The direct injection carbon engine

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Preface

This draft report has been produced by IEA Clean Coal Centre and is based on a survey and analysis of published literature, and on information gathered in discussions with interested organisations and individuals. Their assistance is gratefully acknowledged. It should be understood that the views expressed in this report are our own, and are not necessarily shared by those who supplied the information, nor by our member countries.

IEA Clean Coal Centre is an organisation set up under the auspices of the International Energy Agency (IEA) which was itself founded in 1974 by member countries of the Organisation for Economic Co-operation and Development (OECD). The purpose of the IEA is to explore means by which countries interested in minimising their dependence on imported oil can co-operate. In the field of Research, Development and Demonstration over fifty individual projects have been established in partnership between member countries of the IEA.

IEA Clean Coal Centre began in 1975 and has contracting parties and sponsors from: Australia, Austria, Brazil, Canada, China, the European Commission, Germany, India, Italy, Japan, New Zealand, Poland, Russia, South Africa, Switzerland, Thailand, the UK and the USA. The Service provides information and assessments on all aspects of coal from supply and transport, through markets and end-use technologies, to environmental issues and waste utilisation.

Abstract

Coal is abundant and low cost. Diesel engines are efficient and flexible. Using coal to fuel diesel engines could provide a secure, low cost and efficient power generation technology. Coal-fuelled diesel engines have been investigated previously, but the technology has not yet been commercialised. This report reviews the previous research and development (R&D) programmes on coal-fuelled diesel engines and focuses on the recent developments of the technology in its latest form, micronised refined carbons (MRC) and the direct injection carbon engine (DICE).

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Acronyms and abbreviations

ACALET	Australian Coal Association – Low Emission Technologies
ANLEC R&D	Australian national low emissions coal research and development
BCIA	Brown Coal Innovation Australia
BREE	Bureau of Resources and Energy Economics (Australia)
CCGT	combine cycle gas turbines
Cat-HTR	catalytic hydrothermal reactor
CCS	carbon capture and storage
CFB	circulating fluidised bed
CHTD	continuous hydrothermal dewatering
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
CWF	coal water fuel
CWS	coal water slurry
CWM	coal water mixtures
DICE	direct injection carbon engine
EGR	exhaust gas recirculation
FEED	front end engineering design
GM	General Motors
GE	General Electric
HFO	heavy fuel oil
HWT	hot water treatment
HRC	high rank coal
HRSG	heat recovery steam generator
HTD	hydrothermal dewatering
IEA	International Energy Agency
IER	Ignite Energy Resources (Australia)
IGCC	integrated gasification and combine cycle
LCOE	levelised cost of electricity
LRC	low rank coal
MAN D&T	MAN Diesel & Turbo
MRC	micronised refined carbons
NEDO	New Energy and Industrial Technology Development Organisation (Japan)
O&M	operation and maintenance
PCC	pulverised coal combustion
PFD	process flow diagram (PFD)
SEM	scanning electron microscope
SWRI	South West Research Institute (USA)
UCC	ultra-clean coal
UNDEERC	University of North Dakota's Energy and Environmental Research Center
US DOE	Department of Energy (USA)
WHR	waste heat recovery
XT	Xstrata Technology

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1 Introduction

Using coal to fuel diesel engines has been investigated numerous times over the last 122 years for power generation and transport applications. Historically, coal-fuelled diesel engines have been investigated because of the high cost of petroleum fuels and low cost and abundance of coal. However, technical difficulties and unfavourable economics have ensured the cancellation of previous research and development (R&D) programmes. The present drivers for coal-fuelled diesel engines are environmental as well as economic; coal-fuelled diesel engines could provide an efficient and flexible form of power generation. Previous and current R&D programmes on coal-fuelled diesel engines are shown in the Gantt chart in Figure 1.

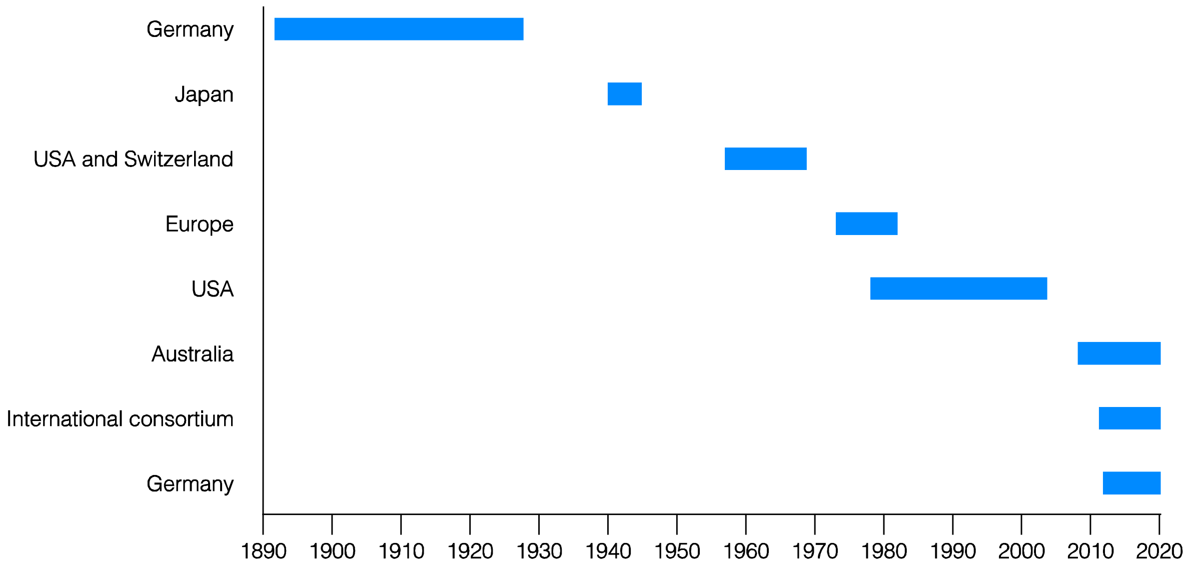

Figure 1 Gantt chart showing coal-fuelled diesel engine R&D programmes

Chapter 2 describes the first use of coal dust in diesel engines. Chapter 3 explains the development of coal water fuels (CWF) and Chapter 4 summarises the main achievements of a comprehensive coal-fuelled diesel engine R&D programme undertaken in the USA and funded by the Department of Energy. Piriou and others (2013) have made a comprehensive historical review of such technology with emphasis on using biomass dust as a fuel in diesel engines. Chapter 5 reviews in detail the recent research undertaken at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia, which concentrates on producing clean CWF, called micronised refined carbons (MRC) for use in adapted diesel engines for power generation, called direct injection carbon engines (DICE). Chapter 6 lists the CWF/MRC producers that are operating demonstration plant and reviews in detail the hydrothermal dewatering process (HTD) processes; the coal beneficiation aspect will be the topic of a future IEA Clean Coal Centre report. Chapter 7 summarises the laboratory-scale test results at CSIRO with MRC produced by multiple companies. Chapters 8 and 9 analyse and compare the technical and economic performance of MRC-DICE with other power generation technologies. Chapter 10 summarises the planned MRC-DICE R&D programme, led by MAN Diesel & Turbo, from pilot-scale testing through to possible commercialisation.

2 Coal dust

2.1 Rudolf Diesel 1892-1906

In 1892, as part of research and development (R&D) funded by the German government, Rudolf Diesel designed an engine to fire coal dust. However, coal dust is difficult to handle, it contaminated the engine oil, leading to wear issues. Additionally, the explosive properties of coal dust are comparable to gun powder which led to explosions in the laboratory. Rudolf Diesel found that it was easier and safer to use petroleum fuels and soon developed the four-stroke diesel engine with Maschinenfabrik Augsburg-Nürnberg (MAN) (Wilson, 2007). The first commercial diesel engine was built and operated in 1897 (Deutsches Museum, 2014).

2.1.1 Four-stroke diesel engines

Diesel engines rely on high pressure and temperature to ignite the fuel; this is known as compression ignition. Each cylinder operates on the following sequence of strokes: intake/induction, compression, combustion/power and exhaust (also known as suck, squeeze, bang and blow). The first stroke draws combustion air in through the open inlet valves. The second stroke compresses the combustion air until the piston reaches the highest point in the cylinder, known as top dead centre. At the end of the second stroke, fuel is injected into the compressed air and combustion occurs in a similar fashion to a flame-thrower, the expansion of the exhaust gases forces the piston back down in the third stroke. The fourth stroke pushes the exhaust gases out of the cylinder through the exhaust valve. All moving pistons are connected to a common crank-shaft with rods and cross-heads in larger engines. The engine speeds are categorised as follows according to their revolutions per minute (rpm) - low-speed (<300 rpm), medium-speed (300-1000 rpm) and high speed (>1000 rpm).

2.2 Rudolf Pawlikowski 1911-1928

In 1911, Rudolf Pawlikowski, a former colleague of Rudolf Diesel, continued work on dust engines. Injection methods included aspiration or fumigation into the inlet air and air-blast injection. Pawlikowski's company, Kosmos, along with I-G Farben Industrie, Schichau Werke, Brunenner Machinefabrik and Hanomag successfully operated 19 dust engines. The engines ranged in size, 6-400 kW, and speed, 160–1600 rpm. The solid fuels contained up to 12% ash, so hardened materials were used to minimise wear. Engine life-times of up to 12,000 hours and mechanical efficiencies of up to 30% (HHV), which was twice that of steam power at the time, were demonstrated. Dust engines were used during the Second World War due to oil shortages, so they cannot be classified as commercial. R&D was terminated when the production facilities were destroyed in 1944 during bombing raids, and not re-established due to consistently low oil prices from 1945 onwards (Wilson, 2007; Ryan III, 1994).

2.3 Japan: 1940-1945

Dust engines were trialled in small transport engines in Japan during the Second World War (DICEnet, 2014).

3 Coal water fuel

3.1 USA: 1957-69

Laboratory-based research from 1957-69 by the South West Research Institute (SWRI), Virginia Polytechnic University and Howard University, funded by the US Department of Energy (US DOE), discovered that firing coal in a water slurry (Figure 2), is safer and causes less wear than dust firing (Ryan III, 1994). Coal and water slurry are known as coal water fuels (CWF), coal water slurry (CWS) and coal water mixtures (CWM). For consistency this report will use the acronym CWF.

Figure 2 Coal water fuel (DICEnet, 2014)

3.2 Europe: 1973-82

High oil prices in the 1970s renewed interest in coal-fuelled diesel engines. Mixing coal dusts with diesel was proposed for small high-speed engines. Sulzer Brothers (Wärtsilä) and Burmeister and Wain (now B&W) tested coal-diesel mixtures in conventional, large, low-speed diesel engines. Tests were unsuccessful due to chronic wear of injector nozzles, poor atomisation and severe cylinder wear. It is speculated that the coal particles agglomerated in the diesel which resulted in low combustion efficiency. The unburnt coal contaminated the cylinder wall, increasing wear and eventually jamming the piston ring (Ryan III, 1994).

4 USA: 1978-2004

The US DOE funded a vast R&D programme to replace petroleum fuel with CWF in gas turbines, steam turbines and diesel engines.

4.1 USA: 1978-82

SWRI and Switzerland based Thermo Electron Corporation and Sulzer Brothers conducted tests to prove that CWF could be used to replace petroleum fuels in diesel engines. Their work concluded that CWF, with coal particles <10 microns, 0.5–1% ash and <1% sulphur (wet basis), could be fired in medium-speed diesel engines, adapted with harder engine materials for the ring-piston-cylinder interface, new lubricants and an engine re-design. At the time the price of CWF was the same as diesel fuel (Nydick, 1987).

4.2 USA: 1982-93

After four years of investigating firing CWF, experience with gas turbines was unsuccessful due to severe erosion, corrosion and fouling. However, tests in a 100 hour continuous diesel engine proved more successful. As a result the focus of funding switched to diesel engines in 1982. This led to a coal-fuelled diesel engine R&D programme, led by Morgantown Energy Technology Center (now part of the National Energy Technology Laboratory) with General Motors (GM), General Electric (GE), Cooper-Bessemer-Bess/Arthur D Little, Detroit Diesel, SWRI, several CWF producers and other research institutes. The following sub-sections summarise the findings of this R&D programme from Wilson (2007); Arthur D Little (1995); Ryan III (1994); Caton and Hsu (1994); General Electric (1994).

4.2.1 Wear sources

The majority of coals contain minerals. Some of these minerals are dispersed throughout the coal structure and some are entrained during the mining and grinding processes (soil, sand, clay and rocks). Some minerals, such as Na, K, S, Cl, Ca and Mg, will combust to create ash in the exhaust gases producing sulphate fumes (Ca, Mg, Fe, Na), iron oxide cenospheres, fused silicates, quartz (<20 μm) and a high proportion of alkali species (CaO, MgO, Na and K salts). With sufficient particle loading, combined with the tars in the unburnt coal particles, piston ring jamming is possible.

Minerals in CWF can wear down the fuel delivery system. These minerals can then contaminate the engine oil, along with the ash created in combustion, which can wear down parts of the engine, particularly the cylinder liner, piston rings and exhaust valves. The minerals and ash will only wear down engine components if they are harder than the engine component materials. Very hard minerals will quickly wear down standard engine components. Figure 3 shows the hardness of ash components and engine materials on the Mohs scale – minerals and ash with hardness values 30% higher than engine components will cause severe abrasive wear. Figure 4 shows the hardness of ash components and engine materials according to the absolute hardness scale, which is a better measure of hardness. It is important to note that the mineral content in raw coal is often referred to as the ash content. Harder cylinder walls, piston rings and exhaust valves can minimise wear.

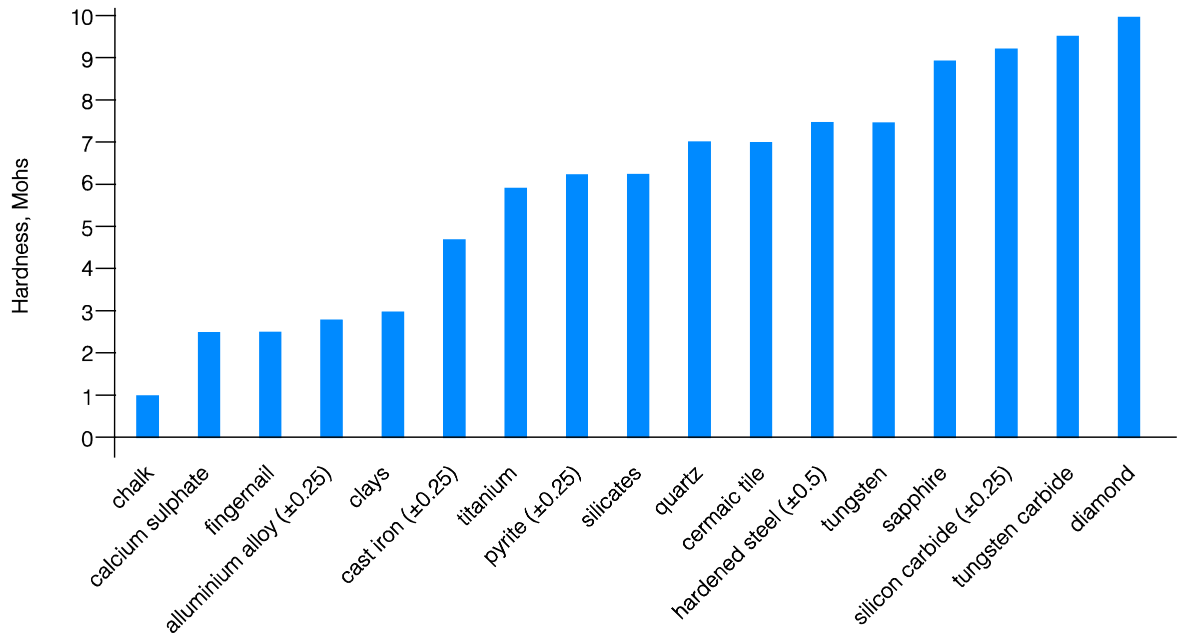

Figure 3 Hardness of materials on the Mohs scale

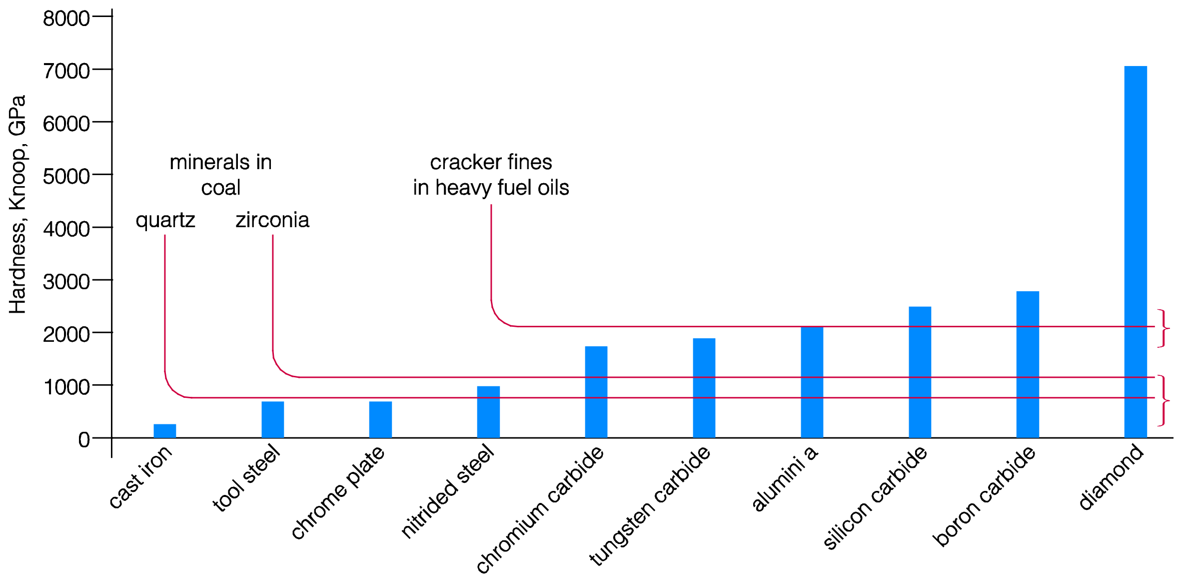

Figure 4 Absolute hardness

Wear can be divided into abrasive wear, adhesive wear and corrosion. Abrasive wear is the removal of materials from surfaces in relative motion by a cutting or abrasive action of a hard particle, such as ash and coal particles. Abrasive wear is also known as scratching, wearing down, marring and rubbing away.

Adhesive wear is the removal of materials from surfaces in relative motion as a result of surface contact when the lubricant film breaks down. Adhesive wear can be sub-divided into galling and scuffing. Galling is a form of wear in which seizing or tearing of the material surface occurs. Scuffing is a form of wear due to localised welding and fracture. Corrosion is the gradual destruction of engine materials by chemical reactions with the fuel (Timken Steel, 2014).

4.2.2 Coal beneficiation

Coals are commonly washed, or beneficiated, to reduce the amount of mineral matter present. Beneficiated coals are extensively used in pulverised coal combustion (PCC) boilers for power production or as a feed for coke ovens in the steel industry. Some is used in integrated gasification combined cycle (IGCC) plant. Both PCC and IGCC plants have improved performance with a cleaner feed coal, and coking coals need to have specific properties. Most internationally-traded coals are beneficiated.

Coals can be beneficiated using both physical and chemical methods. Coal washing involves carefully assessed size reduction, which may liberate some mineral matter particles, making them easier to separate. Organically-bound components which make a contribution to ash formation are not affected by the washing processes. Because the predominant use of coal is for combustion, it is the ash forming materials that are of interest, both the mineral matter and the organically bound components.

Physical beneficiation methods commonly produce coals with 5–30% ash content, although it is possible to achieve lower levels. They use gravity separation methods on coarse to small coal lumps, in equipment such as jigs, dense-medium baths and cyclones. Fine and ultra-fine particles cannot be separated using density separation methods alone. Spirals use density and size for finer particles and flotation uses the difference in wetting properties of coal and the minerals present. Physical beneficiation has low cost and low environmental impact, apart from the volume of waste which may be generated.

Chemical beneficiation uses chemicals to remove minerals from coal, producing, under the right conditions, a coal with ~0.2% mineral content. However, it can be associated with corrosion, it involves high cost, and the chemicals used can contaminate the coal which is produced.

The mineral matter content in coals varies greatly, not just in quantity, but in type, size ranges and how widely dispersed the particles are in the coal. Therefore the beneficiation processes used depend on the coal and on the product specification required – thus each coal beneficiation plant is different. Most coal preparation plants beneficiate black/bituminous coals.

4.2.3 CWF production

The following steps were taken to produce CWF from lump coal;

- grinding the coal to 6–7 mm using ball mills;
- physical or chemical beneficiation;

- micronisation to <10 microns using ball mills;
- dewatering to reduce excess water content using centrifuges, mechanical expression (roller press) or filtration processes;
- formulation – the addition of trace additives to achieve required rheological properties.

Different grades of CWF were produced in this US DOE-funded R&D programme, with ash levels ranging from 1–3% using physical and chemical beneficiation methods. Physical beneficiation methods included froth flotation, selective agglomeration and dense medium separation. Chemical beneficiation methods used solvents. In 1985 there were eleven CWF suppliers, but many were out of business by 1988. Energy International, the University of North Dakota, CQ and Otisca supplied CWF from 1988.

4.2.4 CWF viscosity

CWF are two-phase mixtures that exhibit non-Newtonian behaviour. CWF have a non-linear relationship between the shear stress and shear rate; in other words, the viscosity is variable. Generally, CWF exhibits a shear thinning from 1–30 s^{-1} and a relatively constant viscosity from 30–1000 s^{-1}. The low shear rheology is advantageous for storage (high viscosity at no shear) and advantageous for transport through piping systems (shear thinning at low shear rate). CWF with larger particles exhibited shear thickening tendencies beyond 1000 s^{-1}, but the CWF with smaller particles exhibited constant viscosity beyond 1000 s^{-1}. The viscosity is dependent on mass loading, the particle-size distribution and the shear rate. Generally, as the coal mass loading approaches 50% the apparent viscosity increases dramatically. Naphthalene ammonium sulphate or formaldehyde additives were used as a dispersant to reduce viscosity.

4.2.5 Fuel storage

Once stored, the coal particles in CWF will settle with time. Stabilising additives, such as Xanthan gum, can be used to reduce this settling rate and is effective for medium-term storage. However, long-term storage will require periodic mixing or agitation.

Long-term storage of CWF in a stationary tank was demonstrated by SWRI and the Japanese Coal Water Mixture programme in the 1980s and 1990s. Using a floating intake, CWF was taken from its highest point in the storage tank, and pumped back in through recirculation exit holes in the bottom of the storage tank, so that two counter-rotating eddies ensured thorough mixing. Computational fluid dynamics computer software was used to design the storage tank. The recirculation pumps used were adapted from progressive cavity pumps and air-driven intensifier pumps (used to spray paint); the latter pump performed the best. This system worked for two years at full-scale with CWF that contained 51% coal, recirculation exit holes that produced a certain flow (Re x H = 5.7) and a 15 minute on/off recirculation cycle. The pumping shear rates must be kept low to keep energy consumption down. Cooper-Bessemer also demonstrated two years of CWF storage in a 27 m^3 storage tank.

4.2.6 Test engines

During 1978-85, Cooper-Bessemer, GE and GM worked on single cylinder, pilot-scale, coal-fuelled diesel engines. Cooper-Bessemer conducted pilot-scale demonstrations on one cylinder of a cogeneration engine. GE and GM conducted pilot-scale tests on one cylinder of their diesel-electric engines for train locomotives. The Cooper-Bessemer and GE test engines were medium-speed, four-stroke machines with shallow pistons, low swirl rates, direct injection with a centrally-located injector, turbo-charged, and intercooled with electronic start. The GM Electro-Motive Division 567 was a medium-speed, two-stroke train engine with port scavenging, centrally located direct injection, shallow pistons and four exhaust ports. SWRI worked simultaneously with GM and Cooper-Bessemer.

In 1985, detailed feasibility studies for full-scale demonstration engines were completed. GE found that physically beneficiated CWF, which was half the price of diesel fuel at the time, could be used in adapted four-stroke diesel engines, with a payback period of ~10 years. The main adaptions were the fuel injector and harder wearing engine components for longevity (cylinder liner, piston rings and exhaust valve). Cooper-Bessemer reached similar conclusions. In 1988, Cooper-Bessemer and GE received more funding to progress to full-scale demonstration.

GM followed the route of firing chemically beneficiated CWF, as firing physically beneficiated CWF required substantial re-design and adaption of their two-stroke engine. The chemically beneficiated CWF was higher-cost than physically beneficiated CWF, which led to payback periods of >10 years and subsequent project termination.

In 1992, GE operated a high-speed (1050 rpm), twelve-cylinder (229 mm stroke x 267 mm bore), 2.28 MWe engine fitted on a Dash 8 locomotive on their test train-track (*see* Figure 5).

Figure 5 GE's Dash 8 train locomotive (Wikipedia, 2014)

In 1993, Cooper-Bessemer demonstrated technical viability on a medium-speed (400 rpm), six-cylinder, 1.8 MW, LSB engine. An additional advantage of the Cooper-Bessemer engine is that, if waste heat from the diesel engine exhaust cannot be used in a district heating scheme or for any other process, then it can be used to generate steam for a steam turbine-generator.

During 1978-85 SWRI briefly worked on a Detroit Diesel engine (series 71). In the early 1990s, SWRI adapted a Detroit Diesel 800 kW mine haul truck engine (series 8V-149) and successfully ran it on CWF. The engine was high-speed (1900 rpm), two-stroke, two pistons (146 mm bore by 146 mm stroke), with port scavenging, centrally located direct injection, shallow pistons (Mexican hat shape) and four exhaust ports.

4.2.7 Injectors

The fuel injection systems were designed to prevent settling, and subsequent clogging, by ensuring laminar flow and a consistently high velocity with the use of smooth pipes, no dead volumes or rapid changes in flow area. As fuel injectors require high precision at close-tolerances, wear from coal, ash and dirt can cause significant problems, so hardened materials must be used to reduce wear rates.

