no redesign of plant configuration and/or any major piece of equipment*. The only requirement for DICE CRCC with CAES is the availability of a suitable air storage cavern, e.g., a saline aquifer or depleted natural gas reservoir. DICE CRCC in CAES arrangement is shown in Figure 5-5.

Unlike the existing CAES technology (as demonstrated in Huntsdorf, Germany and McIntosh, Alabama), once constructed and commissioned, DICE CRCC can operate as a straightforward coal-fired power plant or in CAES mode.

In CAES charging mode, the MAC is powered by cheap grid power and supplies air into the storage cavern via a booster compressor (which is the only piece of additional major equipment – the rest is additional piping to/from the cavern and requisite valves), say, at 10 bara.

In CAES generation mode, the MAC is shut down. Charge air to the DICE (at 5 bara) is supplied from the storage cavern through a pressure regulation valve. The rest of the power plant is running in its normal operation mode. In generation mode, even with the PCC on, the plant can deliver 115 MWe at more than 40% net LHV efficiency.

Figure 5-5
DICE CRCC in CAES Mode



It should also be pointed out that the <u>inherent</u> CAES capability of the turbocompound-reheat technology is <u>not</u> limited to DICE (i.e., firing coal fuel). For a standard RICE CRCC with natural gas-fired engines, the same can be accomplished with excellent efficiency (68% net LHV in generation mode) at outputs as low as below 50 MWe (with small, off-the-shelf RICE rated at 5 MWe each). This is described in detail in the Final Report of the DOE/NETL Technical Grant (DE-FE0031618), "Turbocompound Reheat Gas Turbine Combined Cycle"

Section 6 Major Equipment List and Preliminary Plot Plan

Equipment lists for each of the five areas that comprise the overall 100 MWe DICE CRCC plant are provided in this section. These five areas are:

- Coal beneficiation
- DICE CRCC
- CO_2 capture (30 wt%)
- CO_2 compression
- Electrical plant

6.1 COAL BENEFICIATION PLANT

The equipment list for the coal beneficiation plant is provided in Table 6-1.

Table 6-1
Coal Beneficiation Plant Equipment List

Site Quantity	System Code	Description	Rating	Comments
COAL BENEFICIATION EQUIPMENT LIST				
RAW COAL HANDLING				
1	FE-201	Feedstock Coal Receival Dump Hopper Feeder	55 kW	
1	CV-101	Hammer Mill Feed Conveyor	11 kW	Design Capacity/Size: 110 t/h
1	CR-301	Hammer Mill	300 kW	Design Capacity/Size: 42" x 60"
1	CV-201	Surge Bin Feed Conveyor	11 kW	Design Capacity/Size: 110 t/h
1	WT-201	Plant Feed Weigher		
1	BN-301	Surge Bin		Design Capacity/Size: 100 t
1	FE-202	Surge Bin Discharge Feeder	7.5 kW	
PROCESS PLANT				
1	CV-301	Ball Mill Feed Conveyor	7.5 kW	Design Capacity/Size: 110 t/h
1	CR-302	Ball Mill	1,300 kW	Design Capacity/Size: 3.7m x 6.75m
1	PP-301	Ball Mill Cyclones Feed Pump	55 kW	
2	CY-301	Ball Mill Cyclones Cluster		
1	PP-401	Grinding Cyclones Feed Pump	55 kW	
2	CY-401	Grinding Cyclones Cluster		
1	PP-403	Grinding Mill Feed Pump	75 kW	
1	GM-401	Grinding Mill	3,500 kW	Design Capacity/Size: 63 t/h
3	PP-501	Rougher Cell Feed Pump	75 kW	
3	FC-501	Rougher Flotation Cell		
3	PP-521	Cleaner Cell Feed Pump	45 kW	
3	FC-521	Cleaner Flotation Cell		
1	TH-601	Product Thickener	7.5 kW	Design Capacity/Size: 20m ø
1	PP-601	Product Thickener Underflow Pump	11 kW	
1	SM-601	Product Solid Bowl Feed Sump		
2	PP-602	Product Solid Bowl Feed Pump	11 kW	
2	CF-601	Product Solid Bowl	300 kW	Design Capacity/Size: 28 t/h
2	CF-601	Main Drive	200 kW	
2	CF-601	Back Drive	100 kW	
1	PP-605	Solid Bowl Effluent Pump	5.5 kW	

1	CV-601	Product Transfer Conveyor	7.5 kW	Design Capacity/Size: 52 t/h
1	WT-601	Product Weigher		
1	SA-601	Product Cross Belt Sampler	5.5 kW	
1	AN-601	Moisture Meter	1.0 kW	
1	TK-610	Product Slurry Agitation Tank		Design Capacity/Size: 35 m^3
2	TK-620	Product Storage Tank		Design Capacity/Size: 1,000 m^3
1	AG-610	Product Slurry Agitator	15 kW	
1	PP-610	Product Slurry Transfer Pump	7.5 kW	
2	AG-620	Product Slurry Agitator	185 kW	
2	PP-620	Product Distribution Pump	5.5 kW	
1	TH-701	Tailings Thickener	7.5 kW	Design Capacity/Size: 20m ø
1	PP-701	Tailings Thickener Underflow Pump	7.5 kW	
1	PP-901	Process Water Pump	175 kW	
1	PP-510	Plant Water Pump	45 kW	
1	FT-950	Gland Water Filter	0.37 kW	
1	PP-950	Gland Water Pump	22 kW	
2	PP-960	Thickener Area Sump Pump	15 kW	
1	CN-501	Overhead Crane	43 kW	Design Capacity/Size: 20 t
COAL PROCESSING PLANT SERVICES				
1	FL-901	Anionic Flocculant Dosing System	5.55 kW	
1	FL-901a	Polymer Bulk Storage Tank		
1	FL-901b	Blower	3.0 kW	
1	FL-901c	Screw Feeder	0.37 kW	
1	FL-901d	Agitator	1.50 kW	
1	FL-901e	Dust Filter Unit	0.37 kW	
1	FL-901f	Mixing Tank		
1	FL-901g	Dilute Flocculant Storage Tank		
1	FL-901h	Heated Hopper	0.06 kW	
1	FL-901i	Hopper Vibrator	0.25 kW	
2	DP-901	Collector Dosing Pump	0.55 kW	
4	DP-910	Frother Dosing Pump	0.37 kW	
2	DP-930	Dispersant Dosing Pump	0.55 kW	
1	AD-950	Instrument Air Dryer	1.53 kW	
1	AR-901	Air Receiver		

6.2 DICE CRCC MECHANICAL EQUIPMENT

The mechanical equipment list for the main DICE CRCC plant is shown in Table 6-2.

Table 6-2
DICE CRCC Mechanical Equipment List

Site Quantity	System Code	Description	Type	Material	Rating	Capacity (%)	Comments
DICE MECHANICAL EQUIPMENT LIST							
1	AAA	Heat Recovery Steam Generator (HRSG)	Single-Pressure, No-Reheat, Horizontal Gas Flow. With CO Catalyst			1 X 100% Per Unit	276,800 lbs/hr steam @ 668.7 psia & 753.5F
1	AAA	CO Catalyst	Oxidizing Catalyst for 90% CO Reduction			1 X 100% Per HRSG	Provided by HRSG Supplier
1	AAA	HRSG Duct Burner Skid	263 MMBtu/hr			1 X 100% Per HRSG	Provided by HRSG Supplier
1	AAA	Selective Catalytic Reduction (SCR) System For HRSG Flue Gas NOx Reduction	19 % Aqueous Ammonia System			1 X 100% Per HRSG	Provided by HRSG Supplier
1	AB	Steam Turbine Bypass Valve				1 X 100% Per Unit	1
1 Lot	AB	Main Steam Relief Valve Silencers		CS		1 Lot Per HRSG	1 Lot
1	AC	Steam Turbine Generator	Steam Turbine With Separate HP And LP Casings Connected With SSS Clutch		37 MW	1 X 100% Per Unit	Based on Siemens Bid
1	AC	ST Lube Oil Skid				1 X 100% Per Unit	Supplied by STG Vendor
1	AC	ST Control Oil Skid				1 X 100% Per Unit	Supplied by STG Vendor
1	AD	Steam Surface Condenser	Thermal Duty = 64 MW;			1 X 100% Per Unit	
1	AD	Condensate Deaerator	2800 Gallon Storage Volume	CS		1 X 100% Per Unit	
2	AD	Condensate Extraction Pump	Centrifugal, Vertical, CAN Type, Constant Speed, Motor Driven ; 300 GPM @ 130 ft. TDH		15 HP	2X50% Per Unit	

1	AE	Boiler Feedwater Pump	Horizontal Ring-Section Pump, 3600 RPM 600 GPM @ 3000 ft. TDH		655 HP	1 X 100% Per Unit	
1	AG	Hot Gas Expander (HGE)			32 MW	1 X 100% Per Unit	Based on Dresser-Rand Generator Gear E148 Train
1	AG	HE Lube Oil Skid				1 X 100% Per HGE	Supplied by HGE Vendor
1	AG	HE Cooling & Sealing Steam Skid				1 X 100% Per HGE	Supplied by HGE Vendor
1	AJ	Ammonia Dosing Skid	Diaphragm Metering Pumps And Tank	316 / PTFE		1 X 100% Per HRSG	
1	AJ	Oxygen Dosing Panel For HRSG				1 X 100% Per HRSG	
5	ANB	Direct Injection Carbon Engine (DICE)	Wartsila Model 18V46 Modified For Coal Slurry		15.8 MW	5 X 20% Per Site	Tier 3 Machines W/ Coal Slurry Fuel
5	ANB	DICE Auxiliary Module				1 X 100% Per DICE	Supplied by DICE Vendor
1	ANA	Process Compressor	GV(200-3) Compressor Package; Incl. Motor, Air Inlet Filter, Aux. Support & Control Systems		37,000 HP	1 X 100% Per Unit	Based on Dresser-Rand Quote
1	AR	Vacuum Skid	2 Steam Jet Air Ejectors or 2 Liquid Ring Vacuum Pumps			2 X 100% Per Unit	Capacity based on Holding Duty
5	BA	Third Stage Separator (TSS)				1 X 100% Per DICE	Based on UOP Quote
1	BA	Direct Contact Cooler (DCC)	304L SS Column Internals; Sulzer MellapakPlus Packing			1 X 100% Per Unit	Based on Sulzer Chemtech Quote
1	BM	HRSG Blowdown Tank		CS		1 X 100% Per HRSG	
1	BM	Blowdown Heat Exchanger	Shell & Tube Type	CS/ SS Tubes		1 X 100% Per HRSG	
1	BM	Blowdown Tank Vent Silencer		CS		1 X 100% Per HRSG	
1	BS	19% Aqueous Ammonia Storage Tank		CS		1 X 100% Per Unit	Unloading Via Truck Unloading

							Pump (Self Contained).
2	BS	Ammonia Forwarding Pumps	Positive Displacement	316 SS		2 X 100% Per Unit	
1	FG	Fuel Gas Knockout Drum				1 X 100% Per CT	
1	FG	Fuel Gas Drain Tank				1 X 100% Per CT	
1	HA	Boiler Feedwater Pump Maintenance Hoist	Manual Hoist			1 X 100%	
1	HF	Fly Ash Silo				1 X 100% Per Site	Provided by Fly Ash Vendor
2	HF	Fly Ash Blowers				2 X 50% Per Unit	Provided by Fly Ash Vendor
5	HF	Air Lock Feeders				1 X 100% Per TSS	Provided by Fly Ash Vendor
1	PA	Plant Air Compressor	Oil Free Screw		150 HP	1 X 100% Per Unit	Provides Compressed Air to instrument and Service Air Systems
1	PA	Compressed Air Dryer	Dual Tower Heatless Desiccant Type With Dew Point Of -40 Deg. F Or Lower With Pre-Filter, After-Filter, And Bypass Filter			2 X 100% Per Unit	
1	PA	Compressed Air Receiver		CS	150 PSIG	1 X 100% Per Unit	Provides Compressed Air To Instrument And Service Air Systems
1	PF	Electric Fire Pump	Horizontal Centrifugal, 2000 GPM @ 300 ft TDH	316 SS Internals	250 HP	1 X 100% Per Site	Packaged Fire Pump System
1	SL	Gland Steam Condenser				1 X 100% Per Unit	Provided by Steam Turbine Vendor
1	VB	Admin/Control Building HVAC	Air Handling Unit With Heating And Cooling Coils			1 X 100% Per Unit	

1	WBA	Closed Cooling Water Heat Exchanger	Plate And Frame Type, Thermal Duty = 24 MW	316 SS		1 X 100% Per Unit	
2	WBA	Closed Cooling Water Pumps	Horizontal Centrifugal Type; 31,000 GPM @ 65 ft TDH	CI Casing and Impeller	300 HP	2 X 50% Per Unit	
1	WBA	Closed Cooling Water Expansion Tank	Vertical; Atmospheric;	CS		1 X 100% Per Unit	
1	WBA	Closed Cooling Water Chemical Feed System				1 X 100% Per Unit	
1	WBB	DICE Jacket Cooling Water Storage Tank			TBD	1 X 100% Per Unit	
2	WBB	DICE Jacket Cooling Water Pumps	Horizontal, Centrifugal Type	CI Casing and Impeller	TBD	2X 50% Per Unit	
1	WD	Demin Water Storage Tank	Field Erected Bolted Tank	CS W/ Epoxy Lining	50,000 Gal	1 X 100% Per Site	
2	WD	Demin Transfer Pumps	Horizontal, Centrifugal Pumps	SS Casing and Impeller	2 HP	2X100% Per Site	
2	XW	HGE Area Sump Pumps	Vertical Line Shaft	CI Casing and Impeller		2 X 100% Per Sump	Duplex
2	XW	STG Area Sump Pumps	Vertical Line Shaft	CI Casing and Impeller		2 X 100% Per Sump	Duplex
2	XW	Demin Area Sump Pumps	Vertical Line Shaft	CI Casing and Impeller		2 X 100% Per Sump	Duplex
2	XW	Oil/Water Separator (Including 2x100% Effluent Pumps)	Horizontal Centrifugal Pumps Coalescing Type Media Separator			1 X 100% Per Unit	Package by Oil Water Separator Vendor. One Oil/Water Separator With One Positive Displacement Waste Oil Pump and 2x100% Effluent Forwarding Pumps.

2	XW	HRSG Blowdown Sump Pumps	Vertical Line Shaft	CI Casing and Impeller		2 X 100% Per Sump	Duplex

1) The mechanical equipment list provides preliminary data, scope and quantities that may be subject to change during final engineering design

2) Assumptions: STG is not hydrogen cooled; backend recirculation pumps not required for HRSG

6.3 30 WT% MEA CO_2 CAPTURE PLANT

The equipment list for the CO_2 capture plant utilizing 30 wt% MEA is provided in Table 6-3

Table 6-3
30 wt% MEA CO_2 Capture Plant Equipment List

Site Quantity	System Code	Description	Type	Material	Rating	Capacity (%)	Comments
POST-COMBUSTION CAPTURE (30 WT %) EQUIPMENT LIST							
VESSELS & TANKS							
1	C-101	Flue Gas Absorber	Vertical	Kill CS + 304Clad Top		1 Lot Per Unit	Includes overhead wash section (Pall Ring) and absorption section (Structured packing)
1	C-102	Amine Stripper	Vertical	Kill CS + 304Clad Top		1 Lot Per Unit	Includes overhead wash section and stripping section with random packing (Pall Ring)
1	C-103	Stripper OVHD Receiver	Vertical	304Clad		1 Lot Per Unit	
1	C-106	Condensate Flash Drum	Horizontal	Carbon Steel		1 Lot Per Unit	
1	C-108	Carbon Drum(Part of V-102)	Vertical	Carbon Steel		2 Lot Per Unit	
1	D-101	MEA Storage Tank	Cone Roof	Carbon Steel		1 Lot Per Unit	
SHELL & TUBE EXCHANGERS AND AIR COOLERS							
2	E-101	Rich/Lean Exchanger	Plate & Frame	304SS		2 X50% Per Unit	Duty: 274 MMBTU/hr
1	E-102	Lean Amine Cooler	Plate & Frame	304SS		1 X100% Per Unit	Duty: 168 MMBTU/hr
1	E-103	Stripper Condenser	Weld Plate & Frame	304SS		1 X100% Per Unit	Duty: 64 MMBTU/hr
4	E-104	Stripper Reboiler	Kettle	Shell 304SS/ Tube 304SS		4 X25% Per Unit	Duty: 242 MMBTU/hr
1	E-105	Wash Water Cooler	Plate & Frame	304SS		1 X100% Per Unit	Duty: 16 MMBTU/hr
1	E-106	Reclaimer	Kettle	Shell Kill CS/ Tube 304SS		1 X100% Per Unit	Duty: 12 MMBTU/hr

COMPRESSORS, BLOWERS & DRIVERS							
1	K-101	Flue Gas Blower	Centrifugal w/ VFD Motor	304 SS	2,073 BHP	1 X100% Per Unit	
PUMPS & DRIVERS							
2	G-101	Rich Amine Pump	Centrifugal	Impeller: 12 Cr Casing: CS	616 BHP	2 X100% Per Unit	
2	G-102	Lean Amine Pump	Centrifugal	Impeller: 12 Cr Casing: CS	500 BHP	2 X100% Per Unit	
2	G-103	Wash Water Pump	Centrifugal	Impeller: 12 Cr Casing: CS	124 BHP	2 X100% Per Unit	
2	G-104	Stripper Reflux Pump	Centrifugal	Impeller: 12 Cr Casing: CS	11 BHP	2 X100% Per Unit	
1	G-106	Makeup Amine Pump	Centrifugal	Impeller: 12 Cr Casing: CS	28 BHP	1 X100% Per Unit	
1	G-107	Amine Sump Pump	Centrifugal	Impeller: 12 Cr Casing: CS	9 BHP	1 X100% Per Unit	
1	G-108	Soda Ash Pump(Part V-103)	Centrifugal	Impeller: CI Casing: CS	1 BHP	1 X100% Per Unit	
2	G-109	Condensate Return Pump	Centrifugal	Impeller: CS Casing: CS	90 BHP	2 X100% Per Unit	
PACKAGED & MISC EQUIPMENT							
4	V-102	Carbon + Pre&Post Filters	Package	Kill CS		4 X25% Per Unit	
1	V-101	Soda Ash Feed System Pkg	Package	CS		1 X100% Per Unit	
1	L-101	Flue Gas Fd & Exhaust Ducts	Duct	CS		1 X100% Per Unit	

6.4 CO_2 COMPRESSION PLANT

The equipment list for the CO_2 compression plant is shown in Table 6-4

Table 6-4
CO_2 Compression Plant Equipment List

Site Quantity	System Code	Description	Type	Material	Rating	Capacity (%)	Comments
CO2 COMPRESSION EQUIPMENT LIST							
VESSEL & TANK							
1	C-301	1st Stage Compressor Feed KO Drum	Vertical	304SS		1 Lot Per Unit	
1	C-302	2nd Stage Compressor Feed KO Drum	Vertical	304SS		1 Lot Per Unit	
1	C-303	Dryer Feed KO Drum	Vertical	304SS		1 Lot Per Unit	
1	C-304	SuperCritical CO2 Separator	Horizontal	304SS		1 Lot Per Unit	
SHELL & TUBE EXCHANGERS AND AIR COOLERS							
1	E-301	1st Stg Comp CW AfterCooler	Shell & Tube	304SS		1 X100% Per Unit	Duty: 11 MMBTU/hr
1	E-302	2nd Stg Comp CW AfterCooler	Shell & Tube	304SS		1 X100% Per Unit	Duty: 10 MMBTU/hr
1	E-303	3rd Stg Comp CW AfterCooler	Shell & Tube	Shell CS/ Tube 304SS		1 X100% Per Unit	Duty: 19 MMBTU/hr
1	E-304	SC CO2 Product CW Cooler	Shell & Tube	Shell CS/ Tube 304SS		1 X100% Per Unit	Duty: 3 MMBTU/hr
1	E-305	Recycle Cooler	Shell & Tube	304SS		1 X100% Per Unit	Duty: 7 MMBTU/hr
COMPRESSORS, BLOWERS & DRIVERS							
1	K-301	CO2 Compressor	Centrifugal w/ VFD	CS	10,053 BHP	1 X100% Per Unit	

PUMPS & DRIVERS							
2	G-301	Condensate Pump	Centrifugal	Impeller: CS Casing: CS	0.1 BHP	2 X100% Per Unit	
1	G-302	Super-Critical CO2 Pump	Centrifugal w/ VFD	Impeller: CS Casing: CS	409 MHP	1 X100% Per Unit	
PACKAGED & MISC EQUIPMENT							
1	V-301	CO2 Dryer	Package	CS		1 X100% Per Unit	

6.5 ELECTRICAL EQUIPMENT LIST

The equipment list for DICE CRCC electrical plant is shown in Table 6-5

Table 6-5
DICE CRCC Electrical Equipment List

Site Quantity	Description	Type	Comments
6	115kV Circuit Breaker and Associated Buswork	High Voltage Circuit Breaker	115kV, 50kA, 1200A, HVCB with Disconnect Switch and Grounding Switch. Dead Tank SF6 Circuit Breaker
6	115kV System, 84kV MCOV Surge Arrestors	70kV MCOV Surge Arrestors for 115kV System	Switchyard Surge Arrestors
21	115kV PT or CCVT	Potential Transformers or Coupling Capacitor Voltage Transformer	Potential Transformer for Synchronizing and Voltage Measurement
9	115kV CT	Current Transformer, Extended Range	Protection and Metering Current Transformers
1	115kV Motorized Disconnect and Grounding Switch	Disconnect and Grounding Switch	115kV, 50kA, 1200A, 3 pole
1	Switchyard Control Building	Switchyard Electrical Building	Electrical Building for Protective Relaying, SCADA and Switchyard Control Equipment
3	Step-Up Transformer	13.8kV to 115kV Transformer	30/40MVA, 13.8-115kV, ONAN/ONAF, 65 DEG C, Z=8% at 30MVA, HV DETC (STG, Gas Exp, DICE-2)
1	Station Service Transformer	115kV to 13.8kV Transformer	42/56MVA, 13.8-115kV, ONAN/ONAF, 65 DEG C, Z=8% at 42MVA, HV On-Load Tap Changer (Station Service)
1	Step-Up Transformer	13.8kV to 115kV Transformer	45/60MVA, 13.8-115kV, ONAN/ONAF, 65 DEG C, Z=8% at 45MVA, HV DETC (DICE-1)
1	Emergency Diesel Generator	13.8kV, 2MW, Tier 2	2.0MW Emergency Diesel Generator, 13.8kV, Tier 2, with outdoor, sound attenuated enclosure and minimum 12 hour belly tank
1	Boiler Feed Pump VFD	13.8kV Variable Frequency Drive	13.8kV Variable Frequency Drive for 655 HP motor
2	Cooling Pump VFD	13.8kV Variable Frequency Drive	13.8kV Variable Frequency Drive (MV/LV) for 300 HP motor
1	Gas Compressor VFD	13.8kV Variable Frequency Drive	13.8kV Variable Frequency Drive for 37,000 HP synchronous motor. Starting VFD with Bypass Switch.
1	Zig-Zag Grounding Transformer with Resistor	13.8kV Grounding Transformer for Delta System	13.8kV, 250kVA, Zig-Zag Grounding Transformer with Resistor
1	Distribution Transformer	13.8kV - 480V Transformer	Control Building 750kVA transformer, ONAN, Delta-Wye, HV DETC, 5.75% Z
2	Distribution Transformer	13.8kV - 480V Transformer	Common Load Center 2000kVA transformer, ONAN, Delta-Wye, HV DETC, 5.75% Z

1	Distribution Transformer	13.8kV - 480V Transformer	MV EEM MCC 2500kVA transformer, ONAN, Delta-Wye, HV DETC, 5.75% Z
1	DICE MV Switchgear-1	13.8kV Switchgear	Arc Resistant Metal Clad Switchgear, Type 2B, 13.8kV, 3000A, 63kA, 3PH, 3W, 60HZ
1	DICE MV Switchgear-2	13.8kV Switchgear	Arc Resistant Metal Clad Switchgear, Type 2B, 13.8kV, 2000A, 63kA, 3PH, 3W, 60HZ
1	Station MV Switchgear-3	13.8kV Switchgear	Arc Resistant Metal Clad Switchgear, Type 2B, 13.8kV, 3000A, 50kA, 3PH, 3W, 60HZ
1	Common Load Center, 480V	480V Load Center, Arc Resistant	480V Load Center, 480V, 3000A, 50kA, 3PH, 3W, 60HZ with two 2500A ACB incomer & 2000A ACB tie breaker
1	Common MCC-1, 480V	480V Motor Control Center	480V MCC, 480V, 1600A, 65kA, 3PH, 3W, 60HZ, 1600A incomer (10 stacks)
1	Common MCC-2, 480V	480V Motor Control Center	480V MCC, 480V, 800A, 65kA, 3PH, 3W, 60HZ, 800A incomer (6 stacks)
1	MV EEM MCC, 480V	480V Motor Control Center	480V MCC, 480V, 3000A, 40kA, 3PH, 3W, 60HZ, 3000A ACB incomer (8 stacks)
2	Isophase Bus Duct, Gas Exp & STG	13.8kV Isophase Bus Duct	Isophase Bus Duct, 13.8kV, 2000A
1	Non-Seg Bus Duct (DICE Swgr-1 Incomer)	Non-Seg Bus Duct	Non Seg Bus Duct, 13.8kV, 3000A, 63kA
1	Non-Seg Bus Duct (DICE Swgr-2 Incomer)	Non-Seg Bus Duct	Non Seg Bus Duct, 13.8kV, 2000A, 63kA
Lot	Lighting System	Lighting fixtures, panelboards, photocells, transformers, controllers, switches, cabling and raceway	Interior and task lighting shall be 120/208VAC, roadway and floodlighting shall be 480/277VAC. Emergency and egress lighting shall be self-contained battery packs. Lighting is provided at site access points and for all operating areas to support planned maintenance. Perimeter fence lighting is not provided.
Lot	Fire Detection System	System includes Fire protection panels, smoke and fire detectors, horns, strobes, cabling and raceway	Each electrical building is provided with fire alarm panel, smoke and fire detectors, horns, strobes, auditory and visual alarms, and all required wiring and raceway.
Lot	Plant Security & Intrusion Detection System	System includes CCTV, recording & monitoring servers, access points (card readers) for site buildings, gate intercom and controls, cabling and raceway.	Site perimeter and access points monitored by CCTV, video monitoring and recording, card readers for personnel doors in all site buildings, gate access controls, gate card reader, and gate intercom are provided.
Lot	Freeze Protection & Process Heating System	System includes Heat trace panelboards, transformers, thermostats, controllers, power connection boxes, heat trace cabling, cabling and raceway.	Freeze protection system for all exposed piping and equipment subject to damage from ambient temperatures below freezing. Heat trace is 120V, installed directly on pipe and equipment, under insulation, and is controlled by local controllers (mounted on pipe) or from freeze protection panels. Heating and heat tracing required for process fluid temperature regulation and sensitive chemicals will be provided as required.

Lot	Plant Communications System	System includes facility communications and local area network (LAN) including installation of primary phone lines to interface point at plant perimeter, cabling, raceway and outlets for voice and data in all site buildings.	Communications system will provide connectivity for voice and data in all site buildings, including switchyard. Cabling, raceway, data and voice ports are provided, hardware (including telephones) to be supplied by owner.
Lot	DC & UPS System	Batteries, chargers, regulating voltage & bypass transformers, static transfer switch, manual bypass switch, DC switchboard, inverters, and UPS panelboards, cabling and raceway.	DC system will supply DC power to critical loads, including UPS system, STG and Gas Exp turning gear, and emergency lube oil pumps. Chargers are 125VDC, 550A and batteries are UPS system will supply 120VAC single phase power to critical AC loads (including CEMS, DCS, fire protection, communications, security, etc.)
Lot	Welding and Convenience Receptacles	Welding receptacles, disconnect switches, convenience receptacles.	Convenience receptacles (120V, GFCI, weatherproof) provided so that outdoor plant equipment areas are accessible with 100 foot cord. Building interiors provided with receptacles per NEC or as required to support planned maintenance activities. Welding receptacles (480V, 3PH, 3W) are located in all areas where welding is expected to occur.
Lot	Grounding System	Site and switchyard ground grids, including buried bare copper conductors, ground rods, connectors, test wells, and taps to equipment and structure.	Buried stranded copper conductors, ground rods, equipment and structure bonding. Grounding system is designed to NEC, IEEE 142, and IEEE 80 requirements.
Lot	Lightning Protection System	Building, stack, and switchyard lightning protection systems. Air terminals, main conductors, down conductors, connectors, buried conductors and rods.	Building lightning protection systems designed to NFPA 780, but will not be UL Master Labelled. Switchyard lightning protection system designed to IEEE 998.
Lot	Cathodic Protection System	Protection system for buried, coated, carbon steel, cast iron and ductile iron piping. Materials include sacrificial anodes, insulating flanges, over-voltage protectors, test stations, reference electrodes, cable, and cable connectors.	Cathodic protection system is designed to NACE standards.
Lot	MV, LV, Control and Instrumentation Cables	Power, Control and Instrumentation Cables	UL listed cables

6.6 PLANT EQUIPMENT DEVELOPMENT STATUS

6.6.1 Coal Beneficiation Plant

According to Sedgman, each plant unit operation of the flowsheet is currently commercially available and has been demonstrated previously in the mineral processing industry. However, in some cases, the application to coal, or finely ground coal, is novel, and needs to be validated with test work.

6.6.1.1 Flotation Cells

Sedgman C-Cell, an induced air-style flotation cell, was selected as its deep froths with washing is likely to achieve the desired low-ash content in the beneficiated product. Other flotation technologies, such as mechanically agitated flotation cells and column flotation cells may also be suitable for this application. Further test work is required to determine the benefits, if any, of these alternative technologies.

6.6.1.2 Fine Grinding Mill

The FLSmidth VXPMill selected for the concept flowsheet was based on low capital cost, with the tradeoff being that it is a vertical, high intensity grinding mill. Alternate suitable technologies are available from Outotec (HIG Mill) and Glencore Technology (IsaMill). Samples of the coal feed should be provided to these three suppliers to identify which technology provides the most economical solution.

6.6.2 Power Block Equipment

6.6.2.1 Main Air Compressor

Commercially available, procured per material requisition (MR). Siemens Turbocompressor is the potential vendor. Intercooler and aftercooler (shell-tube heat exchangers) are typically in the compressor OEM's scope.

6.6.2.2 DICE

Stock engine is commercially available, procured per MR. (Turbocharger kit is removed to fit into the turbocompound configuration)

Fuel injection system design and development requires R&D as described in Section 3.1.

6.6.2.3 Third Stage Separator

Commercially available, procured per MR. Honeywell UOP is the potential vendor.

6.6.2.4 Hot Gas Expander

Commercially available, procured per MR. Baker Hughes (or Siemens) is the potential vendor.

6.6.2.5 HRSG (Including Duct Burner and SCR/CO Catalyst)

Commercially available, procured per MR. Nooter-Eriksen is the potential vendor.

6.6.2.6 *Steam Turbine Generator (Including SSS Clutch)*

Commercially available, procured per MR. Siemens Dresser-Rand is the potential vendor. The clutch is manufactured by SSS.

6.6.2.7 *STG Heat Rejection System*

Commercially available, procured per MR (air- or water-cooled condenser and cooling tower). Many potential vendors.

6.6.2.8 *Balance of Plant (BOP) Pumps*

Commercially available, each procured per MR.

6.6.2.9 *Balance of Plant (BOP) Heat Exchangers*

Commercially available, each procured per MR. They can be shell-and-tube or plate-frame type. This includes the MRC slurry preheater.

6.6.2.10 *Direct Contact Cooler*

Commercially available, procured per MR

6.6.3 **Capture Block Equipment**

6.6.3.1 *Flue Gas Blower*

Commercially available, procured per MR. Most blower vendors (Howden, Buffalo Blower, New York Blower, Clarage) should be able to provide this piece of equipment.

6.6.3.2 *Absorber/Stripper Columns*

Commercially available, procured per MR. Packing for these columns are also commercially available with Sulzer as the potential vendor.

6.6.3.3 *CO_2 Compressors*

Commercially available, procured per MR. Potential vendors are Dresser-Rand, GE, and MAN among others.

6.6.3.4 *Pumps*

Commercially available, each procured by MR.

6.6.3.5 *Heat Exchangers*

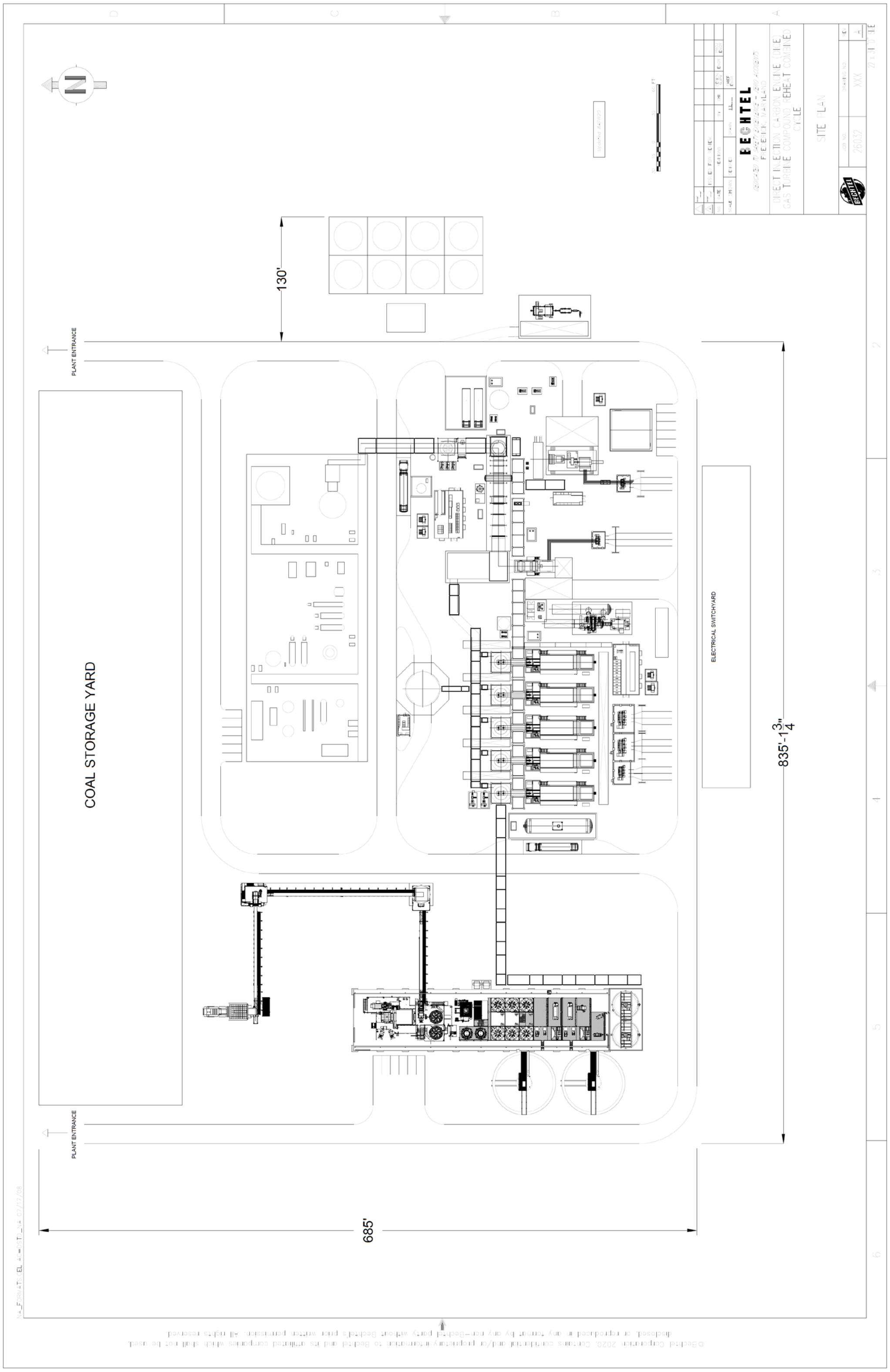
Commercially available, each procured per MR. With the exception of the kettle-type reboiler, heat exchangers will be of plate-and-frame type.

6.7 PRELIMINARY DICE CRCC PLOT PLAN

Figure 6-1 shows the overall plot plan for the coal beneficiation facility, DICE power plant, and carbon capture plant. Also included are a coal yard and cooling tower that will serve as the heat sink for the entire facility.

The complete facility will require approximately 30 to 35 acres of land to accommodate the three parts of the facility as well as administrative and maintenance buildings. The final arrangement for a specific site may change from that shown depending on local conditions.

Figure 6-1
Preliminary Plot Plan for 100 MWe DICE CRCC Plant



Section 7 DICE CRCC Operability

7.1 OPERATION PHILOSOPHY

From a high-level thermodynamic perspective, DICE CRCC is not different from a conventional combined cycle power plant comprising

- a “topping cycle” with one or more “internal combustion” engines and
- a “bottoming cycle” with one “external combustion” engine.

In a conventional gas turbine combined cycle power plant, the topping cycle comprises one or more gas turbines operating in **Brayton** cycle.

In a conventional reciprocating internal combustion engine (RICE) combined cycle power plant, the topping cycle comprises multiple engines operating in **Atkinson** cycle.

In either type of combined cycle, the bottoming cycle is a **Rankine** steam cycle comprising a waste heat recovery boiler (commonly referred to as “heat recovery steam generator” or HRSG) and steam turbine generator.

7.1.1 RICE-Combined Cycle Configuration

Strictly speaking, RICE is not suitable to combined cycle configuration due to its low exhaust energy, flow as well as temperature, which precludes efficient steam generator and turbine design. This difficulty is commonly avoided by using a large number of engines so that the total exhaust energy is commensurate with reasonably efficient bottoming (Rankine) steam cycle design. The number can be as high as 10, 20 or even more than 30 as demonstrated by recent projects in the Middle East and Pakistan.

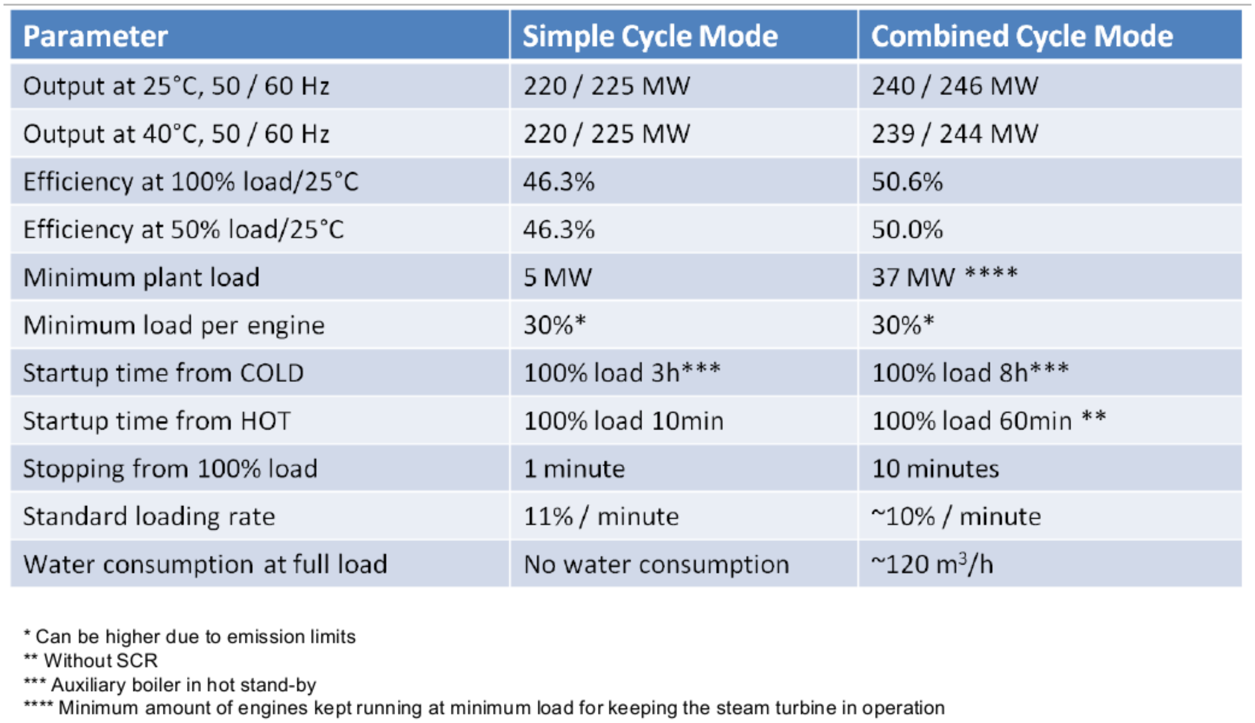
Modern RICE CC power plants almost always utilize modern spark-ignition, medium speed (i.e., about 500 RPM) and large bore engines firing natural gas. Typical rating of these engines is nominally 20 MW with very high thermal efficiency, i.e., 45% or higher. The thermodynamic cycle of these engines can be approximated (for conceptual studies and analysis) by the Atkinson cycle.

High RICE efficiency, pushing towards 50% benchmark in simple cycle, is a direct result of the cycle heat addition process in the cylinder, i.e., constant volume or “explosive” combustion, which simultaneously increases cycle peak temperature and pressure. This limits the parasitic power consumed during the power stroke resulting in high net power output for a given cycle peak temperature.

Furthermore, all modern RICE engines are turbocharged. In this configuration, cycle “charge air”, which otherwise would be at ambient conditions, is compressed to a higher pressure via compression in a centrifugal compressor. If the compressor is driven by taking power directly from the engine shaft through an accessory gearbox, it is referred to as a “supercharger”. If the compressor is driven by a small (usually also centrifugal) turbine utilizing engine exhaust gas, it is referred to as a “turbocharger”, which is essentially a small gas turbine with a balanced shaft – akin to the “gas generator” of an aeroderivative gas turbine. Supercharging increases inlet air density and mass flow for given cylinder volume and enhances engine power output.

Note that multiple engine RICE-CC power plants have large exhaust energy in "quantity" (i.e., high exhaust gas mass flow rate) but not in "quality" (i.e., still relatively low exhaust temperature). This is the reason why the Rankine steam bottoming cycle is still a minor contributor to the overall plant efficiency. For example, for a modern gas turbine combined cycle power plant (GTCC) with advanced class machines, the bottoming cycle enhances simple cycle output and efficiency by almost 50%. In other words, a net 300 MW and 42% simple cycle rating, GTCC performance becomes about 450 MW and nearly 60%. In comparison, the output/efficiency boost in changing from simple to combined cycle is significantly more modest for RICE as demonstrated by the data in Table 7-1.

Table 7-1
Simple and Combined Cycle Performances for Wärtsila's 18V50SG Engine (12 Engines)



Parameter	Simple Cycle Mode	Combined Cycle Mode
Output at 25°C, 50 / 60 Hz	220 / 225 MW	240 / 246 MW
Output at 40°C, 50 / 60 Hz	220 / 225 MW	239 / 244 MW
Efficiency at 100% load/25°C	46.3%	50.6%
Efficiency at 50% load/25°C	46.3%	50.0%
Minimum plant load	5 MW	37 MW ****
Minimum load per engine	30%*	30%*
Startup time from COLD	100% load 3h***	100% load 8h***
Startup time from HOT	100% load 10min	100% load 60min **
Stopping from 100% load	1 minute	10 minutes
Standard loading rate	11% / minute	~10% / minute
Water consumption at full load	No water consumption	~120 m^3/h

* Can be higher due to emission limits
** Without SCR
*** Auxiliary boiler in hot stand-by
**** Minimum amount of engines kept running at minimum load for keeping the steam turbine in operation

7.1.2 Turbocompounding

Turbocompounding is a technique that removes the turbocharger kit from the stock engine and modifies it so that, instead of being a net 0 kW shaft output accessory, it actually contributes to the plant's net shaft output and efficiency. When combined with a second combustor between the RICE exhaust and the turboexpander inlet (i.e., "**reheat**" or "reheat combustion", the impact is fortified via two mechanisms in a combined cycle configuration:

1. higher topping cycle output and efficiency
2. higher bottoming cycle efficiency (higher exhaust gas temperature)

In the introductory version of **DICE CRCC**, which is the subject of the CoalFIRST pre-FEED study, the second (reheat) combustor is eliminated for simplicity. The cycle can still be considered a "reheat" cycle in the sense that the second combustion is moved downstream to the HRSG duct burners. This was necessary for generating enough steam to satisfy the demand of the stripper reboiler in the post-combustion capture (PCC) block. While the five DICE in the power plant are fired with MRC slurry, the HRSG duct burners utilize natural gas. It should be noted that modification requisite for translation from RICE to DICE is exclusively limited to engine accessories, i.e.

1. removal of the turbocharger accessory (its functionality transferred to outside components)
2. replacement of fuel delivery skid and engine fuel injectors

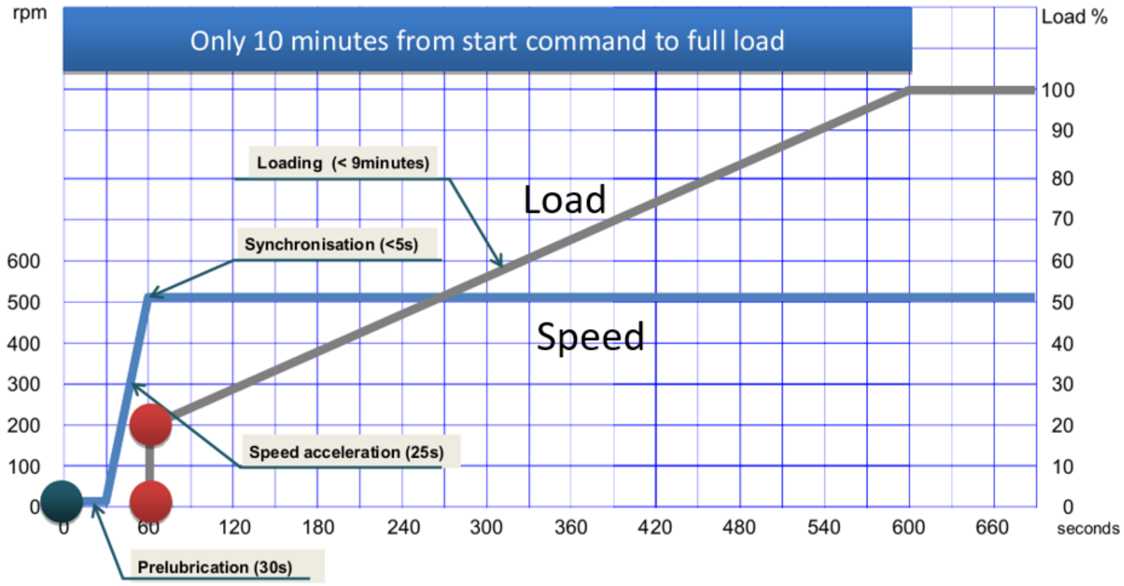
In summary, the DICE CC under investigation is essentially a RICE CC with the only difference being that the five turbocharger accessory kits of the stock RICE engines are replaced by a single air compressor (an intercooled, multi-stage centrifugal process compressor) and a single **hot gas turboexpander**. Consequently, it retains all the operability characteristics of a RICE CC.

7.2 SIMPLE CYCLE RICE/DICE STARTUP

A typical natural gas-fired RICE startup sequence is shown in Figure 7-1. Unlike the gas turbine power plants, overall startup time is 10 minutes or lower. The requirements for the sequence shown are:

1. cooling water is preheated and maintained above 70ºC,
2. engine bearings are continuously pre-lubricated (a "lift" pump supplies oil to the generator bearings) and
3. the engine is on turning gear

Figure 7-1
Typical RICE (or DICE) Starting Speed and Load Curves



If necessary, RICE/DICE can be started "fast", i.e., the engine can be synchronized in 30 seconds (instead of 60 seconds shown in Figure 7-1, and can ramp up to full load in 5 minutes (instead of 9 minutes shown in Figure 7-1), and when needed, be ramped down and stopped in less than a minute.

7.2.1 DICE Startup

It is recommended that engine starting and warm-up to operating temperatures should use fuel oil or diesel. Cold starting of large engines (which tend to use lower quality fuel) is always somewhat marginal, as the heat losses from a cold cylinder and a slow compression stroke, plus cold injection equipment, means that the charge temperature at the start of injection is lower (say 400°C) than when hot and at speed (say 650°C). This is an issue, as all coals have a higher autoignition temperature (530-575°C) than fuel oils (250-375°C).

It is, therefore, unlikely that MRC will be suitable to start a cold engine. Even if the engine started, the higher unburnts from a cold engine would cause problematic contamination of the cylinder bore, with unburnt coal packing behind the piston rings. This packing would cause accelerated ring and cylinder wear, and possibly ring breakage.

The use of diesel fuel oil for starting will require a dual injection system – a small capacity one for starting, and a larger one for MRC. An additional benefit is that the smaller capacity system for diesel fuel oil could also be used for pilot fueling

7.2.2 **Pilot Fueling**

DICE may require some pilot fueling – an established technology with natural gas engines, especially those needed to operate as dual-fuel engines (i.e., as distinct from lower compression spark ignition gas-only engines – Otto cycle). The amount of pilot fuel required needs experimental data. It will depend on the engine (speed, cylinder size, boost, aftercooling etc., which affect the charge temperature at the start of injection) and the effective volatiles content of the MRC. However, it is expected that a fixed 2-5% of the heat rate at maximum output would be sufficient – which automatically provides a higher proportion of heat input when required at idle and lower load settings.

For low-speed engines (<400 rpm), and based on practical experience, it is expected that the engine could operate reliably on 100% MRC, providing the engine is hot and above (say) 35% load. For lower load and higher speed engines, minimum pilot fueling with fuel oil is likely to be required. As both startup and pilot injection will require a separate injection system, operationally, some minimum pilot injection will likely be preferred to provide cooling of the pilot injector nozzles.

Injection timing for the pilot injection would normally be just before, or at the same time, as the MRC –both being electronically timed to allow optimization for different engine conditions and fuel variations.

In addition to a lower speed, derating the engine by reducing the amount of aftercooling (a higher air inlet temperature would give a reduction in cylinder charge, with a disproportionate increase in compression heating) – which may also reduce the need for pilot fueling.

The requirement for assisting ignition with pilot fuel provides an additional implementation strategy: installation of dual fuel NG engines now, being progressively switched to DICE as required using a retrofit kit.

7.2.3 **DICE Shutdown**

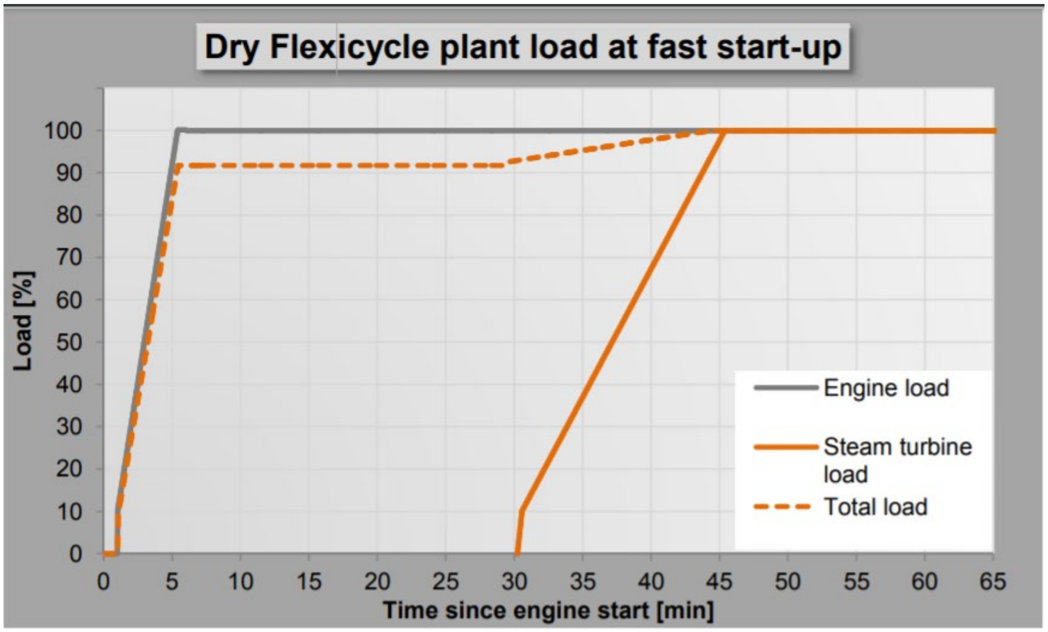
With a correctly designed fuel system, engine shut own can be achieved without any precautions. To achieve this, the fuel system will require some method of controlling a circulating flow of fuel down the injector to the needle valve and back to the service tank – as described in the engine modifications section. If this feature is not included, then a full flush of the fuel system from the feed pump through the injector will be required while the engine is operating to eliminate the possibility of stagnant coal fuel clogging the hot injection system while stopped. With the latter system the engine shut down would be under pilot fueling.