After injection, rapid ignition is critical for engine operation. A pilot injection of some diesel fuel can minimise ignition delay. High pressure injection is needed to create small droplets to allow complete combustion within the residence time available (<5 ms). The wear on the nozzle creates lower pressure injections which starts a sequence of phenomena which lower performance and can destroy an engine within hours of operation. The following list describes what happens: low pressure injection – poor atomisation – large droplet size – low air/fuel mixing – slow ignition – incomplete combustion – fuel spray reaches cylinder walls – low power – unburnt coal and ash deposits on cylinder walls – movement of piston severely wears cylinder walls and ring jamming can seize the engine. Standard soft carbon steel fuel injector nozzles have a practical life-time of just five hours with CWF. Therefore, hard nozzles are required for fuel injector longevity. Additionally, the spray profile of CWF must avoid contact with the cylinder liner to minimise incomplete combustion and contamination of the engine oil, which wears the cylinder liner, piston rings and exhaust valve.

After several tests it was clear that the CWF must be physically separated from the barrel and plunger assemblies of the injection system. SWRI collaborated with Cooper-Bessemer, GM and Detroit Diesel to develop a reliable shuttle-piston-nozzle fuel injector (*see* Figure 6). Based on a conventional pump-line-nozzle injector, a shuttle-piston-nozzle injector has a piston installed in the injection line between the pump and nozzle. The section between the injection pump and the shuttle piston is filled with diesel fuel that acts on one side of the shuttle during the injection cycle. As the shuttle goes up and down, CWF is sucked into the nozzle and injected through the orifices in the nozzle into the piston many times per second. A standard hydraulic pump provides high pressure pulses to the top of the injector to operate it.

For longevity, the nozzle is made of tungsten carbide (WC) or nitralloy and coated with titanium nitride (TiN). The nozzle insert is made from WC, cobalt, cubic boron nitride, diamond compact or sapphire. The needle valve seat insert is WC and the needle valve is steel plasma coated with WC.

A reliable check-valve was developed and demonstrated. Located on the side of the injector, its purpose is to deliver a pre-determined volume of CWF into the injector for each cycle. Water, or other cleaning fluids, can be used to wash out the injector to prevent deposition when shut down. The shuttle piston-nozzle injector is sized to deliver 150% of full-load CWF requirement and with a length to diameter ratio of ~1.

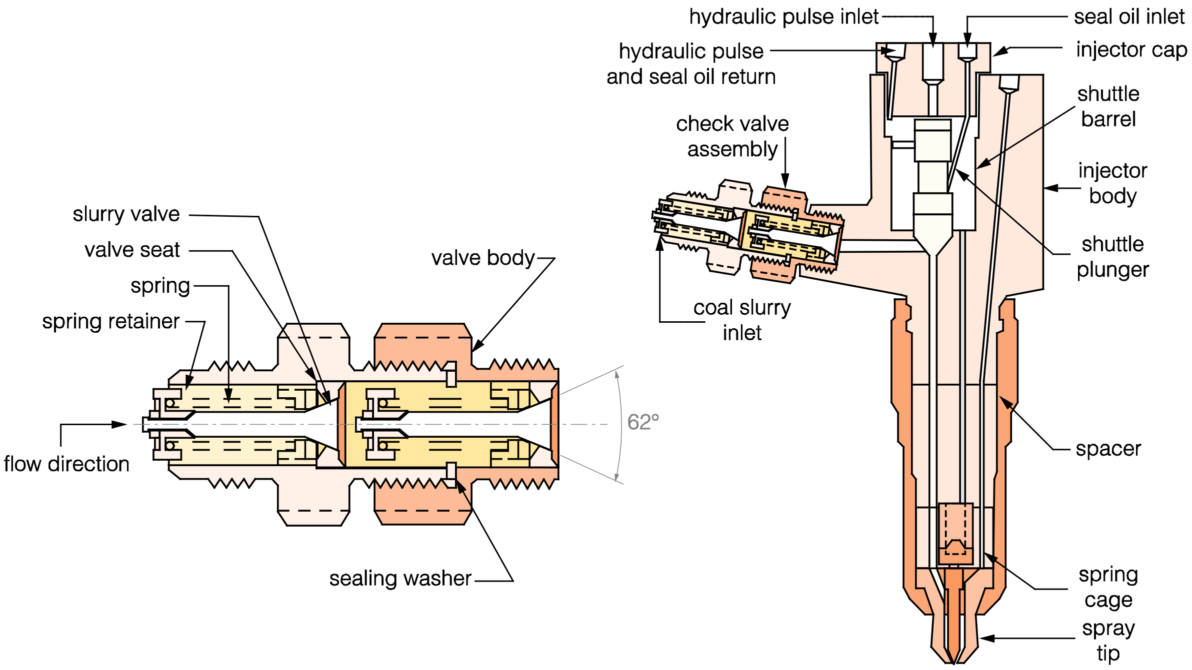

Figure 6 SWRI's shuttle-piston-nozzle injector and fuel check valve (Ryan III, 1994)

GE also developed a positive-displacement injector that uses a free piston. For longevity, the piston was made entirely of WC and the nozzle was re-designed to accommodate carbide seats and compact diamond orifice inserts (0.4 mm or 400 microns in diameter). All free piston fuel injectors had a projected life-time of several thousand hours.

In 1987, GE developed an electronically-controlled accumulator injector that used a free piston (*see* Figure 7). This injector had the highest injection pressure of 80 MPa. GE's injector used an electrically-actuated solenoid valve to vary the injection timing and duration, which allowed optimised operation at all engine loads.

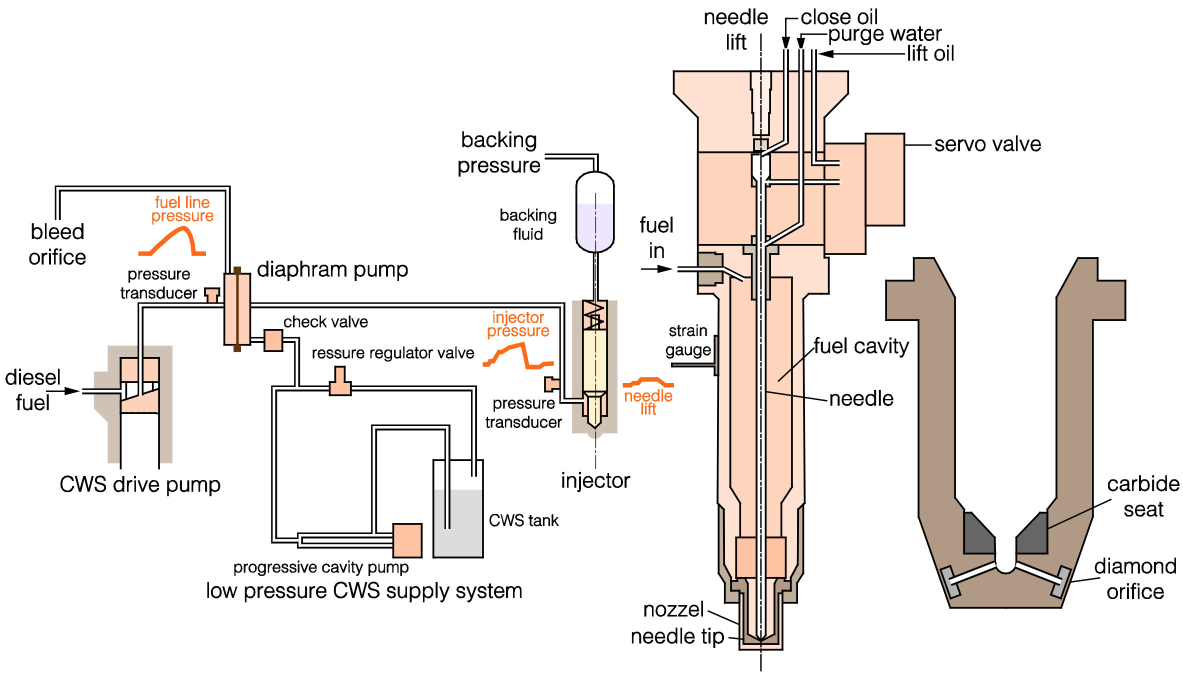

Figure 7 GE's accumulator injector, nozzle and fuel system (Caton and Hsu, 1994)

4.2.8 Combustion

Generally, CWF enters the cylinder at 300 m/s and slows to 20–15 m/s within milliseconds, or 7.5–20 cm prior to impacting in the piston bowl. Higher compression temperatures aid combustion. GE proposed the concept of using a divided chamber, one for injection and one for combustion, which uses thermally insulated surfaces to achieve higher compression temperatures, effective air/fuel mixing and minimal oil contamination. The idea was not pursued as the engine re-design was excessive and combustion efficiencies were already acceptable. Higher compression temperatures can be achieved more conveniently with pilot injection of diesel and less inter-cooling.

For the full-scale demonstration, GE increased the inlet air pressure and temperature as much as possible without exceeding mechanical limitations – up to100°C and 329 kPa. The engine could be operated in compression ignition mode, but pilot injection of diesel (5–6% total energy input) increased combustion efficiency to 99.5%. At high loads the CWF was injected before the pilot diesel injection and at low loads the pilot diesel injection occurred before the CWF injection. The compression ratio was 13:1, the CWF injection pressure was 83 MPa, there were eight holes in the CWF nozzle tip and two holes in the diesel injector and at 1000 rpm there were 500 injections per minute (~8.3 injections per second). GE used high-speed photography in a simulated combustion chamber to examine combustion.

For the full-scale demonstration, Cooper-Bessemer removed the intercooler entirely to increase inlet air temperature (≤135°C) and pressure. Cooper-Bessemer also concluded that pilot diesel injection was required. The set-up was very much the same as with GE, but the low-speed engine operated best with simultaneous pilot of CWF injection at all loads. At 400 rpm there were 200 injections per minute, or ~3.3 per second.

In all of the test engines, the CWF impinged on the piston crown. This was unavoidable and, in most conditions, resulted in further secondary atomisation, which subsequently improved combustion. Diesel acts as an agglomerant for coal, so oil anti-agglomerant Triton X was added when CWF was contaminated with diesel. Figure 8 shows the position of the injectors in the cylinder head of the GE and Cooper-Bessemer engines, with the pilot spray cone and cross-section engine schematic for the GE engine with electronic accumulator injectors.

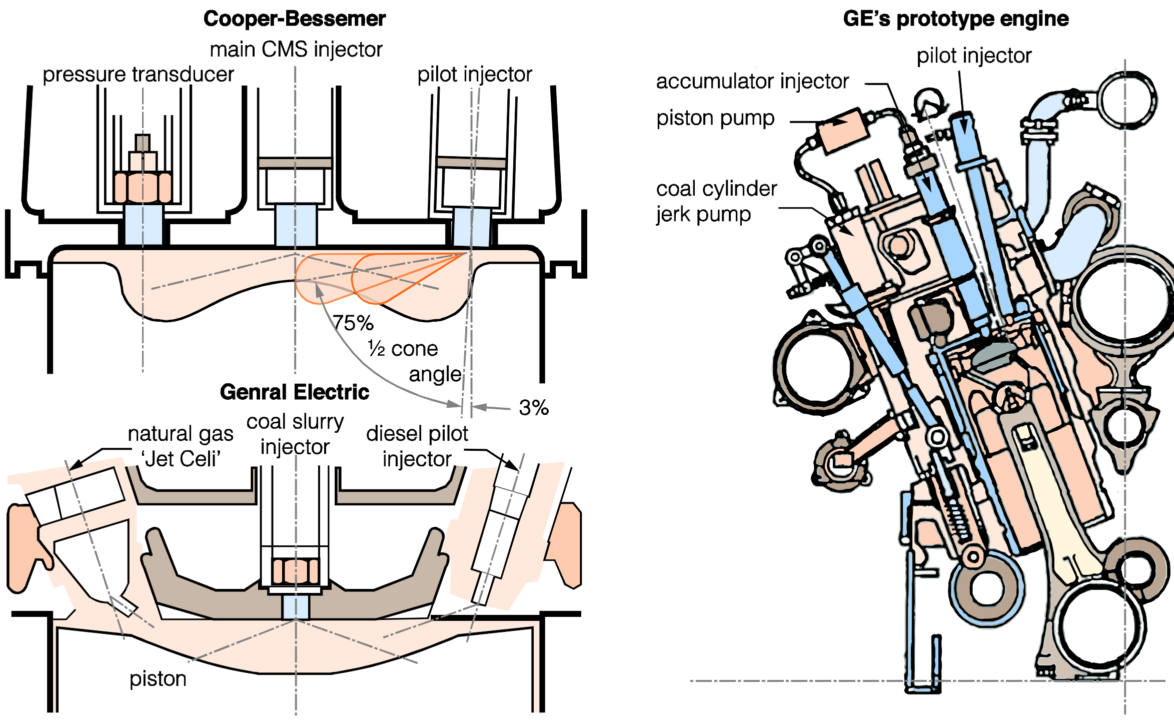

Figure 8 GE and Cooper-Bessemer engine schematics (Ryan III, 1994; ~Arthur D Little, 1995)

For the two-stroke Detroit Diesel engine (series 8V-149), the inlet air temperature and pressure were increased to 125°C and 192 kPa, by closing the blower bypass and stopping the intercooler coolant. Injection timing was varied with engine speed to prevent misfire. The two-stroke engine operated up to 1900 rpm with 1900 injections per minute (~31.6 injections per second).

The combustion process is complex – ultimately the burnout time decides the maximum engine speed. Figure 9 shows the coal burnout times and permitted engine speeds with coal particle size.

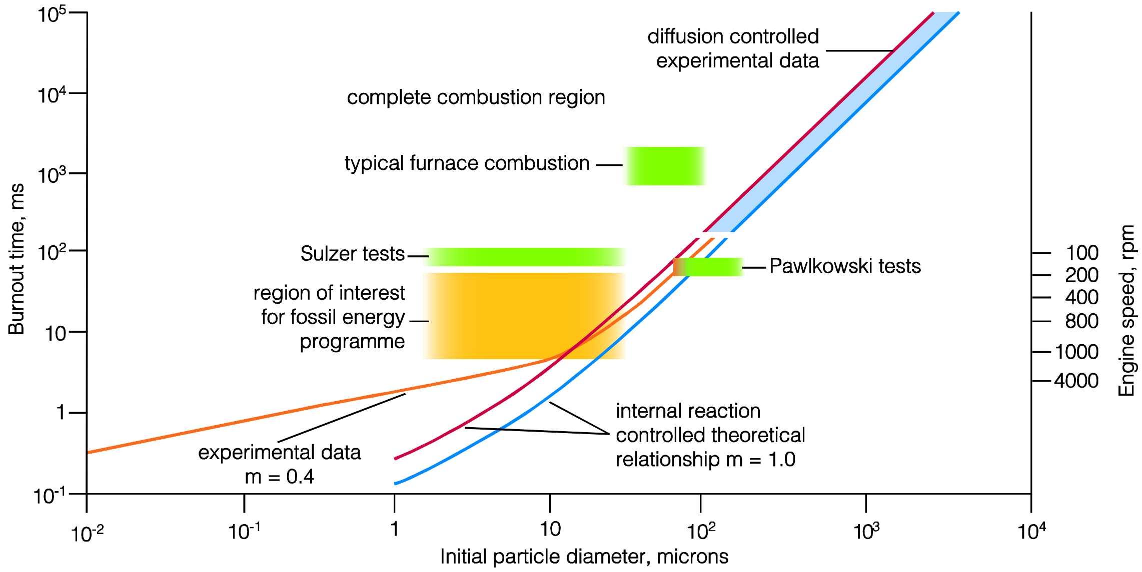

Figure 9 Coal burnout time and engine speed with particle size (Wilson, 2007)

4.2.9 Emission control

Cooper-Bessemer demonstrated a full-scale emission reduction system (*see* Figure 10). It consisted of a cyclone for large particulate removal; ammonia selective catalytic reduction for NOx control, with low nitrogen coals and water in the fuel; sodium-based sorbent injection for SO_2 control, as well as some sulphur cleaning in the fuel production, and fabric filters for sorbent collection and particulate control.

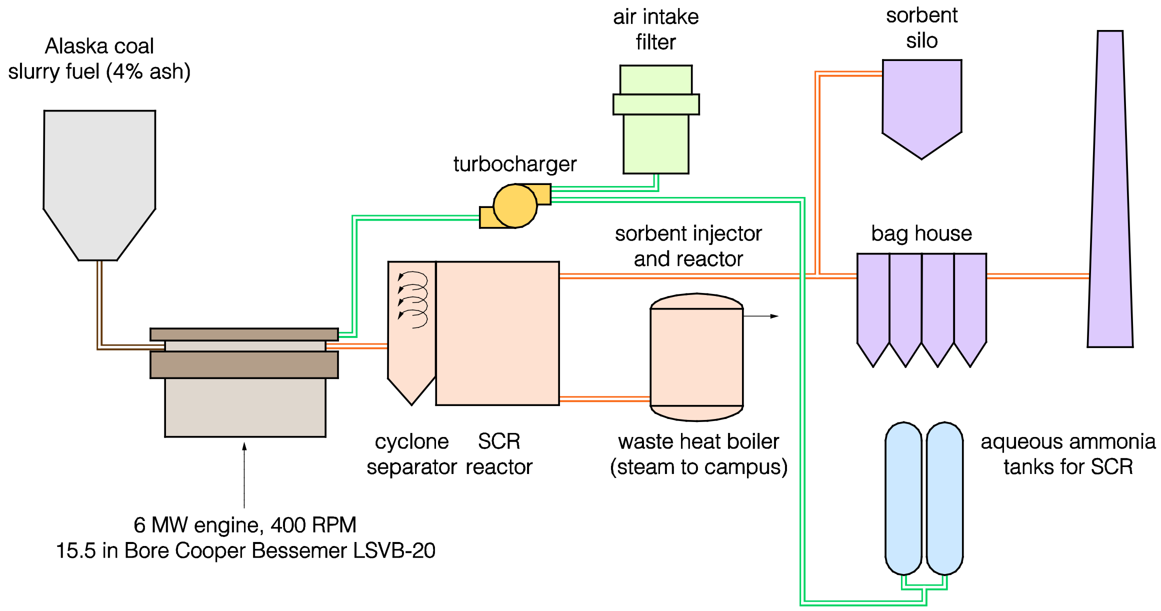

Figure 10 Cooper-Bessemer's coal-fuelled power plant (Wilson, 2007)

GE also developed an emission reduction system with Ca/Cu oxide and ammonia sorbents followed by a metal fabric filter, for the control of SO_2, NOx and particulates. This system was proven on a single cylinder, with 90% SO_2 removal, 85% NOx removal and 99% particulate removal. The system was designed and built in 1992 (*see* Figure 11), but was not operated at full scale.

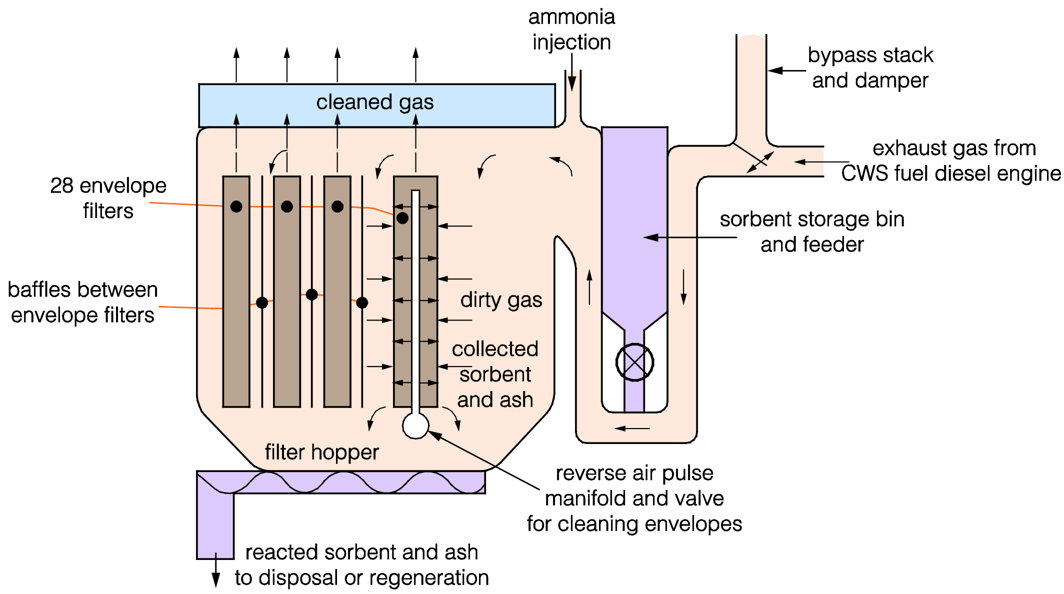

Figure 11 GE flue gas clean-up system (Caton and Hsu, 1994)

4.2.10 Wear

Figure 12 shows that harder materials significantly reduce wear – WC coated materials from the GE and Cooper-Bessemer experiments exhibited sufficient lifetimes. Table 1 lists the durable components developed by Cooper-Bessemer, which are similar to those identified by GE. The lubrication oil used in the Cooper-Bessemer engine contained high amounts of dispersants and was filtered with pleated paper (5 µm pores) to minimise wear. The piston ring life in both demonstrations was 8,000-12,000 hours, which was comparable to diesel fuel at the time.

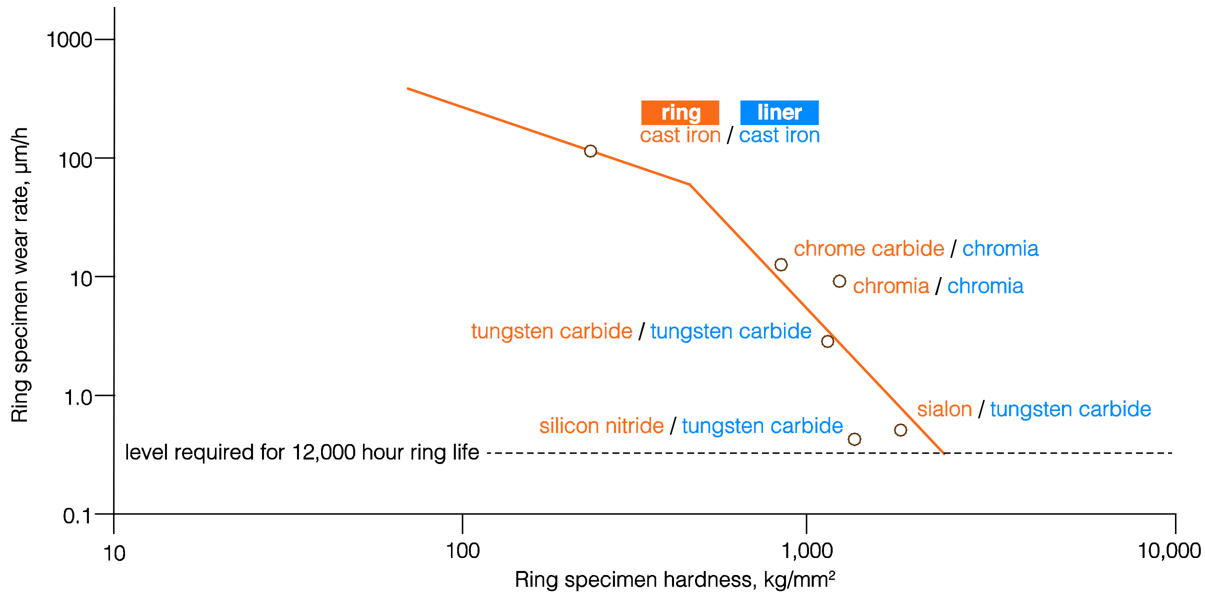

Figure 12 Cooper-Bessemer bench top wear tests (Ryan III, 1994)

Table 1 Durable components developed by Cooper-Bessemer (Arthur D Little, 1995)

Component	Best solution tested	Maximum test time on a single component (h)	Projected life (h)	Target life (h)
Injection nozzle tip orifices	Sapphire inserts	142	>500	500
Injection nozzle valve	TiN steel; monolithic WC tip	142	>500	500
Injection nozzle valve seat	Monolithic WC	142	>500	500
Injection nozzle shutter	TiN steel	400	>500	500
Cylinder liner	WC plasma coating	232	>5000	12,000
Top compression rings	WC detonation gun coating	232	>2000	12,000
Other compression rings	WC detonation gun coating	182	>5000	12,000
Oil control rings	Chrome plate	0	>5000	12,000
Exhaust valves	WC detonation gun coating	181	>500	12,000
Exhaust valve seats	WC detonation gun coating	100	>1000	12,000
Turbocharger rotor and blades	Cyclone plus chrome carbide detonation gun coating	0	>10,000	25,000
Crankcase bearings	Centrifuge	450	In-definite	25,000

4.2.11 CWF specification

The CWF specifications are dependent on engine speed and stroke, and were developed alongside a fuel delivery system. Generally, higher-speed diesel engines have shorter combustion times. For a given amount of atomisation, higher-speed engines require less viscous CWF with a smaller coal particle diameter. Optimum processes for producing CWF from black coal were established.

For a medium-speed (<400 rpm) four-stroke engine, the CWF specification is as follows: the mean coal particle size should be 5–12 µm with a top size limit of 65 µm; sulphur and ash contents in the range of 1-2% each (by mass, wet basis); a coal particle loading of 45–60%; and 200–500 MPa/s at 100/s viscosity.

For a high-speed (400–1000 rpm) four-stroke engine, the CWF specification is as follows: a mean coal particle size of 5–12 µm; a top coal particle size of 15–85 µm; an ash content of 1–2% and sulphur content by of 1–2% (mass, dry basis); and >300 centipoise at 1000^{s-1} viscosity achieved with a dispersant additive.

4.2.12 Results

This R&D programme proved that the most effective method of delivering coal into the cylinder was in a liquid form as opposed to a dust. From >1200 hours of accumulated testing in the Cooper-Bessemer engine, ~200 hours in the GE engine and ~100 hours in SWRI-Detroit Diesel, refined designs for medium-speed (400–1000 rpm), four-stroke engines and provisional designs for high-speed (1900 rpm), two-stroke engines were made. For both four-stroke, full-scale demonstration tests the brake specific fuel consumption when using CWF was comparable to using diesel fuel, the emissions were controlled and there was no fouling. There were no problems with the fuel injectors and the effect of 50% moisture in the fuel on the thermal efficiency of the engine was found to be negligible.