While diesel fuel has been used as the flushing fluid in some previous trials by simply switching the fuel supply to the engine from MRC to diesel, this arrangement is not recommended. In contrast to MRC, diesel fuel requires perfect sealing of valve seats (i.e., the needle or cut off valve in the injector) to ensure that fuel does not leak into the cylinder under the influence of the fuel supply pump. Also, any MRC that is not flushed from the system by the diesel fuel will highly likely result in agglomeration of the residual coal particles, potentially causing blockages. If this method of flushing is chosen, then an alternative flushing fluid should be used, for example, a mixture of long chain polyglycol (e.g., UCON) and water. This fluid would have the advantage of being miscible with MRC. In both cases, the switchover to the flushing fluid needs to be undertaken at less than half-load to avoid overfueling the engine.

7.3 COMBINED CYCLE RICE/DICE STARTUP

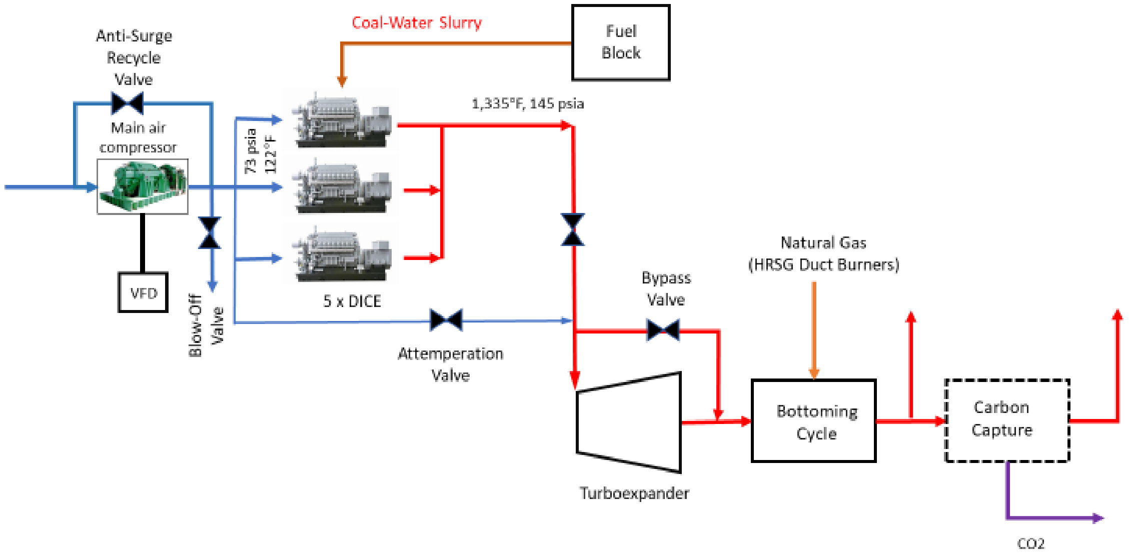
A typical RICE CC fast startup sequence (12 engines) is shown in Figure 7-2. All engines are started simultaneously; thus, 90% of plant full load is reached in slightly over five minutes. Steam turbine roll starts at the 30-minute mark and full plant load is reached 15 minutes after that.

Figure 7-2
Typical RICE CC Startup Speed and Load Trends



A simplified schematic diagram of DICE CRCC is shown in Figure 7-3. During startup the **main air compressor** (MAC) is started by the **variable frequency drive** (VFD). Surge control is accomplished by recirculation and/or blow-off by the MAC controller. Engines are started simultaneously in a manner similar to that shown in Figure 7-1 but in a "fast start" mode.

Figure 7-3
Schematic of RICE CRCC



Note the bypass lines to and around the hot gas expander, which is started using the hot exhaust gas coming from the engines, mixed with air extracted from the MAC to cool it. According to the OEM, the general rule is to control the warming rate at about 100°C/hour until the unit reaches the design temperature.

For a "cold start", the turboexpander startup sequence can be split into four phases after standard pre-start check list including instrumentation, lubrication, etc. (note that the unit is driven by the exhaust gas, i.e., there is no starter motor):

- acceleration to the idle speed (~800-1,500 rpm);
- warming time at idle speed;
- once temperature reaches the 500°C, flue gas valves are set to fully open position, the speed increases to the design value;
- synchronization to the grid is followed by the last temperature increase step, which is completed in few minutes.

At the start of the idle time, gas/air enter into the machine and, in a few minutes, it reaches ~300°C. It takes about 2 to 3 hours for the unit to warm up to 530 °C at idle speed. In this time frame, disc cooling air is activated, machine drains are closed, standard checks are performed (bearing temperatures, vibration readings and so on). During startup, inlet pressure and flow through the unit is controlled by the inlet guide vanes and bypass valve.

Main air compressor startup is straightforward and fast whether it is a “cold” or “hot” start because there is no warm-up period involved. The critical item in process control startup is surge control, which is typically accomplished by recirculation (or recycling) of discharge air through the anti-surge valve into the compressor suction. In intercooled, multi-casing units, each compressor section has its own surge control setup.

Due to the large motor size of the MAC (> 25 MW), a VFD is necessary to prevent current inrush during starting. Typical compressor start sequence is shown in Figure 7-4 using speed and anti-surge valve position trends. The startup process on the performance map is depicted in Figure 7-5. Prior to startup, intercooler circulating water flow starts and anti-surge valves are opened. Unit drains are closed, and standard checks are performed (bearings temperature, vibrations readings, etc.). Typically, inlet guide vanes (IGVs) are set to their lowest setting, which helps with current inrush as well. As shown in Figure 7-5, as the machine is cranked by the VFD, volume flow increases but recycling prevents pressure buildup, which ensures that the unit goes through the low speeds safely removed from the surge line. Once the operating pressure is reached, IGVs are opened and anti-surge valve is closed in a controlled manner to bring the unit to full flow and full load.

The last step is going to be coordinated with the engine startup by the controller. The exact sequence and control algorithm will be determined by dynamic simulation runs during detail engineering. Similarly, dynamic simulation runs are also going to be used to coordinate the turboexpander startup controls with the engines.

Figure 7-4
Typical Centrifugal Compressor Startup – Speed and Anti-Surge Valve Position

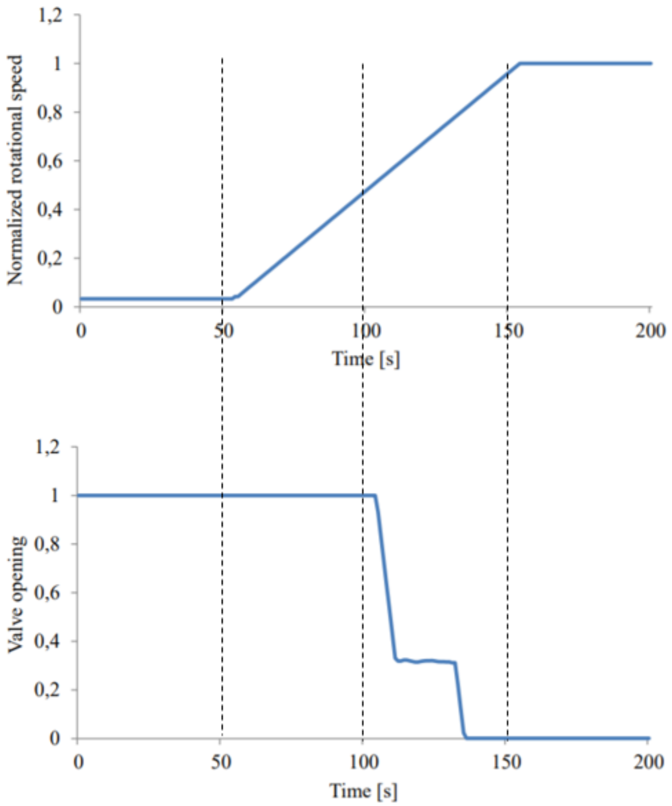
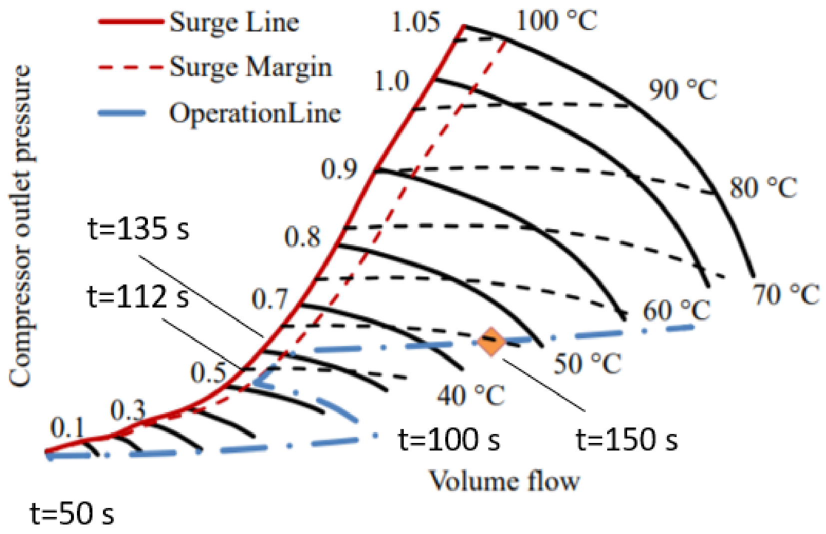
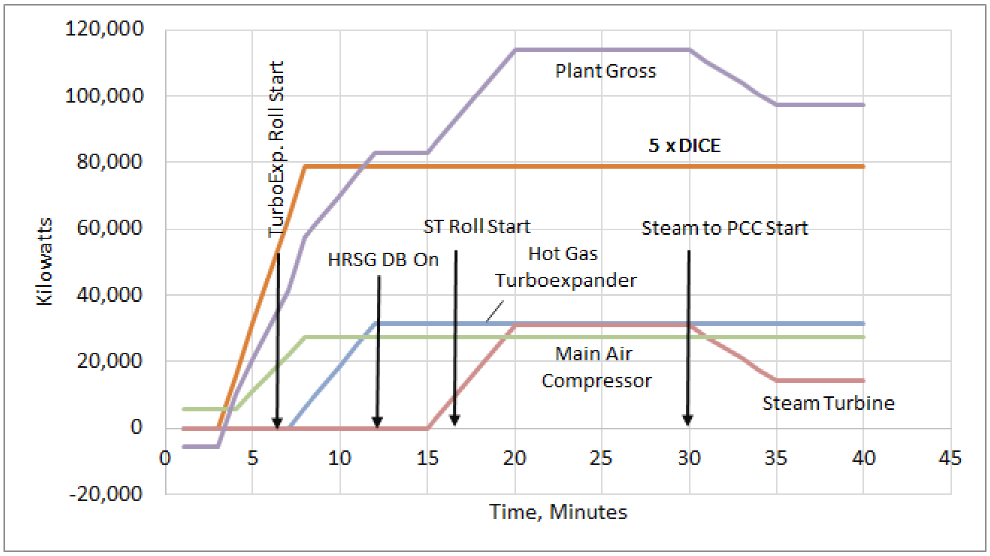


Figure 7-5
Typical Centrifugal Compressor Startup – Pressure and Flow Path



DICE CRCC startup after an overnight shutdown is shown in Figure 7-6. As shown in the figure, MAC is started first by the VFD using power from the grid. Thereafter, first all five DICE are cranked to FSNL, synchronized to the grid and loaded to full load. Once there is enough exhaust gas generated to crank the turboexpander to FSNL, which is about 40% DICE load (equivalent of two engines running at full load), turboexpander roll starts. After the turboexpander is synchronized to the grid and ramped to full load, steam turbine roll and load process starts. Once all the five engines have started, the HRSG receives its full exhaust gas flow. After the turboexpander start has been completed, the duct burners are lit. Steam produced by the HRSG until the steam turbine roll and loading is rerouted to the condenser via the bypass line. Steam turbine is loaded by the controller via synchronized opening and closing of the admission and bypass valves, respectively. Plant full load is reached at twenty-minute mark. During the startup sequence shown in Figure 7-6, the PCC block is off-line.

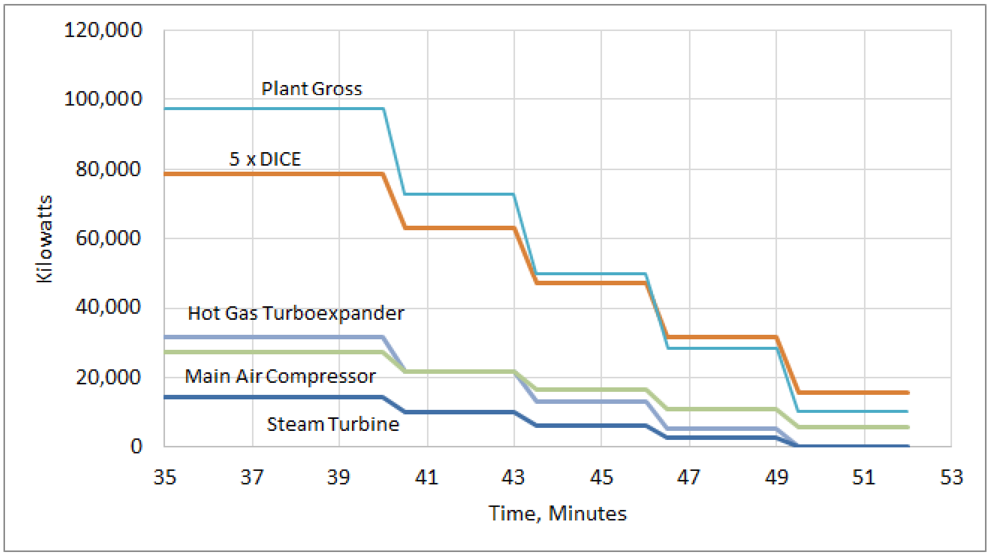
Figure 7-6
DICE CRCC Hot Start



PCC startup is started at the 30-minute mark. Detailed pre-start preparation and startup procedure are described in detail below. Once steam starts to be directed from the HP turbine exhaust to the stripper reboiler, steam turbine starts going down. Once the steam flow through the LP turbine reaches its minimum value, it is taken off-line by the SSS clutch. Steam turbine generator is driven by the HP turbine in a backpressure operating mode.

DICE CRCC can be ramped down to about 30% plant load (two DICE operating) by turning down the engines in sequence. In this mode, hot gas turbo expander and the steam turbine are in a load following mode. This is shown in **Error! Reference source not found.** with a ramp-down rate corresponding to 90 seconds for shutting down one DICE, which is typical and easily doable. Even shorter times are possible based on OEM requirements and input. Note that load ramps (up or down) with all engines in operation are practically instantaneous. As noted above, bringing up an engine from standstill to full load is about 5 minutes.

Figure 7-7
DICE CRCC Load Ramps



Conceptually, as shown in Figure 7-7, the plant can be brought down to one DICE on-line with the plant running at 10% load. This has to be confirmed by the MAC and turboexpander OEMs during detail design, i.e., whether their equipment can run at that low level of load. In the case that this is an issue for the MAC, it can be alleviated during the detail design by specifying two parallel MAC trains. While this would increase the total installed equipment cost, it would be countered by the cost saving from the elimination of the VFD and associated electrical BOP. Even if the plant equipment can take the lowest flow and stay in operation, there is the question of whether the PCC can operate at such low flue gas flow. This requires careful engineering design of the capture block for maximum turndown.

It should be mentioned that the plant can run with only <u>one</u> (or more) DICE in operation. This can be easily accomplished by providing a bypass stack downstream of the DICE (upstream of the hot gas expander) or between the turboexpander and the HRSG. While this is a straightforward plant option, it should be carefully investigated at the beginning of the project based on the environmental regulations at the chosen site. The bypass stack can discharge directly to the atmosphere (the most economic option) or its flue gas can be directed to the PCC (unlikely to be cost-effective).

7.4 STARTUP TIME AND RAMP RATES SUMMARY

A summary of the DICE CRCC startup times for various conditions is shown per the following. The values cited are based on starting up from cold iron to 100 percent load but exclude PCC start.

- Hot start (overnight shutdown) in 30 minutes
- Warm start (48-72 hours down) in 1 to 2 hours
- Cold start (> 72 hours down) in 2 to 3 hours

Exact values for these start up times depend on the hot gas turboexpander allowable ramp rate. Operation at less than 100 percent load can be achieved in 30 minutes, regardless of hot, warm or cold start.

RICE is able to ramp at ~20% per minute from full speed no load (FSNL) to full speed full load (FSFL). From 100% plant (not engine) load to 60% engine load is 4 minutes, at which point the plant is at 50% load. Therefore, the % MCR/min is 12.5% (plant) normal.

On an emergency basis, two engines can be tripped instantaneously, ramping down to 60% engine load (50% plant load). With the inertia of the other systems, at 2 minute maximum, the MCR can be as high as 25% per minute under emergency circumstances.

Appendix A References

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

VOLUME V: COST RESULTS REPORT

U. S. Department of Energy (DOE)

Contract No. 89243319CFE000025, Coal-Based Power Plants of the Future

By

Nexant, Inc

and

Bechtel Power and Infrastructure

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Section 1 Capital Cost Estimate

1.1 COST ESTIMATION METHODOLOGY

Capital costs for the small-modular DICE CRCC plant (nominally a 100 MW "power block" but less than 100 MW with post-combustion capture for this introductory variant) were derived based on the following methodology:

- Capital costs for the coal beneficiation system were estimated by Sedgman and presented as a turnkey subcontract cost in this report. The capital cost estimate is reflective of the facility fully designed, supplied, fabricated and delivered to site, constructed and commissioned in accordance with the coal beneficiation plant scope of work detailed in the pre-FEED performance results study. For this study phase, Sedgman has utilized its historical cost information for procurement, fabrication and installation pricing and rate and this information will be validated in future study phases.

  Sedgman's bulk material and labor cost estimating procedures are based on quantity take-offs and construction rates respectively. The Sedgman in-house cost estimating database for the development, design and construction of coal handling and preparation plants and associated mine infrastructure is comprehensive and is continuously being updated.

- The costs for certain specialized, commercial equipment associated with the DICE CRCC plant, such as the air compressor, hot gas combustor, hot gas expander and the various generator equipment, were estimated and verified with budgetary quotes from equipment vendors. These were then 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. Costs associated with common equipment types (pumps, heat exchangers) were estimated using commercial cost estimation software (Aspen In-Plant Cost Estimator, Thermoflow PEACE)
- Post combustion capture (PCC) plant cost was determined via a bottoms-up cost estimate based on major equipment sizing and using past quotes from equipment vendors or cost curves derived from commercial cost estimate software
- DICE CRCC balance of plant (BOP) systems were estimated via a bottoms-up cost estimate based on major equipment sizing and developed to total plant cost level using historical factors
- The DICE CRCC solids handling systems (coal handling and ash handling) were scaled via capacity factor, using appropriate scaling parameters and capacity factoring exponents stated in NETL's Quality Guidelines for Energy System Studies (QGESS) Cost Scaling Report

Table 1-1 shows the methodology used to estimate the costs for each of the major accounts and subaccounts of the DICE CRCC plant.

Table 1-1
100 MWe DICE CRCC Cost Accounts and Estimation Methodology

Acct No.	Item/Description	Cost Estimate Methodology
1	COAL HANDLING	Included in Sedgman scope
2	COAL & SORBENT PREP & FEED	
2.1	Coial Receiving, Conveying & Crushing	Each area estimated as turnkey subcontract cost based on Sedgman's in-house estimation database
2.2	Grinding	
2.3	Flotation	
2.4	Product Dewatering	
2.5	Product Slurry Storage	
2.6	Tailings Dewatering	
2.7	BOP and Reagents	
3	FEEDWATER & MISC BOP SYSTEMS	
3.1	Feedwater System	Included in HRSG cost
3.2	Deaerator, Water Treatment & Tanks	Bottoms-up, major equipment factored estimate
3.3	Service Water Systems	Bottoms-up estimate, includes service water pumps and headers
3.4	Natural Gas Pipeline	Bottoms-up estimate based on inch-mile of pipeline; pipeline used is 6" ID, 10 mile length
3.5	Waste Treatment Equipment	Bottoms-up estimate, includes waste water discharge pumps, tanks, and headers
3.6	Plant Instrument Air System	High-level estimate based on plant and instrument air consumption
3.7	Fire Protection System	Bottoms up estimate based on fire water requirement
3.8	Miscellaneous Pumps and Tanks	Bottoms-up cost estimate
4	DICE GT	
4.1	DICE and Generator (5)	Per MAN, equipment engines of this type are between $6 and $7 million
4.2	Air Compressor	Equipment cost quoted by Siemens Dresser-Rand
4.3	Hot Gas Expander + Generator (1)	Equipment cost quoted by Siemens Dresser-Rand
4.4	MRC Preheater	Estimated from Thermoflow PEACE
4.5	Fin-Fan Air Cooler	Estimated from Thermoflow PEACE
4.9	DICE-GT Foundation	Bulk foundation material and labor factored from DICE GT equipment costs
5	FLUE GAS CLEANUP	
5.1	Caustic scrubber/direct contact cooler	Sulzer quote for packing/internals and literature
5.2	Third-Stage Separator	Quote from UOP Honeywell
5B	CO2 REMOVAL & COMPRESSION	
5B.1	MEA CO2 Capture	Nexant bottoms-up cost estimate
5B.2	CO2 Compression & Drying	Nexant bottoms-up cost estimate
5B.9	CO2 Capture & Compression Foundation	Bulk foundation material and labor factored from CO2 capture and compressions equipment costs
7	HRSG, DUCTING & STACK	
7.1	Heat Recovery Steam Generator (w/ SCR)	Nooter & Eriksen bid for TC-RHT GTCC
7.2	Ductwork	From layout using other CCS cost estimates as guide
7.9	HRSG, Duct & Stack Foundations	Bulk foundation material and labor factored from HRSG equipment costs
8	STEAM TURBINE GENERATOR	
8.1	Steam TG & Accessories	Siemens Industrial bid
8.2	Condenser & Auxiliaries	Thermoflow PEACE
8.3	Steam Piping	From layout using other Bechtel power projects as guide
8.9	TG Foundations	Bulk foundation material and labor factored from steam turbine equipment costs
9	COOLING WATER SYSTEM	
9.1	Cooling Towers	Quote from Cooling Tower Depot
9.2	Circulating Water Pumps	Bottoms-up cost estimate based on pump sizing
9.3	Circ. Water Piping	Estimate based on underground CW piping length
9.4	Make-up Water System	Bottoms-up estimate, includes makeup water pump, filter, and headers
9.9	Circ. Water System Foundations	Bulk foundation material and labor factored from cooling water/cooling tower equipment costs

Table 1-1 (cont'd)
100 MWe DICE CRCC Cost Accounts and Estimation Methodology

Acct No.	Item/Description	Cost Estimate Methodology
10	ASH/SPENT SORBENT HANDLING SYS	
10.6	Ash Storage Silos	Scaled via QGESS capacity factoring using Low Rank Coal Baseline Report as reference
10.7	Ash Transport & Feed Equipment	
10.9	Ash/Spent Sorbent Foundation	
11	ACCESSORY ELECTRIC PLANT	
11.1	Electical Equipment	Bottoms-up cost estimate based on electrical single-line
11.2	Transmission Lines and Switchyards	
11.9	Electrical Bulks and Foundations	
12	INSTRUMENTATION & CONTROL	
12.1	DICE GT-CRCC Control Equipment	Factored from DICE GT-CRCC equipment costs
12.2	PCC Control Equipment	Factored from CO2 capture and compression equipment costs
13	IMPROVEMENTS TO SITE	
13.1	DICE GT-CRCC Sitework	Factored from DICE GT-CRCC equipment costs
13.2	PCC Sitework	Factored from CO2 capture and compression equipment costs
14	BUILDINGS & STRUCTURES	
14.1	DICE Area	Factored from DICE GT equipment costs
14.2	Steam Turbine Building	Factored from steam turbine equipment costs
14.3	Administration Building	Based on labor position requirements
14.4	Circulating Water Pumphouse	Factored from cooling water associated equipment costs
14.5	Water Treatment Buildings	Based on rough square footage requirements
14.6	Machine Shop	
14.7	Warehouse	
14.8	Other Buildings & Structures	
14.9	Waste Treating Building & Structures	

1.2 CAPITAL COST ESTIMATE

1.2.1 Total Plant Cost (TPC)

Table 1-2 provides a breakdown of the DICE 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.

The estimated TPC for the small, modular (nominal 100 MW "block") DICE CRCC plant is $422.4 million (MM), or $5,419/kW-net,

Table 1-3 presents the breakdown of the additional costs required to develop the TPC to total overnight cost (TOC), per the assumptions used in the NETL coal and natural gas baseline power plant cases. The resulting TOC, at $525 MM, or $6,732/kW-net is used for the calculation of the levelized cost of electricity (LCOE).