GE faced the challenge of system integration into a locomotive and subsequent control and operation. As Cooper-Bessemer had demonstrated their engine and integrated emission control system, cogeneration seemed the most viable route for commercialisation.

However, the price of petroleum fuels decreased in the 1990s and coal-fuelled diesel engines could not compete. Consequently commercial interest waned, and, combined with a federal deficit in the USA at the time, the coal-fuelled diesel engine R&D programme gradually came to a halt.

4.3 USA: 1994-2006

In 1994, the US DOE awarded a consortium of TIAX, Cooper-Bessemer/Arthur D Little, Fairbanks-Morse and the University of North Dakota's Energy and Environmental Research Center (UNDEERC) funding for a large-scale, long-term demonstration to prove technical viability of coal-fuelled cogeneration diesel engines, provided half of the costs were met by universities and industry. The project cost was $41.6 million, of which the US DOE provided fifty per cent. Both Wilson (2007) and NETL (2007) published reports on the findings, which are summarised in this sub-section.

4.3.1 CWF specifications and production

Table 2 shows the CWF speciation evaluated in previous studies which led to this project.

Table 2 CWF speciation evaluated in tests up to 1994 (% mass, wet basis) (NETL, 2007)

Effect	Coal property	Range tested	Results
Combustion performance	Volatile content	27–41%	Satisfactory
	Rank	Bituminous and subbituminous	Both satisfactory
	Heating value	10,000–15,000 Btu/lb (dry)	Satisfactory
	Particle size	3–20 microns mean 10–85 micron max	Satisfactory
Emissions	Sulphur	0.7–1%	<2% is OK
	Nitrogen	1.2–1.8%	To be decided
Handling	Solids content	48–55%	Satisfactory
	Viscosity	200–400 cP	Satisfactory
Wear	Ash content	0.5–3.8%	<1.8% is OK
	Hard mineral content	–	To be decided

The beneficiation techniques tested in this programme were heavy media separation, coarse and fine flotation, oil agglomeration and chemical methods. Predominantly the coal was milled to 6–7 mm, beneficiated with heavy media separation, and micronised to 20 microns, to produce coal with 2–5% ash.

Chemical beneficiation processes produced <1% ash. A number of commissioning tests in 2001-03 proved that the test engine was ready to run on CWF. A series of tests were undertaken to develop a final additive package, which included Xanthan gum, surfactant and dispersants (0.5–1 weight % each).

In 1990-91, the UNDEERC demonstrated the production of CWF, with 60% coal content and no costly additives, from Alaskan subbituminous coal in a 7.5 t/d pilot plant with the following processes:

- milling;
- physical beneficiation;
- hydrothermal dewatering (UNDERC's hot water drying process), which reduces the moisture in the pores of the coal to increase heating value and enhance rheological properties (*see* section 4.3.2);
- dewatering to reduce excess water content;
- micronisation to an average of 10 microns, with a 65 µm maximum diameter.

Huettenhain and Chari (1997) of the Bechtel Corporation prepared a front end engineering design (FEED) study for a commercial CWF production facility. For a CWF production plant processing 1.5 million tonne of coal per year, the cost was estimated at 0.91 $/million Btu (0.96 $/GJ) with froth flotation and at 1.18 $/million Btu (1.25 $/GJ) with selective agglomeration. There were twelve commercial-sized froth flotation columns and ten commercial-sized selective agglomeration columns. In both cases demonstration of a single train is needed to prove availability, ability to process harder coals and CWF quality.

4.3.2 Hydrothermal dewatering

Water is held in coal in two forms. As moisture on the surface of the coal or in the pores of the coal structure, and as hydrates chemically bound to the coal structure. The moisture in low rank coals (LRC) (lignite, subbituminous coals or brown coal) is found in three forms:

- 44–65% as surface moisture;
- 20–44% in the macro-pores (20–120 nm in diameter) of the coal structure, for which the heat of desorption is simply the heat of evaporation of water;
- 20% in the micro-pores (3–5 nm in diameter) of the coal structure, for which the heat of desorption is higher than the heat of evaporation of water due to hydrogen bonding causing surface bonding forces and capillary action.

Surface moisture can be removed with standard mechanical dewatering techniques; moisture in the macro-pores can be effectively driven away with low grade heat at 110–120°C. Removing the micro-pore moisture is difficult. However, the micro and macro-pore moisture can be removed with hydrothermal dewatering (HTD), also known as densification or upgrading. HTD essentially speeds up the coalification process.

Initially, LRC is beneficiated to remove the majority of minerals and thus minimise any limiting kinetic mechanisms that occur during HTD. The coal is then heated to 200–350°C and >3 MPa, the pressure purely to prevent evaporation, where a few key mechanisms permanently remove pore moisture. The oxygen containing functional groups, chiefly the hydrophilic carboxyl, carbonyl and hydroxyl groups decompose, which renders the coal hydrophobic, and tar is created which fills the pores. The HTD process is illustrated in Figure 13.

The release of water in the liquid phase is essential, as this means the latent heat of vaporisation is not overcome, unlike with liquefaction, pyrolysis, gasification, and, is therefore a low-energy process. As LRC is usually treated in slurry form, the product slurry has excess water. However, this water now contains organic compounds (up to 1.5% total carbon in feedstock) and therefore has to be treated, before being recycled or discarded. Depending on the HTD process, the use of catalysts and feedstock, other products can be produced as well as upgraded coal, such as a type of crude oil (Yujie and Jianzhong, 2011, 2014; Dong, 2011; Couch, 1990, 2002).

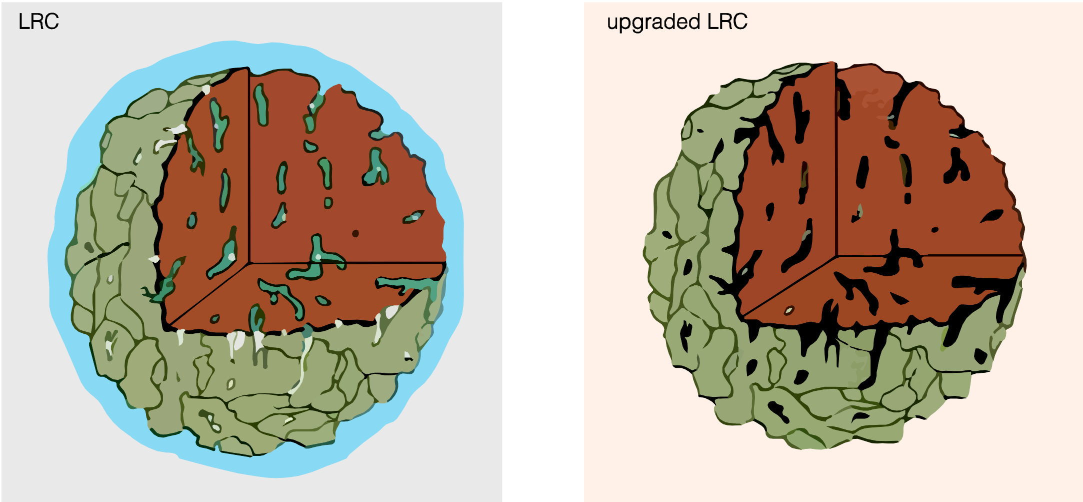

Figure 13 The effect of HTD on LRC (JGC Corporation, 2010)

Many HTD processes have been developed over the last century. Couch (1990) reviews the following HTD processes: the batch Fleissner process (the only one to enter commercial service); Evans-Siemon process; UNDERC's hot water process; Bechtel hydrothermal process; SPC process; IGT process; Koppelman process; WECO process; Hitachi process; Mitsubishi process; Kawasaki Industries' DK process; and Russia's thermal coal process. Dong (2011) reviews the UNDERC's hydrothermal dewatering process.

4.3.3 University of Alaska, Fairbanks: 1994-2003

An eighteen cylinder, four-stroke, medium speed (<500 rpm) 6.2 MWe engine was built by Fairbanks-Morse (Pielstick Model PC-2.6) for long-term demonstration (*see* Figure 14). Large four-stroke medium-speed (<500 rpm) diesel engines are well developed and are used for distributed 1–20 MWe power plant with 39–49% electrical efficiency (HHV) (Henderson and others, 2005).

Figure 14 Pielstick Model PC-2.6 (Wilson, 2007)

The original host site in Easton (Maryland) withdrew from the project, so in 1998 the engine was re-sited to the University of Alaska, Fairbanks. The test engine was then adapted to fire CWF using injectors and hardened engine technology developed by Cooper-Bessemer. Cooper-Bessemer's CWF injector was re-designed to suit the Fairbanks-Morse engine (Figure 15), to accommodate a proximity pickup and a pressure transducer, and modified with a smaller shuttle mechanism, enhanced pressure amplification system and WC coated shuttle and oiler pistons. Initial wear problems with the shuttle piston and shuttle bore were resolved. Fairbanks-Morse used two nozzles, one monolithic ceramic nozzle and one based on Cooper-Bessemer's original hardened nozzle design. The sapphire tips showed some wear after 263 hours of operation. The check valve used the same design with stronger and harder materials. The exhaust valve was made up of a nickel alloy (Inconel 750) head and chromium carbide coated steel (AISI-3100) stem. WC coated steel piston rings exhibited two orders of magnitude less wear than standard steel piston rings. WC coated cylinder liners showed negligible wear after 263 hours of operation. A selective catalytic reduction system and fabric filter were installed in 2000 and commissioning test were conducted from 2001-03 using diesel.

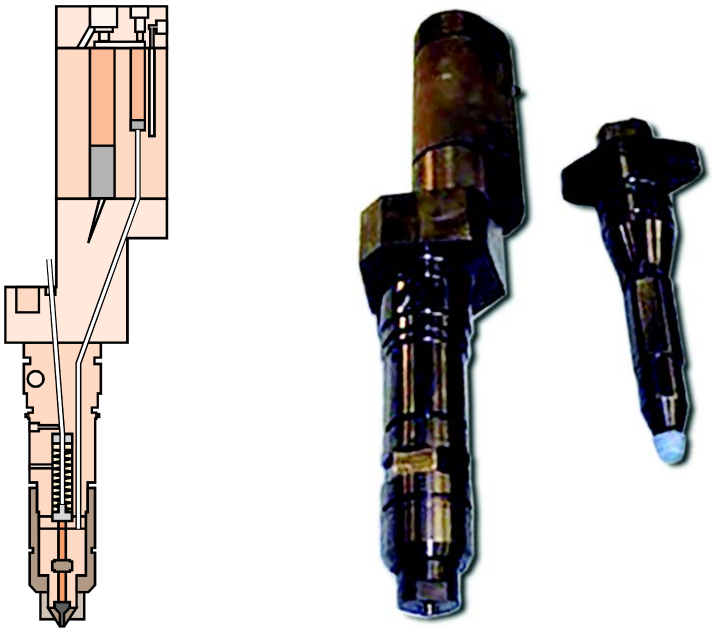

Figure 15 Fairbanks-Morse CWF injector and pilot diesel injector (Wilson, 2007)

In 1998 plans were made to process five tonne per hour of Alaskan subbituminous coal (from Usibelli Coal Company) into CWF using UNDERC's hot water drying process. A detailed front end engineering design (FEED) study was completed with a parts list and process and instrumentation diagrams (P&ID). However, as the design for the CWF production plant progressed the estimated cost exceeded the budget allocation, so it was not constructed. No other companies could process Alaskan subbituminous coal into CWF due to the specific production process, so the engine was not run on CWF at the University of Alaska, Fairbanks. This is a good example of the chicken or the egg causality dilemma. Without CWF, the engine cannot be demonstrated, and without the engine, the CWF cannot be demonstrated. Therefore, to successfully commercialise coal-fuelled diesel engines, the fuel and the engine must be developed simultaneously.

4.3.4 Cooper Bessemer: 1996

In 1996, Cooper-Bessemer operated their medium-speed (400 rpm), four-stroke, six-cylinder, 6.2 MW, LS engine at their test facility in Mt Vernon with CWF made from coal from Ohio. The engine run was successful and the amount of pilot fuel was reduced. Cooper-Bessemer withdrew from the project as they ceased production of diesel engines in 1997.

4.3.5 Fairbanks-Morse: 2003-06

As no CWF could be sourced by the University of Alaska, Fairbanks, the project was relocated to Fairbanks-Morse's test facility in Beloit, Wisconsin in 2003. The test engine was changed to an almost identical two cylinder engine, the Fairbanks Morse model PC2. The CWF used was made by UNDEERC with Alaskan LRC (Usibelli Mine). The CWF specification used was as follow: 47.7% coal loading; energy content of 24.7 MJ/kg; a stabiliser content of 32 g Xanthan Gum; and a slurry density of 1.1 g/ml. Cooper-Bessemer's 1.8 MWe emission reduction system used in the previous project was re-commissioned at Fairbanks Morse test facility for the engine runs in 2003-04, and safety features were designed to prevent fabric filter fires. A FEED study was completed for an improved emission reduction system with heat recovery and silencing (*see* the process flow diagram (PFD) in Figure 16).

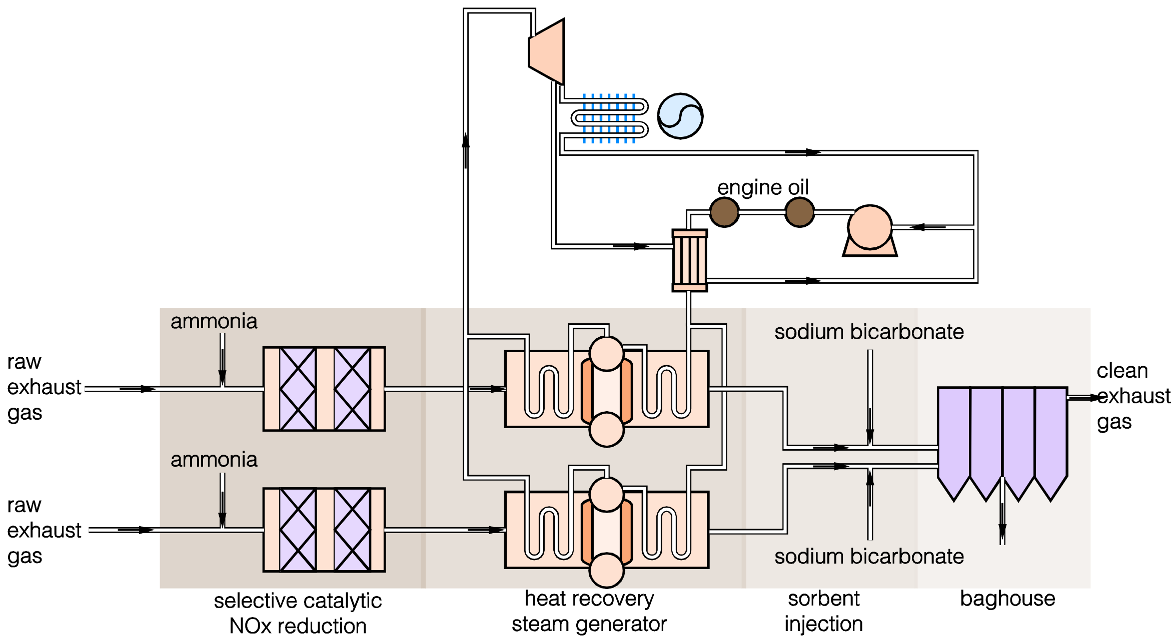

Figure 16 PFD of emission reduction and heat recovery systems by Fairbanks-Morse (Wilson, 2007)

The two cylinder test engine was successfully operated on this CWF in April 2004 for one hour and nine minutes with the following results:

- the special CWF injectors functioned well;
- the CWF fuel ignited and burned well with no cylinder deposits;

- engine efficiency was as expected, a small drop in efficiency was observed relative to using diesel fuel;
- emissions were low. At 25% engine load the NOx emissions were 150 ppm. The equivalent conditions for diesel fuel would create NOx emission at 430 ppm. The selective catalytic reduction unit would reduce these NOx emission by 80–85%, resulting in around 30 ppm NOx emissions for CWF, which is well below the required standards for coal fired power plants at the time;
- Fairbanks Morse gained the know-how to build and operate a diesel engine burning CWF.

In 2006, the capital cost for a 6 MWe coal-fuelled diesel engine was estimated at US$5.2 million (~150% the cost of a standard engine). The projected levelised cost of electricity (LCOE) for coal-fuelled diesel engines over a 20-year period was 7.6 ¢/kWh, which competes with natural gas at 7.3 ¢/kWh (diesel engines were 13 ¢/kWh). The total CWF cost must be kept below US$3.7/$GJ_{FUEL}$ and the total emission reduction system costs must be kept below US$2.64 GJ_{FUEL}; these economics make chemical beneficiation economically unviable. The maintenance costs are more than double those of a standard diesel engine at 0.52 ¢/kWh, since the frequency of component replacement and the component cost are both higher. At the time the potential market for CWF was estimated to be 60 Mt/y, or 1% of world coal consumption, which equates to 30 GW power generation capacity, or 0.8–1.2% of world power generation capacity.

The next step was to be demonstration with a 6000 hour full-scale engine run time over three years. However, with funding and site issues and decreasing gas prices, the coal-fuelled diesel engine project was eventually cancelled in April 2006. Research interests shifted to advanced gas utilisation technology.

5 CSIRO: 2008 onwards

Interest in coal-fuelled diesel engines increased with a demand for flexible (especially the ability for rapid start/stop, as well as fast ramping), secure and clean power generation (with overall lower costs for carbon capture relative to conventional power generation technologies) coupled with technical advances and higher gas and oil prices. Technical advances since the US DOE coal-fuelled engine R&D programme include the availability of large and efficient mills for producing micronised coal, developments in froth flotation beneficiation, the availability of larger and lower-cost diesel engines, electronic engine management and new materials of construction.

In 2008, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia started laboratory experiments to revitalise the development of the coal-fired diesel engine. This work has focused on producing micronised refined carbons (MRC), which is a higher quality fuel than CWF, from coal and other carbons for use in adapted low- to medium-speed (<500 rpm) diesel engines, known as direct injection carbon engines (DICE).

5.1 Direct injection carbon engine

The US DOE coal-fuelled engine R&D programme worked on two-stroke engine. CSIRO are investigating two-stroke engines, as well as four-stroke engines.

5.1.1 Two-stroke diesel engines

Large two-stroke, low-speed, diesel engines are used to power cargo ships. Figure 17 shows the Emma Maersk, the world's largest container ship in 2014. The Emma Maersk was built by Odense Steel Shipyard in Denmark and is owned by the A.P. Moller-Maersk Group.

Figure 17 Emma Maersk (Logistiikka Verkko, 2014)

The Emma Maersk is powered by the Wärtsilä 12RT-flex96C (*see* Figure 18). This 2300 tonne engine has 14 cylinders (0.965 m bore x 2.49 stroke) and is capable of delivering 81 MWe (108,000 horsepower) at 49% mechanical efficiency (Logistiikka Verkko, 2014). Exhaust gas recirculation is used to lower emissions and sophisticated waste heat recovery (WHR), using heat from lubrication oil, water jacket, scavenge air water cooling, exhaust gases and condenser, generates 8.5 MWe. A heat recovery steam generator (HRSG) and steam turbine is used, increasing the total efficiency by 5.9% points to 54.9% (Wartsila, 2014).

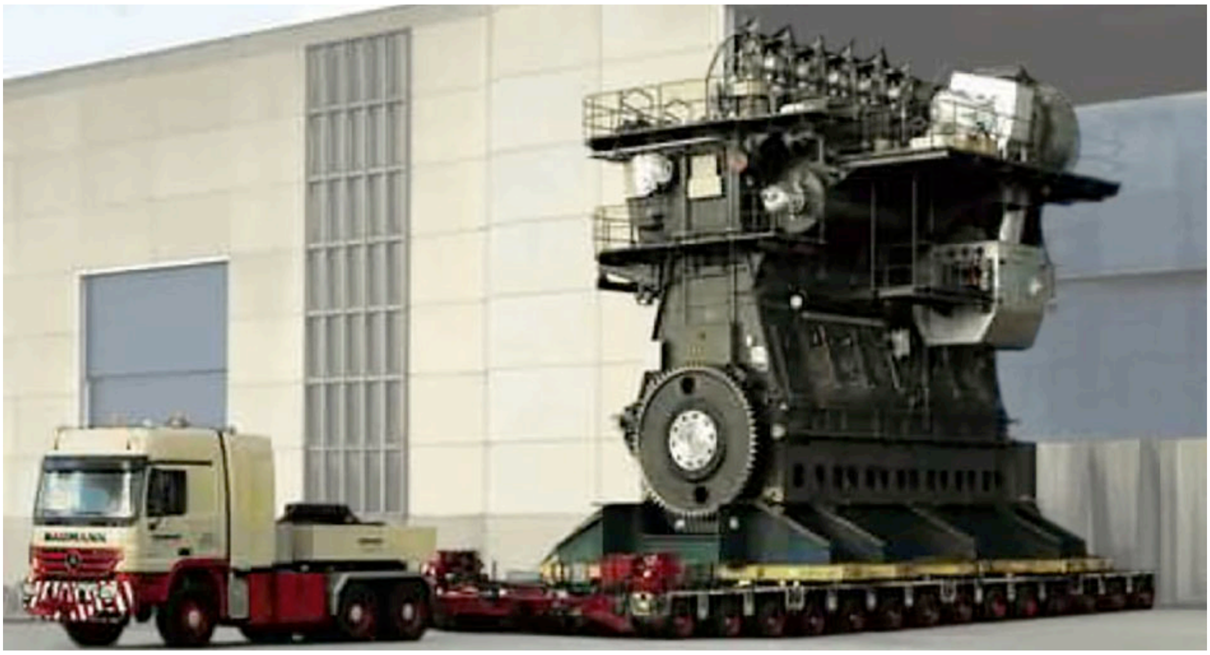

Figure 18 Wärtsilä 12RT-flex96C (Logistiikka Verkko, 2014)

Lower quality MRC, with lower production costs, could be used in large two-stroke engines for the following reasons. Firstly, larger clearances minimise contact with hard particles, which decreases wear. Secondly, longer combustion times allow easier atomisation and combustion, so coarser coal can be used, which requires less micronising. Large 80 MWe two-stroke engines, that reach 54.9% net electrical efficiency, can be used as a template for coal-fuelled diesel engines.

5.1.2 Operation of two-stroke

Two-stroke diesel engines operate on a sequence of combustion and compression strokes; the intake and exhaust strokes happen at the bottom half of each stroke. In the combustion stroke, fuel is injected directly into the compressed air when the piston is near top dead centre and the cylinder is forced down. Towards the end of the stroke the air intake ports are uncovered and the exhaust valves open in the cylinder head. Residual pressure in exhaust gases combined with the pressurised intake air flooding in forces the exhaust gases out of the cylinder. The intake air is pressurised by a turbocharger, which uses energy from the exhaust gases, or a supercharger, which uses energy from the crank shaft. When the piston reaches bottom dead centre (BTC), the exhaust valves close. During the compression stroke, the air intake ports are covered and then the air is compressed (Brain, 2014).

5.1.3 DICE power plant

Diesel engines are currently used for distributed power plant, such as remote mining operations. Diesel engines are also used as back-up services due to their rapid start-up time and black-start capability (electric start). Multiple engines can be placed together to create a single centralised power plant. Modular construction allows 10–100 MWe steps of capacity to be added or taken away as and when required to minimise costs. Diesel engines can be operated in load following and peaking modes, to balance supply and demand on the power grid, allowing high amounts of intermittent renewable energy penetration, such as wind and solar. The world's largest planned diesel engine-based power plant, consisting of 120 units totalling 1000–1100 MW, is in Bahia (Brazil); 355 MWe has been installed to date (Figure 19). The power will be used to balance hydroelectric power and to act as standby-by power during times of low rainfall. Other large engine-based power plants worldwide, using coal, oil and gas, range from 267.2 to 573 MWe (Modern Power Systems, 2011, 2014).

Figure 19 IPP3 573 MWe gas engine power plant (Modern Power Systems, 2011, 2014)

Diesel engine power plants have high part-load efficiency as some of the units can simply be switched off. Additionally, large reciprocating engines can use a combined cycle auxiliary generator, such as a turbo compound generator and/or HRSG and steam turbine, to gain 3–4% points in electrical efficiency. Turbo compounding generates electricity instantly whereas the HRSG and steam turbine combination has a start-up time of roughly 45 minutes.

As the units utilise a common cooling system, engines can be kept warm and quickly hot-started from 0-100% load in 6–9.6 minutes, *see* Section 8.2 for more information. Large engines are also started with compressed air, which enables black start. Another possibility is to build gas engines now with the option to fire MRC, if it becomes lower cost than gas, in the future and vice-versa. This essentially creates a multifuel engine that can run on the lowest cost fuel, which helps to prevent the stranding of assets. Modular construction protects investors from changes in electricity demand or fuel costs and uncertain regulations and policies. This introduces 'economies of modularity' as opposed to the 'economies of scale' that are seen with large coal-fired boilers.

The IEA World Energy Outlook (2013) projects the global growth in coal and gas power plant capacity (*see* Table 3). The demand for new coal and gas power plant is large and DICE could play a significant role.

Table 3 Global electrical capacity from coal and gas (IEA, 2013)

Year	2011	2020	2025	2030	2035
Coal (GW)	1739	2147	2264	2393	2503
Change	–	+408	+117	+129	+110
Gas (GW)	1414	1854	2058	2247	2462
Change	–	+440	+654	+189	+215

ESKOM and various South African mining companies are interested in coal-fuelled diesel engines, especially for the use of distributed generation. The Monolith Group has considered several coal-fuelled diesel engine proposals in the South African region through several partnerships. Newcrest are assessing coal-fuelled diesel engines to replace diesel power at large gold mines. RWE are assessing coal-fuelled diesel engines for balancing renewable power. The Lignite Energy Council in the USA is assessing the use of North Dakota lignite in coal-fuelled diesel engines (Wibberley, 2014c).

There are 1.3–1.4 billion people in sub-Saharan Africa and the Indian sub-continent without access to electricity and in most cases they have coal reserves. Coal-fuelled diesel engines could play a large role in alleviating energy poverty.