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

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

5x1x1x1 100 MW DICE CRCC PLANT WITH 30 WT% MEA CO2 CAPTURE

Cost Basis 2018 ($x1000)
Plant Size 78 MWe, net

Acct No.	Item/Description	Equipment Cost	Material Cost	Labor Direct	Labor Indirect	Sub Contract	Bare Erected Cost $	Eng'g CM H.O & Fee	Contingencies Process	Contingencies Project	TOTAL PLANT COST $	TOTAL PLANT COST $/kW
1	COAL HANDLING		incl in Coal Beneficiation Scope									
2	COAL BENEFICIATION											
2.1	Coal Receiving, Conveying & Crushing	$0	$0	$0	$0	$4,648	$4,648	$1,118	$937	$577	$7,280	
2.2	Grinding	$0	$0	$0	$0	$16,159	$16,159	$3,887	$3,257	$2,005	$25,308	
2.3	Flotation	$0	$0	$0	$0	$4,050	$4,050	$974	$816	$502	$6,343	
2.4	Product Dewatering	$0	$0	$0	$0	$4,705	$4,705	$1,132	$948	$584	$7,369	
2.5	Product Slurry Storage	$0	$0	$0	$0	$2,838	$2,838	$683	$572	$352	$4,445	
2.6	Tailings Dewatering	$0	$0	$0	$0	$1,997	$1,997	$480	$403	$248	$3,128	
2.7	BOP and Reagents	$0	$0	$0	$0	$5,383	$5,383	$1,295	$1,085	$668	$8,431	
	SUBTOTAL 2.	**$0**	**$0**	**$0**	**$0**	**$39,780**	**$39,780**	**$9,568**	**$8,019**	**$4,935**	**$62,302**	**$799**
3	FEEDWATER & MISC BOP SYSTEMS											
3.1	Feedwater System			incl w/ HRSG			$0	$0	$0	$0	$0	
3.2	Deaerator, Tanks and Water Treatment	$145	$425	$133	$0	$0	$703	$70	$0	$155	$928	
3.4	Service Water Systems	$71	$83	$137	$0	$0	$290	$29	$0	$64	$383	
3.6	Natural Gas Pipeline	$0	$9,076	$0	$0	$0	$9,076	$908	$0	$1,497	$11,481	
3.7	Waste Treatment Equipment	$196	$220	$330	$0	$0	$747	$75	$0	$164	$986	
3.8	Plant and Instrument Air System	$911	$902	$720	$0	$0	$2,533	$253	$0	$418	$3,204	
3.8	Fire Protection System	$150	$179	$237	$0	$0	$565	$57	$0	$93	$715	
3.9	Misc Pumps and Tanks	$500	$607	$773	$0	$0	$1,880	$188	$0	$310	$2,378	
	SUBTOTAL 3.	**$1,973**	**$11,491**	**$2,329**	**$0**	**$0**	**$15,794**	**$1,579**	**$0**	**$2,702**	**$20,075**	**$258**
4	DICE-GT SYSTEMS											
4.1	DICE and Generator (5)	$30,000	$4,500	$5,400	$0	$0	$39,900	$3,990	$8,778	$7,900	$60,568	
4.2	Air Compressor	$8,300	$3,633	$4,259	$0	$0	$16,192	$1,619	$0	$2,672	$20,483	
4.3	Combustor, Expander and Generator	$17,000	$837	$1,274	$0	$0	$19,111	$1,911	$0	$3,153	$24,175	
4.4	MRC Preheater	$150	$130	$133	$0	$0	$413	$41	$0	$68	$522	
4.5	Fin-Fan Air Cooler	$1,000	$867	$884	$0	$0	$2,751	$275	$0	$454	$3,479	
4.9	DICE-GT Foundation	$0	$2,469	$4,805	$0	$0	$7,274	$727	$0	$1,200	$9,202	
	SUBTOTAL 4.	**$56,450**	**$12,435**	**$16,755**	**$0**	**$0**	**$85,640**	**$8,564**	**$8,778**	**$15,447**	**$118,429**	**$1,519**
5	FLUE GAS CLEANUP											
5.1	Direct Contact Cooler	$1,275	$1,284	$1,325	$0	$0	$3,884	$388	$0	$427	$4,700	
5.3	Third Stage Separator	$6,000	$4,916	$5,426	$0	$0	$16,342	$1,634	$0	$1,798	$19,774	
5.3	Flue Gas Cleanup Foundation	$0	$575	$1,120	$0	$0	$1,695	$169	$0	$186	$2,051	
	SUBTOTAL 5.	**$7,275**	**$6,775**	**$7,871**	**$0**	**$0**	**$21,921**	**$2,192**	**$0**	**$2,411**	**$26,525**	**$340**
5B	CO2 REMOVAL & COMPRESSION											
5B.1	CO2 Removal System	$12,984	$5,838	$11,595	$0	$0	$30,416	$3,042	$0	$5,019	$38,476	
5B.2	CO2 Compression & Drying	$11,061	$4,060	$5,175	$0	$0	$20,296	$2,030	$0	$3,349	$25,674	
5B.3	CO2 Removal & Compression Foundation	$0	$877	$1,417	$0	$0	$2,294	$229	$0	$378	$2,902	
	SUBTOTAL 5B.	**$24,044**	**$10,775**	**$18,186**	**$0**	**$0**	**$53,006**	**$5,301**	**$0**	**$8,746**	**$67,052**	**$860**
7	HRSG, DUCTING & STACK											
7.1	Heat Recovery Steam Generator (w/ SCR)	$6,000	$2,775	$6,018	$0	$0	$14,792	$1,479	$0	$2,441	$18,712	
7.2	Deaerator			incl in 3.2			$0	$0	$0	$0	$0	
7.3	Ductwork	$1,675	$0	$0	$0	$0	$1,675	$168	$0	$276	$2,119	
7.9	HRSG & Duct Foundations	$0	$297	$679	$0	$0	$976	$98	$0	$215	$1,288	
	SUBTOTAL 7.	**$7,675**	**$3,072**	**$6,696**	**$0**	**$0**	**$17,443**	**$1,744**	**$0**	**$2,932**	**$22,119**	**$284**

Table 1-2 (cont'd)
100 MWe Nominal DICE CRCC Capital Cost Breakdown

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

5x1x1x1 100 MW DICE CRCC PLANT WITH 30 WT% MEA CO2 CAPTURE

Cost Basis 2018 ($x1000)
Plant Size 78 MWe, net

Acct No.	Item/Description	Equipment Cost	Material Cost	Labor Direct	Labor Indirect	Sub Contract	Bare Erected Cost $	Eng'g CM H.O & Fee	Contingencies Process	Contingencies Project	TOTAL PLANT COST $	TOTAL PLANT COST $/kW
8	STEAM TURBINE GENERATOR											
8.1	Steam Turbine & Accessories	$4,850	$421	$741	$0	$0	$6,013	$601	$0	$661	$7,275	
8.2	Steam Turbine Condenser	$400	$347	$354	$0	$0	$1,100	$110	$0	$121	$1,331	
8.4	Steam Piping	$0	$4,500	$6,667	$0	$0	$11,167	$1,117	$0	$1,843	$14,126	
8.9	Steam Turbine Foundations	$0	$329	$640	$0	$0	$969	$97	$0	$213	$1,280	
	SUBTOTAL 8.	**$5,250**	**$5,597**	**$8,402**	**$0**	**$0**	**$19,249**	**$1,925**	**$0**	**$2,838**	**$24,012**	**$308**
9	COOLING WATER SYSTEM											
9.1	Cooling Towers	$2,216	$346	$943	$0	$0	$3,504	$350	$0	$385	$4,240	
9.2	Circulating Water Pumps	$1,204	$1,387	$1,570	$0	$0	$4,161	$416	$0	$458	$5,035	
9.4	Circ. Water Piping	$1,075	$596	$2,632	$0	$0	$4,303	$430	$0	$710	$5,444	
9.5	Make-up Water System	$951	$591	$813	$0	$0	$2,355	$236	$0	$389	$2,979	
9.9	Circ. Water System Foundations	$0	$767	$1,491	$0	$0	$2,258	$226	$0	$497	$2,980	
	SUBTOTAL 9.	**$5,446**	**$3,688**	**$7,449**	**$0**	**$0**	**$16,582**	**$1,658**	**$0**	**$2,439**	**$20,679**	**$265**
10	ASH/SPENT SORBENT HANDLING SYS											
10.6	Ash Storage Silos	$95	$0	$290	$0	$0	$385	$38	$0	$42	$465	
10.7	Ash Transport & Feed Equipment	$847	$0	$839	$0	$0	$1,686	$169	$0	$185	$2,040	
10.9	Ash/Spent Sorbent Foundation	$0	$29	$35	$0	$0	$64	$6	$0	$14	$85	
	SUBTOTAL 10.	**$942**	**$29**	**$1,165**	**$0**	**$0**	**$2,135**	**$214**	**$0**	**$242**	**$2,591**	**$33**
11	ACCESSORY ELECTRIC PLANT											
11.1	Electrical Equipment	$13,175	$0	$1,867	$0	$0	$15,042	$1,504	$0	$1,158	$17,704	
11.2	Transmission Lines and Switchyards	$6,300	$0	$0	$0	$0	$6,300	$630	$0	$485	$7,415	
11.9	Electrical Bulks and Foundations	$0	$3,000	$6,133	$0	$0	$9,133	$913	$0	$2,009	$12,056	
	SUBTOTAL 11.	**$19,475**	**$3,000**	**$8,000**	**$0**	**$0**	**$30,475**	**$3,048**	**$0**	**$3,653**	**$37,175**	**$477**
12	INSTRUMENTATION & CONTROL											
12.1	DICE-GT CRCC Control Equipment	$0	$5,000	$3,706	$0	$0	$8,706	$871	$0	$1,436	$11,013	
12.2	PCC Control Equipment	$0	$1,751	$758	$0	$0	$2,509	$251	$0	$414	$3,173	
	SUBTOTAL 12.	**$0**	**$6,751**	**$4,463**	**$0**	**$0**	**$11,214**	**$1,121**	**$0**	**$1,850**	**$14,186**	**$182**

Table 1-2 (cont'd)
100 MWe Nominal DICE CRCC Capital Cost Breakdown

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

5x1x1x1 100 MW DICE CRCC PLANT WITH 30 WT% MEA CO2 CAPTURE

Cost Basis 2018 ($x1000)
Plant Size 78 MWe, net

Acct No.	Item/Description	Equipment Cost	Material Cost	Labor Direct	Labor Indirect	Sub Contract	Bare Erected Cost $	Eng'g CM H.O & Fee	Contingencies Process	Contingencies Project	TOTAL PLANT COST $	TOTAL PLANT COST $/kW
13	IMPROVEMENTS TO SITE											
13.1	DICE GT-CRCC Sitework	$0	$623	$1,360	$0	$0	$1,983	$198	$0	$436	$2,617	
13.2	PCC Sitework	$0	$682	$1,472	$0	$0	$2,154	$215	$0	$474	$2,843	
	SUBTOTAL 13.	**$0**	**$1,305**	**$2,832**	**$0**	**$0**	**$4,137**	**$414**	**$0**	**$910**	**$5,460**	**$70**
14	BUILDINGS & STRUCTURES											
14.1	DICE-GT Building	$0	$370	$0	$0	$0	$370	$37	$0	$61	$468	
14.2	Steam Turbine Building	$0	$216	$0	$0	$0	$216	$22	$0	$36	$273	
14.3	Administration Building	$0	$252	$0	$0	$0	$252	$25	$0	$42	$319	
14.4	Circulating Water Pumphouse	$0	$120	$0	$0	$0	$120	$12	$0	$20	$152	
14.5	Water Treatment Buildings	$0	$180	$0	$0	$0	$180	$18	$0	$30	$228	
14.7	Warehouse	$0	$211	$0	$0	$0	$211	$21	$0	$35	$267	
14.9	Waste Treating Building & Structures	$0	$59	$0	$0	$0	$59	$6	$0	$10	$75	
	SUBTOTAL 14.	**$0**	**$1,409**	**$0**	**$0**	**$0**	**$1,409**	**$141**	**$0**	**$232**	**$1,782**	**$23**
	CALCULATED TOTAL COST	**$128,530**	**$66,327**	**$84,147**	**$0**	**$44,485**	**$323,489**	**$38,600**	**$17,745**	**$49,921**	**$422,387**	**$5,419**

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

Description	$/1,000	$/kW
Preproduction Costs		
6 Months All Labor	$6,197	$79
1 Month Maintenance Materials	$388	$5
1 Month Non-Fuel Consumables	$878	$11
1 Month Waste Disposal	$2,388	$31
25% of 1 Months Fuel Cost at 100% CF	$712	$9
2% of TPC	$8,448	$108
Total	**$19,010**	**$244**
Inventory Capital		
60-day supply of fuel at 100% CF	$4,130	$53
60-day supply of non-fuel consumables at 100% CF	$1,242	$16
0.5% of TPC (spare parts)	$2,112	$27
Total	**$7,484**	**$96**
Other Costs		
Initial Cost for Catalyst and Chemicals	$782	$10
Land	$300	$4
Other Owner's Cost	$63,358	$813
Financing Costs	$11,404	$146
Total Overnight Costs (TOC)	**$524,724**	**$6,732**

Section 2 Plant Operating Costs

2.1 FUEL SPECIFICATIONS

2.1.1 PRB Coal

The design fuel for the DICE CRCC is low-sulfur sub-bituminous Montana Rosebud Powder River Basin (PRB) coal, with an as-received heating value of 8,564 Btu/lb HHV (8,252 Btu/lb LHV).

Based on 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.

2.1.2 Beneficiated Coal Yield

The raw coal has an ash content of 11.03 percent by weight (wt%) on a dry basis, and needs to be micronized and de-ashed to an appropriate level in order to protect the moving parts of the engine that are exposed to either the micronized coal-water fuel or the solid particulate products of combustion which contain both ash and traces of unburned coal.

The DICE CRCC conceptual design utilizes physical beneficiation to remove the minerals and sulfate/pyritic sulfur in the PRB coal. Sedgman's physical beneficiation process, as described in the Performance Results Report, reduces the ash content to about 2 wt% on a dry basis, which is considered suitable for combustion in DICE. On a mass basis, the yield of beneficiated coal product to raw coal feed is 47.5 percent.

2.1.3 Natural Gas Price

Based on the most recent DOE Bituminous Baseline Report (rev 4, 2019), the current levelized natural gas price is $4.19/GJ ($4.42/MMBtu) on an HHV basis, delivered to the Midwest, and reported in 2018 U.S. dollars.

In its reference Midwestern NGCC case, DOE assumes that the natural gas feed is delivered to the power plant via a 10-mile long underground, carbon steel gas pipeline. The DICE CRCC plant in this conceptual design accounts for the cost associated with the same pipeline length but for a smaller diameter (6 inch-piping) due to the much smaller natural gas demand.

2.1.4 Diesel Price

Based on EIA data, the average annual wholesale price for U.S. No.2 diesel is $2.12/gallon. For this study, a price of $2.50/gallon of No.2 diesel is assumed to account for transportation costs to the DICE CRCC plant. Since the real escalation rate is assumed to be zero percent, all real dollar amounts stay the same as in the base year, 2018, and thus the levelized cost of fuel is the same as the estimated 2018 cost at $2.50/gallon.

2.2 OPERATING COST

Table 2-1 presents a breakdown of the nominal 100 MWe DICE CRCC fixed and variable operating costs related to operations and maintenance (O&M) of the facility, including the cost of fuel, in 2018 dollars, based on the performance of the plant as presented in the Pre-FEED Performance Results Report.

It is notable that the low recovery of beneficiated product from processing PRB coal, at less than 50 percent, results in a large consumption of the PRB coal feed. Additionally, it generates a significant quantity of coal tailings slurry that needs to be disposed of. While these tailings still contain significant heating value, there appears to be no commercial or non-monetary disposal methods for the tailings slurry. A conventional wet disposal method is proposed and a $38/ton disposal cost was used in the cost estimate, as referenced from the DOE Bituminous Baseline Report.

This disposal cost is considered conservative, since the tailings contain significant heating value, as much as the product itself, albeit with higher ash content and in the form of a slurry. Its quality can be comparable to that of lignite coals found in the Gulf Coast region, which have heating values as low as 4,000 Btu/lb, and moisture contents as high as 55 percent). It could therefore be potentially useful as a fuel for slurry-based gasification or for combustion after suitable processing (e.g. briquetting). Additionally, research has shown that such wastes can be used as a material for filling abandoned workings in mines or to seal surface stockpiles. Post-flotation wastes from beneficiation of coking coals with calorific value more than 5,000 kJ/kg can be used as fuel for the production of building construction ceramics, and after further beneficiation as an additive to energy fuel.

A sensitivity analysis is conducted in a later section which assumed a disposal cost ranging from -$10/ton to $38/ton. The former assumes that the tailings are a useful byproduct with a free on board (FOB) price of $10/ton, or about $1.4/MMBtu. The latter, as used in this base case analysis, simply assumes that there is no market for this product, and it must be disposed of at the full-on disposal cost of $38/ton.

Table 2-1
100 MWe Nominal DICE CRCC Annual Operating Cost Breakdown

INITIAL & ANNUAL O&M EXPENSES

Case:	DICE GT-CRCC		
Plant Size (MWe)	**78**		
Primary/Secondary Fuel:	**Wyoming PRB**	**Fuel Cost ($/MMBtu):**	
Design/Construction	3 years	**Book Life (yrs):**	20
		Cost Base	Dec-18
Capacity Factor (%)	85	**CO2 Captured (TPD)**	1857

OPERATING & MAINTENANCE LABOR

Operating Labor

Operating Labor Rate (base):	$38.50	$/hr
Operating Labor Burden:	30.0	% of base
Labor Overhead Charge	25.0	% of labor

Coal Beneficiation Plant Operating Labor Requirements	**per Shift**
Skilled Operator	1.0
Operator	5.0
Foreman	1.0
Lab Tech's etc	1.3

DICE GT-CRCC Operating Labor Requirements	**per Shift**
Skilled Operator	2.0
Operator	4.3
Foreman	1.0
Lab Tech's etc	1.0
TOTAL Operating Jobs	**16.6**

	Annual Cost $	$/kW-net
Annual Operating Labor Cost	$7,278,071	$93.37
Maintenance Labor Cost	$2,636,417	$33.82
Administration & Support Labor	$2,478,622	$31.80
Property Taxes and Insurance	$8,447,741	$108.37
TOTAL FIXED OPERATING COSTS	**$20,840,851**	**$267.36**

VARIABLE OPERATING COSTS

					$	$/MWh-net
DICE GT-CRCC Plant Maintenance Material Cost					**$3,954,626**	**$6.81**
Coal Beneficiation Plant Maintenance Cost					**$2,043,113**	**$3.52**

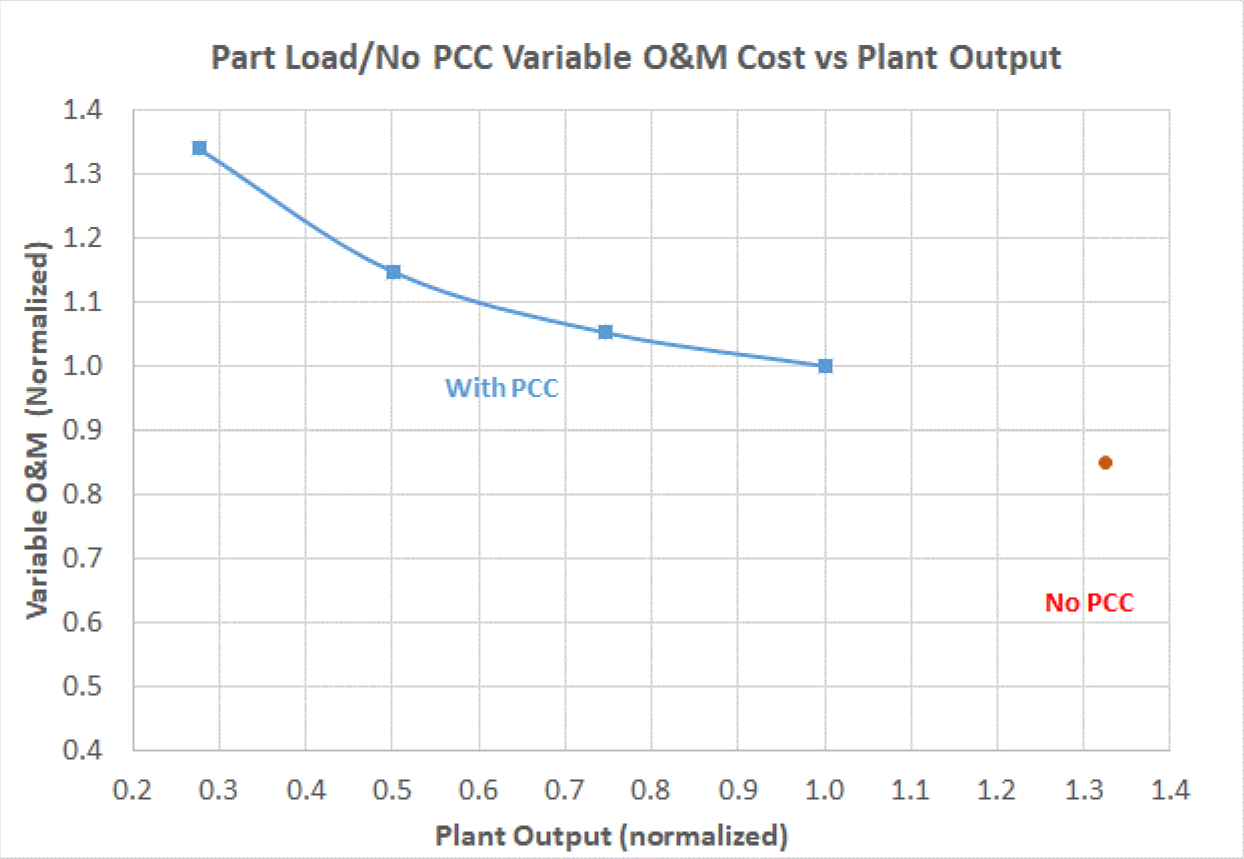
Consumables	Consumption Initial	Consumption /Day	Unit Cost	Initial Fill Cost	$	$/MWh-net
Water(/1000 gallons)	0	902	1.90	**$0**	**$531,901**	**$0.92**
Chemicals						
MU & WT Chem (ton)	0	3.87	550.00	$0	$660,221	$1.14
MIBC Frother (ton)	0	1.1	4082	$0	$1,332,000	$2.29
Collector (diesel) (gal)	0	315	2.50	$0	$244,386	$0.42
Flocculant (ton)	0	0.2	2948.38	$0	$168,350	$0.29
Lube Oil for DICE					$468,979	$0.81
SCR Catalyst (ft2)	0	0.43	150.00	$0	$19,815	$0.03
Ammonia (19% NH3) (ton)	0	0.18	300.00	$0	$16,615	$0.03
NaOH (tons)		16.3	300.00	$0	$1,515,531	$2.61
Carbon (Mercury Removal) (ton)	0	0.1	1600.00	$0	$64,871	$0.11
MEA Solvent (ton)	279	3.8	2721.80	$759,280	$3,208,156	$5.53
Corrosion Inhibitor				$0	$339,454	$0.58
MEA Reclaimer Additive (ton)		3.8	181	$0	$212,436	$0.37
Lean Amine Carbon Filter Package (lb)	6723	242	1.2	$8,336	$93,113	$0.16
Pre- and Post- Cartridge Filter (ea)	2	0.04	6964	$13,928	$77,784	$0.13
Subtotal Chemicals				**$781,544**	**$8,421,712**	**$14.51**
Waste Disposal:						
Coal Beneficiation Slurry Reject	0	2054	38.00	$0	$24,213,934	$41.72
Fly Ash (ton)	0	12.1	38.00	$0	$143,069	$0.25
PCC Thermal Reclaimer Waste	0	3.8	38.00	$0	$44,492	$0.08
Subtotal Waste Disposal				**$0**	**$24,401,495**	**$42.04**
TOTAL VARIABLE OPERATING COSTS				**$781,544**	**$39,352,846**	**$67.80**
FUEL COSTS						
PRB Coal (ton)	**0**	**1786**	**38.21**	**$0**	**$21,170,246**	**$36.47**
Diesel (gal)	**0**	**238**	**2.50**	**$0**	**$184,471**	**$0.32**
Natural Gas (MMBtu)	**0**	**5743**	**4.42**	**$0**	**$7,875,770**	**$13.57**
TOTAL FUEL COSTS				**$0**	**$29,230,487**	**$50.36**
TOTAL VARIABLE OPERATING + FUEL COSTS					**$68,583,333**	**$118.16**

2.3 OPERATION & MAINTENANCE (O&M) COSTS AT TURNDOWN (PART LOAD) CONDITIONS

The variable O&M costs associated with the plant part load operating conditions are shown in Figure 2-1. These costs include the consumables (water, chemicals and catalysts), waste disposal, and fuel costs, while excluding fixed O&M costs associated with operating and maintenance labor costs, as well as maintenance material costs. These are reported on a normalized basis. For reference purposes, the variable operating cost associated with the base case of 5 DICE with PCC is $100.7/MWh.

The horizontal axis indicates the part load variable O&M cost expressed as a fraction of the full load (5 DICE, with PCC) net output, and is based on an operational range of two DICE through the maximum of all five DICE. The right-most point on the graph shows the variable O&M cost of the plant when the PCC is not in service and steam is routed to a condensing turbine to generate additional power instead of the PCC reboiler.

Figure 2-1
DICE CRCC Part Load Variable O&M Costs



Section 3 Estimated Levelized Cost of Electricity and Sensitivity Analysis

3.1 DESIGN LEVELIZED COST OF ELECTRICITY (LCOE)

Based on the overall performance, TOC, and annual operating cost of the 100 MWe DICE CRCC plant, its levelized cost of electricity (LCOE) was estimated to be $223.9/MWh. The LCOE was estimated based on the methodology established in the previously submitted Design Basis Report. The parameters used in estimating the LCOE are summarized in Table 3-1.

Table 3-1
LCOE Parameters and Cost Breakdown

Plant	**DICE CRCC**
Size	**78 MWe**
Capacity Factor (CF)	**85%**
Years of Construction	**3**
Total As-Spent Cost/Total Overnight Cost Ratio	**1.093**
Fixed Charge Rate (FCR)	**0.0707**
Total Overnight Cost (TOC), $MM	525
Total As-Spent Cost (TASC), $MM	574
Fixed Operating Cost, $MM/yr	20.8
Variable Operating Cost @ 100% CF, $MM/yr	46.3
Fuel Cost @ 100% CF, $MM/yr	34.4
Annual 1000 MWh (100% CF)	683
LCOE (excl. CO_2 T&S), $/MWh	**223.9**
LCOE Breakdown, $/MWh	
Fuel (incl. coal beneficiation)	50.4
Variable O&M	67.8
Fixed O&M	35.9
Capital Charges	69.9
Total LCOE, $/MWh	**223.9**

Note: 3 year construction for DICE CRCC is consistent with NGCC construction period assumption as used by NETL in its reference reports. TASC/TOC ratio used for LCOE evaluation for such 3-year capital projects is 0.0707

3.2 LCOE OF POTENTIAL VARIANTS

3.2.1 No Post-Combustion Capture

Implementing post-combustion capture (PCC) to the DICE CRCC system imposes a significant penalty on its efficiency, capital cost, and operating cost, thereby resulting in a high LCOE. A parametric scenario without PCC was evaluated to quantify the performance and cost impact. For this parametric case, exhaust steam from the main steam turbine that would have been diverted to the PCC is sent to a condensing turbine to produce more power, resulting in greater power generation from the steam cycle. As shown in the Performance Results Report of this pre-FEED study, eliminating PCC results in a 35 percent increase in net power generation. The calculated efficiency of this case is 39.9 percent on an LHV basis (37.7 percent HHV).

3.2.2 Centralized Coal Beneficiation Plant

For a small, modular power plant such as the DICE CRCC (< 100 MW for this introductory variant), the performance and cost estimates presented in previous reports suggest that it makes no economic sense to install a coal beneficiation plant on-site, analogous to building a crude oil refinery on-site at every gas station. For the modular DICE CRCC plant to be feasible, there must be multiples of such power plants, each receiving fuel from a centralized coal beneficiation plant, thereby taking advantage of the economies-of-scale benefits that the large central beneficiation plant possesses.

A parametric case was run to denote the ideal future deployment of the DICE CRCC technology. This case utilizes a centralized coal beneficiation plant which distributes beneficiated coal to the multiple small-scale DICE CRCC power plants in operation. The performance of this plant was presented in the Performance Results Report, which was estimated by eliminating all auxiliary loads and utilities associated with the coal beneficiation plant. The gross power remains the same as the on-site beneficiation case but the auxiliary power is reduced by about 10.5 percent or 5 MW. The net power increases similarly by 5 MW, or a 7 percent increase. The estimated efficiency for this case is 32.7 percent LHV (31.0 percent HHV).

3.2.3 LCOE Estimates of Variants

Table 3-2 presents the summary comparison of the capital costs, operating costs, and LCOE breakdown of the DICE CRCC plant with and without PCC, and the envisioned "ideal" DICE plant that receives coal feed from a centralized coal beneficiation plant.

Table 3-2
Performance and LCOE Summary Comparison for DICE CRCC Parametric Cases

Plant	DICE CRCC No PCC	DICE CRCC with PCC (on-site beneficiation)	Ideal DICE CRCC with PCC (centralized beneficiation)
Size	**105 MWe**	**78 MWe**	**83 MWe**
Plant Efficiency, LHV	**39.9%**	**30.8%**	**32.7%**
Plant Efficiency, HHV	**37.7%**	**29.1%**	**31.0%**
Capacity Factor (CF)	**85%**	**85%**	**85%**
Total Overnight Cost (TOC), $MM	433	525	450
TOC, $/kW	4,123	6,732	5,558
Total As-Spent Cost (TASC), $MM	474	573	492
Fixed Operating Cost, $MM/yr	17.6	20.8	15.2
Variable Operating Cost @ 100% CF, $MM/yr	40.8	46.3	13.4
Fuel Cost @ 100% CF, $MM/yr	35.8	34.4	33.7
Annual 1000 MWh (100% CF)	921	683	726
LCOE (excl. CO_2 T&S), $/MWh	**148.6**	**223.9**	**145.7**
LCOE Breakdown, $/MWh			
Fuel (incl. coal beneficiation)	38.9	50.4	46.4
Variable O&M	44.4	67.8	18.4
Fixed O&M	22.5	35.9	24.6
Capital Charges	42.8	69.9	56.4
Total LCOE, $/MWh	**148.6**	**223.9**	**145.7**

For the case without PCC, the capital costs and operating costs associated with the PCC were eliminated in the parametric cost analysis. The resulting TOC is about 18 percent lower at $433MM. The fixed operating cost is about 15 percent lower while the variable operating cost is 12 percent lower, primarily because the amine make-up requirement, the largest PCC variable cost contributor, has been eliminated. Fuel cost is slightly higher due to the higher natural gas consumption requirement in the supplementary fired HRSG in order to raise the steam quality such that it is suitable for the condensing turbine downstream of the HRSG.

The DICE CRCC plant without PCC has an LCOE of $148.6/MWh, or 66 percent of the same plant with PCC. Essentially, adding the PCC plant to capture 90 percent of the CO_2 in the DICE CRCC flue gas increases its cost of electricity by 50 percent.

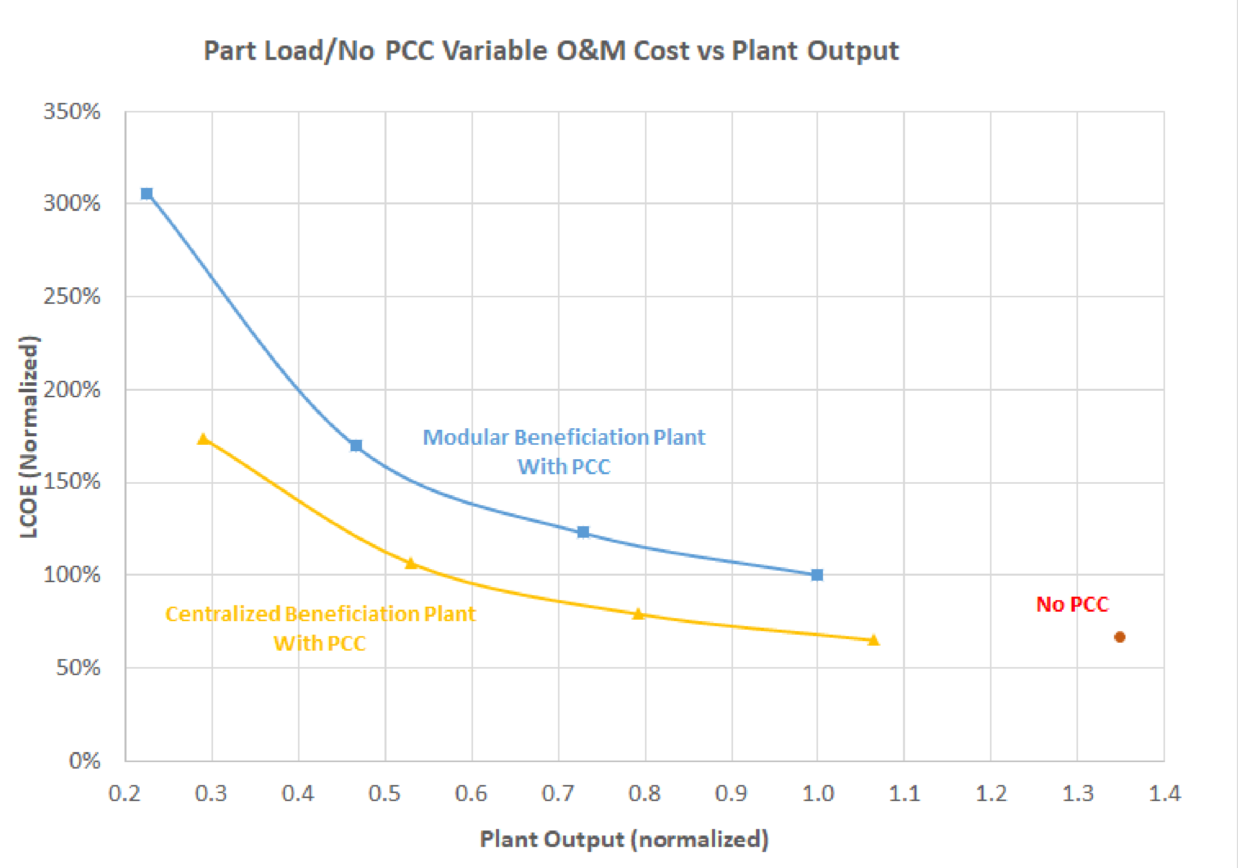
For the ideal DICE CRCC plant, the capital and operating costs associated with the modular coal beneficiation plant were eliminated in the analysis. The resulting TOC is 14 percent lower at $450MM. Fixed operating cost is about 27 percent lower due to the much lower staffing requirement as a result of eliminating the labor-intensive on-site beneficiation plant. In terms of fuel cost, the beneficiated coal cost was estimated to be $4.3/MMBtu, in line with CSIRO's estimates from **DICEnet** literature, and the resulting fuel cost, at $33.7MM/yr, is about 2 percent lower than the base case. Additionally, the variable operating cost is significantly reduced as there are no reject tailings to dispose of on-site since the plant uses beneficiated coal directly. Elimination of the tailings slurry waste disposal operating cost results in a 71 percent reduction in variable operating cost.

The ideal DICE CRCC plant using coal received from a centralized beneficiation plant and with 90 percent CO_2 capture has a more reasonable LCOE of $145.7/MWh, or about 65 percent of the base case plant with on-site beneficiation.

3.3 LCOE AT TURNDOWN CONDITIONS

The LCOEs associated with the plant part load operating conditions are reported on a normalized basis in Figure 3-1 and includes the estimated part load conditions for a DICE CRCC plant receiving coal from a centralized coal beneficiation facility.

Figure 3-1
DICE CRCC Part Load LCOE



3.4 REFERENCE SUPERCRITICAL PC PLANT LCOE

For reference purposes, the cost and performance estimates of a conventional 650 MWe supercritical pulverized coal (SC PC) plant with CO_2 capture (Case B12B) from the most recent NETL Bituminous Baseline Report (BBR rev4) are shown in Table 3-3.

Table 3-3
Reference NETL 650 MWe SC PC Plant Performance and Cost Summary

Plant	**SC PC (NETL)**
Size	**650 MWe**
Gross Power Production, MWe	**770**
Total Auxiliaries, MWe	**120**
Net Efficiency, HHV	**31.5%**
, LHV	**32.7%**
Capacity Factor (CF)	**85%**
Years of Construction	**5**
Total As-Spent Cost/Total Overnight Cost Ratio	**1.154**
Fixed Charge Rate (FCR)	**0.0707**
Total Overnight Cost (TOC), $MM	3,023
TOC, $/kW	4,654
Total As-Spent Cost (TASC), $MM	5,372
Fixed Operating Cost, $MM/yr	78.1
Variable Operating Cost @ 100% CF, $MM/yr	79.7
Fuel Cost @ 100% CF, $MM/yr	137.3
Annual 1000 MWh (100% CF)	5,694
LCOE (excl. CO_2 T&S), $/MWh	**105.3**
LCOE Breakdown, $/MWh	
Fuel (incl. coal beneficiation)	24.1
Variable O&M	14.0
Fixed O&M	16.1
Capital Charges	51.0
Total LCOE, $/MWh	**105.3**

While the base case DICE CRCC plant has almost double the LCOE of that of a conventional 650 MW SC PC with CO_2 capture, it utilizes the modular coal beneficiation plant, oft-repeated in this report to be not cost-competitive. With the centralized beneficiation plant variant, the DICE CRCC plant's LCOE is reduced to $145.7/MWh. While still almost 40 percent higher than the SC PC plant, it is important to note that the SC PC plant's LCOE is for a base-loaded, 650 MWe plant, with huge economy-of-scale benefits compared to that of the modular DICE CRCC plant.

A comparable modular SC PC plant generating 78 MW net was estimated based on the performance and cost estimates for the reference plant and the results are shown in Table 3-4. The TOC for this modular 78 MWe plant was estimated by scaling the costs using a capacity factor exponent of 0.7 to arrive at 3,023 x $(78/650)^{0.7}$ = $685 million. The same exponent of 0.7 was used to calculate the modular plant's fixed operating cost.

Variable and fuel costs were estimated by pro-rating the consumptions for 78 MW of net power generation, assuming that the plant net efficiency remains the same, while maintaining the same unit costs. The resulting LCOE of this plant is $164.9/MWh, which is 13 percent higher than the DICE CRCC plant burning beneficiated coal from a centralized facility.

Table 3-4
Scaled Modular 78 MWe SC PC Plant Performance and Cost Summary

Plant	**Modular SC PC**
Size	**78 MWe**
Net Efficiency, HHV	**31.5%**
, LHV	**32.7%**
Capacity Factor (CF)	**85%**
Years of Construction	**5**
Total As-Spent Cost/Total Overnight Cost Ratio	**1.154**
Fixed Charge Rate (FCR)	**0.0707**
Total Overnight Cost (TOC), $MM	685
TOC, $/kW	8,786
Total As-Spent Cost (TASC), $MM	791
Fixed Operating Cost, $MM/yr	17.7
Variable Operating Cost @ 100% CF, $MM/yr	9.6
Fuel Cost @ 100% CF, $MM/yr	16.5
Annual 1000 MWh (100% CF)	683
LCOE (excl. CO_2 T&S), $/MWh	**164.9**
LCOE Breakdown, $/MWh	
Fuel (incl. coal beneficiation)	24.1
Variable O&M	14.0
Fixed O&M	30.4
Capital Charges	96.3
Total LCOE, $/MWh	**164.9**

3.5 SENSITIVITY ANALYSIS

3.5.1 Coal Beneficiation Yield

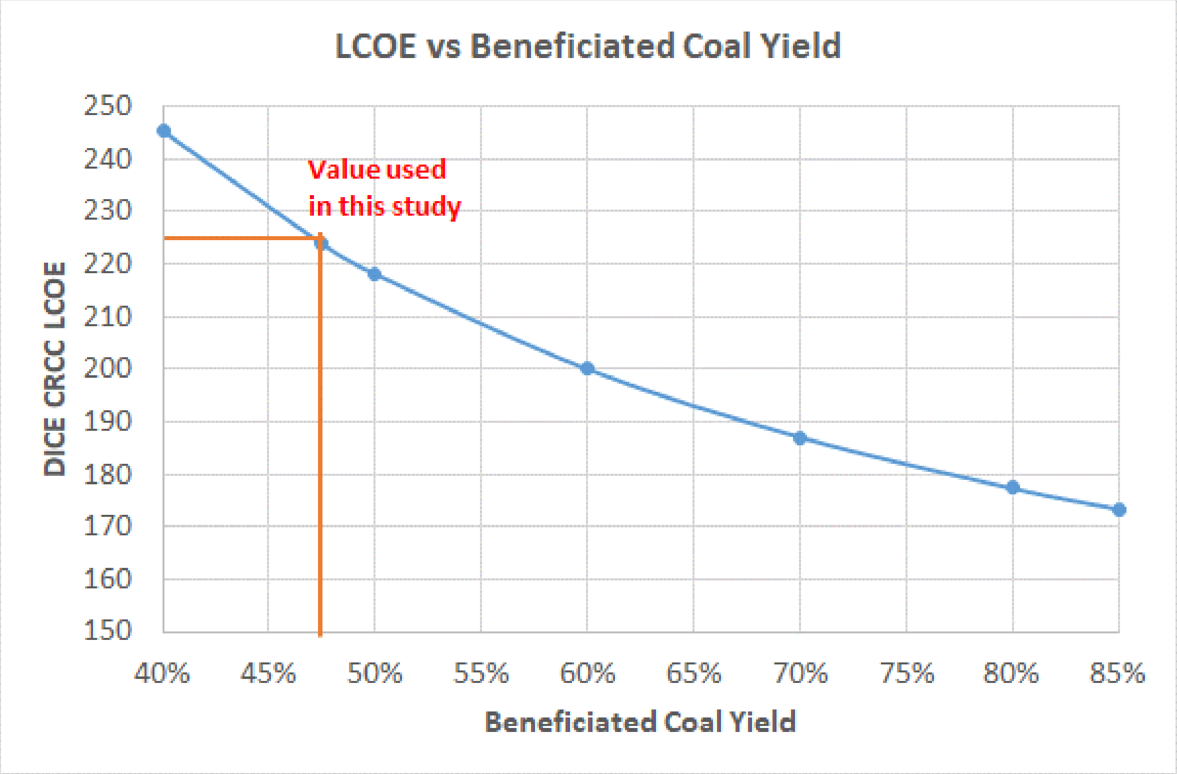
Based on Section 2.1.2, the beneficiated coal product yield from the as-received PRB coal is only 47.5 percent on a mass basis. Sedgman, the coal beneficiation process OEM, has indicated that its experience with low rank bituminous coal with high inherent moisture levels such as PRB shows that they are not amenable to upgrading with conventional coal flotation reagents, due to the high inherent moisture rendering the coal particle surface hydrophilic. It can thus be concluded that the design PRB coal used in this study was not an ideal choice for the beneficiation process.

Additionally, beneficiated product yield is inversely proportionate to its ash target. The relatively low ash target of 2 percent thus renders its low yield based on Sedgman's experience. A more ideal choice would therefore be a hydrophobic coal such as a bituminous coal with low inherent moisture and low ash content. Nevertheless, Sedgman acknowledged that the stated product recovery rate was on the conservative end and the actual yield could potentially be higher.

A sensitivity analysis was conducted to determine the impact of the coal beneficiation yield on the DICE CRCC plant LCOE, with a product recovery rate ranging from 40 percent to 85 percent. The high end of the recovery rate can be justified by using a coal that is more amenable to upgrading as well as a more developed DICE that can potentially tolerate higher ash beneficiated coal.

Figure 3-2 illustrates the relationship between the DICE CRCC plant LCOE and coal beneficiation yield. The effect of a larger beneficiation yield is twofold. First, a higher recovery rate leads to less as-received coal feed required for the process, resulting in a lower fuel cost. Second, the tailings reject rate is also reduced since more of the coal is recovered as product, thus reducing the waste disposal cost. At the most optimistic recovery rate of 85 percent beneficiated coal product yield, the plant LCOE is estimated to be $173/MWh.

Figure 3-2
Plant LCOE vs Beneficiated Coal Yield



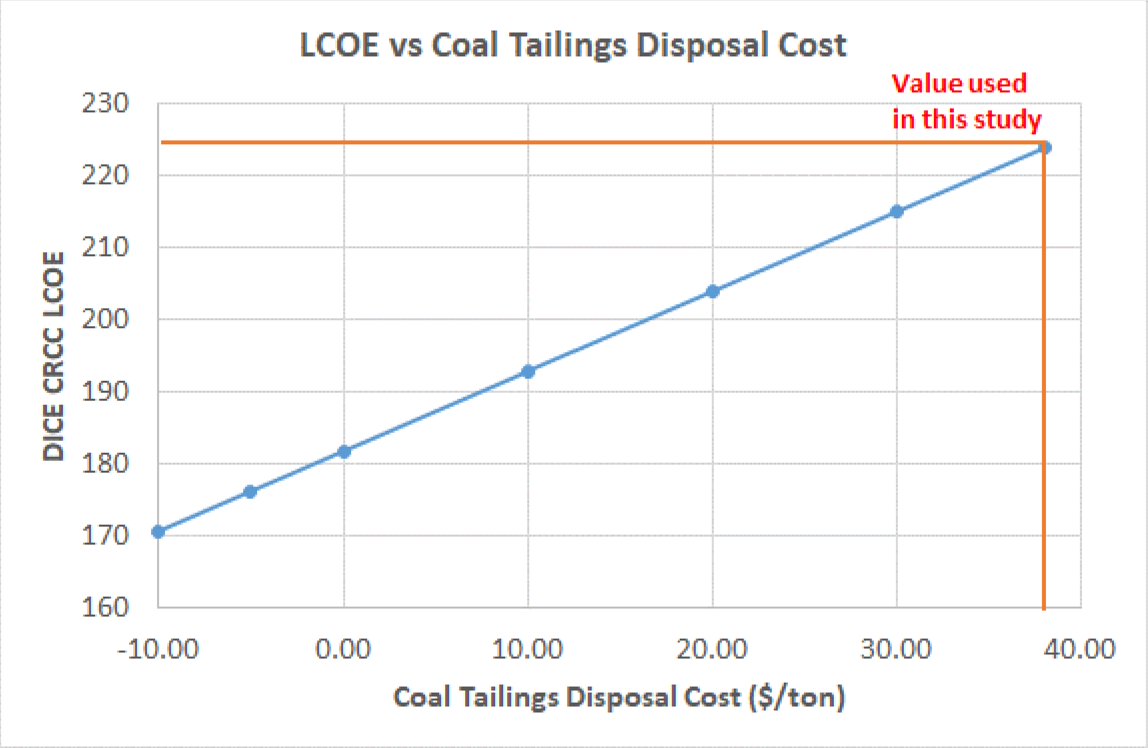
3.5.2 Beneficiation Process Reject Disposal

The current study assumes that the coal tailings from the beneficiation process have no market value and have to be disposed at the full-on disposal cost of $38/ton. However, the tailings still contain significant heating value, as much as the product itself, albeit with higher ash content and in the form of a slurry. Its quality is actually comparable to that of lignite coals found in the Gulf Coast region, which have heating values as low as 4,000 Btu/lb, and moisture contents as high as 55 percent). It could therefore be potentially useful as a fuel for slurry-based gasification or for combustion after suitable processing (e.g. briquetting). Additionally, research has shown that such wastes can be used as a material for filling abandoned workings in mines or to seal surface stockpiles. Post-flotation wastes from beneficiation of coking coals with calorific value more than 5,000 kJ/kg can be used as fuel for the production of building construction ceramics, and after further beneficiation as an additive to energy fuel.

For this sensitivity analysis, a disposal cost range of -$10/ton to $38/ton was used. The former assumes that the tailings are a marketable byproduct with a free on board (FOB) price of $10/ton, or about $1.4/MMBtu. The latter simply assumes that there is no market for this product, and it must be disposed of at the full-on disposal cost of $38/ton per the base case.

Figure 3-3 depicts how the DICE CRCC plant LCOE varies with the coal beneficiation tailings disposal cost. Due to the large quantity of rejects generated by the coal beneficiation plant, the LCOE is sensitive to the disposal cost, ranging from $169/MWh when the tailings are considered most valuable to $222/MWh when they have no value and the full disposal cost has to be paid.

Figure 3-3
Plant LCOE vs Coal Tailings Disposal Cost

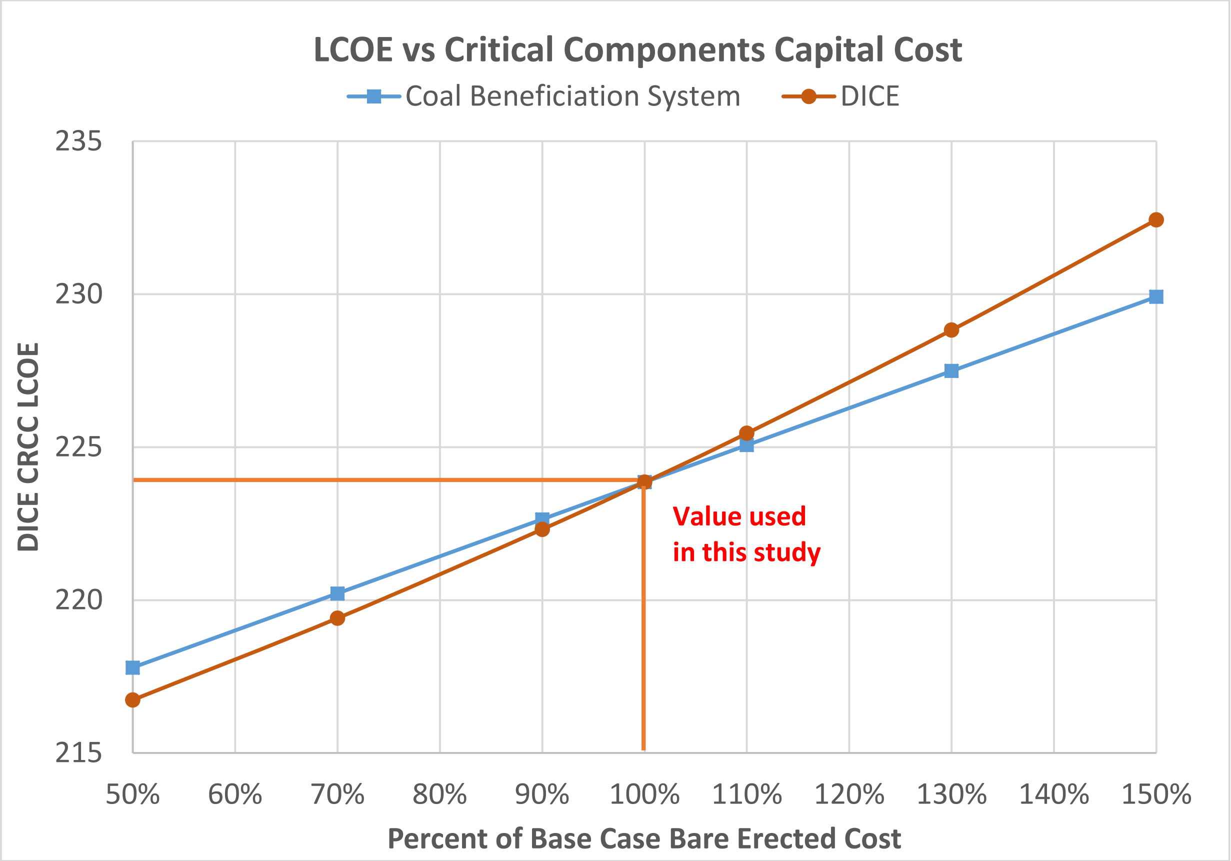


3.5.3 DICE and Coal Beneficiation Plant Capital Cost

The two components considered most critical to the DICE CRCC plant's success are the DICE itself and the coal beneficiation plant. A sensitivity analysis was therefore conducted to determine the variation of the plant's LCOE on the capital costs of these components. A range of +/- 50 percent from the baseline cost estimate was assumed for both systems and the results are shown in Figure 3-4.

From Figure 3-4, it can be concluded that the capital cost variation for both the DICE and coal beneficiation plant causes similar impacts on the LCOE. This is not surprising since, as shown in Table 1-2, the DICE and coal beneficiation plants have similar costs at around $60 MM on a total plant cost basis.

Figure 3-4
Plant LCOE vs Coal Beneficiation Plant and DICE Bare Erected Cost



3.5.4 Equivalent Beneficiated Coal Cost

As described in Section 3.2.2, there is no economic sense in installing a coal beneficiation plant on-site at every modular DICE CRCC power plant. This is somewhat analogous to appending an oil refinery to each fuel oil-fired power generation facility (they rarely exist anymore, at least in the developed world, but makes the point). For the modular DICE CRCC plant to be feasible, there must be multiples of such power plants, each receiving fuel from a centralized coal beneficiation plant to take advantage of its inherent economies-of-scale advantages.