5.1.4 Thermodynamics

CSIRO have undertaken a detailed thermodynamic model of MRC-DICE which shows that the negative effect of fuel water (45–50%) on thermal efficiency is smaller than in boilers, and that high thermal efficiency is obtained. It is noted that up to 50% water, by weight of the fuel (equivalent), can be added to diesel fuel or directly injected into the cylinder, to lower the peak flame temperature and reduce NOx emissions. In most cases, the addition of water decreases efficiency by roughly <0.5% points (DICEnet, 2014). If water is added into the cylinder by fumigation of the inlet air, using waste heat for evaporation, then there is a negligible loss in efficiency as the energy consumption of the cooling water pump decreases. DICE is expected to produce electricity at an efficiency of around 50% LHV (48.1% HHV) (*see* Table 4).

Table 4 Efficiency breakdown for DICE (Wibberley, 2013d)

	% (LHV)
Mechanical efficiency of 50 MWe engine on HFO in 2019 (with improved processing and larger engine)	56.7
Percentage change in heat rate for MRC-DICE over base HFO engine	
Fuel processing	–4
Dry coal versus diesel fuel (dry coal has higher theoretical efficiency)	+2
Slurry penalty (MRC normally @ 20°C)	–9
Fuel preheat from waste heat	+1.75
Combustion penalties (due to excess jet penetration, poor atomisation and ignition delay)	Nil with suitable design
Generator and balance of plant	–3
Overall generation efficiency of MRC-DICE	50 (48.1 HHV)
CO_2 emissions on a life cycle analysis basis (kg_{CO2}/MWh)	720

5.1.5 Engine

The US DOE coal-fuelled engine R&D programme showed that the main components to be changed to fire CWF in diesel engines were the fuel system, rings/piston ring grooves, cylinder coatings and exhaust valves/seats.

The use of bitumen water emulsions and slurries in diesel engines provides a good analogue for MRC, to some extent. Over the last 20 years there have been a number of initiatives to produce bitumen water fuels to replace heavy fuel oil (HFO) in boilers, and these fuels have also been used in diesel engines. Such fuels include Orimulsion produced from natural bitumen, and MSAR (multiphase superfine atomised residue) produced from refinery residue (an extremely heavy tar, which is solid at room temperature). MSAR was developed as an Orimulsion replacement, and is really a bitumen-MRC (solid bitumen particles in water). While it is a difficult fuel, giving both poor atomisation and ignition, and contains highly abrasive catalyst fines, it has been used in large adapted diesel engines.

Although the list of adaptions to modern diesel engine remains to be defined (and will be an outcome of the upcoming 1 MWe engine tests by MAN), based on past experience, the modifications could include (*see* Figure 20):

- a corrosion resistant fuel system – conventional steels will rust with MRC (as can be the case for some bio-oils);
- ability to flush the fuel system for shut-down;
- dual fuel system to allow starting and low load operation with the assistance of lighter fuels;
- low intensity agitation of storage tanks (current commercial systems for CWF should be appropriate);
- different fuel pre-conditioning system to enable viscosity trim control by additives or water, and for fuel straining at ~250 µm;
- seal oil protected, hydraulically actuated fuel pump plungers (similar to the latest HEUI type atomisers), to avoid needing to meter MRC directly;
- ceramic cut off valve/seat;
- ceramic nozzle block with nozzles optimised for MRC's unusual high shear flow characteristics;
- ceramic coated rings and lower ring grooves;
- revised lamp black/grunge oil drainage system (cross-head engines);
- upgraded lubrication oil filtration system (four-stroke engines);
- lubricants optimised for solid carbon fuels (probably with lower base number with higher detergency than HFO);
- de-gritting separator upstream of the turbo expander;
- grit removal system for the exhaust ducting;
- heat recovery boiler designed for coal;
- NOx, SOx and particulate removal system designed for coal.

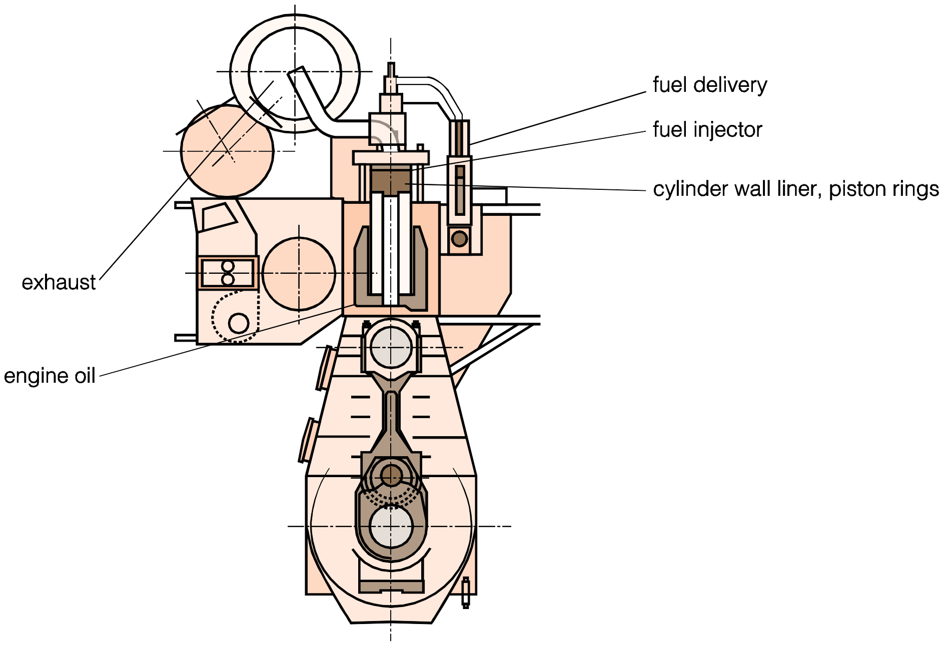

Figure 20 Two-stroke DICE (Wibberley, 2011a, 2013a)

5.1.6 Fouling

During combustion, minerals in coal form complex low melting temperature compounds, which can adhere to metal heat transfer surfaces. The heat transfer through the metal is reduced and the deposit outer surface increases in temperature, which allows ash and unburnt fuel to stick to the deposits, and causes corrosion of the metal through numerous complex mechanisms. This is known as fireside fouling – a summary based on past experience in pulverised coal-fired boilers is as follows:

- fouling is often worse for low ash coals and finer fly ash;
- fouling is usually due to reactive phases formed from a minor component in the coal, either during combustion, or formed in-situ in the deposit;
- temperature-time history is always important – for both the gas and deposit-metal layer;
- flame impingement is always problematic;
- the elements Fe, Na, and Ca are most often associated with slagging and fouling – this is highly dependent on the form of occurrence in the coal;
- fouling precursors have highly non-linear and complex interdependencies that remain uncertain;
- in diesel engines, ash forming constituents in fuel oils and lubricants (Ca, Na, V, S and K) can also cause fouling in the cylinder, exhaust and turbocharger. Fouling will occur with certain ratios of elements, as opposed to quantities. For example, Na: V ratio of 0.1–5 and high Ca: S ratios can cause fouling. For MRC, as the bulk of the ash forming minerals are removed this leads to a higher Na to SiO_2 ratio (exacerbated by the use of Na-based additives to control slurry viscosity), which could cause fouling in DICE.

Fouling cannot be determined accurately by calculations or models, due to its complexity. Only long-term operation in full-scale engines for a specified MRC and DICE type combination can determine fouling behaviour. If fouling becomes an issue, then preventative measures could be taken, which include: further mineral reduction in the MRC production; reduction of metal temperatures; and the use of additives in the lubricating oil and/or the fuel (DICEnet, 2014).

5.1.7 Emissions

There are various ways to reduce emissions:

- diesel engines run with an excess of air, which allows efficient (99%) combustion; emission of unburnt hydrocarbons and CO are inherently low;
- NOx emissions can be controlled by exhaust gas recirculation (EGR). EGR is the recirculation of inert exhaust gases (CO_2, H_2O and N_2) into the cylinder. The inert gases cool the flame, which reduces NOx formation. Between 5% and 10% EGR is likely to halve NOx emissions. If not, then selective catalytic reduction can be used;
- modern electrostatic precipitators can remove 99.81% of particulates and fabric filters can remove up to 99.95%, on a mass basis (Nicol, 2013). Cyclones could meet emission standards;
- low sulphur coals could meet SO_2 emissions limits. MRC can be desulphurised to <0.5% during the coal beneficiation stage with conventional hydro-desulphurisation (HDS) and alternative desulphurisation methods, such as selective adsorption, bio-desulphurisation, oxidative desulphurisation, reductive desulphurisation and chemical and electrochemical reduction (CECR) of sulphur. Or the flue gases can be desulphurised using sorbent injection and fabric filters or conventional wet scrubber flue gas desulphurisation plant using limestone.

5.1.8 Carbon capture

According to Wibberley (2013b), compared to combine cycle gas turbines (CCGT) and pulverised coal combustion (PCC) power plants, DICE assists the deployment of carbon capture and storage (CCS). Firstly, DICE is more efficient than PCC, which means there is less CO_2 produced for a given power load, resulting in a substantially smaller CCS plant and smaller auxiliary load. Secondly, waste heat (which is used for solvent regeneration in CCS) from the air-cooled circuits of DICE (such as the jacket cooling and scavenger air cooling) is available in greater relative quantities and at a higher temperature than that of waste heat from CCGT and PCC power plants. By comparison, significant steam extraction from the steam turbine is required to achieve the heat required for CCS from PCC and CCGT power plants, which substantially reduces the electrical efficiency and increases capital expenditure; significant amounts of steam would not be required for an equivalent DICE facility with CCS. Exhaust gas heat recovery from DICE could power compressors, such as those required in CCS. Running coal-fuelled diesel engines in oxy-fuel mode, with little to zero nitrogen in the combustion gas, could allow lower cost carbon capture. Relatively minor engine modifications would be required, given the current practice of high levels of exhaust gas recirculation with diesel engines. One study estimates that carbon capture (using like-for-like capture technology) is 30–40% lower cost ($/t$CO_2$ abated) with DICE compared to PCC and CCGT (BCIA, 2013).

5.1.9 Water consumption

The most efficient way to cool inland power stations is with river water – on average 2000 litres of water per megawatt-hour is required (L/MWh). However, this is not possible in arid areas of the world, for example, in parts of Australia, India, South Africa and China. Dry cooling is used in such areas. Dry cooling reduces water consumption to 300 L/MWh but has an electrical efficiency penalty of 1–3% to operate the cooling fans. Coastal power plants may have access to sea water cooling. DICE does not need cooling water, as it rejects heat at a high temperature and can employ a closed loop water cooling system. Roughly 300 L/MWh of water is used in MRC production, but the MRC production plant can be located in a water rich area (Wibberley, 2014c).

5.2 Micronised refined carbons

MRC is higher quality than CWF and can be made from any carbonaceous material, such as biomass and biochar. The micronising and beneficiation technologies are commercial, well-known to the coal industry and can be deployed on a large scale. MRC is therefore not subject to intellectual property constraints. Different processing routes for MRC production are in development (Wibberley, 2013a,b).

5.2.1 Micronising

Micronising mills that employ stirred bead mill technology are commercial. The IsaMill has a horizontal configuration, can be scaled up to 8 MWe and produces a suitable particle-size distribution for MRC production (IsaMill, 2013). It is important to note that dry micronised coal is explosive

5.2.2 High rank coal

CSIRO are using the following process to produce physically beneficiation MRC from high rank coal (HRC). HRC includes bituminous and anthracite coals and is also known as black coal:

- either; micronising to <50 µm. Pulverised coal is typically 65-70 µm in diameter and represents 0.2% of the auxiliary load. For MRC it is typically ~15 µm, which represents 0.6% of the auxiliary load and ~60% of fuel production cost (DICEnet, 2014), or utilising coal tailings from a coal beneficiation plant, which contain 40–60% coal fines which are in the desired size range (*see* Section 5.2.4);
- physical beneficiation using froth flotation to remove up to 99% of the mineral content. Froth flotation is efficient and has low energy consumption. Diesel can be used as a coal agglomerant in froth flotation. As HRC can have very low mineral content, then HRC-MRC may have ultra low ash;
- dewatering using centrifuges or a short thickening stage followed by filtration;
- formulation to control the rheology (stability, viscosity and atomisation characteristics).

Figure 21 shows some options for HRC-MRC production. The specific process depends on the feed coal properties. Generally, HRC-MRC has an energy density of ~20 MJ/kg, which is roughly half that of HFO (DICEnet, 2014).

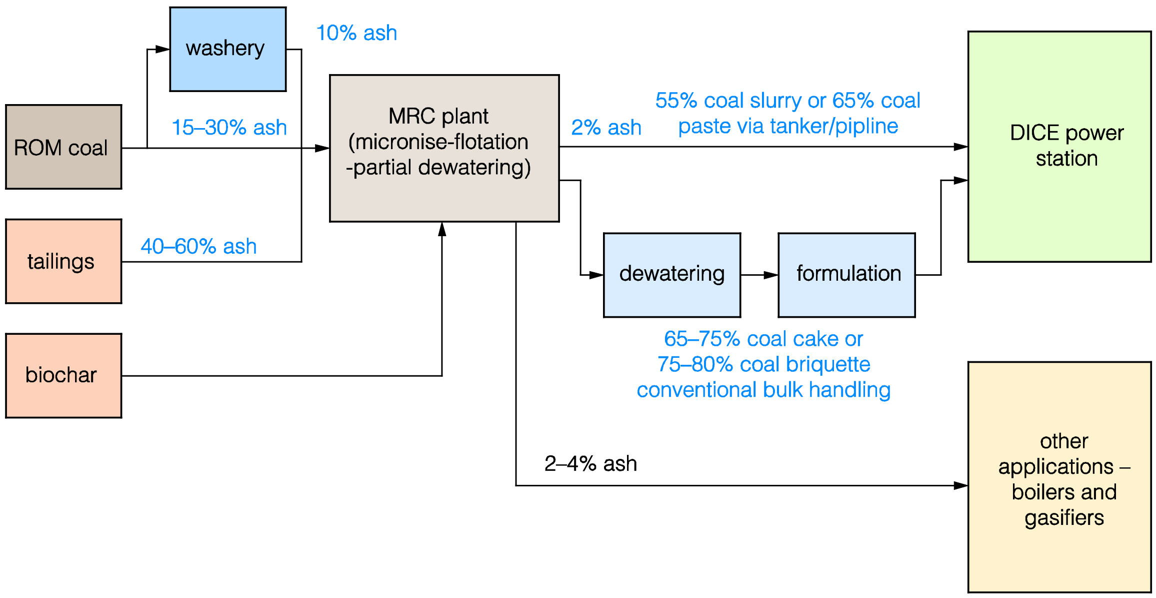

Figure 21 MRC processing steps for HRC (DICEnet, 2014)

Yoon (2009) of Virginia Tech has achieved similar results using ball mills and Microcells. Yoon has also shown that MRC quality fuels can be produced even from the very difficult Indian bituminous coals. Chemical beneficiation processes to produce ultra low ash MRC are also in development.

5.2.3 Low rank coal

Low rank coals (LRC) (lignite, subbituminous coals or brown coal) have moisture contents in the range of 30–70% (dry basis) and are rich in oxygen, 10–30% (dry basis). The ash content of LRC varies widely, with most falling within the range 3–40%. Due to the moisture and ash content, the lower heating value (LHV) of the coal is generally in the range of 4–16 MJ/kg, considerably below that for HRC (Couch, 2002).

In 2012 the global economically extractable lignite reserves were around 283 Gt and resources were estimated at around 4164 Gt. Regions with the largest lignite reserves are Russia (32%), Australia (15.6%), Germany (14.3%), USA (10.8%) and China (3.9%). Regions with the largest lignite resources (economically extractable now) are the USA (32.8%, 1368 Gt), Russia (30.5%) and China (7.4%) (BGR, 2013). As the reserves and resources of lignite are so large, the potential benefits of using low cost LRC to create MRC are significant.

A few proprietary LRC to MRC processing routes are in development for LRC from Victoria (Australia); Figure 22 shows LRC-MRC. These processing routes use beneficiation and HTD to increase the energy density. Such LRC-MRC generally has an energy density of ~15 MJ/kg and significant shear thinning over 0.1–200,000/s (DICEnet, 2014). Victorian LRC contains relatively low ash levels compared to other LRC globally. Further research is needed to clarify whether there are beneficiation methods capable of reducing the ash content in high ash LRC to an acceptable level for use in MRC.

Figure 22 MRC made from Victorian LRC (Wibberley and Wonhas, 2014)

5.2.4 Coal tailings

As shown in Figure 21 HRC tailings can be used as a feed coal for MRC. The ability to process coal tailings in MRC production provides the opportunity to utilise a waste stream as a valuable fuel and removes the need to manage an accumulating waste (Ikin, 2014). Additionally, the beneficial utilisation of HRC tailings provides the opportunity to increase the overall yield of coal from a wash plant while remaining within moisture/ash limits on washed coal product (Oettinger, 2014).

5.2.5 MRC specification testing

MRC specifications include ash chemistry and quantity, stability, atomisation quality, ignition delay, viscosity, volatile burnout time, char burnout time, quantity of hard particles and particle-size distribution of particulate formed. CSIRO have used the following MRC specification tests for their laboratory work (Wibberley, 2011a):

- viscosity is measured over a wide range of shear rates (100–500,000/s at 0–150°C) using both standard instruments and calibrated nozzles. These measurements are supplemented with Zeta measurements to improve stability;
- the formation of abrasive particles is measured from operation of the test engine and SEM imaging of ash from plasma ashing and combustion in a high-pressure spray chamber;
- the fuel atomisation has been measured by direct observation of spray development in a high pressure spray chamber which simulates engine combustion chamber conditions;
- the fuel stability is measured via a number of techniques, including measuring fuel density profiles with depths of fuel stored over a three-month period, with settling behaviour related to Zeta, surface tension, particle size and viscosity measurements.

5.2.6 Transport

MRC has similar rheological properties to CWF, so it is reasonable to assume that MRC can be safely transported, via pipeline, marine tankers and road lorries, and stored in storage tankers. For long distance transportation of LRC-MRC, it could be beneficial to dewater the LRC-MRC to minimise transportation costs. For example, a paste/cake LRC-MRC intermediate can be transported and processed nearer the end-user, using a mixer and additional water and dispersant. Briquetted LRC-MRC would require milling as well as mixing. MRC produced from HRC coal tailings at a coal wash plant would likely be beneficiated near the source, to avoid transporting minerals, and could then be transported by pipeline, rail tankers or road lorries, or shipped as a paste/cake or briquette, dependent on the type of application. HRC can be transported as lump coal and converted to MRC nearer the source, thus minimising transportation costs and storage requirements (DICEnet, 2013).

5.3 Laboratory MRC production

MRC was produced from seventeen different HRC, LRC and coal tailings from Bulga, Wambo, Lithgow, Moolarbin, Loy Yang, Yallourn, Kalimantan, Rhenish coals, and eucalyptus biochar. A small upgraded M4 ISA mill was used to produce micronised coal with <50 μm. The energy requirement was ~65 kWh/t_{COAL}. The performance of various flotation methods were measured using a combination of methods, which included a Universal Flotation Test (UFT) and a laboratory mechanical cell. Figure 23 compares the recovery curve for a range of particle sizes, showing a significant improvement in both ash recovery obtained by micronising the coal before flotation (Wibberley, 2012).

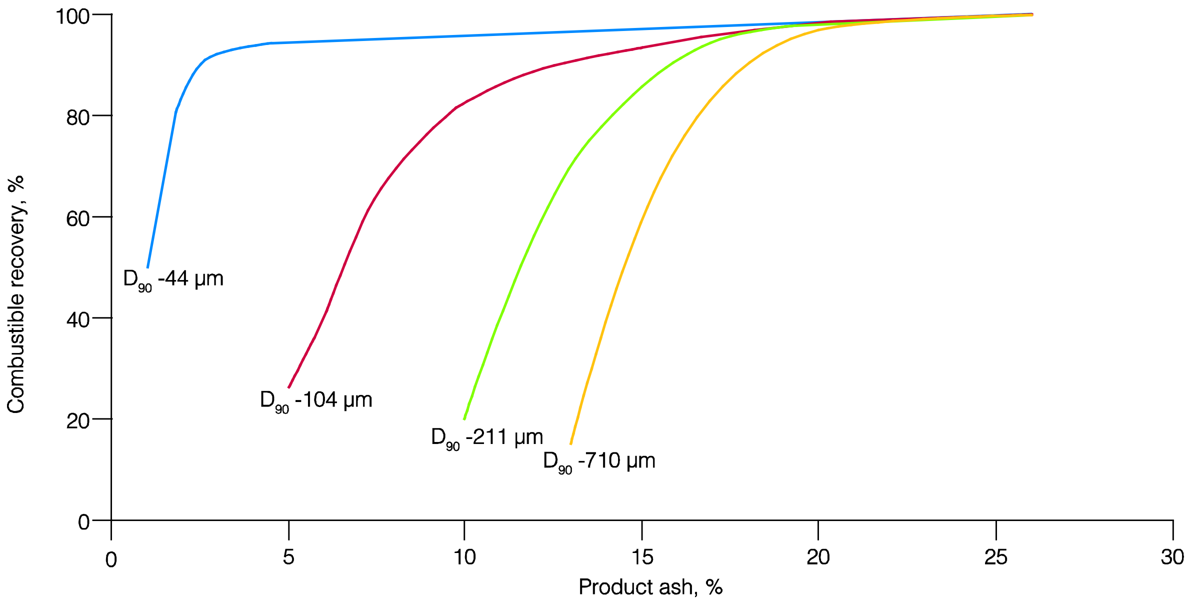

Figure 23 Recovery versus ash curve for flotation (Wibberley, 2012)

Generally, reagent use in the floatation beneficiation methods was low (<<0.3 L/t diesel) and around 30 ppm of frothing additive was required (Wibberley, 2011a). Table 5 shows the additives needed in froth flotation.

Table 5 Additives in froth flotation (DICEnet, 2013)			
Additive	**Rate (kg/t of dry coal)**	**Cost (A$/GJ)**	**Comments**
Diesel	0.1–0.2	0.004–0.009	Rate depends on coal hydrophobicity and extent of micronising
Methyl isobutyl carbinol (MIBC)	0.1	0.006	Low cost as micronising increases froth stability

For bituminous coals a combustible recovery of 85–93% was achieved. A combustible recovery of 85—93% does not mean a loss of 15–7% of the coal, as the higher ash MRC can be produced from current waste streams and the large amount of coal tailings. The combustible recovery was ~65% for a partially oxidised subbituminous coal. Coals from the Hunter Valley produced MRC with minerals mostly 2–3 µm in diameter and all <5 µm, largely consisting of ultra-fine quartz with a smaller proportion of clay (DICEnet, 2014; Wibberley, 2011a).

Figure 24 is a scanning electron microscope (SEM) of the MRC with the coal particles and residual minerals present (Wibberley, 2012). Analysis of the SEM shows that 99% of the minerals can be liberated from coal by micronising followed by froth flotation (Wibberley, 2011a).

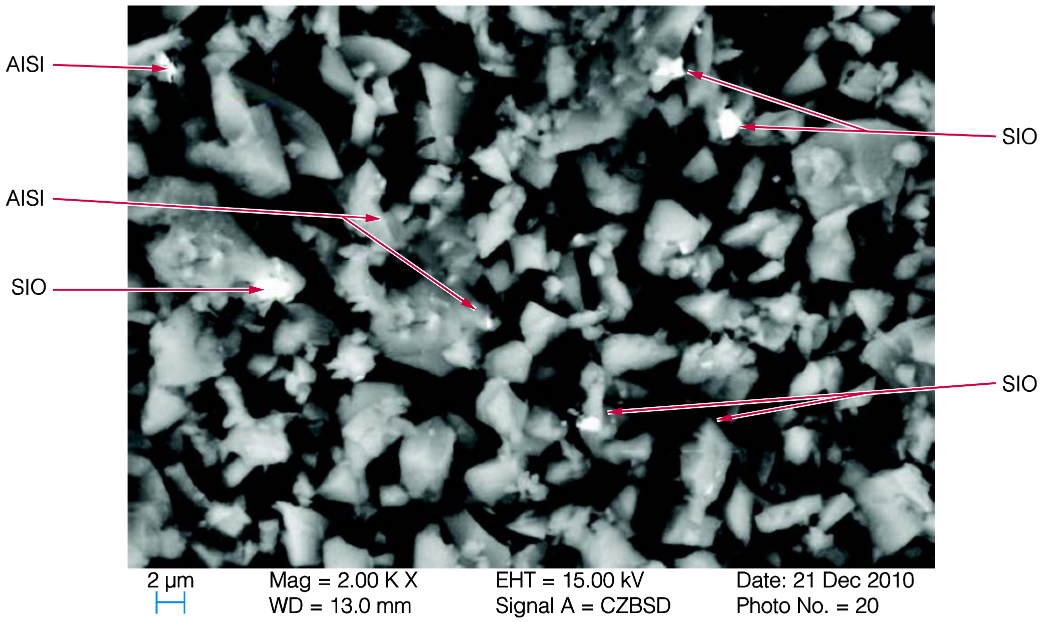

Figure 24 SEM showing minerals in MRC (Wibberley, 2012)

The dispersant requirements depend on coal type, but, typically 0.05–0.5% of dispersant achieves a suitably low viscosity. CSIRO have used a range of dispersants. Most work undertaken used NaPSS produced by LION of Japan (similar to that produced for Japan COM and Joban Power for the 500,000 tonne trial of CWF in the Nakoso power plant up to 2003).

The stability requirement depends on the transport and storage requirement. CSIRO found that MRC is stable for a few months, without the use of stabilisers or agitation, especially for higher concentrations of solids. However if required, MRC tanks can be equipped with low-intensity tank agitators, analogous to HFO (Wibberley, 2011a, 2014b; DICEnet, 2014).

Using bituminous coal (including tailings), the MRC fuel properties are 0.5–0.8% ash (wet), 55% coal, 21 MJ/L (HHV), 200–500 mPa.s (Wibberley, 2012).