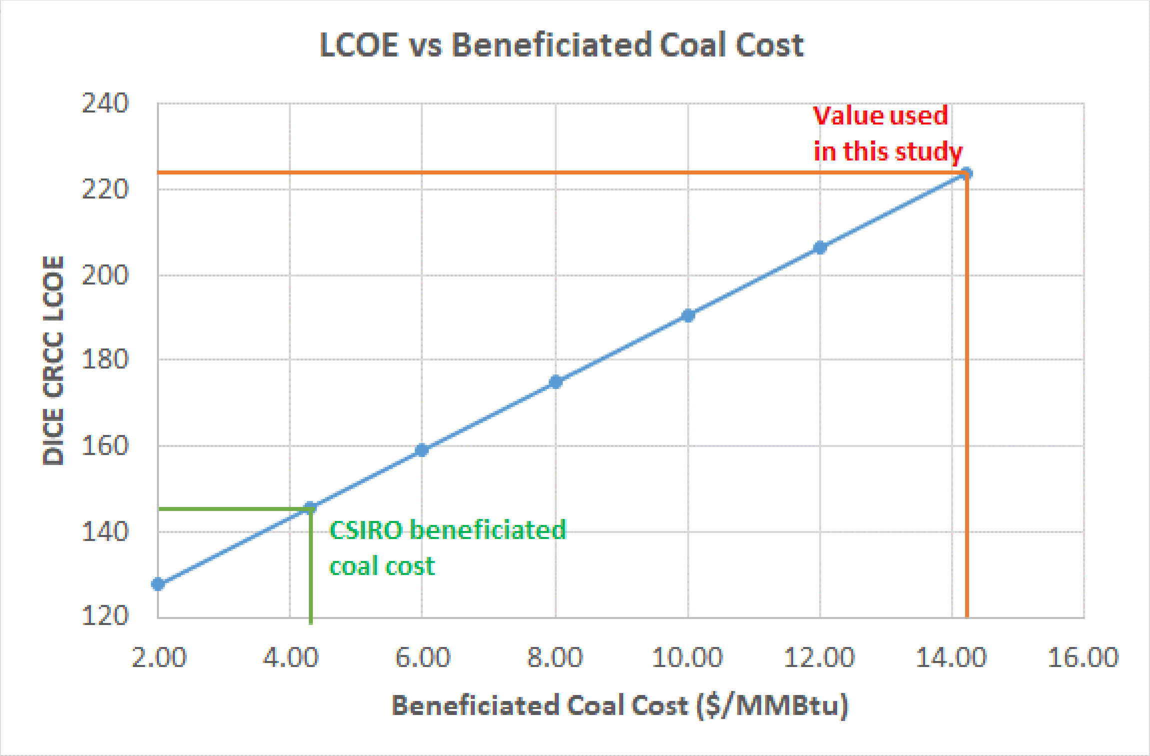
For the base case, an “equivalent beneficiated coal cost” was determined on a $/ton basis. This was calculated by eliminating all auxiliary power and capital and operating costs associated with the on-site coal beneficiation plant. After removing all coal beneficiation related costs and utilities, the coal cost was back-calculated on a “net-back” basis to arrive at the original LCOE of $223.9/MWh. This equivalent beneficiated coal cost was calculated to be $14.2 per MMBtu (HHV), compared to the original PRB coal price of $2.23 per MMBtu (HHV) based on the $38.2/ton cost. This represents a more than 6-fold increase in coal cost due to the modular, economically disadvantaged coal beneficiation plant.

Based on CSIRO’s research involving Australian coals, it has been suggested that the cost of beneficiated coal is about AUD 6/GJ (USD 4.3/MMBtu), so a cost of USD 14.2/MMBtu of beneficiated coal in the baseline case is therefore unrealistically high.

A sensitivity analysis was conducted to determine the impact of the beneficiated coal cost on the DICE CRCC plant LCOE, using a range of beneficiated coal costs from $2/MMBtu (essentially no associated beneficiation costs) to the current calculated value of $14.2/MMBtu.

Figure 3-5 plots the variation of LCOE against beneficiated coal cost. Clearly, this cost has an extremely large impact on the economic performance of the DICE CRCC plant. With the modular beneficiation plant resulting in a cost of $14.2/MMBtu of beneficiated coal, the baseline plant’s LCOE stands at $223.9/MWh. However, if this cost was reduced to $4.3/MMBtu per CSIRO’s estimates, with a path toward achieving this via a centralized beneficiation plant, then the LCOE could be reduced to a much more reasonable $145.7/MWh.

Figure 3-5
Plant LCOE vs Beneficiated Coal Cost

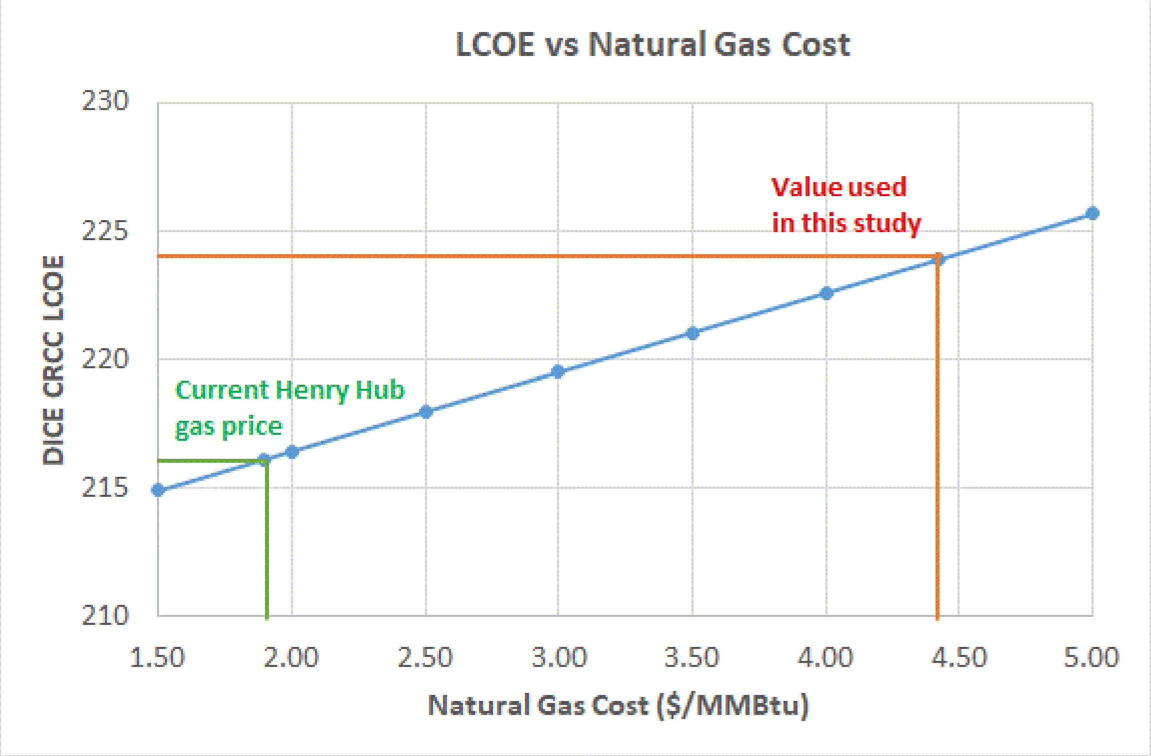


3.5.5 Gas Pricing

For this study, a levelized natural gas price of $4.42/MMBtu (HHV) for delivery to the Midwest was used in the operating cost analysis, which is consistent with that used in the most recent DOE Bituminous Baseline Report (rev 4, 2019). Natural gas delivered to power plants in the Midwest was estimated to be about the same price as those delivered to the Texas area, based on DOE's most recent QGESS Fuel Pricing document. However, it is noted that current Henry Hub gas prices is only about $1.9/MMBtu, so the assumed cost of $4.42/MMBtu (HHV) may be too high.

A sensitivity analysis on gas pricing is therefore conducted to determine its impact on the DICE-GT CRCC LCOE, using a range of $1.5/MMBtu to $5/MMBtu. At the current Henry Hub natural gas pricing of $1.9/MMBtu (HHV)[1], the estimated LCOE is reduced to $216/MWh.

Figure 3-6
Plant LCOE vs Natural Gas Cost



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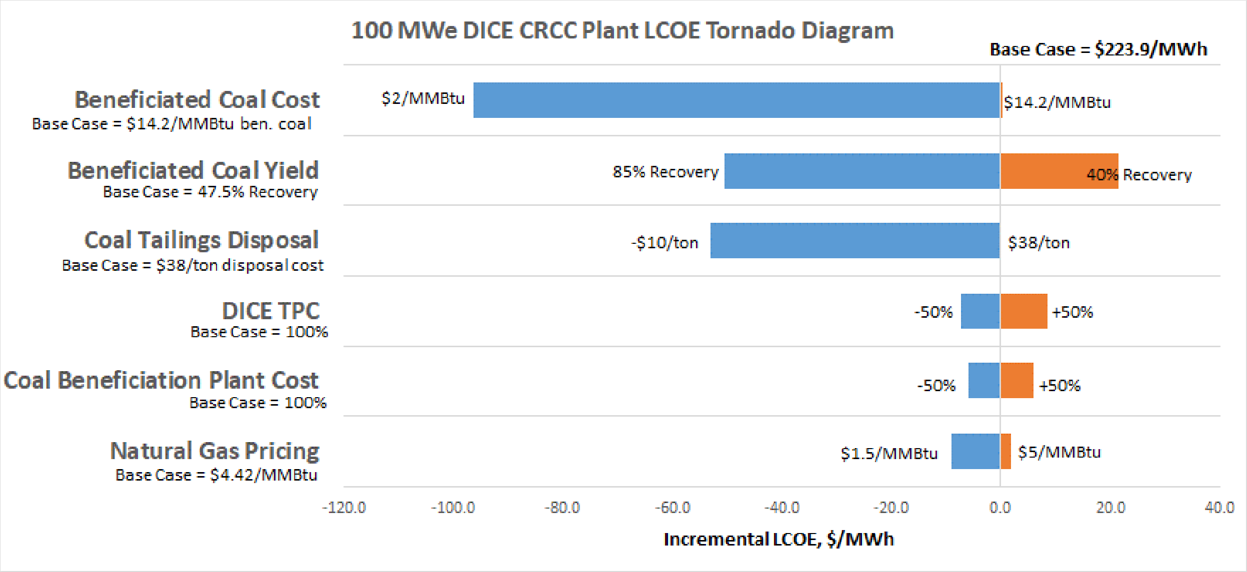
[1] Henry Hub Natural Gas Spot Price was 1.89 USD/MMBtu for Mar 17 2020 https://ycharts.com/indicators/henry_hub_natural_gas_spot_price.

3.5.6 Tornado Chart

Figure 3-7 depicts the tornado chart that provides both a ranking and measure of magnitude of the impact that each of the parameters described above has on the LCOE. It is clear from this figure that the LCOE is most sensitive to the performance and cost of the coal beneficiation plant. It would therefore be most beneficial to the DICE CRCC technology if there was a centralized coal beneficiation plant with maximum economy-of-scale that also maximizes the yield of the beneficiation process (which simultaneously minimizes the tailings to be disposed of), thus reducing the beneficiated coal cost to be delivered to the modular DICE CRCC plant.

Figure 3-7
LCOE Tornado Chart



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Coal-Fired Direct Injection Carbon Engine (DICE) Compound-Reheat Combined Cycle (CRCC)

Contract No. 89243319CFE000025

Coal-Based Power Plants of the Future

Appendix A: Project Execution Plan Presentation

Contents

1. Project Structure and Framework

In the present situation, DICE (“Product”) is an integral part of DICE CRCC (“Project”), a novel concept, requiring development of key components

The development of DICE (“Product”), which is an integral part of a DICE CRCC power plant (“Project”), is presented. The DICE CRCC consists of fuel preparation and post-combustion capture (PCC) blocks which is actually a “Project within a Project”. This presentation provides the Project Structure and Framework:

- **DICE CRCC**[1] is a novel power plant concept for burning a coal-based fuel
- While there is a ***need*** for a small, modular and flexible power plant to burn coal efficiently and cleanly
- There is no readily identifiable market **demand** for it (in the USA and other developed countries)
- Coal as a power generation fuel has a negative image
- Major engine OEMs do not plan to invest in this technology
- There is ongoing research in DICE technology (CSIRO in Australia)
- In cooperation with Chinese engine manufacturer (licensee not an original OEM)

[1] *DICE-Gas Turbined Compound Reheat Combined Cycle (Direct Injection Carbon Engine – i.e., coal-fired diesel engine)*

PEP covers prerequisites and acquisitions which are based on key technology innovation, market opportunity, specific components, and development

- Under the light of the present situation stated above, the following **Project Execution Plan (PEP)** is based on following prerequisites and assumptions:
- A new and positive image for coal (already so in Asia – opens up the door to US technology export)
- Market opportunity to entice major engine OEMs into their own R&D and/or cooperation with third-party component R&D organizations (e.g., CSIRO in Australia)
- Fuel injection system basic design already complete
- Customer identified
- Site selection and logistics in place

This PEP is exclusively prepared for the DICE component of the DICE CRCC

PEP addresses key prerequisites and acquisitions related to DICE technology, fuel preparation, and differentiates steps which required additional R&D

- Coal feedstock selection – current preferred study is using PRB coal, which is not the ideal feedstock for widespread deployment of the DICE technology (difficult to store, spontaneous combustion)
- Fuel preparation technology in place (which is predicated upon selected coal feedstock)
  - Grinding/micronizing
  - Washing/cleaning
  - Stabilization
  - Storage
- These steps do not require R&D ***per se*** (they are not identified as ***technology gaps***)
- However, a careful front-end study is needed to settle on these two items before proceeding with the power project

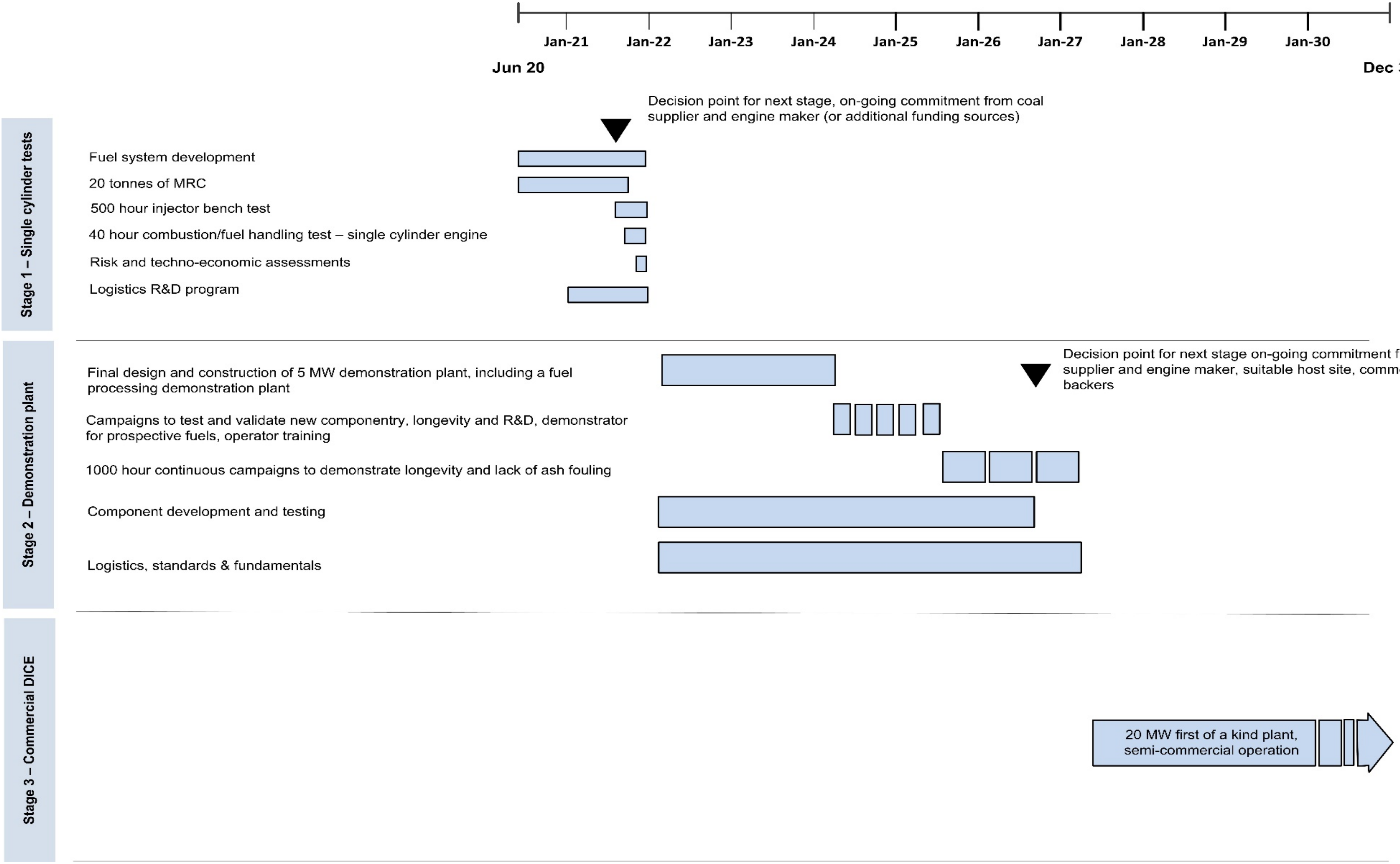
Project overview focuses on the scope related to DICE, key objectives, project execution strategy, permitting, cost and schedule, and other related areas

- Client and Project: TBD
- Contract Basis and Terms: TBD
- Scope of Work: Design, development and manufacturing of a **Direct Injection Carbon Engine (DICE)**
- Project Objective: Delivery of multiple DICE with requisite BOP ready for installation on DICE CRCC construction site (“The Product”)
- Project Execution Strategy
- Project Cost and Schedule

DICE product development pathway requires definitive focus on identifying key OEMs, business case to OEMs, building test facility and risk review

- Should be already in place
  - Fuel selection and assessment
  - Fuel supply secured
  - Basic fuel design completed
- “Piggyback” on existing work (DOE and others)
- Identification of key OEMs
  - Stock engine
  - Fuel injector
- Business case made to the OEMs
- Forming a consortium with an OEM
- Building a test facility
- Test campaign
- Risk review

DICE PEP timeline covers a phased 10 year period leading to a semi-commercial DICE plant by 2030



Jan-21 Jan-22 Jan-23 Jan-24 Jan-25 Jan-26 Jan-27 Jan-28 Jan-29 Jan-30

Jun 20

Dec 30

Stage 1 – Single cylinder tests

Decision point for next stage, on-going commitment from coal supplier and engine maker (or additional funding sources)

- Fuel system development
- 20 tonnes of MRC
- 500 hour injector bench test
- 40 hour combustion/fuel handling test – single cylinder engine
- Risk and techno-economic assessments
- Logistics R&D program

Stage 2 – Demonstration plant

- Final design and construction of 5 MW demonstration plant, including a fuel processing demonstration plant
- Campaigns to test and validate new componentry, longevity and R&D, demonstrator for prospective fuels, operator training
- 1000 hour continuous campaigns to demonstrate longevity and lack of ash fouling
- Component development and testing
- Logistics, standards & fundamentals

Decision point for next stage on-going commitment from coal supplier and engine maker, suitable host site, commercial backers

Stage 3 – Commercial DICE

20 MW first of a kind plant, semi-commercial operation

Fuel development is expected take place concurrently as part of the Stage 1 test programs

2. Non-Commercial Component Development

Product definition of DICE covers engine block (cylinder liners, fuel injectors), air starter, fuel supply system, and other key components

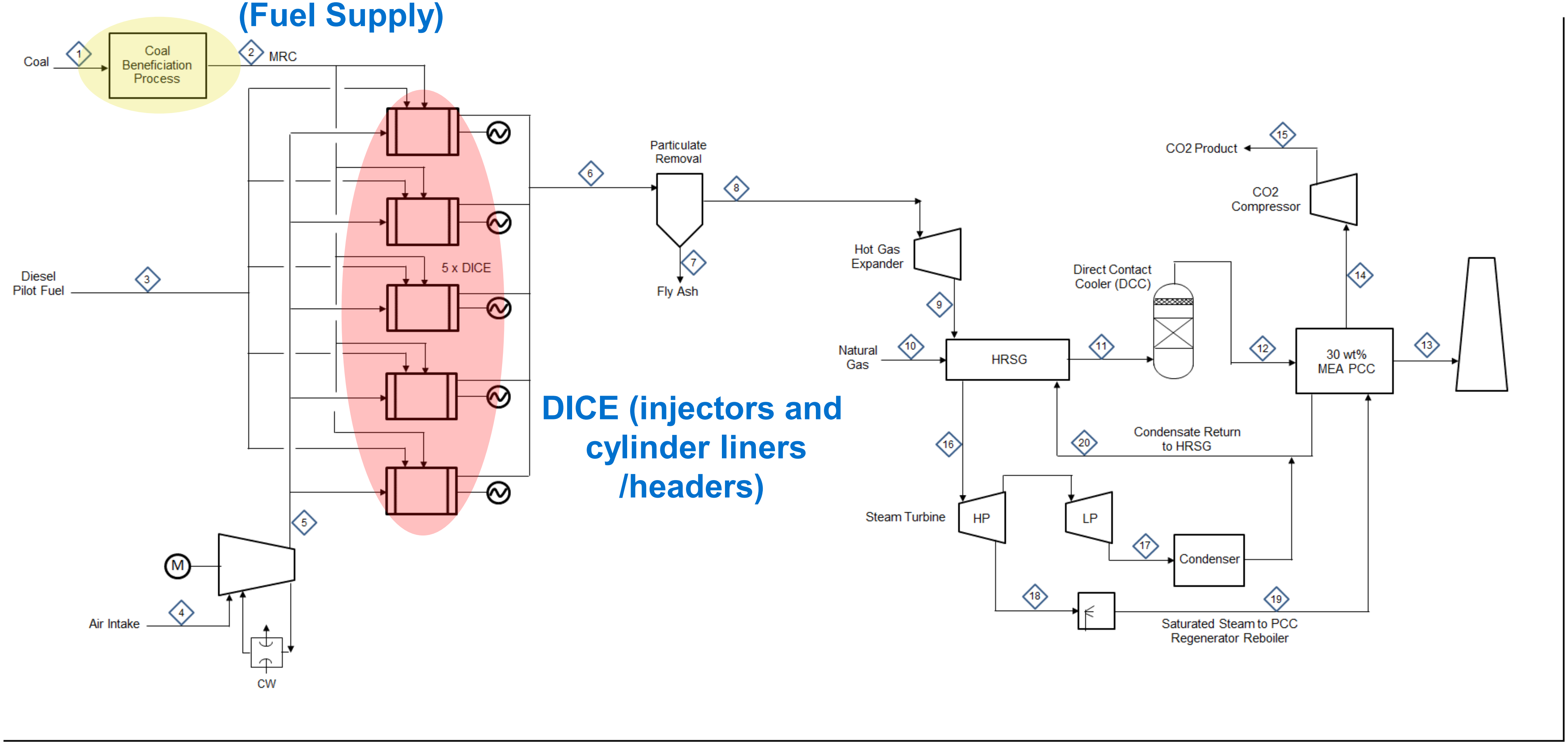
- The product is one DICE comprising
  - Multi-cylinder engine block
    - Crankshaft and main bearings
    - Pistons and connecting rods
    - **Cylinder liners and headers**
    - Valve train (camshaft w/ valves)
    - Flywheel
    - **Fuel Injectors**
  - Air starter
  - Synchronous a/c generator
    - Excitation system
    - Oil skid
    - Flexible coupling
  - Engine coolant system
  - Lube-oil system
  - **Fuel supply system**
  - Exhaust gas system
  - Control system

Majority of DICE product is “off-the-shelf” and there are other product components requiring R&D which consist of several key components

- The product is one DICE comprising
  - Multi-cylinder engine block
    - Crankshaft and main bearings
    - Pistons and connecting rods
    - **Cylinder liners and headers**
    - Valve train (camshaft w/ valves)
    - Flywheel
    - **Fuel Injectors**
  - Air starter
  - Synchronous a/c generator
    - Excitation system
    - Oil skid
    - Flexible coupling
  - Engine coolant system
  - Lube-oil system
  - **Fuel supply system**
  - Exhaust gas system
  - Control system

- To a great extent, “off-the-shelf”
- Several key components require R&D or further testing and validation

Overall DICE CRCC Process Flow Diagram



Coal Beneficiation System (Fuel Supply)

DICE (injectors and cylinder liners /headers)

● Components require R&D

● Components require testing and validation

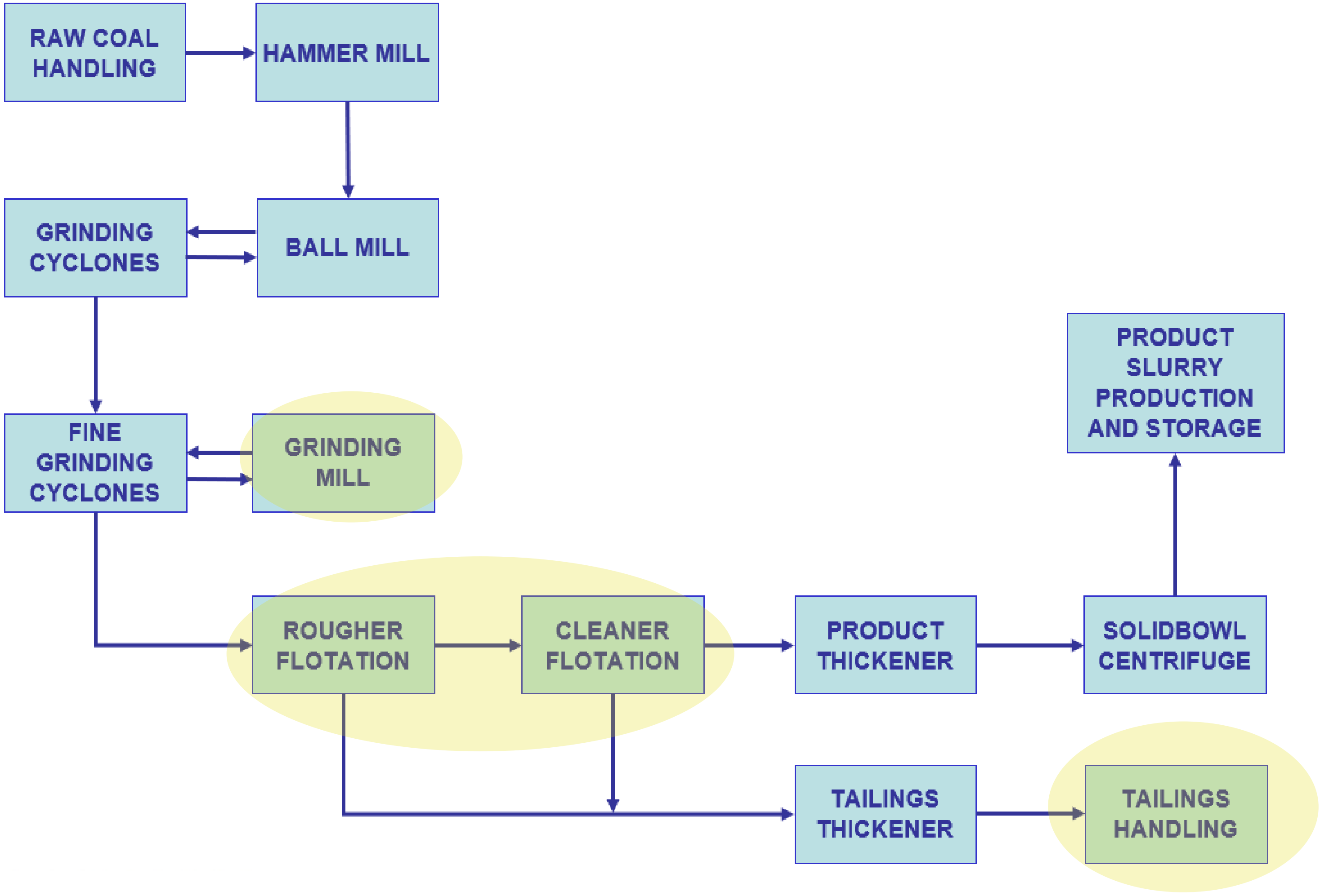
Technology gaps for the product only cover fuel-engine interactions, fuel injector design, combustion stability, exhaust valve wear, and fuel system