5.4 Laboratory DICE testing

5.4.1 Spray chamber

Atomisation and combustion testing of MRC from Australian, German and Indonesian coals, have been undertaken at CSIRO in high pressure spray chambers to evaluate the atomisation (such as the spray angle, the droplet size distribution and the axial jet velocity) and combustion (ignition delay and combustion efficiency) characteristics. The spray chamber has a volume of nine litres, can be pressurised to 200 bar, and it has injectors with interchangeable nozzles (including a blast atomiser), that can inject fuel with viscosities up to 1000 mPa.s at peak pressures of 1200 bar. A high speed video camera captures injection profiles (with laser backlighting) and combustion profiles (Wibberley, 2012).

5.4.2 16 kW DICE

CSIRO have built a 16 kW DICE to gain practical experience with using MRC in DICE. It is based on a direct injection, medium speed (200–800 rpm), four-stroke, naturally aspirated, single cylinder (3814 cc) diesel engine (Indian Lister-pattern) – *see* Figure 25. Some adaptions were made so it operated as a low-speed engine (Wibberley, 2013a):

- replaced fuel injector with a CSIRO developed HEUI-type (hydraulically operated electronically controlled unit injector), which has an injection profile to optimise MRC combustion and to match the heat release of HFO or diesel;
- 300 µm carbide nozzle;
- Stellite coated valves and Stellite seats;
- heavier steel flywheels;
- instrumentation to measure most aspects of engine performance;
- external oil filtration.

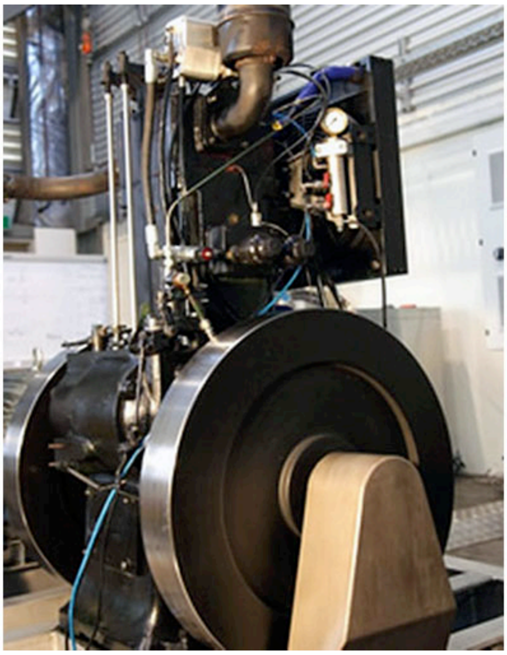

Figure 25 CSIRO's 16 kW DICE (DICEnet, 2014)

A standard lubrication test of diesel fuels used by the American Society of Testing and Materials (D6079-11 using a high frequency reciprocating rig) has been adapted by CSIRO to test wear rates of different materials with lubrication oils contaminated with coal/ash. The temperature of the apparatus can be set up to 150°C, standard SAE-AMS 6440 steel balls and discs are used and the contact pressures can cause scuffing with the best of lubricants. More than 130 tests have been completed to date, which show unusual lubricity benefits of Victorian LRC, and the ability of carbide coatings to eliminate abrasive wear.

5.4.3 Computer models

A quasi-dimensional computer simulation programme has been used to model DICE operation to determine the sensitivity to MRC loading, preheat, blast atomisation and carbon capture. A multi-dimensional model is not presently justified due to lack of fundamental data. The quasi-dimensional model uses a number of sub-models to describe the processes of internal combustion (such as atomisation, evaporation, ignition delay, burnout rate, peak pressure, combustion efficiency) and then continuously evaluates the thermodynamic state of the cylinder charge throughout the cycle. This model has allowed some preliminary research into large engine configurations and adaptions fitted with post combustion carbon capture or oxy-combustion carbon capture (Wibberley, 2011a).

6 Micronised refined carbons

Chapter 6 lists the CWF/MRC producers that are operating demonstration plant and reviews in detail the hydrothermal dewatering process (HTD) processes.

6.1 Coal beneficiation

Physical and chemical coal beneficiation technologies for boiler applications are reviewed and assessed by the following IEA Clean Coal Centre reports, Mills (2014), Baruya (2012), Dong (2011), Lewitt (2011), Nunes (2009), Couch (1990, 1995, 1998, 2000, 2002); Thambimuthu (1994). This sub-section shows the scale of the physical coal beneficiation market. It is expected that coal beneficiation for DICE, with LRC and HRC, will be covered in detail in a future IEA Clean Coal Centre report.

In 2014, MRC is being produced in <1 t/d pilot-scale demonstration plants. However, scaling up the technology should have low technical risk as most of the processes are already deployed commercially at large-scale. In 2006, there were over 2200 coal preparation plants (milling and beneficiation) globally, accounting for around one third of global coal production. A typical US-based coal preparation plant includes circuits for coarse (>10 mm), medium (1–10 mm), small (1–0.15 mm) and fine (>0.15 mm) coal. Figure 26 shows the flow sheet of typical coal preparation plant. In 2006, flotation was the preferred method of beneficiating fine coal in both the US and Australian coal industries. Since the 1990s, pneumatic flotation cells, that incorporate froth beneficiation, are replacing the conventional mechanical cells. Dewatering of fine coal can be achieved with screen-bowl centrifuges, vacuum disc filters and horizontal belt vacuum filters (Bethell and others, 2006).

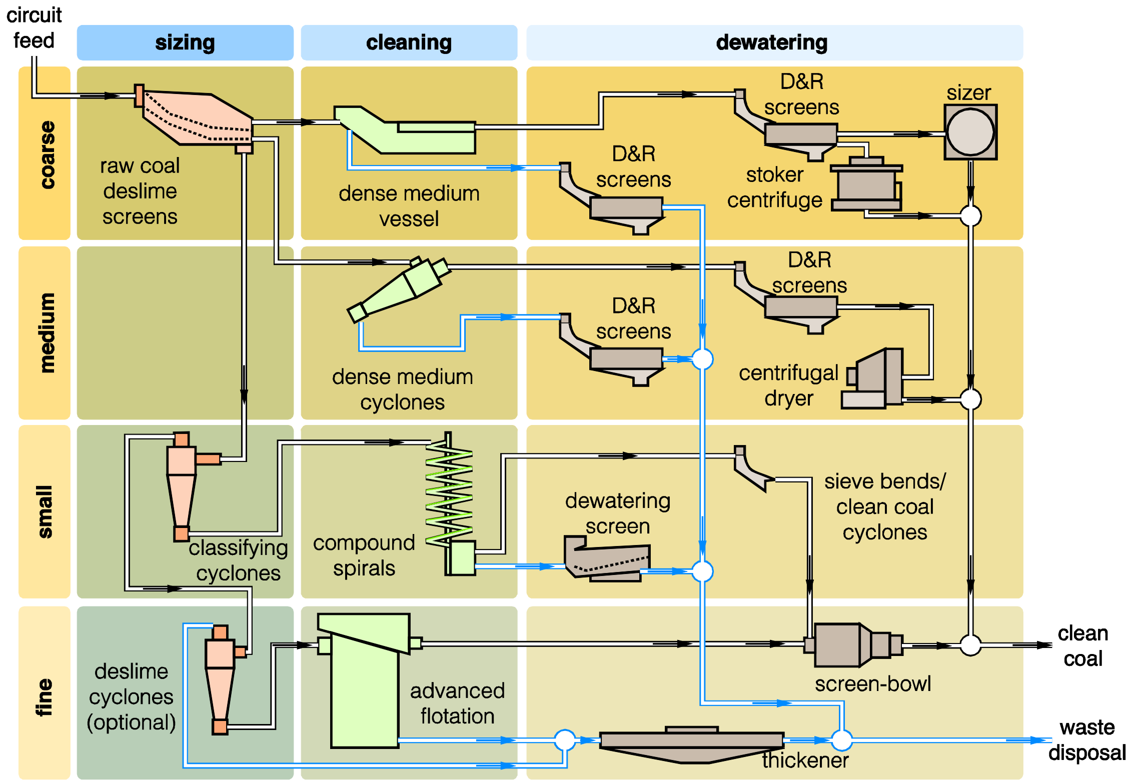

Figure 26 Flow sheet of typical coal preparation plant (Bethell and others, 2006)

In 2012, the production of CWF in China for boilers was >140 Mt and is projected to be >200 Mt/y by 2014. Additionally, 40 Mt/y of CWF is produced commercially for a gasification process in China. The CWF has 5–8% ash, mostly less than 90 ~150 µm, typically 70% coal and 2000 mPa.s @ 100/s (Wibberley, 2012). In 2003, 500,000 t/y of CWF was produced and transported through a 9 km pipeline (350 mm diameter) to fire a 600 MWth boiler at Nakoso power station (12 x 11 t/h burners). China produced 300,000 t/y of CWF, which was stored in 10,000 m^3 tanks, transported 1100 km to Japan in a modified 5000 tonne (dead weight) HFO tanker and again transported 700 km along Japan's coast in a modified 700 tonne (dead weight) HFO tanker (DICEnet, 2013).

In Turkey, >52 Mt/y of coal is beneficiated before transportation to end-users in 45 coal beneficiation plants, with capacities ranging from 50 to 1000 t/h. Figure 27 shows a 500 t/d hard coal beneficiation plant operated by Deka Mining in Turkey. The products have the following fuel specifications, 12–45% moisture, 7–49% mineral content, 0.6–4% S and 6–22 MJ/kg CV. Most lignite preparation plants are based on dense-medium separation processes. Static (drums, baths, vessels) are used to treat coarse coal (+18 mm) and dynamic heavy medium (cyclones) equipment is generally used to treat fine coal (0.5-18 mm). Wet beneficiation processes require a water supply, waste slurry disposal and in some cases fuel dewatering. Dry fluidised bed gravity fines separators are used to reduce ash levels in lignite coal from 40% to 15%. Hard coal beneficiation facilities process between 60 and 300 t/h using heavy media coarse coal beneficiation plant (drum or Drewboy heavy media plant), heavy media fine coal beneficiation plant (heavy media cyclone plant), heavy media gravity feed cyclone plant, spiral beneficiation plant and filtration units for fines (0–0.5 mm). Rotary vacuum disc filters are used for reclaiming slimes. Coal screening/beneficiation plants are modular and therefore only take 4–5 months to fully-assemble and commission (Mills, 2014).

Figure 27 Co-beneficiation plant in Turkey (Mills, 2014)

Figure 28 compares the beneficiation costs with end mineral content (labelled as ash) for chemical and physical beneficiation techniques. The cost of chemical beneficiation processes to produce coals with <1% ash is ~2.5 A$/GJ of coal, whereas the cost of physical beneficiation to <2% ash is 1–1.5 A$/GJ of coal (Wibberley, 2013a). MRC produced with chemically beneficiated coal has higher cost and has higher quality and could be economically competitive when used in high speed engines used in transport and small-scale power generation.

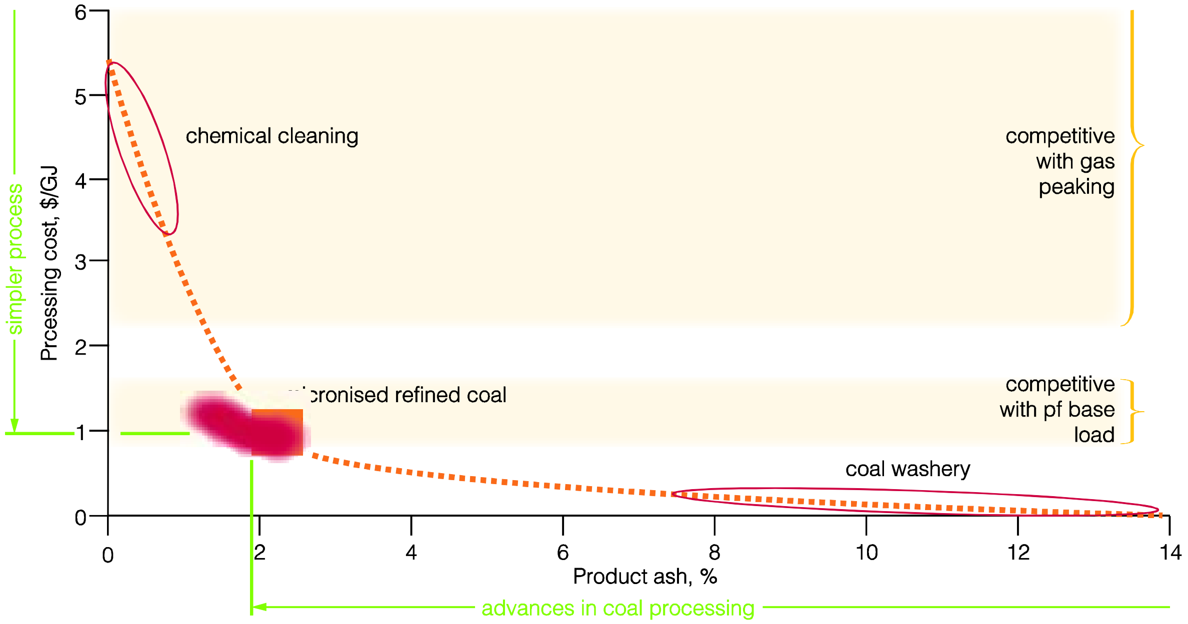

Figure 28 Product ash (dry basis) of coal beneficiation techniques with cost (Wibberley, 2013a)

This chapter mentions the MRC producers with details of the HTD processes.

6.2 Physical beneficiation of HRC for MRC

CSIRO and Xstrata Technology (XT) have partnered to produce HRC-MRC, using the two stage froth flotation process developed by CSIRO. XT is operating a HRC-MRC pilot plant in Bulga (NSW, Australia) that can produce one tonne of HRC-MRC, per day (Wibberley, 2014b). MRC with 2% ash has been made from coal tailings with 54% ash using only low-cost physical beneficiation (DICEnet, 2013). XT subsequently decided to build a commercial-scale plant, targeting initially low ash coal products (Wibberly, 2014d).

6.3 Chemical beneficiation of HRC for MRC

Yancoal produce ultra-clean coal (UCC) MRC with chemical beneficiation on pilot-scale. UCC-MRC contains <0.2% ash. In 2012, Yancoal tested UCC in a modified 1 MWe 6-cylinder EMD two-stroke test engine, located in Cessnock (NSW, Australia). Earlier work with UCC was focused on gas turbines (Yancoal, 2014a,b). Intertech, KIER, AMAX and Kobe have developed chemical beneficiation methods for HRC.

6.4 Upgrading of LRC and biomass

LRC-MRC has been produced successfully by Exergen, IER and JGC Corporation in pilot-scale demonstration plants. This section will assess the HTD processes that can be used to create LRC-MRC. Generally, LRC is beneficiated before HTD.

6.4.1 JGC Corporation

JGC Corporation of Japan started R&D on CWF in the 1980s. From 1992 to 1996, bituminous coal CWF was produced commercially. From 1995-96, upgrading (known as Hot Water Treatment [HWT]) and slurrification technology for LRC-CWF was tested at pilot-scale (350 kg/h) in Japan – this is now branded as JGC Corporation coal fuel (JCF). In 2012, with Japanese subvention through NEDO, a large-scale JCF demonstration plant started operation in Karawang (Java, Indonesia) processing 750 kg/h or 10 kt/y of LRC into CWF – *see* Figures 29 and 30. A commercial plant, of 1 Mt/y, is under construction and is expected to start operation in 2018 in Indonesia. The initial market is for fuelling boilers and furnaces, with expected markets in gasifiers and diesel engines in the future. The PFD of the JCF process is shown below, with a photo of the demonstration plant and JCF-MRC. Initially, LRC is crushed and pulverised to a bimodal size distribution, with a mean particle diameter of 50 mm.

The HWT process immerses the LRC in water at 12–15 MPa and 300–330°C for 30 minutes, which decomposes the carboxylic groups, creates tars which fill the pores and the coal becomes hydrophobic. The combination of these mechanisms permanently expels water from the pores thus increasing the CV. After dewatering, an additive is used to prevent hydrophobic agglomeration and ensure an even distribution of particles. Finally, the JCF is micronised to a mean particle size of 20 microns by a ball mill. Using run-of-mine LRC with the following properties of 40–65% moisture, 10.5–14.7 MJ/kg and a bulk density of 0.7 kg/m³, the JCF produced has 35–40% moisture, mean coal particle size of 20 µm, 16.8-21 MJ/kg, a viscosity of 1 Pa.s (@25°C) and a bulk density of 1.2 kg/m³. The JGC Corporation also have a R&D programme to process peat and biomass into JCF (JGC Corporation, 2014; Tange, 2012; Ueno, 2010).

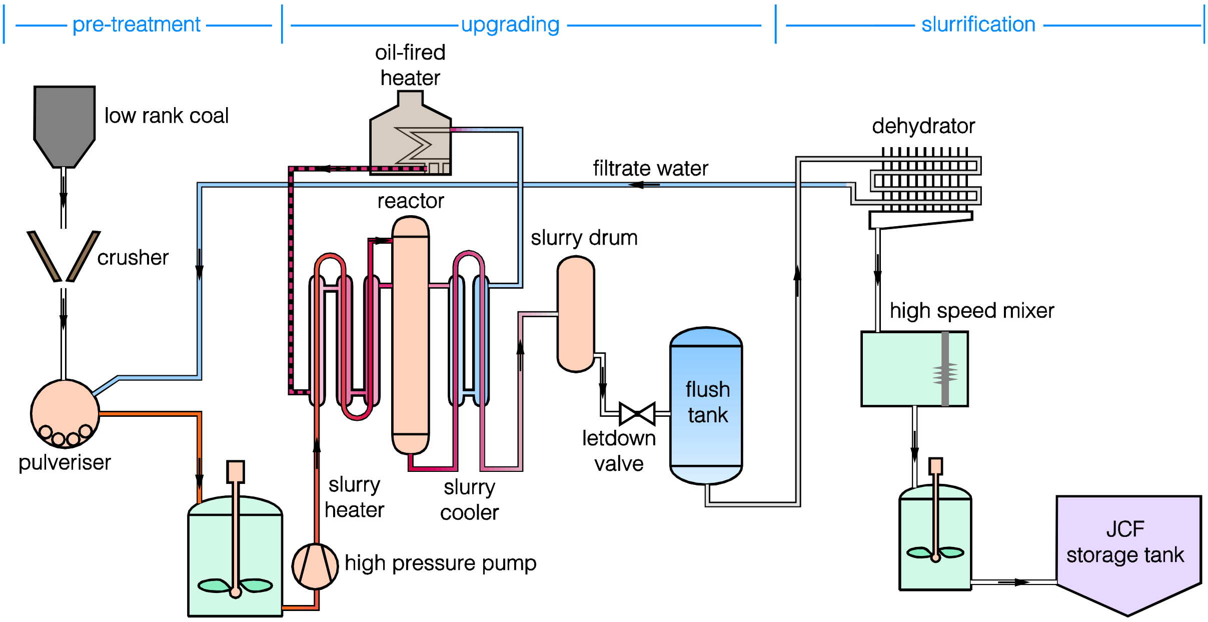

Figure 29 JCF process flow diagram (JGC Corporation, 2014)

Figure 30 Photo of JCF demonstration plant and JCF fuel (JGC Corporation, 2013, 2014)

6.4.2 RWE Power

By the end of 2013, the energy supply in Germany included 35.7 GW of solar power and 33.7 GW of wind power. This changes the traditional base-load, flexible-load and peaking-load energy supply curve. RWE Power are currently investigating whether coal-fuelled diesel engines, using German lignite, could compete with open cycle gas turbines for balancing intermittent renewable energy and supplying peak demand.

Since early 2012, RWE Power have developed paste and liquid CWF, from German lignite, with a high solids content with 98% of the particle diameter <20 μm. Proof-of-concept tests were conducted at an engine development institute, using an adapted diesel engine fuel delivery system and an automotive injector. In these tests, CWF has been injected and combusted in a high pressure combustion chamber, operating at diesel engine conditions. The injection and combustion properties were analysed and displayed complete combustion and short ignition delays. The high volatile oxygen and hydrogen content of lignite favour internal combustion.

In these initial tests, low ash lignite was selected, wet-milled and micronised. The CWF production process needs to be simple, with minimal upgrading and beneficiation steps to be cost competitive. The drawbacks are that engine longevity is compromised, which is less important for peak demand operation, and the engine injection and combustion section will need modifying. RWE Power does not intend to develop the engine technology, but they will co-operate with an engine manufacturer. Figure 31 shows photos of the CWS, part of the CWS delivery system and CWS combustion (RWE, 2013; Stahl, 2014).

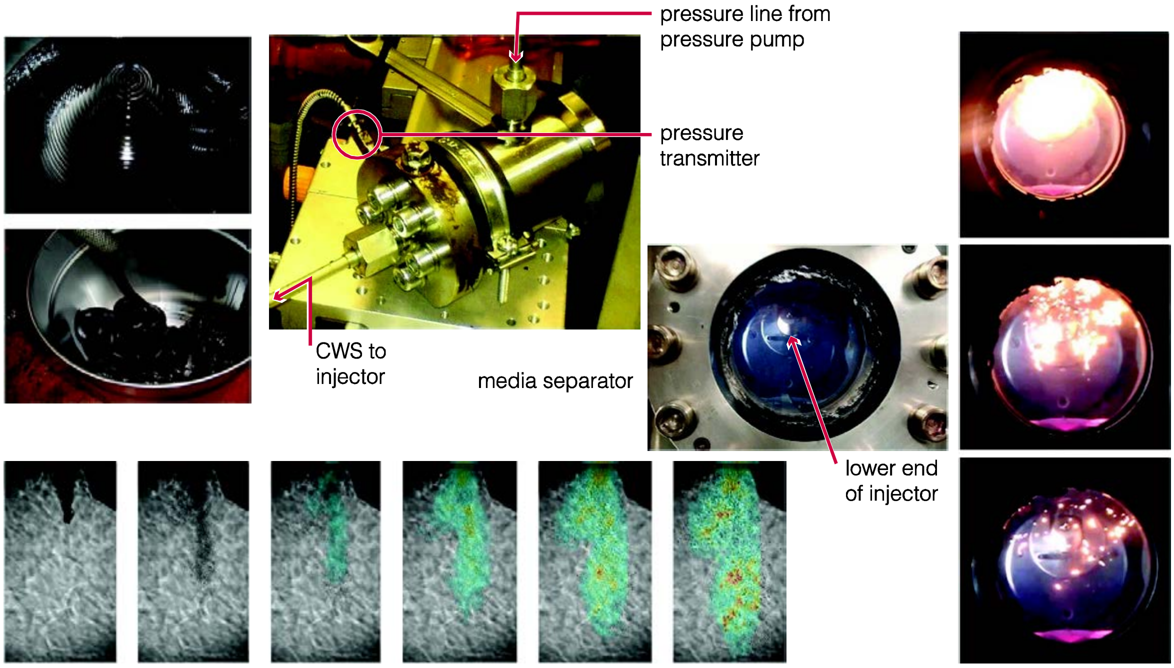

Figure 31 CWF testing by RWE Power (RWE, 2013; Stahl, 2014)

6.5 LRC upgrading in Australia

It is estimated that Australia holds approximately 22.6% of the world's recoverable, economically demonstrated resource of lignite. Approximately 78% of the economically demonstrated resource is presently accessible. The resource life, estimated at 34,095 Mt, at the 2012 rate of production, is 510 years (Geoscience Australia, 2014). Presently, LRC is mostly used in low efficiency PCC plant. Some is used in briquettes and some in soil additives, none is exported. Figure 32 shows a photo of the Loy Yang opencast mine. The typical composition of LRC from Victoria is 65% moisture, 35% carbon, 25% oxygen, 5% hydrogen, 1% S and N. The mineral content is relatively low at 2%, most of which is sand and clay entrained during mining operations. The finely dispersed minerals (mainly Ca, Na, Mg, Fe and Al) can be as low as 0.3% (Woskoboenko, 2012; Wibberley, 2011b). This naturally low ash level makes Victorian LRC a suitable coal for DICE.

Commercial DICE using LRC-MRC could provide an export route for Australia's vast LRC resource, as well as creating a new industry and providing a suitable technology to replace Australia's aging fleets of LRC-fired PCC plant. LRC-MRC would be transported as a paste to minimise transportation costs and explosion/fire risk. Economic analysis shows that MRC can be delivered at a third of the cost of LNG. A mine the same size as Loy Yang opencast mine has an estimated value of $2 billion per year and employs hundreds of workers (DICEnet, 2013).

Figure 32 Loy Yang opencast mine

6.5.1 Ignite Energy Resources

Ignite Energy Resources (IER) have the licence to explore ~16.4 billion tonnes of shallow lignite resources that is inherently high in moisture (50–70%) and low in ash (3–7%). IER have developed a continuous catalytic hydrothermal reactor (Cat-HTR) technology to upgrade this resource. Figure 33 shows a process flow diagram of Cat-HTR. The lignite, biomass, water and catalyst feedstock are mixed in a slurry tank, pre-heated and pressurised to reaction conditions, passed through Cat-HTR reactors, cooled and then separated *via* a continuous flow process into 'oily coal' that can be separated into the following products (IER, 2014; Rowlands, 2014; Stewart, 2014):

- 80–84% upgraded coal (~32 MJ/kg dry basis) – now equivalent to a high quality black coal grade, this coal can be used in steel making, in pulverised coal boilers or physically beneficiated by flotation, micronised and mechanically dewatered to create MRC, which has been tested in DICE. Briquetting the upgraded coal can lower long-distance transportation costs;
- 16–20% synthetic crude oil or syncrude (38–39 MJ/kg) – waxy brown oil, comparable to partially refined crude oil, such as light cycle oil or vacuum gas oil, with higher oxygen (6–8 %) and typically lower sulphur. Syncrude can be blended with conventional LCO/VGO and refined to gasoline, diesel, kerosene and waxes by hydro-treating, under mild conditions with commercial catalysts, or in fluidised catalytic cracking units in conventional refineries with minimal adaptations (simulated by a European laboratory).

The feedstock moisture is sufficiently high that the process is a net water producer – the surplus water is treated and recycled in the process or discarded. The waste gas is mostly CO_2 (>95%), any H_2S is scrubbed out before the remainder is flared.

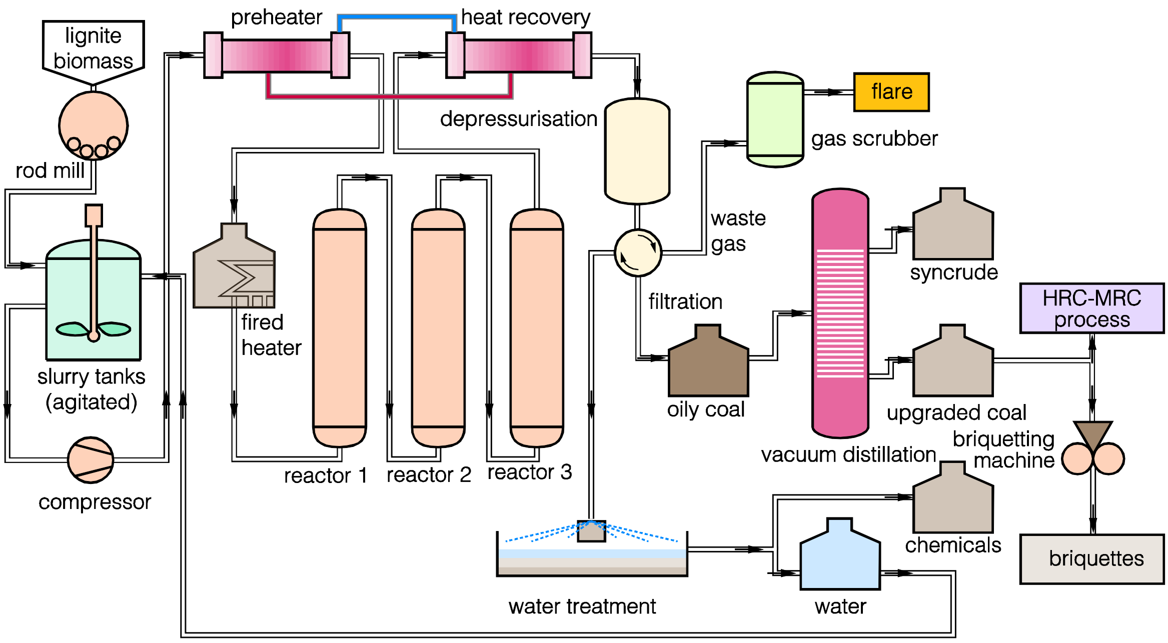

Figure 33 Cat-HTR PFD (IER, 2014; Rowlands, 2014)

Cat-HTR technology is an advanced form of HTD which uses catalysts for selective liquefaction, coalification and de-oxygenation. Surface and pore moisture are significantly reduced, polycyclic aromatic rings are fused together to create graphitic sheets (or HRC), and also aromatics and aliphatic compounds create a high-grade oil product. The syncrude has a neutral pH and is stable, due to the low oxygen and high hydrogen content which lessens the degree of unsaturation – important as unsaturation can lead to undesirable re-polymerisation (Maschmeyer and Humphreys, 2011). The process consumes 15% of the calorific energy (HHV) contained in the coal, prior to any heat recovery, which translates to 0.75 tCO_2/MWh when the upgraded coal is used for MRC. Despite this, the life-cycle CO_2 emissions for LRC-MRC produced by Cat-HTR and DICE are estimated to be half of those for existing lignite minemouth PCC plant (IER, 2014; Rowlands, 2014).

IER are operating a large pilot-scale Cat-HTR demonstration plant in Somersby (NSW, Australia) that processes 10,000 t of lignite and biomass per year – *see* Figure 34. A commercial-scale Australian-based Cat-HTR plant processing 3 Mt of lignite (65% moisture) per year is estimated to produce syncrude for A$42 per barrel and upgraded coal for A$55 per tonne (amortised capital costs included).

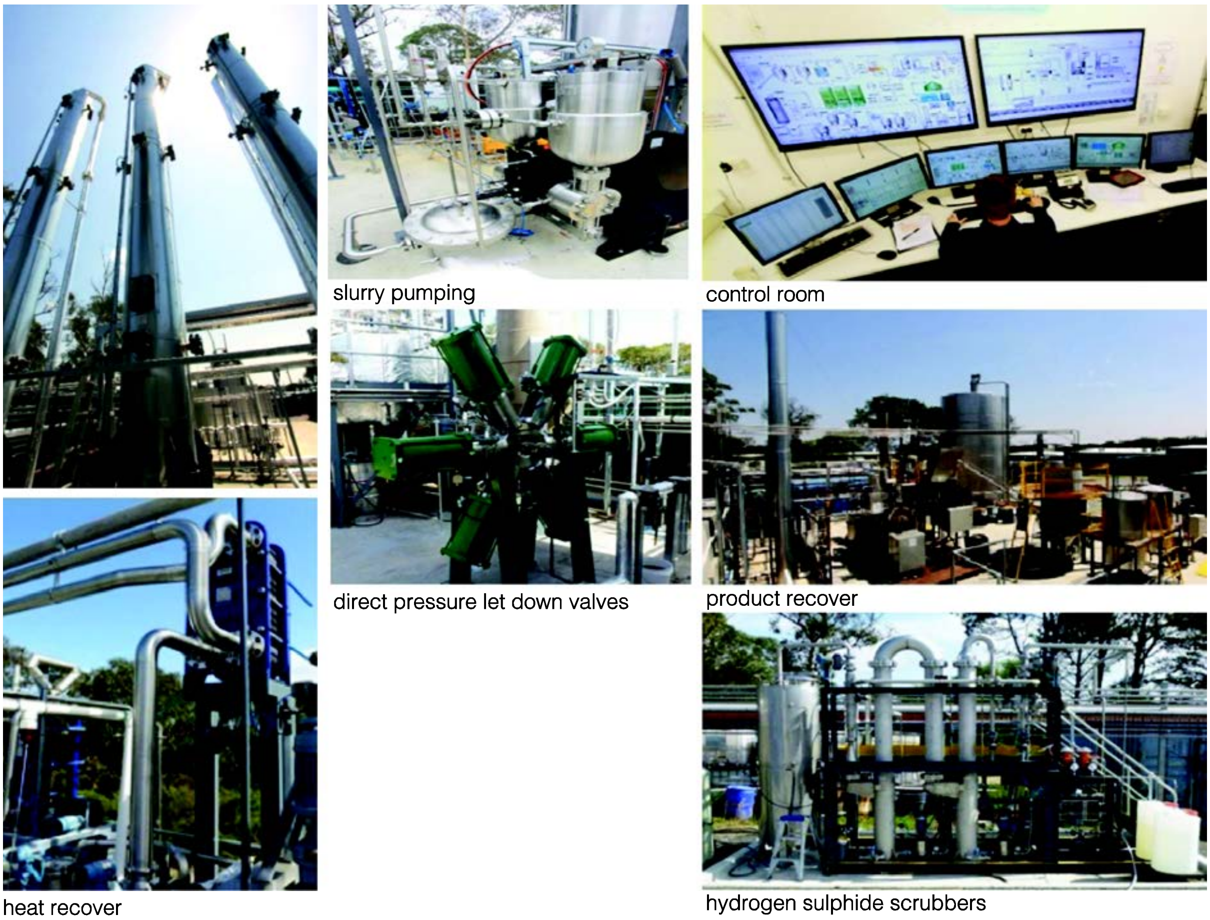

Figure 34 Pilot-scale Cat-HTR demonstration plant (IER, 2014; Rowlands, 2014)

On the 30 April 2014 IER and the Bukit Asam (a government-owned coal mining company in Indonesia) entered a Memorandum of Understanding to use Cat-HTR technology in Indonesia and Australia (IER, 2014). On the 16 May 2014, in a joint media release, the Australian State Government of Victoria announced that IER has been granted $20 million from the Advanced Lignite Demonstration Program (ALDP) for the development of an $84.3 million large-scale Cat-HTR demonstration plant, processing 140,000 t/y of lignite, planned to start-up in 2016 for 18 months (*see* Figure 35). The objective of the demonstration plant is to prove technical performance and full-scale transport of products and sale to markets (Macfarlane and others, 2014; Stewart, 2014).

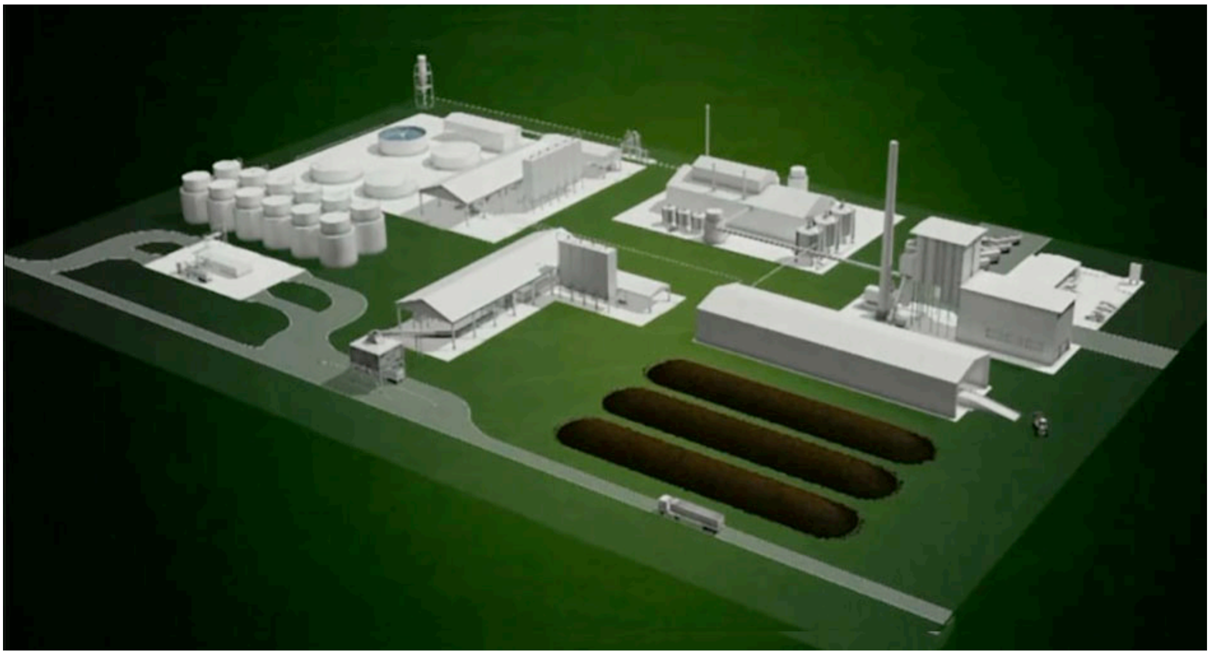

Figure 35 3-D model of large-scale Cat-HTR demonstration plant (Stewart, 2014)

Through a wholly-owned subsidiary Licella, IER operate a variant of the Cat-HTR technology especially developed for biomass to create biological synthetic crude oil (bio-crude) and bio-chemicals (*see* Figure 36). The bio-crude (which is very similar to coal-derived syncrude) can be refined as a 100% stream or co-refined with conventional oil (LCO or VGO) in standard refineries and the bio-chemicals can be used as the building blocks for plastics and other synthetic materials. Figure 36 shows the Licella process flow diagram which has a different processing route from the vacuum distillation column onwards. In 2010-13, Licella received A$9.7 million from the government and in 2014 it received a further A$5.4 million to develop an investment case for the construction of a large-scale demonstration plant (~125,000 bbl/y) in Australia. To date, Licella operates using the same pilot-scale Cat-HTR demonstration plant in Somersby and plans to do the same with the large-scale Cat-HTR demonstration plant (IER, 2014; Stewart, 2014; White, 2014), thereby sharing investment and de-risking scale-up across two projects.

Additionally, the humate by-product from the Cat-HTR technology, as applied to biomass, might be used as a soil supplement in agriculture to increase carbon fixation within the soil, creating biological carbon capture and storage (bio-CCS). This has the added advantage of improving the soil quality for farming. Bio-CCS is under investigation by groups such as Soils For Life.

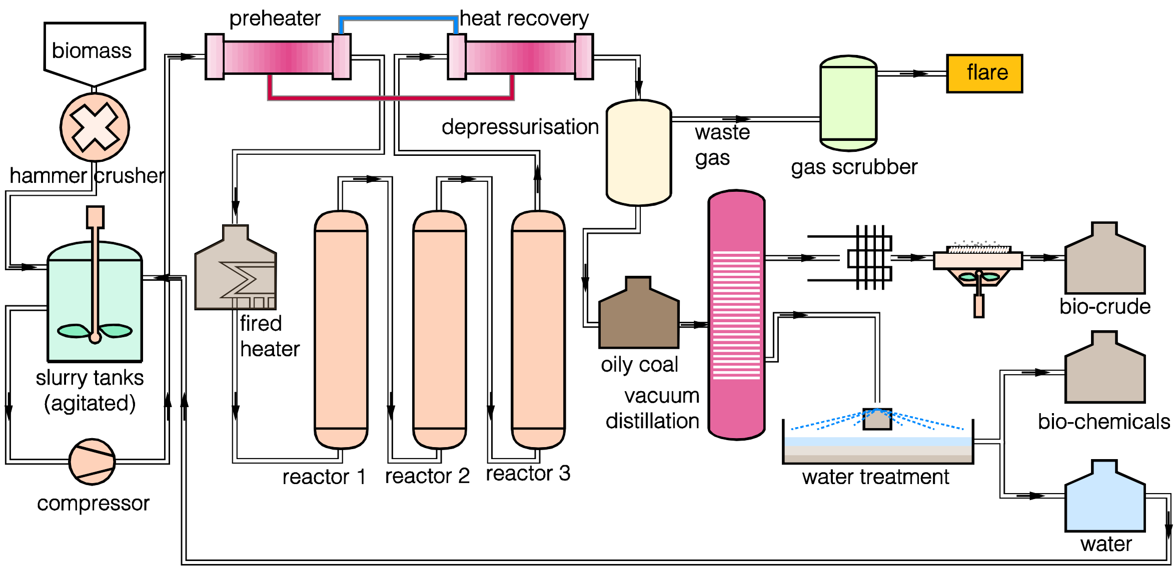

Figure 36 Licellas Cat-HTR PFD (IER, 2014; Rowlands, 2014)

Using lignite and biomass to create MRC for DICE with bio-CCS and geological carbon capture and storage (geo-CCS), IER have devised a sustainable carbon and energy cycle, potentially with negative carbon emissions (*see* Figure 37). The cycle uses DICE for electricity and transport and to balance a large capacity of intermittent renewable energy (White, 2014; Wibberley, 2014c).

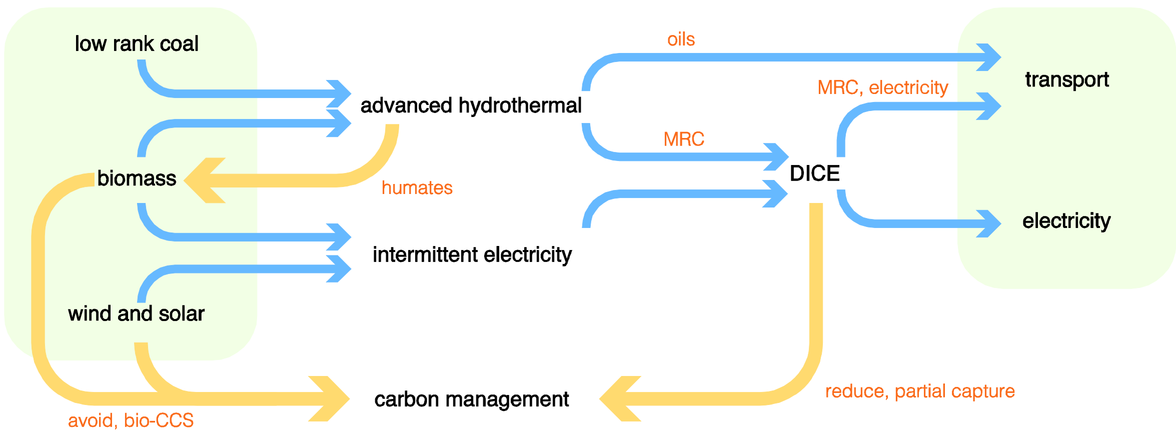

Figure 37 Sustainable carbon and energy cycle (Wibberley, 2014c)

6.5.2 Exergen

Exergen have developed a continuous hydrothermal dewatering technology, called continuous hydrothermal dewatering (CHTD). The process pumps a CWF through a vertical autoclave, an array of shell and tube heat exchangers that penetrate ~1000 m below ground level, where the CWF reaches ~10 MPa, due to hydrostatic pressure, and ~300°C, due to the exothermic hydrothermal reactions, partial combustion and steam heating or electrical preheating. Figure 38 shows Exergen's CHTD process. In the autoclave, the carboxylic groups of the LRC decompose (de-carboxylation) which closes the coal pores and makes the coal hydrophobic. Only a low pressure pump is required due to the pressure provided by the gravity feed. Excess water from the CHTD-CWF is separated, via mechanical expression or filtration processes, and then treated before recycling or disposal. LRC slurry with 60–70% moisture and a net wet CV of 9 MJ/kg is converted to upgraded coal slurry with 20–25% moisture and a net wet CV of 19.5 MJ/kg. The CHTD process consumes only ~2% of the LRC energy and no fossil-fuelled heaters are required.

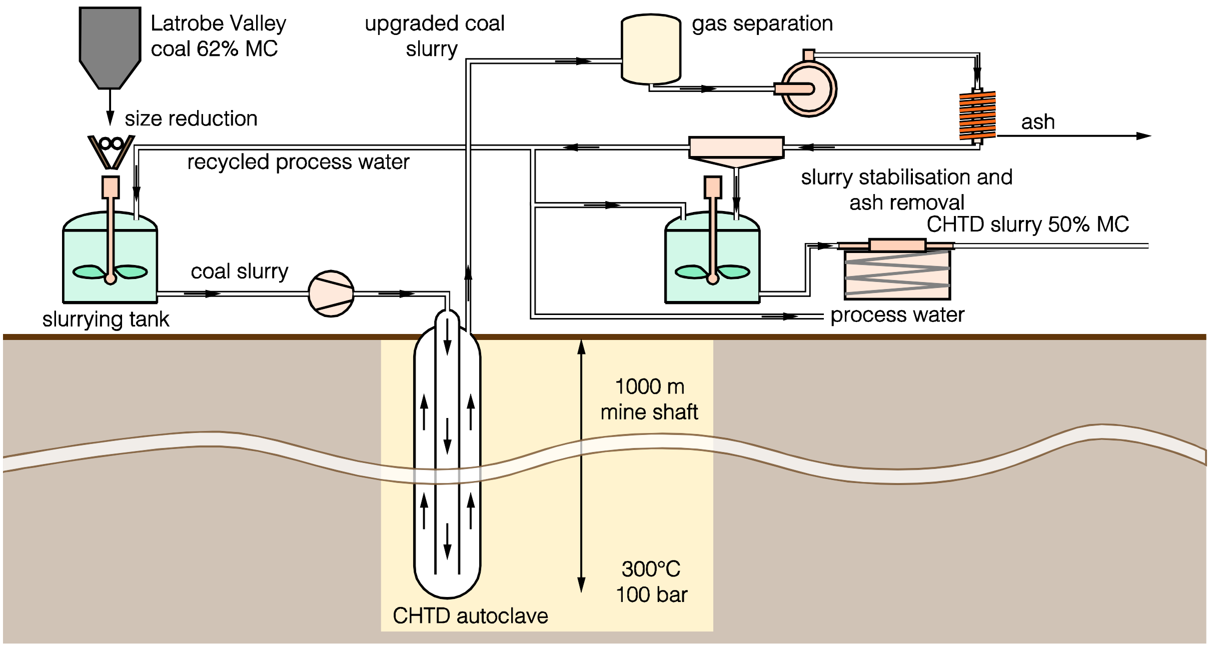

Figure 38 PFD of Exergen's CHTD (Bourne and Wormington, 2014)

Since 2004, Exergen have been operating a pilot-scale CHTD demonstration plant producing 4 t/h of MRC in Beaconsfield, Tasmania. Numerous coals have been processed in the CHTD successfully (Exergen, 2014; Wormington, 2014; Dong, 2011).

Exergen plan to design, build and operate a large-scale CHTD demonstration plant near the Morwell Power Station in the Latrobe Valley. A detailed feasibility study was completed in 2012 and construction is planned to start in 2015. The large-scale demonstration plant is estimated to cost $40–45 million and will process 50 t/h of LRC. Investors include Tata Power, Itochu Corporation, Sedgman and Thiess. Mantle Mining Corporation and Exergen have formed a joint venture to use CHTD technology to process the ~1 billion tonne LRC deposit at Bacchus Marsh, which has existing rail and port infrastructure (Proactive Investors Australia, 2013; Exergen, 2014; Wormington, 2014a,b; Bourne and Wormington, 2014).

6.5.3 Coal Energy Australia

Coal Energy Australia has developed a HTD process that converts coal into fertiliser, oil and upgraded coal, which involves (Macfarlane and other, 2014):

- building a pre-commercial lignite upgrading plant to process high value metallurgical grade carbon and other hydrocarbon products;
- integrating technologies for the pyrolysis of coal, based on coking, semi-coking and advanced heating technology;
- applying coal pyrolysis technology;
- production of three products:

- low volatile solid fuel or char (upgraded coal), a substitute for coal in steel manufacture;
- pyrolysis oil, which can be distilled into various oils, including diesel oil for industrial heating;
- ammonium sulphate for use as a fertiliser or soil conditioner.

On the 16 May 2014, in a joint media release, the Australian State Government of Victoria announced that Coal Energy Australia has been granted $30 million from the ALDP, for the development of a $143 million demonstration plant.

6.6 LRC upgrading in Inner Mongolia

Yujie and Jianzhong (2014) tested HTD on Mongolian LRC. The moisture content decreased from 28.2% to 7.77%. Nitrogen, sulphur, oxygen and functional groups (such as carboxyl, carbonyl and hydroxyl) are lowered. More organic compounds enter the water as the hydrothermal processing temperature rises. Ions dissolved in the water improve the rheology of CWF.

6.7 Charcoal

Patton and others (2009) conducted laboratory tests which show that MRC can be produced from charcoal with lower total mineral content than coal-based MRC. Based on the previous US DOE study, DICE should run on charcoal-MRC without any problems. A study shows that, in 2010, charcoal-MRC was lower cost than diesel, and that there is enough biomass to replace 75% of the current diesel demand.

6.8 Biomass

Piriou and others (2013) present a case for using biomass dust in diesel engines. The advantages are that biomass dust contains little ash, or what ash there is can be removed with water leaching, which removes the need for harder engine materials; biomass dust has combustion properties suitable for the combustion times in high speed engines; biomass is sulphur free; biomass is readily available; and biomass pulverisation technology is well developed. The study showed that issues encountered with research, with dust feeding, metering and ignition, could be resolved with new technology.

The production of MRC from biomass and algae, using HTD is under investigation at CSIRO.

7 Laboratory testing

MRC produced by multiple companies have been tested at CSIRO with the following results. All LRC-MRC tested here has been upgraded.

7.1 Combustion

MAN Diesel & Turbo (MAN D&T) say that an ignition delay of <10 ms is required for maximum performance in low-speed, two-stroke diesel engines. CSIRO and RWE have shown that the ignition delay for the average MRC, providing atomisation that produces droplets with a mean size of ~75 µm, is around 5 ms at 7–10 MPa and 600°C, which is comparable to HFO (DICEnet, 2013). Biochar has an ignition delay of 15 ms at 600°C - this is shortened to 5–10 ms at 700°C and when sweetened with coal-MRC (Yancoal, 2014b).

For 39% coal LRC-MRC, the atomisation time was 1ms, the ignition delay was around 15 ms and the after burn time was 3 ms (time for complete combustion after end of injection). However, the more viscous 51% coal MRC had an ignition delay of 9 ms and after burnout time of 11 ms, which is just acceptable for large two-stroke engines.

7.2 Wear

When testing LRC-MRC for wear rates, no signs of wear were found. In some cases, LRC-MRC can decrease wear, compared to lubrication oil alone – LRC particles and sulphates in the lubricating oil could be acting as a solid lubricant when the liquid lubricant breaks down. Lubrication oil contaminated with HRC-MRC resulted in wear rates of 23–24 µg, which is slightly more than that of clean oil. Laboratory tests prove that WC coated surfaces do not wear in contact with engine contaminated lubrication oil at 200 MPa – as indicated the US DOE coal-fuelled engine R&D programme (Wibberley, 2013c; DICEnet, 2013).

7.3 Fouling and emissions

Short-term tests, of up to forty hours, have not revealed any fouling. This is probably due to the cyclic heat flux caused by the batch process of the Carnot cycle – the cylinder surfaces are only exposed to gases >800°C for 10% of the time and most of the metal surfaces are below 300°C. However, long-term operation in large-scale engines for a specified MRC type and DICE type combination is required to accurately quantify fouling (Wibberley, 2014b).

Compared to single shot MRC injection, double shot MRC injection, with 20% MRC in the first shot and 80% in the second (both at 100 MPa) reduces NOx emissions by 70% (Wibberley, 2011a, 2014b).

7.4 Formulation

Table 6 shows the additives used in MRC (DICEnet, 2013). Formulation costs make up <5% of the total cost of HRC-MRC (Wibberley, 2014b).

Table 6 Additives in MRC (DICEnet, 2013)			
Additive	**Rate (kg/t of dry coal)**	**Cost (A$/GJ)**	**Comments**
Polystyrene sulphonate sodium salt (PSS-Na)	1.2–2	<0.2	Anionic dispersant, cost based on data from LION
Ammonium lignosulphonate	5–10	>0.08–0.16>	Dispersant
Naphthalene sulphonate formaldehyde condensate sodium salt (NSF)	5–10	0.15–0.3	Dispersant
Carboxy-methyl cellulose sodium salt (CMC)	0–1	<0.06	Stabiliser and dispersant

7.5 MRC properties

Table 7 shows the nominal MRC properties and costs for physically beneficiated LRC (Victorian) and HRC-MRC (including tailings).