- Fuel-engine interactions
  - Special coatings to protect cylinder liners, headers and valves
- Fuel injector design
  - Air-blast atomizer
  - Atomizer nozzle longevity
- Combustion stability
  - Ignition delay
  - Diesel pilot
- Exhaust valve seat wear
- Fuel system design to eliminate blockage
  - Fouling
  - Corrosion

The DICE product R&D requirements which must be addressed consist of specific key components which require further advanced development efforts

- Engine atomizer development
- Ceramic materials development
- Injection configuration development
- Piston shape optimization
- Ducting optimization
- Fuel filtration

Coal Beneficiation Process Flow Diagram



- No components are technology gaps *per se* since each plant unit operation of the flowsheet is currently commercially available but application to coal is novel
- Testing opportunities on coal are limited (market-driven)

Further testing and development required on specific coal types for optimal yield and efficiency

- Fine grinding mill
  - Available technologies include impact and attrition mills
  - Selection of most suitable grinding technology depends on various factors
  - Factors include product size, feed size, energy consumption
- Ash Removal (via flotation)
  - Different flotation technologies available with different energy and reagent input requirements
  - Low ash concentration in product coal (2 wt% db) is a challenge
- Tailings Disposal/Utilization
  - No market value in slurry form
  - Additional energy/cost to process (dewatering, briquetting)
  - Function of product yield (< 50% for PRB coal)

Feed coal selection and development of centralized coal beneficiation plant are vital to success of DICE CRCC

- Feed coal selection
  - PRB coal shown to be not suitable in current pre-FEED study
  - Low product yield results in large as-received feed requirement and tailings for disposal
  - Bench-scale tests needed on various coals to establish and select feed with best available yield
- Centralized beneficiation plant
  - No economy of scale for modular beneficiation plant at every DICE CRCC plant
  - Centralized beneficiation plant maximizes capital and labor effectiveness
  - Need to consider product stability at delivery (slurrying process on-site?)
- Coordination with DICE OEM
  - Need to work in close coordination with DICE developer
  - Ash content, sulfur content, rheology, among other properties, need to be established between DICE and coal beneficiation developers
  - Intend to develop this coordination under DOE CoalFIRST Critical Components development program

Development Needs and Work Plan

- Feed coal analysis and selection
- Coal grain analysis
- Crushing and grinding test work
- Flotation tests
- Thickening and dewatering tests
- Rheology characterization
- Pilot plant operation

Details are provided in the report from coal beneficiation OEM Sedgman

3. Project Financing

Project financing assumptions for DICE–GT CRCC (Project) include TRL, equity, debt, and grants for pilot plant and a next-of-a-kind (NoaK) commercial plant

Key Project Finance Parameter	**Pilot Plant**	**NoaK[1] Commercial Operation Plant**	**Commentary**
Technology Readiness Level (TRL) [2]	5 to 6	9	▪ TRL assumes pilot project will be pre-demonstration phase and beyond bench-scale unit ▪ TRL for NoaK assumes advanced commercialization of technology and market ready for deployment
Type of Project Financing	Not Applicable	Limited Recourse or Non-Recourse	▪ Limited recourse wherein NoaK project assets are mortgaged or hypothecated or collateralized to lenders ▪ Non-recourse wherein NoaK project's EBITDA and cash flows provide debt service coverage (DSC) over entire duration of repayment of loans and supported by bankable offtake agreements
Debt : Equity Ratio (DER)	Not Applicable	60 : 40 or 1.5 : 1 70: 30 or 2.33 : 1	▪ Typical values are shown. Lower DER is for first 1 to 3 plants ▪ May vary depending on lenders requirements
Equity Sources	Venture Capital, Risk Capital, Project Sponsors, and Developers	Private Equity, Project Sponsors and Developers EPC and O&M Contractors	▪ Assumes equity investment is made into special purpose Project Company specifically set-up for the Project ▪ Equity sources execute Shareholders Agreement with SPC
Debt Sources	Not Applicable	Federal Government Loan Guarantee and syndication by Commercial Banks	▪ Pilot plant assumes no debt financing but only equity and grants ▪ NoaK commercial plant debt financed based on limited recourse or non-recourse financing. Debt is senior debt, subordinate debt, and working capital
Grants Sources	Federal Government State Government Non-Profits	Not Applicable	▪ Grants (e.g. R&D grants and project grants) assumed for pilot plant since technology is in pre-commercial stage ▪ Grants not applicable for NoaK plant which is an advanced commercialized stage

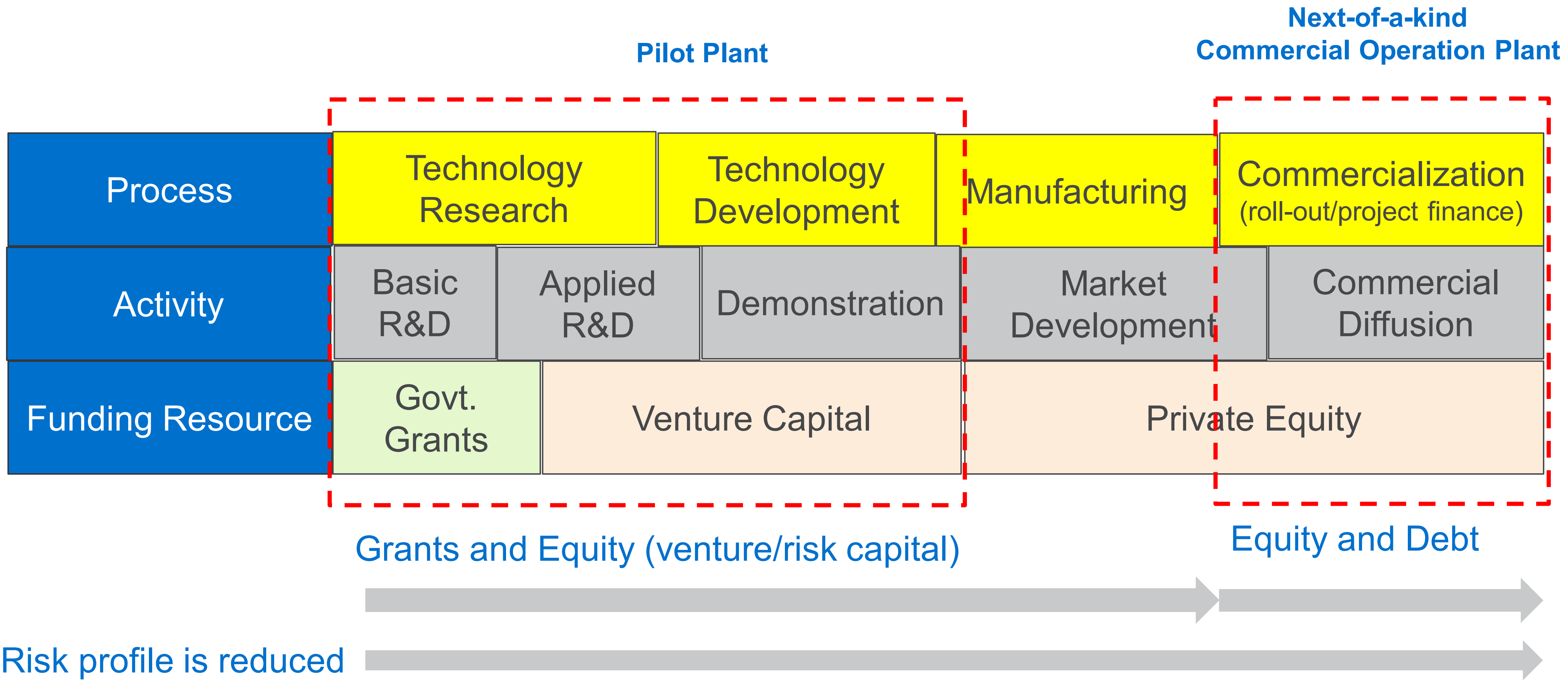
Notes:
1. Next-of-a-kind (NoaK) commercial operation of modular coal plant
2. TRLs defined based on USDOE's Technology Readiness Assessment Guide

Project financing parameters for both pilot and NoaK plant include fiscal/ financial incentives, economic/financial analysis, contracts, and key norms

Key Project Finance Parameter	Pilot Plant	NoaK[1] Commercial Operation Plant	Commentary
Fiscal and Financial Incentives	Subsides via grants, income tax credits (ITCs), accelerated depreciation, carbon credits (CO_2)	Loan guarantees, income tax credits (ITCs), accelerated depreciation, carbon credits (CO_2)	▪ At federal level and possibly at state level ▪ Both pilot and NoaK plants need to consider potential changes in regulatory framework, policy, and directives
Elements of economic modeling and financial proforma analysis	Capex, Opex, Total Installed Cost, Levelized Cost of Electricity (LCOE)	Same as Pilot Plant plus projections over economic life along with financial profitability indicators	▪ NoaK plant must also consider power tariffs, electricity merit-order dispatch scenarios, lifecycle assessment (LCA), and cost insurance, variable//fixed Opex, and working capital margin ▪ NoaK plant must include payback period, internal rate of return (IRR), rate of return on equity (RROE), net present value (NPV) and debt service coverage ratio (DSCR)
Requirements for transaction contracts	Technology license agreement (if req'd.), EPC and O&M Contract	Same as Pilot Plant plus fuel supply agreement (FSA) and power purchase agreement (PPA), agreement for purchase of carbon (CO_2) credits	▪ Pilot plant and NoaK plant's EPC contract must consider "wrap" to cover warranties and guarantees ▪ NoaK plant's O&M contact must consider long-term service agreement (LTSA) ▪ NoaK plant contracts and agreements must be "bankable" with provisions for back-to-back arrangements to mitigate counterparty risks and downside risks
Likely project financing norms	Not applicable	NPV (subject to prevailing interest rates), RROE of 8-10 percent, IRR of 10-12 percent, DSCR of 1.5 to 2.0, Payback period of 5-10 years	▪ Project financing norms based on financial proforma analysis over NoaK plant economic life and subject to sponsors and lenders criteria ▪ Project financing norms subject to conducting a sensitivity and scenario analysis with respect to schedule delays, cost overruns, changes in interest rates with impact on IRR, RROE, DSCR, and payback period

For the pilot project for DICE CRCC, key technology investing stages and funding gaps cover basic R&D, applied R&D, and demonstration activities

The traditional funding and investment stages of progression of energy technology and and investments, including funding sources, development processes and activities:



Pilot Plant

Next-of-a-kind Commercial Operation Plant

Process	Technology Research	Technology Development	Manufacturing	Commercialization (roll-out/project finance)	
Activity	Basic R&D	Applied R&D	Demonstration	Market Development	Commercial Diffusion
Funding Resource	Govt. Grants	Venture Capital	Private Equity		

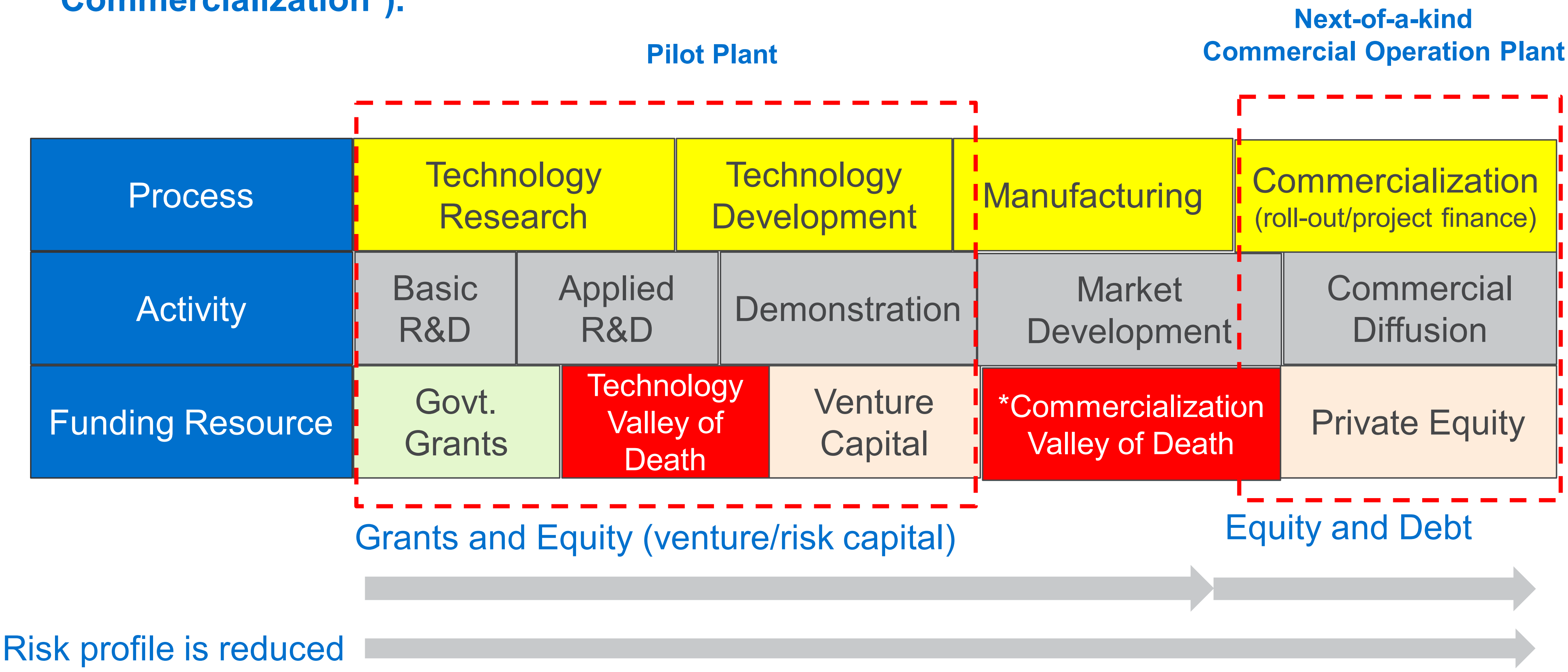
Grants and Equity (venture/risk capital)

Equity and Debt

Risk profile is reduced

Any technology investing and funding gaps must be avoided for pilot project as well as pre-commercialization stages in order for success of DICE CRCC

It is important to overcome any potential funding gaps which may arise for the pilot project during the applied R&D phase and post-demonstration phase (prior to advanced Commercialization*).



Pilot Plant

Next-of-a-kind Commercial Operation Plant

Process

Technology Research

Technology Development

Manufacturing

Commercialization (roll-out/project finance)

Activity

Basic R&D

Applied R&D

Demonstration

Market Development

Commercial Diffusion

Funding Resource

Govt. Grants

Technology Valley of Death

Venture Capital

*Commercialization Valley of Death

Private Equity

Grants and Equity (venture/risk capital)

Equity and Debt

Risk profile is reduced

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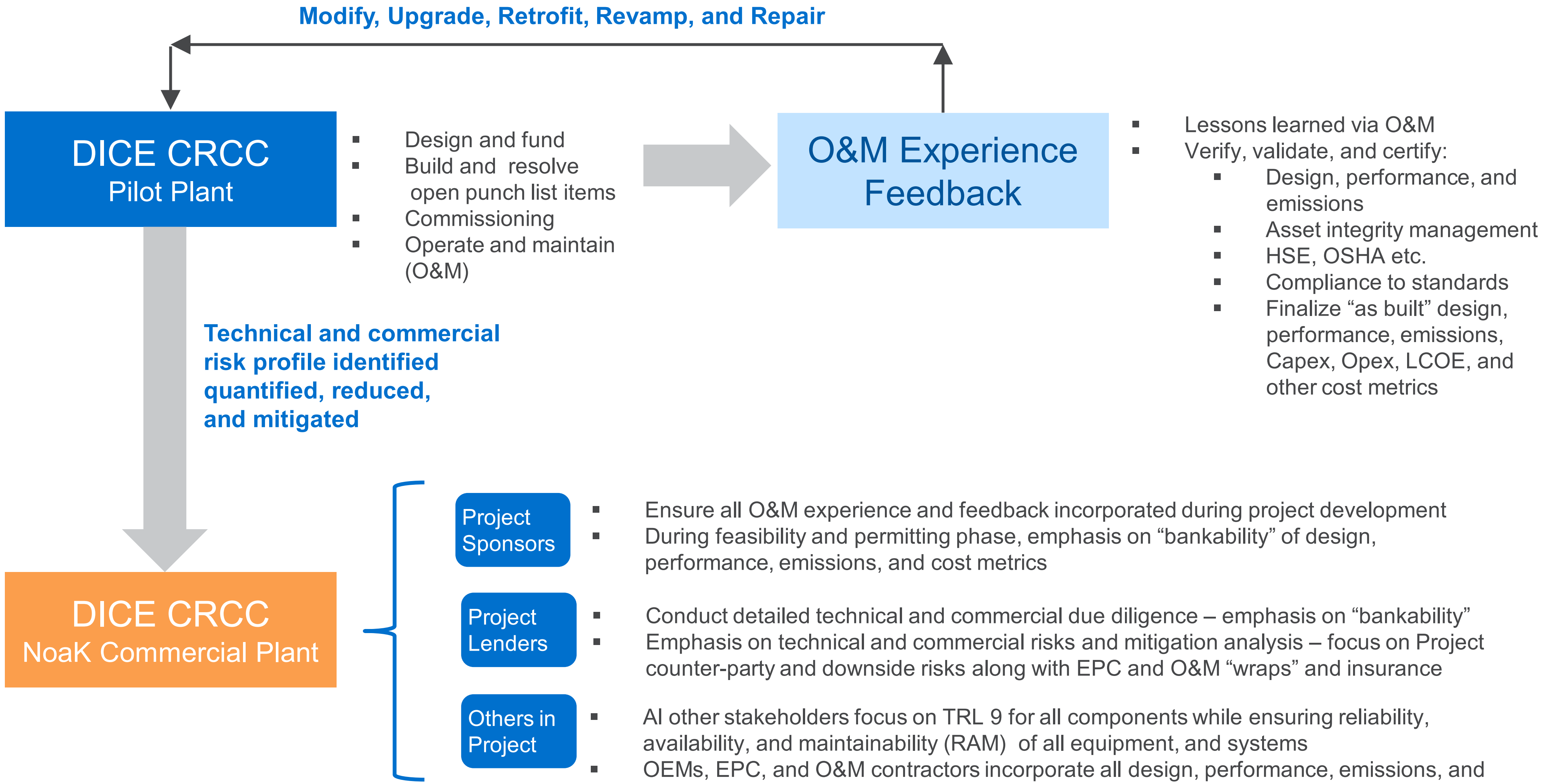
* "Debt-Equity Gap" as capital requirements for commercializing energy technologies is beyond the risk tolerance and timelines of most existing debt and equity markets.

Definitive O&M experience feedback from DICE CRCC pilot plant can identify, quantify, and mitigate risks for implementing NoAK commercial plant



Modify, Upgrade, Retrofit, Revamp, and Repair

DICE CRCC
Pilot Plant

- Design and fund
- Build and resolve open punch list items
- Commissioning
- Operate and maintain (O&M)

O&M Experience Feedback

- Lessons learned via O&M
- Verify, validate, and certify:
    - Design, performance, and emissions
    - Asset integrity management
    - HSE, OSHA etc.
    - Compliance to standards
    - Finalize “as built” design, performance, emissions, Capex, Opex, LCOE, and other cost metrics

Technical and commercial risk profile identified quantified, reduced, and mitigated

DICE CRCC
NoaK Commercial Plant

Project Sponsors

- Ensure all O&M experience and feedback incorporated during project development
- During feasibility and permitting phase, emphasis on “bankability” of design, performance, emissions, and cost metrics

Project Lenders

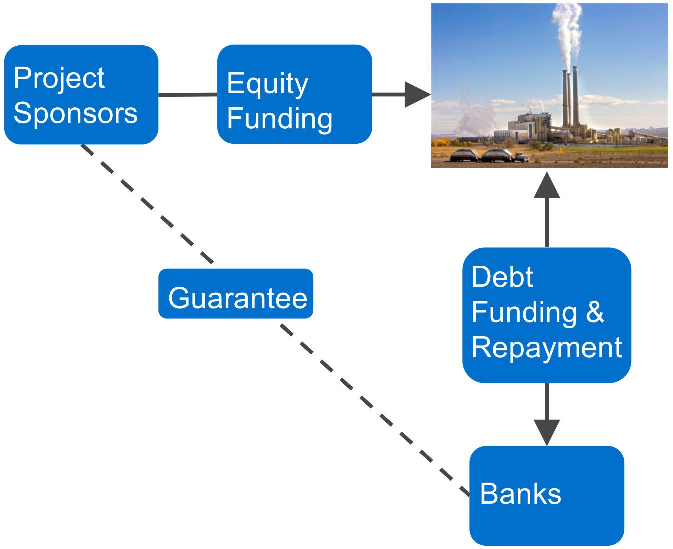
- Conduct detailed technical and commercial due diligence – emphasis on “bankability”
- Emphasis on technical and commercial risks and mitigation analysis – focus on Project counter-party and downside risks along with EPC and O&M “wraps” and insurance

Others in Project

- Al other stakeholders focus on TRL 9 for all components while ensuring reliability, availability, and maintainability (RAM) of all equipment, and systems
- OEMs, EPC, and O&M contractors incorporate all design, performance, emissions, and cost metrics as part of specifications and contracts

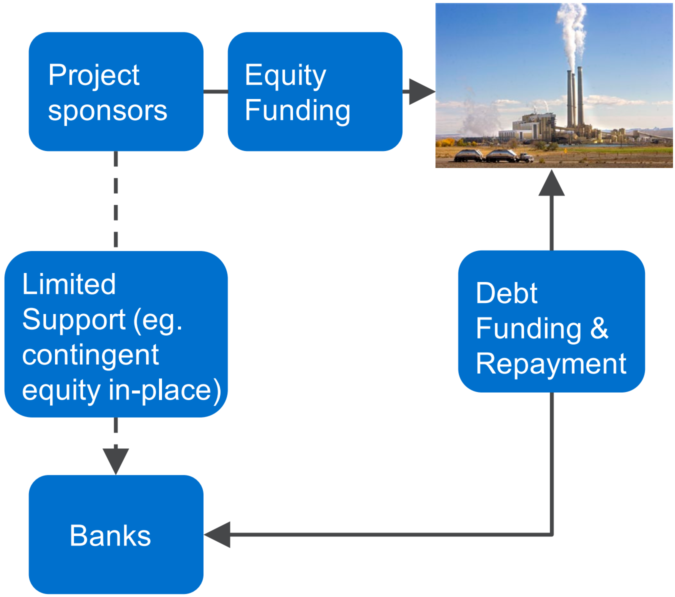
Next-of-a-kind (NoaK) commercial modular plant for DICE CRCC would most likely attract limited recourse financing initially for the first 1 to 3 plants

Full-Recourse Financing



- Repayment of loan fully guaranteed project sponsors (total balance sheet exposure)

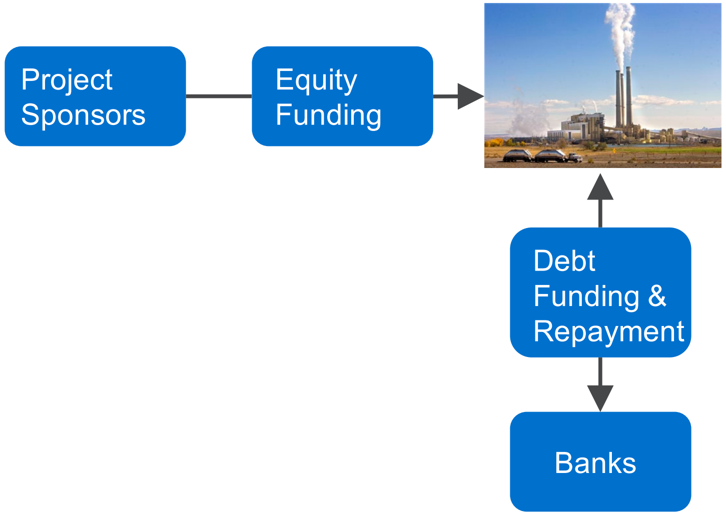
Limited Recourse Financing



- Repayment of loans directly related to the success of the project, with limited support from the project sponsors