Table 7 Nominal MRC properties and costs (DICEnet, 2013, 2014; Oettinger, 2014)		
	HRC (including tailings)	**LRC**
HHV (MJ/l)	21–25	16–19
Oxygen content (% dry basis)	5	22–24
Mineral ash (% dry basis)	1–2 (quartz and clay <5µm)	0.1–2 (quartz and siderite 0–200 µm)
Non-mineral ash (% dry basis)	Negligible	1–2 (Ca, Mg, Fe, Na which forms sulphate fumes)
Total water in MRC (%)	40–50	50–60
Ignition delay (ms @ 600°C)	5	3–5
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
Effect of efficiency relative to diesel (%HHV)	−1%	−1 to −2%
Abrasive wear relative to oil steel – steel	2x	1.2x
Abrasive wear relative to oil carbide-carbide	1x	1x
Total cost (A$/GJ)	2–6 (including tailings)	2–3
Percentage of life-cycle CO_2 emission from MRC production	3%	2–5%

Engines operating at different speeds will require a specific quality of MRC, which the specification will include a maximum mineral content and particle size, and a certain range of viscosity and heating value. The mineral content is of principal concern as this has a large impact on MRC production costs. Smaller medium-speed, four-stroke engines are suited to higher quality MRC and larger low-speed, two-stroke engines are suited to lower quality MRC (because larger clearances minimise contact with hard particles which decreases wear and they have longer atomisation and combustion times). In both cases, several thousands of hours of large-scale DICE testing is required to establish MRC specifications which will result in the lowest life-cycle cost for MRC-DICE. The life-cycle cost depends on the engine performance, engine life-time and maintenance costs.

Once sufficient information from large scale demonstration tests is obtained, it is anticipated that new MRC testing procedures will be required. As the components in DICE develop, such as the design and use of harder materials, the MRC specifications should become less demanding, allowing higher ash, coarser coal and higher viscosity, thus reducing fuel processing costs (Wibberley, 2013a; DICEnet, 2014).

7.6 Testing of Yancoal UCC-MRC

Yancoal UCC-MRC was tested in a three hour engine run at CSIRO in 2010 and other tests have been undertaken by Yancoal at their Cessnock site using one cylinder of an EMD 645E locomotive engine during 2012-13. CSIRO recently finished a 40 hour engine run with UCC-MRC to gain further information on the fuel before using it to run a pilot-scale DICE demonstration in 2015-16.

The UCC-MRC recently tested by CSIRO had the following properties: 48% coal, 0.5% ash on a dry basis/0.29% ash as-fired, particle size of d_{98} of 45 µm, a viscosity of 202 mPa.s @ 100/s and a specific energy of 18.5 MJ/L (HHV). CSIRO's 16 kW DICE was successfully operated for 40 hours on the UCC-MRC with the following results:

- an ignition delay of 3 ms;
- brake specific fuel consumption was 230 g/kWh (slightly lower than that of the standard engine);
- lubricant contamination and wear rates were low, 0.7 µm/h was found on the piston rings, which is slightly more than that of clean oil. Using estimates from earlier US DOE developments, a piston ring life of 12,000 hours could be achieved using ceramic ring/cylinder coatings and acceptable nozzle life could be achieved using diamond compacts or ceramic fuel nozzles;
- despite high Na: Si ratios, the fouling was low. Figure 39 shows fouling on the cylinder from three hours running on diesel (left) and 40 hours running of UCC-MRC (right). The circular shaped deposit with UCC-MRC is due to turbulence from the edge of the piston bowl. The deposits mostly contained Na, S and Si, and the largest deposit was 0.3mm deep in the exhaust valve (the hottest engine component);
- arrangements are under way for testing in larger (1 MWe low-speed two-stroke) engines (Yancoal, 2014b).

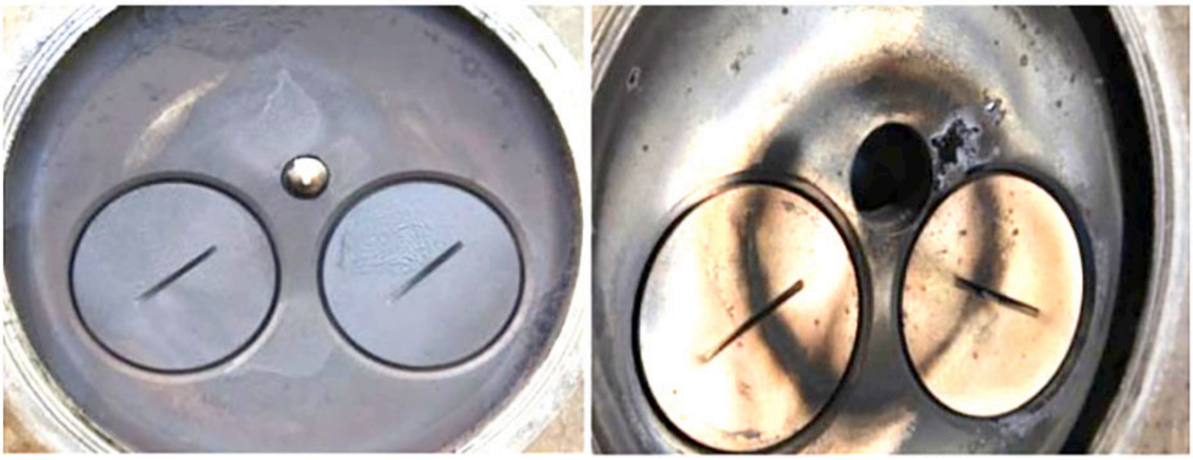

Figure 39 Cylinder head deposits from diesel (left) and UCC-MRC (right) (Wibberley, 2014c)

7.7 Paste MRC

Instead of firing liquid MRC in a fuel injector, paste MRC could be fired using an air-blast injection. Work at CSIRO has shown a significant improvement in combustion, with shorter ignition delays, less energy penalty from water and 80% lower injection velocities (which dramatically increases nozzle life). Additionally, low moisture MRC increases fuel stability and lowers the cost of the entire MRC fuel cycle. Figure 40 shows direct injection of paste LRC-MRC (>2000 mPa.s 100/s) into a 7–10 MPa pressure chamber, without an air-blast on the left and with an air-blast on the right. Air consumption is ~0.3 kg of air per kg of MRC. Carbide nozzles, with air-blast atomisation, are predicted to last over 20,000 hours (Wibberley, 2013a,d, 2014b).

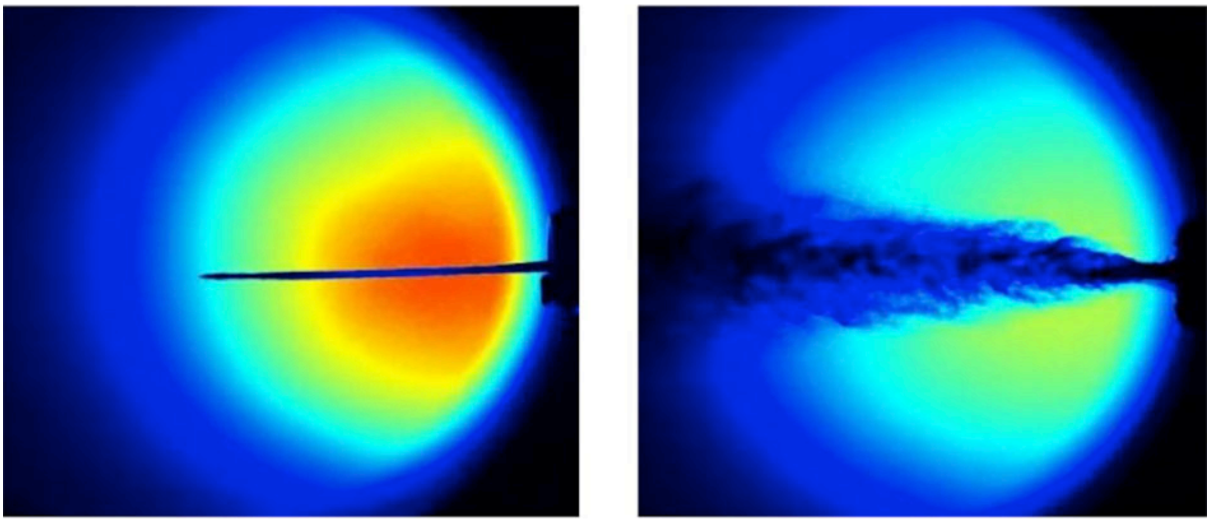

Figure 40 Air blast atomisation of paste MRC (Wibberley, 2014c)

Development of the diesel engine continues, through smarter electronic control, higher injection pressures, larger cylinders and more efficient turbo chargers. R&D programmes, such as the Hercules project in the EU, aim to increase the total mechanical efficiency of large diesel engines to 60% (LHV). The fourth generation of DICE is estimated to reach mechanical efficiencies up to 54.3% LHV (52.4% HHV) (*see* Table 8).

Table 8 Potential mechanical efficiency of DICE (Wibberley, 2013d)	
	% (brake, LHV)
Mechanical efficiency of 100 MWe engine on HFO	60
Percentage change in heat rate for MRC-DICE	
Fuel processing	-3
Dry coal versus diesel fuel (dry coal has higher theoretical efficiency)	+2
Slurry penalty (MRC normally @ 20°C)	-8
Fuel preheat from waste heat	+2.5
Generator and balance of plant	-3
Overall efficiency of MRC DICE	54.3 (52.4 HHV)
CO_2 emissions on a life cycle analysis basis (kgCO_2/MWh)	660

7.7.1 Negative carbon emissions

Figure 41 shows the potential of MRC-DICE to reduce carbon emissions in Victoria (Australia). The first step reduction in CO_2 emissions is the increased efficiency when replacing low efficiency pulverised LRC-fired power plant with high efficiency DICE. The second step reduction is when biomass is used to make MRC. The third step is to utilise DICE to underpin a higher penetration of renewables without compromising power grid security. The fourth step is using MRC products to increase CO_2 fixation in soils and the fifth step is using post-combustion carbon capture and geological storage. The fourth and fifth steps give negative carbon emissions through biomass energy carbon capture and storage (BECCS) (DICEnet, 2014).

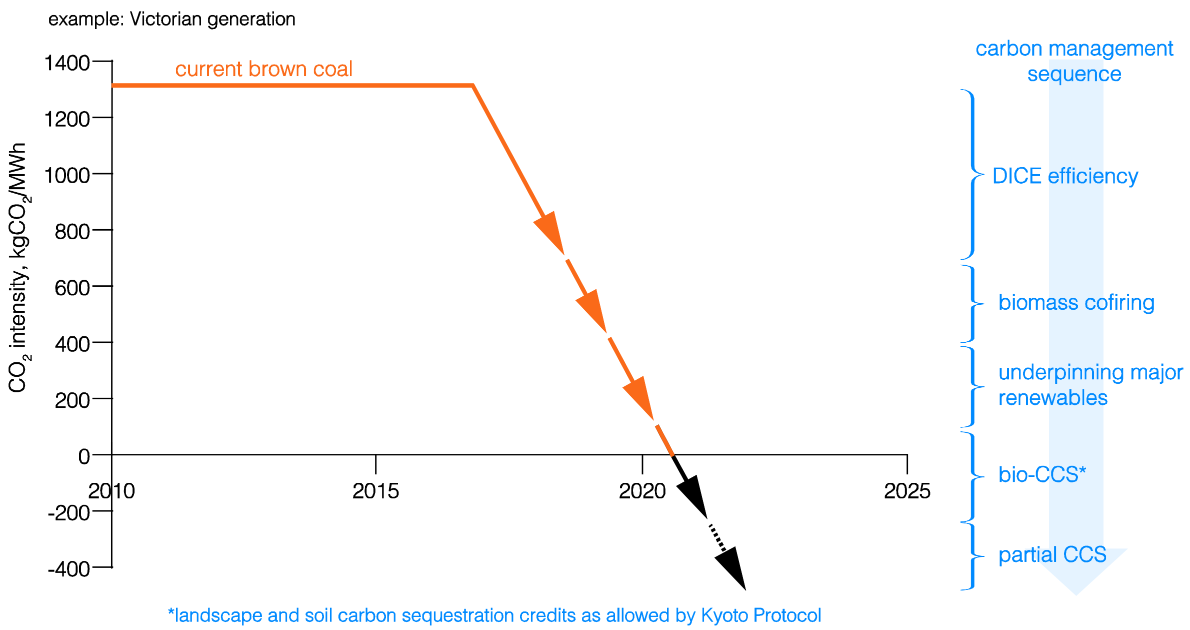

Figure 41 Potential to reduce CO_2 emissions from LRC fired power plant (DICEnet, 2014)

8 Technology comparison

With results from the US DOE coal-fuelled engine R&D programme, CSIRO's MRC-DICE R&D programme, pilot-scale MRC demonstration plants, combined with performance data from commercial equipment, the following sub-sections compare the efficiency, flexibility and other performance figures of MRC-DICE with other power generation technologies. Once results from pilot-scale DICE are obtained, a more accurate technical comparison can be made.

8.1 Efficiency

Figure 42 compares the mechanical efficiencies (HHV) of MRC-DICE with other power generation technologies from 1–1000 MW. In addition to high efficiencies, DICE has high part-load efficiency, requires no derating up to an ambient temperature of <45°C or with high altitude, and the smaller scale units can minimise transmission losses.

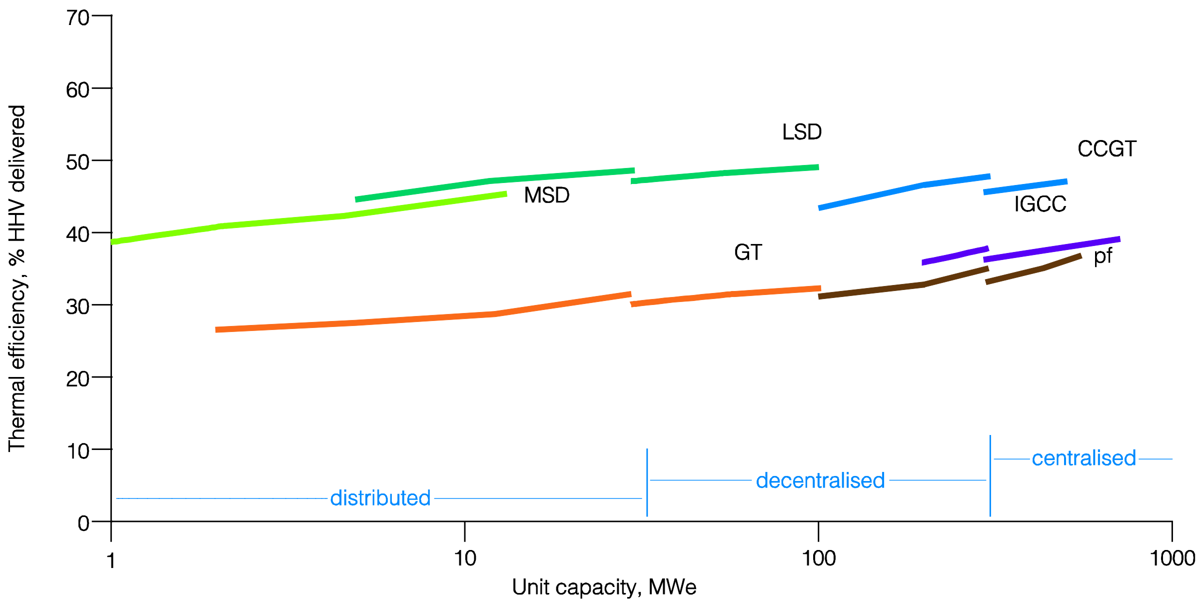

Figure 42 Efficiency comparison of power generation methods (Wibberley, 2014d)

Figure 43 converts mechanical efficiencies (HHV) from Figure 42 into specific CO_2 emissions. Key: medium speed dice (MSD), low-speed dice (LSD), open-cycle gas turbines (GT), combined cycle gas turbines (CCGT), and integrated gasification and combined cycle (IGCC), and pulverised coal-fired power plant (PF).

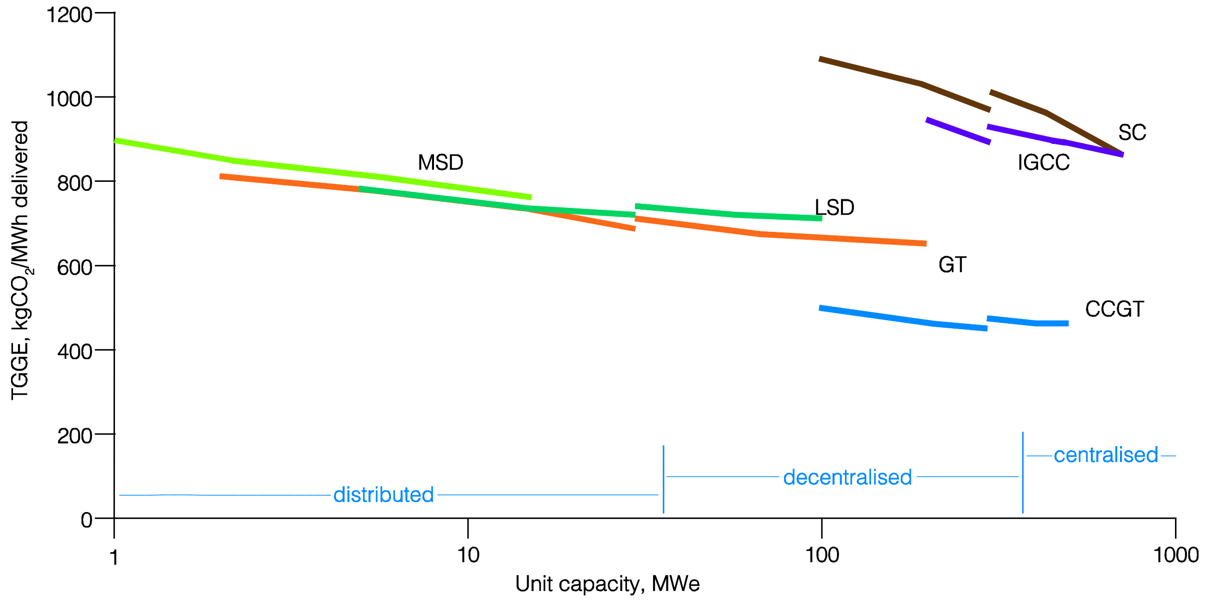

Figure 43 Greenhouse gas equivalent (Wibberley, 2014d)

8.2 Flexibility

Table 9, taken from the IEA's (2014) publication *'The Power of Transformation'*, shows that reciprocating engines (gas, diesel or petrol fired internal combustion engines) are more flexible than all other power generation technologies, with a minimum stable output of 0% (which means it can be turned off easily), a ramp rate of 10–100% of rated capacity per minute and 0.1 to 0.16 hours lead time (start-up time) when warm.

Table 9 Flexibility comparison of DICE with other power generation technology (IEA, 2014)

Technology	Minimum stable output (%)	Ramp rate (%/min of rated capacity)	Lead time, warm (h)
Reservoir hydro	5–6	15–25	<0.1
Solar thermal	20–30	4–8	–
Geothermal	10–20	5–6	1–2
Reciprocating engine	0	10–100	0.1–0.16
Gas combined-cycle inflexible	40–50	0.8–6	2–4
Gas combined-cycle flexible	15–30	6–15	1–2
Gas open-cycle	0–30	7–30	0.1–1
Gas/oil steam turbine	10–50	0.6–7	1–4
Coal inflexible	40–60	0.6–4	5–7
Coal flexible	20–40	4–8	2–5
Lignite	40–60	0.6–6%	2–8
Nuclear inflexible	100%	0	N/A
Nuclear flexible	40–60	0.3–3.5	N/A

8.3 Multiple parameters

Table 10 compares the performance of DICE with other power generation technologies (comprehensive information is beyond the scope of this report).

Table 10 Technical comparison of DICE with other power generation technology (Wibberley, 2012, 2013a,b,d; 2014b; Nicol, 2013: Lockwood 2013; Jeffery, 2014)

Item	DICE (two-stroke)	DICE (four- stroke)	USC PCC	IGCC	USC CFB	OCGT	CCGT
Capacity	10–100 MW	<20 MW	>300 MW	>300 MW	>300 MW	>100 MW	>400 MW
Cyclic operation / flexibility	High	Very high	Medium	Low	Medium	High	Medium
Efficiency at part-load	High	High	Medium	Medium	Medium	Low	Low
Solid fuel	HRC, LRC, biomass	HRC, LRC, biomass	HRC, LRC, biomass	HRC, LRC, biomass, waste	HRC, LRC, biomass, waste	N/A	N/A
Fuel flexibility (without substantial plant modification)	High	High	Medium	Medium	Medium	Low	Low
Cooling water consumption (L/MWh)	300	300	300–2000	N/A	300–2000	N/A	<2000
HRC-MRC CO_2 (g/kWh)	636–700	670–800	780–830	–	780–830	700	450
LRC-MRC CO_2 (g/kWh)	750	685–850	1200–1400 (subcritical)	–	–	N/A	N/A
Build time	2–3 y (12–15 month construction)	<4 y (7–9 month construction)	4 y	5 y	4 y	2–3 y	3–4 y
Life-time	>40 y	>25 y	>25 y	>25 y	>25 y	>25 y	>25 y

Using fuel costs from technology developers in Victoria, CSIRO calculated that a minemouth LRC-MRC-DICE would have a nominal sent out cost of electricity (COE) of 50 $/MWh from product coal and 40 $/MWh on tailings. The CO_2 emissions would be 690 kg/MWh, which are almost half those of currently operating LRC-fired PCC plant (Wibberley, 2013b).

9 Economic analysis and comparison

This chapter will summarise recent preliminary economic analyses for MRC-DICE and compare the results with other power generation technologies. Economic projections for non-commercial technology are based on assumptions for capital, O&M costs, variable fuel prices and carbon taxes. These figures should be used as a guide only – more accurate economic analysis can be made as the programme progresses.

9.1 CSIRO

Provisional economic analysis by CSIRO estimates that MRC-DICE becomes more competitive than gas when natural gas prices rise above 6–7 A$/GJ. Table 11 shows the current and forecast gas prices for certain regions globally. If MRC-DICE technology were commercially available now, there would be a market for it in Eastern Australia, China, Europe, Japan and Korea (assuming additional capacity is required in these markets). The 2020 gas price forecast projects that MRC-DICE will be competitive with gas in the same regions, assuming the technology is commercialised. Gas prices are increasing in Australia for the following factors, the carbon tax, renewable energy target scheme, solar tariffs and the increased export of liquefied natural gas (Wibberley and Wonhas, 2014; Wibberley, 2014c).

Table 11 Current and forecast gas prices (Wibberley and Wonhas, 2014)

Region	Current (A$/GJ)	Forecast 2020 (A$/GJ)
Australia (East)	5–6	>8.5
China	13.7	>10
Europe	10.8–12.2	>8.8
UK	10–14.6	>10
Japan/Korea	14.2–16	>13
USA	3.4–4.2	<6

9.2 BREE

In 2012, the Bureau of Resources and Energy Economics (BREE), of the Australian Government, conducted a techno-economic assessment of MRC-DICE, assuming that it has been commercialised by 2020. Using CSIRO's capital cost of 1600 A$/kW for a 100 MWe engine, the balance of capital costs, including local equipment, labour and owners costs, increases the turnkey capital cost to 2285 A$/kW. Table 12 lists the assumptions made for DICE in BREE's study (BREE, 2012).

Table 12 Assumptions in BREEs techno-economic analysis of DICE (BREE, 2012)	
Capital cost	2285 A$/kW net
Local equipment/construction costs (includes commodities)	22%
International equipment costs	70%
Labour costs	8%
Engineering procurement contractors (EPC)	95%
Owners costs	5%
Construction profile % of capital cost	100% in year 1
First year available for construction	2020
Typical new entrant size	300 (3 x 100MWe units)
Economic life	25–30 y
Lead time for development	1 y
Average capacity factor	83%
Mechanical efficiency (sent out – HHV)	50%
Mechanical efficiency learning rate (sent-out HHV)	0% improvement per annum
Auxiliary load	5% (assumes no fuel processing)
Fixed O&M costs ($/MW/y) for 2012	150,000
Variable O&M ($/MWh sent out) 2012	10%
Percentage of emissions captured	0%
Emissions rate per	700 kgCO_2/MWh
Carbon price	23 $/t$CO_2$-e leading to a 5% reduction in CO_2 by 2020, and 80% by 2050.

The techno-economic analysis based on using Victorian LRC shows that the LCOE in Victoria should be 129 A$/MWh in 2020, which increases with time as shown in Table 13.

Table 13 Current and forecast electricity prices (BREE, 2012)					
LCOS (A$/MWh) for Victoria	**2020**	**2025**	**2030**	**2040**	**2050**
Without carbon tax	89	90	92	96	99
With carbon tax	129	143	157	184	200

Figure 44 shows the projected LCOE for DICE and other technologies for New South Wales (Australia) with a carbon price. DICE has a LCOE of 105–145 $/MWh, which is the 7th lowest out of 29 technologies that were assessed.

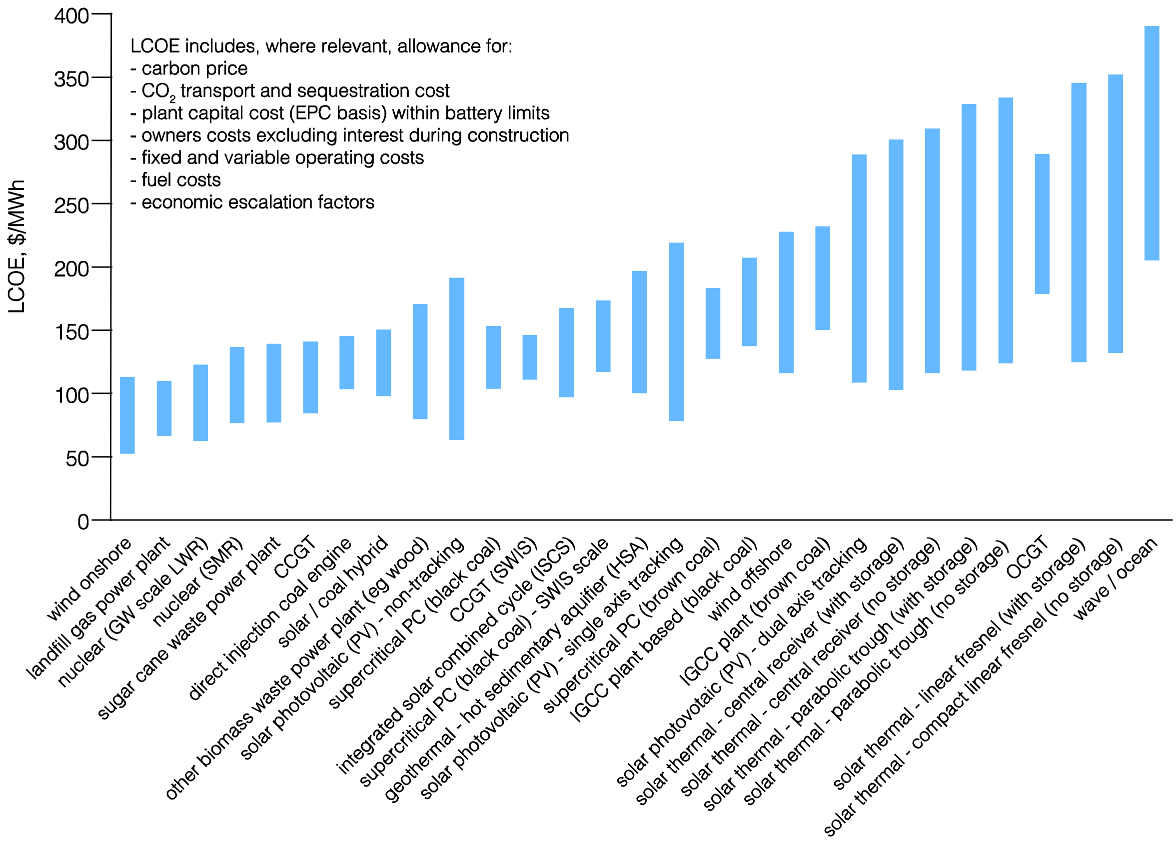

Figure 44 LCOE for DICE and other technologies for 2020 in Australia (BREE, 2012)

Figure 45 shows the projected LCOE for DICE and other technologies in Australia in 2025 without a carbon price. DICE has a LCOE of 75–110 $/MWh, which is the 4th lowest out of 40 technologies that were assessed.

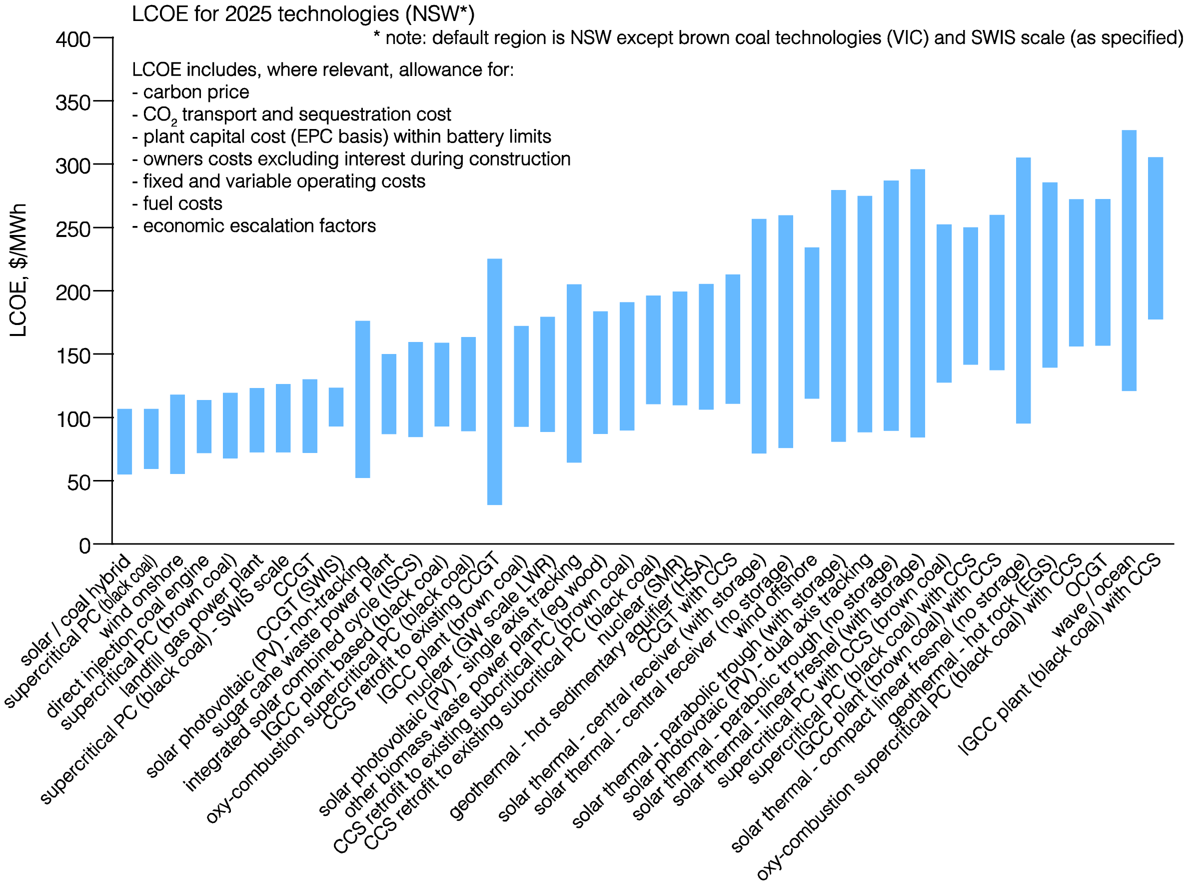

Figure 45 LCOE for DICE and other technologies for 2025 in Australia (BREE, 2013)

Figure 46 shows the projected LCOE for DICE and other technologies in Australia in 2050 without a carbon price. DICE has a LCOE of 80–130 $/MWh, which is the 10th lowest out of 40 technologies that were assessed. Despite no carbon tax, solar energy is projected to have the lowest costs.

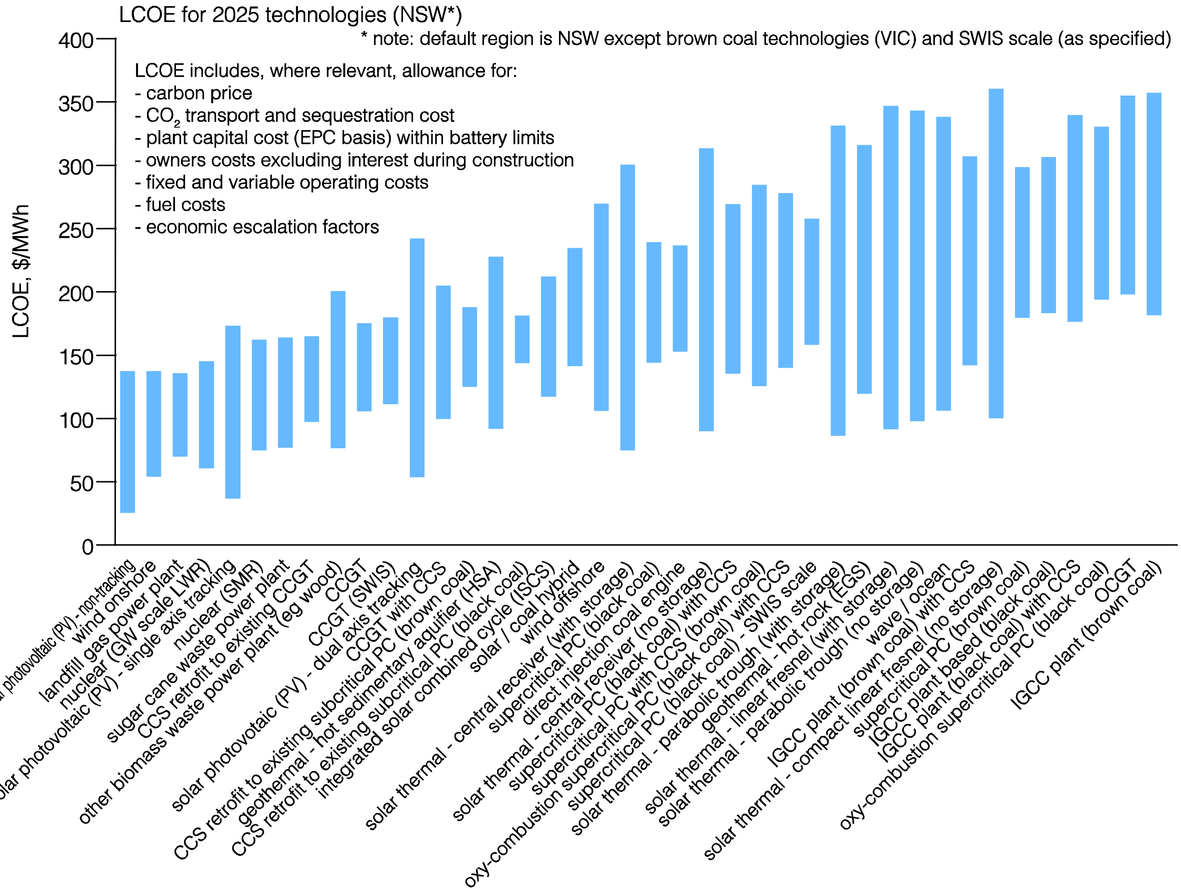

Figure 46 LCOE for DICE and other technologies for 2050 in NSW with no carbon price (BREE, 2013)

In early 2014, Jeffery (2014) was engaged by Australian National Low Emissions Coal Research and Development (ANLEC R&D) to conduct a preliminary techno-economic analysis of MRC-DICE in order to quantify the number of operational hours before a major maintenance is required to compete with other power generation technologies. The outcome provides information to investors with regards to supporting MRC-DICE and sets targets for the R&D programme.

Different scenarios were modelled to find potential markets for MRC-DICE. Assumptions made throughout the model were that CO_2 emissions were taxed at 33 A$/t and that DICE has the same performance and costs as a commercial diesel engine. All costs were based on 2013 estimates and actual values and projected over a 10-year life-cycle.

The first scenario uses coal tailing MRC produced by XT's pilot-scale demonstration plant at the Bulga mine (all costs and performance data were provided by XT) to fuel a DICE power plant. It showed that MRC-DICE can compete with piped gas (at ~8.60 A$/GJ) for distributed power generation provided the major maintenance intervals are ≥2000 hours. Also, MRC-DICE can compete with trucked diesel for distributed power generation provided the major maintenance interval is ≥500 hours.

The second scenario is based on coal tailing MRC produced by an Australian mine shipped to Japan to fuel a DICE power plant. It showed that MRC-DICE could compete with LNG-CCGT provided the major maintenance interval is ≥1000 hours. However, MRC-DICE does not compete with PCC.

The third scenario ships Australian lump coal (15% ash) to South Korea to fuel a MRC-DICE power plant. This was compared against Indonesian LNG for CCGT plant and Australian coal for PCC plant. MRC-DICE could compete with LNG-CCGT provided the major maintenance interval is ≥1000 hours. However, MRC-DICE does not compete with PCC.

The fourth scenario builds minemouth brown coal MRC-DICE in Australia. A major maintenance interval of ≥4000 hour is needed to compete with new-build CCGT and gas for distributed power. If LRC-MRC is produced for <3.9 A$/t and the major maintenance interval ≥1000 hour, then DICE is competitive with exported LNG for CCGT. Brown coal MRC-DICE can compete with trucked diesel for distributed power generation provided the major maintenance interval is ≥500 hours.

Table 14 summarises the results of an ANLEC R&D economic analysis of MRC-DICE. Limited development could see MRC from coal tailings used in DICE for distributed power generation. MRC-DICE is competitive where LNG is imported for CCGT power plant although this would require significant engine development. The incentive for engine manufacturers to develop and make DICE is high, with new markets for distributed and centralised power generation. However the incentive for coal producers to develop and produce MRC is low as coal is already sold for PCC and circulating fluidised bed (CFB) power plants. Despite this, there is interest where coal can displace gas and where coal tailing can be utilised.

Table 14 Summary of economic analysis by ANLEC R&D (BREE, 2012)

Major maintenance interval (hours)	**Scenarios where MRC-DICE is competitive**	**Incentive for engine manufactures to develop and make DICE**	**Incentive for coal producers to develop and make MRC**
500 (US DOE achieved 142-400)	Distributed power where alternative is trucked diesel	Small – already have this market	Medium – new small market, could use coal tailings
1000	Imported LNG for CCGT	High – new and significant market	High – new and significant market
2000	Distributed power where alternative is CCGT	High – new market	Medium – new small market
4000 (equivalent to HFO)	New build base-load power in Australia if gas price >7.7 $/GJ and MRC 2.5 $/GJ	High – new market	Medium – DICE could be economically favourable over CCGT and PCC

9.3 Fossil Fuel Institute

The Fossil Fuel Institute (IGI) of Moscow (Russia) performed a techno-economic study on the use of automotive coal slurry fuel for diesel engines based on experimental data from laboratory tests. Although called automotive coal slurry fuel, the coal particles are micronised and the slurry is demineralised to

<0.5% ash (dry basis), so this fuel is classified as an MRC by CSIRO. IGI found that a third of the auxiliary load in MRC-DICE is used in MRC production – this must be accounted for in lifecycle emissions.

Table 15 shows the electricity cost from coal and oil derived fuels with different power generation technologies. The study concludes that physically beneficiated MRC for two-stroke DICE, or even gas turbines, could compete with HFO. The degree of beneficiation plays a large role in determining the cost of MRC; chemically beneficiated MRC increases costs (Red'kina and others, 2013).

Table 15 Electricity costs from the Fossil Fuel Institute (2012)

Fuel – power generation technology	¢/kWh
Coal-PCC	2.1
CWF-boiler	2.2
MRC-DICE	2.5
MRC-gasification	1.9
Diesel–internal combustion	4.7
Mazut HFO–internal combustion	2.3
Bunker HFO–internal combustion	2.6

9.4 Marine engines

MRC-DICE could be designed for use in container ships. The total capacity of diesel engines in container ships is estimated at 85 GW or 2.5–5% of the total gas and coal power generation market (DICEnet, 2013). To date there has not been any economic analysis which compares MRC-DICE to HFO-diesel in the marine industry, such as cargo ships. The market is new for coal producers but the engine manufactures are already there, so there is no incentive for the engine manufacturers to develop marine DICE. One problem is that the energy density of MRC is half that of HFO. However, paste MRC, with 25 MJ/L, can be bought and water from the on-board desalination plant can be used to create liquid MRC. The use of paste MRC also eliminates stability issues (Wibberley, 2014d). Maersk, D/S Norden and SEACO have also expressed interest in paste fired DICE (Wibberley, 2013c).

9.5 Economic comparison

Table 16 compares the economics of DICE with other power generation technologies (comprehensive information is beyond the scope of this report).

Table 16 Economic comparison of DICE with other power generation technology (Wibberley 2012, 2013a,b, 2014b; Nicol, 2013; Lockwood 2013; Jeffery, 2014)

Item	DICE (2 stroke, 10-100 MWe)	DICE (4 stroke, <20 MW)	USC PCC (>600MW)	IGCC	USC CFB	OCGT	CCGT
Capital costs (A$/MW)	1.8-2.315	1.14-2.315	2.4-2.6 +15% dry cooled	>2.6	>2.6		
Operating costs (80-90% fuel)	£	£	£	£	£	£££	£££
Maintenance costs	££	££	££	££££	££	££	£££
Fixed O&M costs ($/MWe per year)	25000 (100 MWe engine)	50000 (18 MWe engine)					
Variable O&M costs ($/MWh sent out) 2	15 (100 MWe engine)	9 (18 MWe engine)					
LCOE ($/MWh)	£	££	££	£££	££	£££	££
Cost per tCO_2 captured	60-70%	60-70%	100%	<100%	100%		
Key: £ low cost, ££ medium cost, ££ high cost, ££££ prohibitively expensive							

10 MAN Diesel & Turbo

MAN D&T, the world's largest diesel engine manufacturer, have taken a lead position in the development of DICE. In 2011, CSIRO and MAN D&T assembled an international consortium of sixteen companies and devised a staged R&D programme to validate and de-risk MRC-DICE technology by testing MRC in different engines. The consortium, known as DICEnet, consists of MAN D&T and RWE Power of Germany; JGC Corporation of Japan, Sinarmas of Indonesia; Exergen, IER, Energy Australia, AGL, TRUenergy, Newcrest, Yancoal, BCIA and CSIRO of Australia; GHD, Worley Parsons, XT and Australian Coal Association - Low Emission Technologies (ACALET). Further details on DICEnet can be found at the following link http://www.dice-net.org/ (Wibberley, 2013a,b, 2014c; Gay and White, 2013; DICEnet, 2014). Figure 47 shows a Gantt chart for the staged R&D programme for MRC-DICE, with the subsequent sections describing each stage (McManus, 2014).

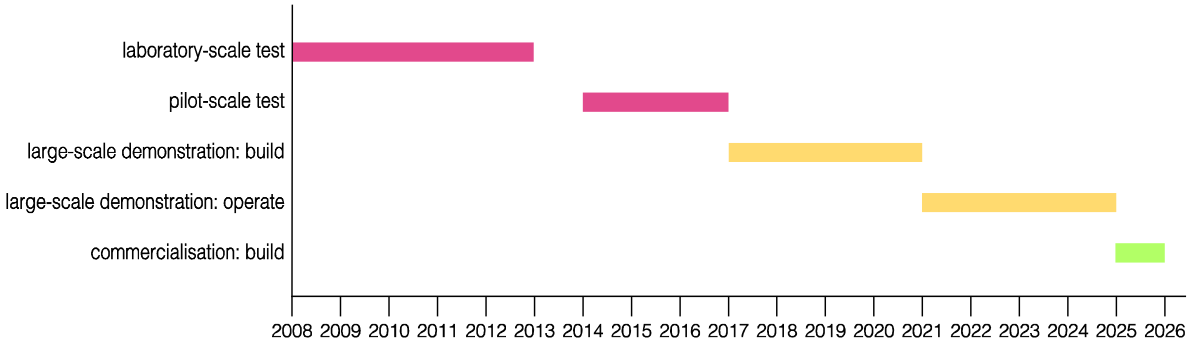

Figure 47 Gantt chart for the MRC-DICE R&D programme (McManus, 2014)

10.1 Pilot-scale testing

Planning for a 1 MWe pilot-scale DICE trial started in 2014. Work at CSIRO has developed the MRC delivery and injector system. With this information MAN have got plans to adapt a 1 MWe single cylinder, low-speed (170 rpm), two-stroke Mitsui diesel engine (7K60ME-DI-S9). The pilot-scale DICE would most likely be run in MAN D&T's research facility in Japan.

During validation on the pilot engine, further development work on the engine components can commence. MAN D&T estimate it will take one year to refine the fuel delivery system and engine design. The MRC fuel delivery system will be based on MAN D&T's new methanol fuel delivery system that has similar requirements to MRC. The following actions can also be undertaken during pilot-scale testing: accurate economic analysis; value-chain risk review; development of MRC fuel cycle, which includes solving the logistical barriers and establishing international standards for how the MRC is transported and stored; and the development of an MRC-DICE commercialisation plan. Pilot-scale work is expected to finish in 2017 (Wibberley, 2013a,b, 2014a,b; Gay and White, 2013; DICEnet, 2014; Oettinger, 2014; McManus, 2014).

10.2 Large-scale demonstration

Large-scale demonstration of MRC-DICE will be required to validate both the fuel preparation cycles and the performance of individual engine components. It is estimated to take 2–4 years for MAN, or others, to design and develop the relevant engine components and systems for a prototype engine. Demonstration-scale operation of MRC production with 8000 hours of operating a prototype engine will be required. Information from 8000 hours of operation will establish the performance life of individual engine components and provide a basis for performance guarantees. The operation is expected to take a further 2–4 years. Potential sites for the demonstration plant include Australia, Germany, Indonesia and India. The cost of the demonstration plant is likely to be in the order of A$40–80 million. A business case to justify this investment is under development (Wibberley and Wonhas, 2014; DICEnet, 2014; Gay and White, 2013; Wibberley, 2013a, c, 2014a, b, d; McManus, 2014).

10.3 Commercialisation

If the large-scale tests are successful, building of a 50–100 MWe commercial DICE could start in 2025. Four-stroke engines with estimated capital costs of around A$1.2 million per MWe could be used for smaller applications. Two-stroke engines are larger, more efficient and require less maintenance, but have higher capital costs of A$2 million per MWe. The economy of modularity gives lower capital investments, which are favoured in privatised energy markets (Wibberley, 2013b, 2014a; Gay and White, 2013).

Figure 48 lists the components in MRC-DICE; items highlighted in green are commercially available and items in yellow have been proven at pilot scale.

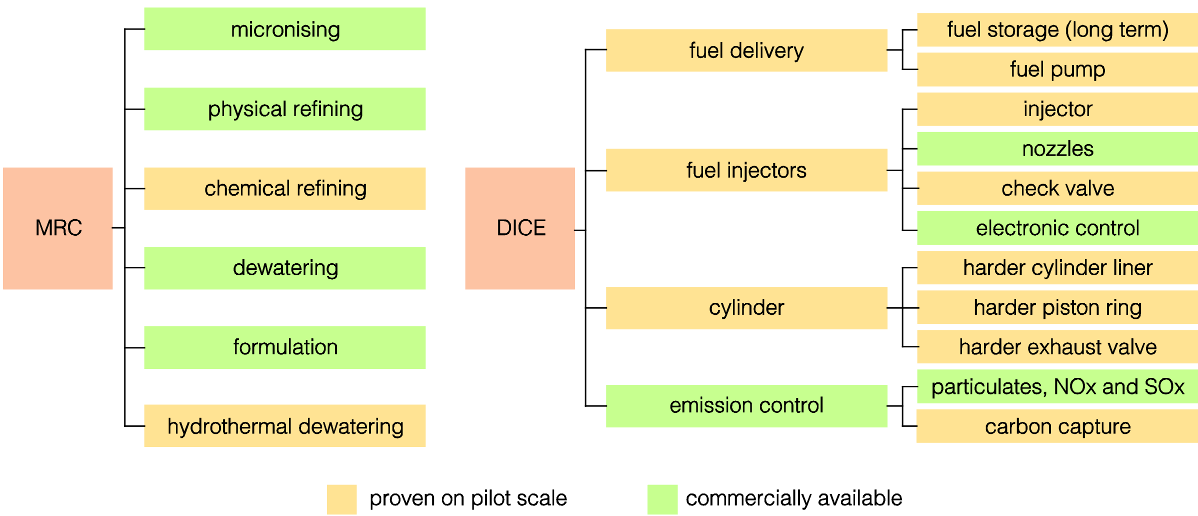

Figure 48 Checklist for MRC-DICE

11 Summary and conclusions

From the 1890s to the 1950s coal dusts were used in small internal combustion engines with <0.1 MWth cylinders. High mechanical efficiencies of 33% were achieved, which was twice that of steam power at the time, with engine life-time up to 12,000 hours. However, coal dusts cause severe wear, due to contamination of the dust with the lubrication oil. More importantly, coal dust is comparable to gun powder which led to explosions in the laboratory. Additionally, some coals required drying which added an energy penalty. Rudolph Diesel found that it was much easier to fire low-cost liquid petroleum fuels, which led to the development of the diesel engine as we know it.

In the 1960s laboratory research in the USA and Switzerland discovered that firing coal dust in a water slurry, split ~50/50, directly into the engine is more effective than dust firing. Coal water fuels (CWF) have higher combustion efficiency, they cause less wear, the water has a small effect on efficiency, slurries are not explosive and CWF can be washed to reduce wear and lower emissions.

The oil-crisis in the 1970s prompted the US Department of Energy (US DOE) to fund a comprehensive coal-fuelled diesel engine R&D programme from 1978-2004, which led to successful full-scale demonstration of coal-fuelled diesel engine in train locomotive, mine haul trucks and small-scale power generation engine. The minerals were removed with physical and chemical methods. At the time, physical beneficiation could produce CWF with 2–3% ash and chemical beneficiation could produce CWF with <0.5% ash at a higher cost. Additives were used to control viscosity and stability. To further minimise wear an adapted diesel engine was used which employed harder engine materials and a purpose built fuel injector. The engines had cylinders <0.3 MWth in size, reached efficiencies in the range 40–45% (HHV) and short-term results indicated that the engine life-time was acceptable. A promising coal-fuelled diesel engine for power generation was on track for long-term full-scale demonstration, until low gas prices in the 2000s removed the financial incentive to continue testing. The US DOE coal-fuelled diesel engine R&D programme concluded a CWF specification range for a medium-speed and high speed adapted four-stroke diesel engine.

More recently, higher oil and gas prices, tougher environmental and energy security drivers, coupled with advances in coal processing and diesel engine technology (such as electronic control and larger cylinders), have renewed interest in the commercialisation of coal-fuelled diesel engines for power generation. These engines promise high flexibility, black-start capability and high efficiency at all loads. The Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Australia have been investigating firing micronised refined carbons (MRC), a finer and cleaner coal water fuel, in direct injection carbon engines (DICE). Laboratory-scale tests at CSIRO with HRC and LRC-MRC have been successful.

MRC can be made from high rank coal (HRC), low rank coal (LRC), coal tailings, biomass and biochar. LRC and biomass can be hydrothermally treated (HTD) to upgrade their energy density. Ignite Energy Resources, Exergen, JGC Corporation, Xstrata Technology; Yancoal and Intertech are all producing MRC at pilot scale, the first three with HTD. As larger cylinders are more tolerant to low quality MRC, DICE will use 1–5 MWth cylinders, which include the large two-stroke engines used on large ships. DICE is based on technology developed by the US DOE coal-fuelled engine R&D programme. Analyses conducted by CSIRO, ANLEC R&D and MAN D&T show favourable economics in power generation applications, such as against diesel in distributed generation and gas in centralised generation.

MAN Diesel & Turbo plan to operate a 1 MWe pilot-scale DICE in Japan with MRC produced my multiple companies. The next development in DICE will be pilot-scale testing due in 2017. Long-term, large-scale demonstration of DICE is needed to give accurate measures of engine performance and to establish MRC specifications which will result in the lowest life-cycle cost for MRC-DICE. The MRC fuel cycle, which includes coal beneficiation and hydrothermal treatment, also has to be demonstrated at large-scale to determine whether MRC of acceptable quality can be produced economically.

Coal-fuelled diesel engines are not a new idea; the concept of firing a washed coal and in water slurry in an adapted diesel engine has been technically proven in the USA on pilot-scale and short-term large-scale demonstration. However, large-scale demonstration of both the DICE engine and the MRC fuel cycle are required before such technology can be commercialised.

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