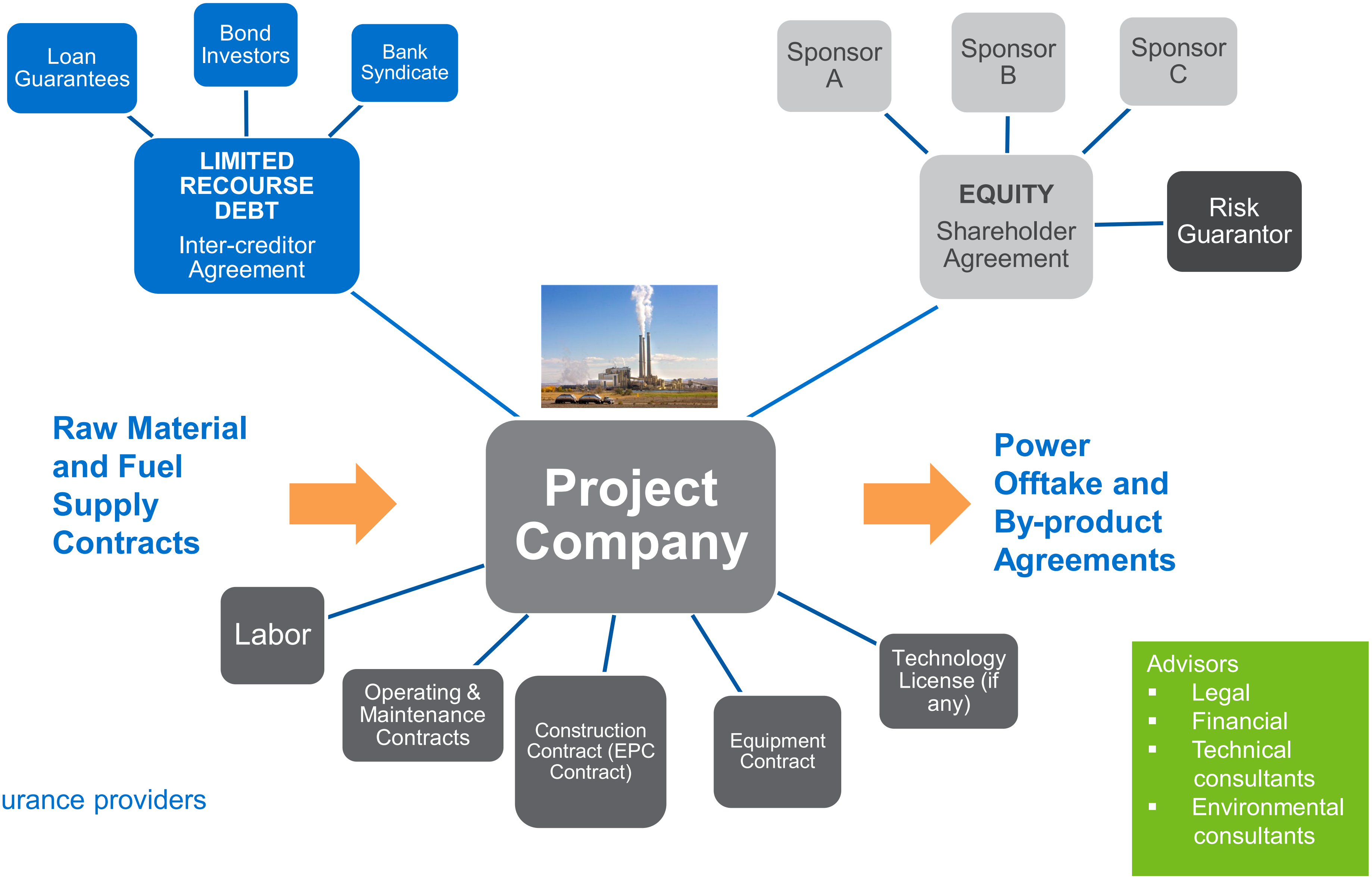
Most Likely

Non-Recourse Financing



- Repayment of loans solely dependent on the success of the project

Project financing structure consists of key stakeholders* covering debt, equity, risk guarantors, EPC and O&M contractors along with bankable contracts



Loan Guarantees

Bond Investors

Bank Syndicate

LIMITED RECOURSE DEBT

Inter-creditor Agreement

Sponsor A

Sponsor B

Sponsor C

EQUITY

Shareholder Agreement

Risk Guarantor

Raw Material and Fuel Supply Contracts

Project Company

Power Offtake and By-product Agreements

Labor

Operating & Maintenance Contracts

Construction Contract (EPC Contract)

Equipment Contract

Technology License (if any)

Advisors

- Legal
- Financial
- Technical consultants
- Environmental consultants

*includes insurance providers

Financing norms include three main phases for NoaK DICE CRCC plant which cover pre-, during, and post-financing stages including financial closure

Pre Financing Stage

- Project identification
- Risk identification, minimization, and mitigation
- Technical and financial feasibility

Financing Stage

- Equity arrangement
- Negotiation and syndication
- Commitments and documentation
- Disbursement

Post Financing Stage

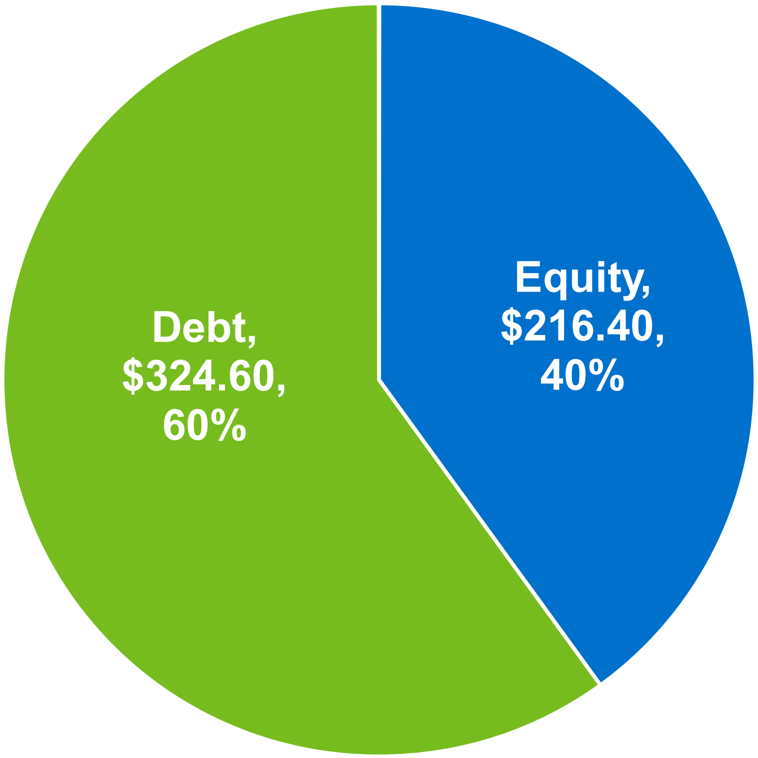
- Monitoring and review
- Financial closure / project closure
- Repayments & subsequent monitoring

Structuring of project financing for DICE CRCC's NoaK plant with total overnight cost of $541 million is based on a Debt : Equity Ratio of 60:40 or 1.5:1

An example of structuring of the project financing is provided based on the Cost Report dated February 15, 2020,. Key assumptions are:

- DICE GT-RCCC Project Capacity: 77 MW
- Total Overnight Cost (TOC): $541 million
- Debt : Equity Ratio: 60 : 40 or 1.5 : 1
- Debt: $324.60 Million
  - Senior and subordinate debt
  - Sources: US Government loan guarantee and lenders (financial institutions, investment banks, and commercial banks)
- Equity: $216.40 Million
  - Common and preferred stock
  - Sources: Project sponsors, developers, private equity (PE) firms, OEMs, EPC and O&M contractors
- Grants: Non assumed since this is not at pilot stage

$ million and percentage



The three stages of project financing for pilot plant and NoaK plant must identify, minimize, and mitigate project risks, external risks, and financing risks

Project financing risks can be divided into 3 key categories which must be considered in order to meet Lender's comfort for the syndication of entire debt for the project:

Project Risks

- Site Selection
- Permitting
- Construction and Completion
- Cost Overruns
- Technology
- Operating
- Sponsor/Developer

External Risks

- Environmental
- Infrastructure
- Political and Regulatory Framework, Policy, and Directives
- Inflation
- Demand and Market

Financing Risks

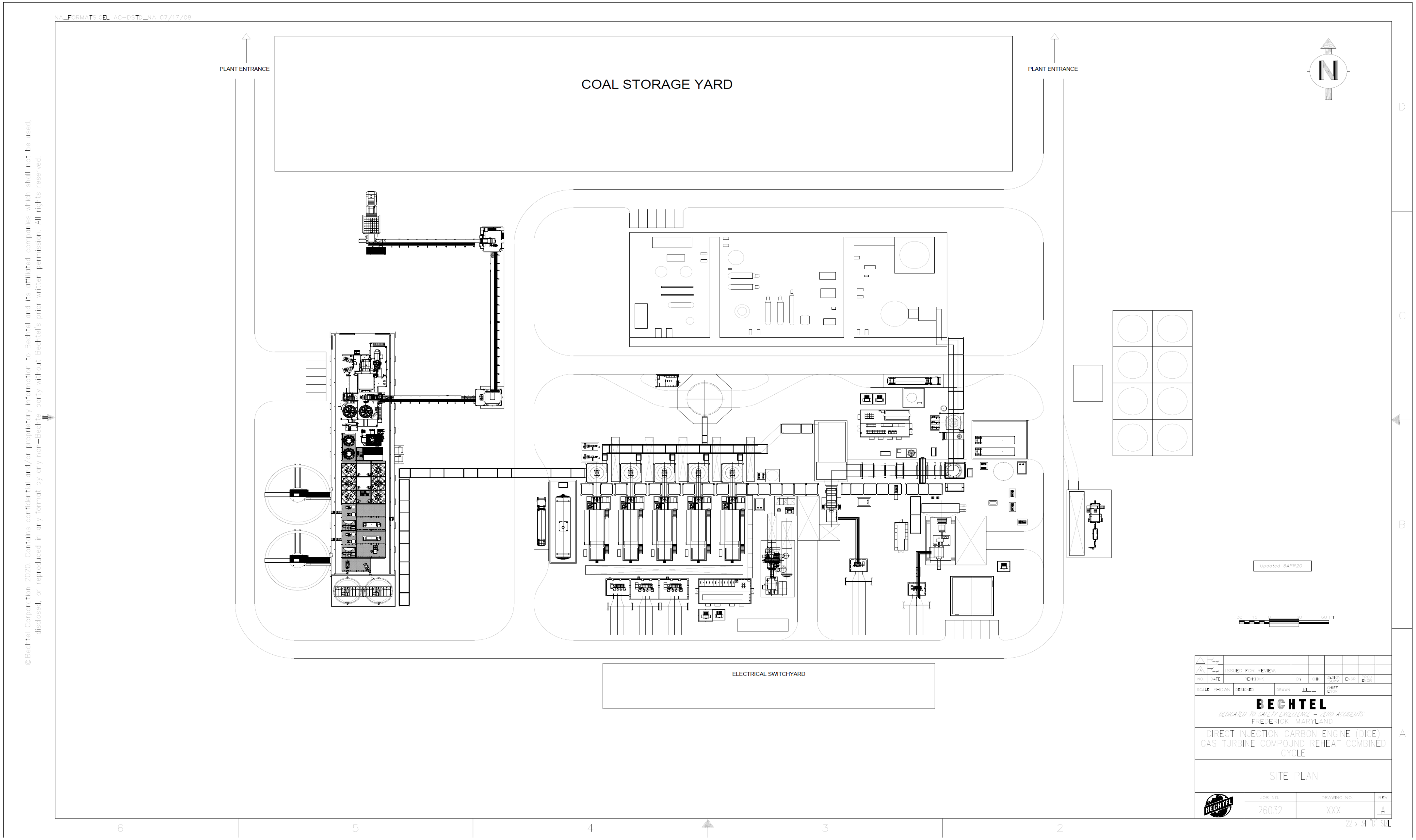
- Floating Interest Rates (currently very low)
- FX Rate on imported technology and equipment

4. Site Selection

DICE plant description consists of 4 main processing blocks – coal beneficiation, power block, post combustion capture, and utilities and off-sites

- DICE plant will consist of the following processing blocks:
  - Coal Beneficiation Plant
  - Power Block
  - Post Combustion Capture (PCC) Block
  - Utilities and Off-sites
- The coal beneficiation plant receives coal from the mine and processes it into a refined, micronized coal-water slurry which is transported to the DICE engines
- The power block consists of the DICE generators, gas expander generator, Heat Recovery Steam Generator (HRSG), steam turbine generator and direct contact cooler
- The cooled exhaust gas is ducted to the PCC unit which produces supercritical carbon dioxide at a pressure of ~2,250 psig for routing to the end user via pipeline
- A waste slurry stream is produced by the coal beneficiation plant which is disposed off-site

DICE CRCC layout is modular in design, highly integrated with key systems, sub-systems, equipment, components, and auxiliaries



Key site selection criteria is based on process requirements - availability of land, CO_2 storage, access to water, logistics, power interconnection, and others

- Key criteria for site selection are driven by the process requirements including:
  - Availability of adequate land suitable for proposed facilities
  - Access to sufficient volumes of water for cooling tower makeup
  - Proximity to carbon dioxide storage location or end user, alternatively proximity to an existing carbon dioxide pipeline which has spare capacity to transport the produced carbon dioxide
  - Proximity to rail or ocean/river ports for transport of coal or proximity to an existing coal fired plant which is willing to allow sharing of unit coal trains or ocean/river ports for transport of heavy equipment
  - Distance from power grid for inter-connection
  - Site should not be located in a non-attainment area for air pollution standards
  - Proximity to rail

These criteria are elaborated in the following slides.

Availability of suitable land is dependent upon specific pre-requisites, design criteria which will enable proper development, execution, and operations

- Availability of suitable land
  - Land should be reasonably flat and not prone to landslides
  - Land should not be located in 100 year floodplain or on wetlands
  - The land should not be in a high seismic zone prone to frequent earthquakes
  - Proposed site should have satisfactory geological and hydrological characteristics
  - The proposed site should not be located in areas of historical, religious or cultural importance
  - The proposed site should not be too close to urban areas or areas where population may grow rapidly
  - The proposed site should not be in proximity to existing hazardous areas or facilities
  - The proposed site should allow disposal of waste streams from the facility (coal beneficiation waste tailings, fly-ash, process wastes, waste water, etc.)
  - In the event that limited supply of makeup water is available, account for additional land for installing **Air Cooled Condensers (ACC)** and **Zero Liquid Discharge (ZLD) systems**

Availability of adequate water with proper quality, sufficient volumes, proximity, backup sources, and proper discharge are key to project development

- Access to adequate water
  - Availability of water supply of reasonable quality and sufficient volume for cooling tower and cooling water makeup, coal slurry preparation, and other consumptive uses
  - Source of water should not be too distant from the potential site and the route should not entail significant physical or legal obstacles
  - Allowance should be made for backup/emergency source of water
  - Site should have provision for discharge of waste water streams
  - In the event that limited supply of makeup water is available, consider optional use ACC and ZLD systems

Carbon dioxide, heavy equipment, and coal transport must be addressed as part of project execution plan focusing on proximity, easy access, and transport

- Proximity to carbon dioxide storage location or end user
  - Site should not be too distant from where the carbon dioxide will be used or stored, or near an existing carbon dioxide pipeline that can take the additional carbon dioxide produced by the facility.
  - Pipe route should not present significant physical or legal obstacles
  - If the gas is to be stored in a saline reservoir, conditions in the reservoir need to be considered during site selection
- Proximity to rail or ocean/river ports for transport of heavy equipment, coal, etc.
  - Proposed site should allow for transport of heavy and large pieces of equipment by river and/or ocean freight
  - Adequate facilities should be available to trans-ship equipment by rail and/or truck, as required
  - Proposed site should have rail or road access for transporting coal from the mine and should be located a reasonable distance from the mine

Distance from nearest power grid is key for interconnection and evacuation, and site should address non-attainment areas for air pollution standards

- Distance from power grid for inter-connection
  - Proposed site should be within a reasonable distance from the power grid for evacuation of power
  - The transmission line route should not present significant physical, technical or legal obstacles
- Site should not be located in a non-attainment area for air pollution standards
  - Proposed site should not be located in areas designated as non-attainment for pollutants

Unique requirements for selection of first DICE plant cover preferable location in US Gulf Coast, proximity to PRB coal and CO_2 storage, and other key areas

- Preferable location shall:
  - Be close to the **US Gulf Coast** for ease of transportation of large modules and equipment, including trans-shipment via barge
  - Be close to an existing coal fired plant that uses PRB coal
  - Locate near an end user/storage location for the produced carbon dioxide or to an existing carbon dioxide pipeline with enough spare capacity to handle the additional output from the DICE plant
  - Provide potential users who can receive the tailings from the coal beneficiation plant and use them productively
- **US Gulf Coast** as DICE CRCC plant location of choice:
  - The US Gulf coast has several power plants that use or used PRB coal and get regular shipments from the mines by rail and/or barge. The Big Cajun power plant located in Louisiana is one example of such a facility.
  - In addition, there is an existing carbon dioxide pipeline (Denbury pipeline) located not too far from the Big Cajun power plant that transports CO_2 to customers and points of use that could potentially be used for transporting the carbon dioxide capture in the DICE plant
  - With regards to the use of the tailings from the coal beneficiation process, the potential use will need to be explored and users will need to be developed as part of the next phase of the Project

5. Partnering with Technology Providers

Coal Beneficiation Plant

- Sedgman is able to perform design, supply, fabrication, delivery, construction and commissioning of the coal beneficiation plant
- Technologies of note that require further test work and validation
    - Flotation cells: Sedgman C-Cells
    - Fine Grinding Mill: FLSmidth (VXPMill); Outotec (HIG Mill); Glencore Technology (IsaMill)
- For CoalFIRST Critical Component development, plan to partner with Virginia Tech (Prof Roe-Hoan Yoon) to develop and test beneficiation process on variety of coals, including PRB, Eastern coals, and coal fines
    - Convert low-rank PRB coal from hydrophilic to hydrophobic
    - Electrochemical treatment to remove mineral matter
    - Convert mineral matter to fertilizer

DICE

- Reaching out to major engine OEMs (Wartsila, MAN) did not bear fruit
  - *“Coal slurry is a cheap fuel that is locally available in the world. There are investigations, in accordance with MAN ES’ own experience on that matter, showing that this fuel is very abrasive. First tests on our engines and evaluations from our experts have shown, that it causes high war in the engine and its subsystems like the Fuel Injection Equipment. Additionally it has to be ignited by an additional pilot fuel (e.g. DMA) by using a high pressure injection system. This would result in a new engine and fuel injection equipment concept, with significant efforts for MAN Energy Solutions to handle this fuel. The current strategy of MAN Energy Solutions does not foresee a development in this direction”*
  - *[Wartsila has] a record of developing recip engines to burn some pretty challenging fuels, such as Orimulsion. But aligning ourselves to explore coal combustion is at odds with our corporate identity of supporting carbon reduction and high renewable systems…[Wartsila is] currently investing in alternative fuel R&D, but more aligned with renewable and carbon-neutral, which fit into a “net zero” paradigm”*
- “Piggyback” on existing work by CSIRO
  - CSIRO has a long history in DICE development
  - Currently working with Yancoal and Chinese engine developer (Zichai)
  - Progress is delayed by the COVID-19 crisis
- For CoalFIRST Critical Component development, plan to partner with CSIRO to further develop DICE fuel injector and cylinders and conduct series of tests for coal-fired engines

Recent CSIRO work on DICE

- A recent study with the Australian Coal Industry and MAN involving a MAN-LGI system modified for MRC by the CSIRO. Tests involved passing nearly 50 tonnes of MRC through the 600 bar injector on a spray bench. Terminated due to disagreements between MAN and the coal industry on engine development, the coal industry's concern over the potential competition with supercritical PC with PCC, and MAN's focus on next-generation engines for ammonia and hydrogen fuels.
- A recent study with Maersk and WING&D on the use of MRC for deepwater marine. CSIRO designed the injectors and fuel system for a 10 MW 4-cylinder engine which was successfully trialed in Switzerland showing excellent combustion results. Terminated due to the IMO's new regulations on the decarbonization of shipping by 2050.
- Use of biomass in DICE to halve the cost and double the benefit of biomass for electricity generation. Includes triple bottom line studies using saltbush (animal feed, fuel and soil carbon).
- Production of high quality MRC fuel from a wide range of coals - Australian (bituminous, sub-bituminous, brown), German, Indonesian (hydrothermally treated), and Venezuelan.

6. Permitting

Permitting for DICE requires prompt action from site selection, emissions estimates, meeting state requirements and timelines, and pre-/post-approval

- The permitting process should be initiated as soon as a site has been selected for the DICE power plant and the scale of the plant is established
- Initial estimates of plant capacity and emissions of regulated pollutants (based on manufacturers data) should be tested against applicable thresholds to determine application requirements
- Permit requirements vary by state and within states as well based on whether an area is classified as attainment or non-attainment
- For planning purposes it may be prudent to allow 12 to 18 months for obtaining the air permit
- Most states have specific guidelines and instructions for preparation of the air permit application
- In general the types of documents required to be submitted with the application include site plans and facility design documents in sufficient detail to establish location, scale, and relationships, horizontally and vertically, to and between adjacent properties

Permitting must address physical locations, equipment emissions, plant load data, air quality impact, EPA’s NSR program, and other specific documentation

- Stack and building heights and locations are established in these documents
- Equipment manufacturer’s emissions data are required. This information may be representative as actual equipment sources may not be known at this stage of the project
- Estimated plant load data – both peak and annual – should be calculated
- Determine potential emissions by applying the above factors and assuming that all new capacity operates at full rated load for 24 hours per day, 365 days per year
- **Air Quality Impact Assessment** may be required depending on the scale of the project
- The EPA’s **New Source Review (NSR)** permitting program will apply, it’s goal is to maintain air quality when major new sources of emissions are built
- NSR requirements may fall under one of the following categories:
  - **Prevention of Significant Deterioration (PSD)** permits are required for new sources in areas which meet the **National Ambient Air Quality Standards (NAAQS)**
  - Nonattainment NSR permits are required for major new sources in areas that do not meet NAAQS

DICE permitting must include BACT, LAER, SIPs, regulated GHG emissions, Title V, onsite record keeping, and key certification of compliance requirements

- Under the PSD permit new plants are required to include **Best Available Control Technology (BACT)**
- Non attainment areas require application of **Lowest Achievable Emission Rate (LAER)** technology, in addition to emission offsets and public involvement
- **State Implementation Plans (SIP’s)**: Most states have developed SIP’s under a mandate by the EPA to issue air permits, while the EPA maintains general oversight
- Regulated emissions include NOx, SOx, mercury, VOCs and particulate matter, among others
- When the plant reaches the operational phase a **Title V** permit is required as a means to provide a database for monitoring and enforcement
- Title V applications require as a minimum, a means of reporting air emissions either by CEMS or other means
- Onsite record keeping of relevant data
- Certification of compliance with applicable emission limitations

Indicative list of permits required cover a wide range of federal, state, and local requirements including US Army Corps of Engineers, and other documentation

- Indicative list of other permits required for power plant projects include wetlands permit, water withdrawal permit, waste water discharge permit, natural heritage program permit, certificate of public convenience and necessity, traffic plan consultations and agreements, parks and recreation historic preservation, storm water control permits, no hazard to aviation permit, threatened and endangered species consultation, local jurisdiction permits, **US Army Corps of Engineers** permits, state permits, noise permit, and others as applicable
- An environmental commitments matrix is developed during the project phase to track regulatory based design requirements. That document should tabulate the requirements from the various permits as well as action items, action owner and status
- In addition to the permits described above, there may be others required for construction of power plants that are issued by local and state agencies. Those permits would need to be obtained before start of construction

7. Detailed Design of Project Concept

Detailed design of project concept of process/power units requires proper planning, execution, and coordination with OEMs and lead EPC contractor

- Correct execution of the detailed design phase of the project is critical to ensure project success
- The detailed design of the plant will entail engineering of the following process/power units, carried out by different entities and coordinated by the lead EPC contractor:
  - Coal beneficiation plant
  - DICE CRCC power plant including as expander generator, heat recovery steam generator and steam turbine generator
  - Carbon capture and compression plant
- The detailed design of the plant will entail engineering of the following process/power units, carried out by different entities and coordinated by the lead EPC contractor:
  - Execution strategy, plan and schedule
  - Focus areas based on the overall project schedule
  - Delineation of work performed by various groups during the detailed design phase
  - Staffing forecasts and implementation
  - Major engineering risks and mitigation
  - Detailed design execution budget and performance

Each of the above tasks is discussed in detail in the following slides.

Detailed design execution strategy must be goal driven covering scope and schedule, coordination, 3D models, risk management, and schedule tracking

- Detailed Design Execution strategy has the following goals:
  - The contract will determine the scope and schedule of detailed design engineering
  - Detailed design will be performed in accordance with the contract
  - Develop quality engineering design that minimizes re-work
  - Coordinate detailed design with construction, startup, and overall project schedules for optimizing overall project duration
  - Ensure physical design coordination by developing a 3D model to eliminate interferences and ensure operability and access for maintenance
  - Manage risks associated with detailed design development
  - Control design interfaces with equipment suppliers and sub-contractors
  - Implement a management of change process
  - Engage, challenge and grow engineer’s skill in the detailed design process
  - Track key metrics to ensure quality, budget, cost and safety compliance
  - Detailed design to account for sustainability and energy efficiency

Overall project schedule must address task sequencing, impacts, procurement, construction, coordination interfaces, staffing, and design of physical plant

- Focus areas based on the overall project schedule
  - Engineering provides input to Project schedule accounting for construction sequencing, weather related impacts and project turnover and completion dates
  - Project procurement, construction and startup schedules shall drive detailed design execution
  - Develop detailed design plans to cover major systems and equipment
  - Coordinate design interfaces with vendors and sub-contractors to ensure a functional and efficient power plant
  - Identify and manage critical interfaces between the power and coal beneficiation and carbon capture blocks, and coordinate with the entities responsible for their detailed design
  - Develop staffing plans based on project schedule
  - Initial design activities are geared to design of earthworks, foundations and underground structures, underground piping and ducts, grounding and storm water systems

Design phase must cover work execution by groups, coordination, implement design guidelines, staffing forecasts, deliverables, and critical-path milestones

- Delineation of work performed by various groups during the detailed design phase
  - Coordinate schedule and interfaces between the entities designing the coal beneficiation, power plant and carbon capture blocks
  - Develop and implement design guidelines and engineering procedures
  - Set up a design organization that will carry out detailed design and interface with vendors and contractors who will be responsible for certain aspects of the design
  - Identify electronic tools to be used for detailed design for all aspects and disciplines
- Staffing forecasts and implementation
  - Develop organization chart and staffing levels for all teams working on the three blocks of the project
  - Establish division of responsibilities for the detailed design teams
  - Each team will have their own teams and deliverables that support the overall project schedule
  - The lead EPC contractor will be responsible for overall schedule and internal coordination
  - Initiate regular meetings to track status and resolve issues that may impact design progress

Major risks must be identified and mitigated measures implemented along with focus on project execution, budgets, regular tracking, and performance metrics

- Major engineering risks and mitigation
  - Develop a detailed design risk register at the beginning of the project to identify risks and potential strategies for their mitigation
  - Risks to include those related to all parts of the project including coal beneficiation, power block and carbon capture and compression units
  - Risks can be associated with first-of-a-kind equipment, integrated functionality and control, and performance guarantees
  - Include risks associated with unique manufacturers supplying specialized equipment
- Detailed design execution budget and performance
  - Set up detailed design budgets, deliverables and schedule for design deliverables for each discipline for each of three entities designing the coal beneficiation plant, power plant, and carbon capture plant
  - Track progress by each discipline to ensure project stays on track for timely completion
  - Establish plans to mitigate and minimize schedule slippage by adding resources as appropriate, in a timely manner
  - Ensure motivation of the design team by holding team building activities and providing incentives for innovative design and execution that improves quality and reduces cost