ALTERNATIVE PATHWAY TO LOWER EMISSIONS

'While current clean coal technologies are based on large-scale centralised plants with major CO_2 capture and storage – the alternative pathway is about smaller, more efficient plants that underpin renewables, and using niche capture as a last step.'

By Dr Louis Wibberley, CSIRO Energy Technology, Newcastle

At the Coal21 Annual Conference in 2007, the author proposed an alternative pathway to low CO_2 emissions electricity with coal as the key fuel. The proposed pathway avoids or minimises many of the issues facing current clean coal technologies focused on CO_2 capture and geological storage (CCS). These include supercritical pulverised coal with post-combustion capture (PCC), gasification with capture, and oxy-pulverised coal with flue gas liquefaction. The current focus on CCS is because improvements in efficiency for conventional coal technology will not give anything like the step reduction in greenhouse gas emissions required. This means that only limited reductions in CO_2 will occur (via efficiency improvements) until around 2025 when CCS is expected to be rolled out on a meaningful scale.

Presently, if a new coal plant were built in Queensland or NSW, there would be a strong preference for it to be a 700MW, dry-cooled, advanced supercritical unit, with provision for future staged CO_2 capture using PCC. With capture at the current stage of development, this technology would give a delivered cost of electricity (including capture, transmission and distribution penalties), of around $125/MWh, and with a fuel cycle thermal efficiency for delivered electricity of around 30%.

This article considers an alternative technology pathway to that of current clean coal technologies.

EFFICIENCY CHALLENGE FOR CLEAN COAL

The following graph (Figure 1) shows that the delivered thermal efficiency of coal-based generation (i.e. with transmission) has improved at a relatively constant rate over the last 115 years. Although there have been a number of disruptive technologies (the steam turbine, suspension or pulverised fuel (pf) firing, large unified designs, and supercritical steam conditions), when graphed over a longer time interval up to the present, there has been a steady increase in efficiency.

Based on best current estimates from the technology developers, efficiencies for dry-cooled plants under Australian conditions will increase by around 4% points by 2030. However, if CO_2 capture were adopted, there will be an efficiency penalty of around 8% points – which will effectively wipe out 50 years of efficiency improvements.

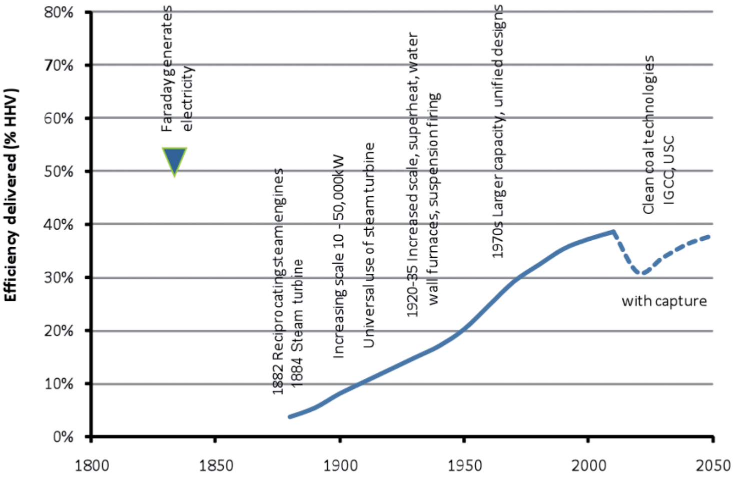

Figure 1 *Thermal efficiency of coal fired power generation over time*

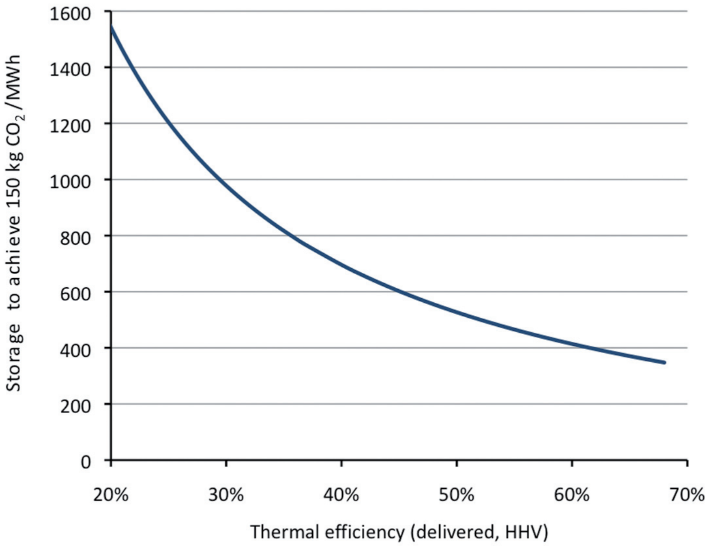

Figure 2 *CO_2 storage to achieve 150kg/MWh vs delivered thermal efficiency of the coal fired generation plant*

ENERGY PENALTY INCREASES STORAGE

The important point is not the efficiency number itself, but the proportional increase in the amount of CO_2 that will need to be stored as efficiency is reduced: if the overall efficiency of the system is reduced, then more CO_2 is produced and more must be captured, which increases the energy penalty for capture and further lowers the overall efficiency. This results in a disproportionate increase in the amount of CO_2 to be captured and stored to meet a given emissions intensity.

Figure 2 shows the amount of CO_2 to be stored to meet an emissions intensity of 150 kg/MWh versus the effective thermal efficiency (delivered electricity including capture).

With best current black coal plants, for each MWh delivered, around 1000 kg of CO_2 will need to be stored. This increases to around 1550–1600 kg/MWh for current brown coal plants.

Continued page 6 ▶

Continued from page 5

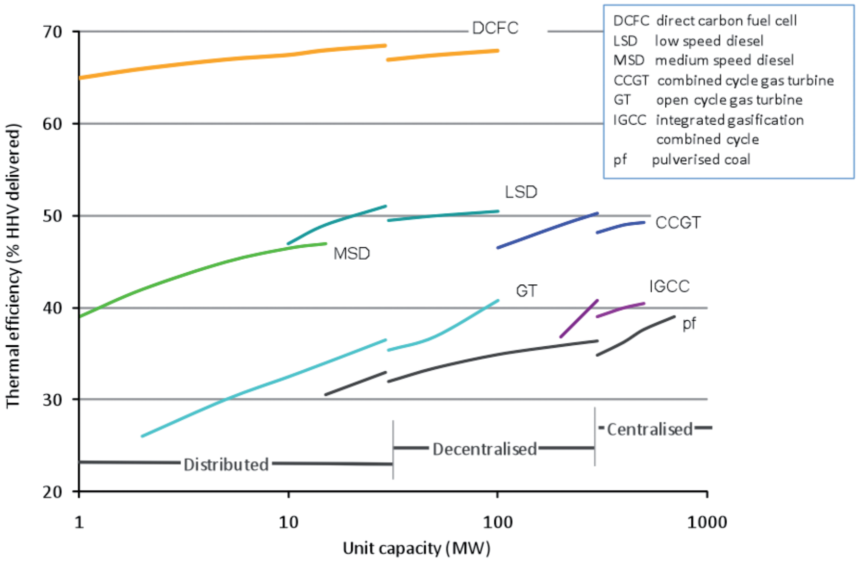

Figure 3 *Delivered efficiency vs unit capacity of a range of technologies*

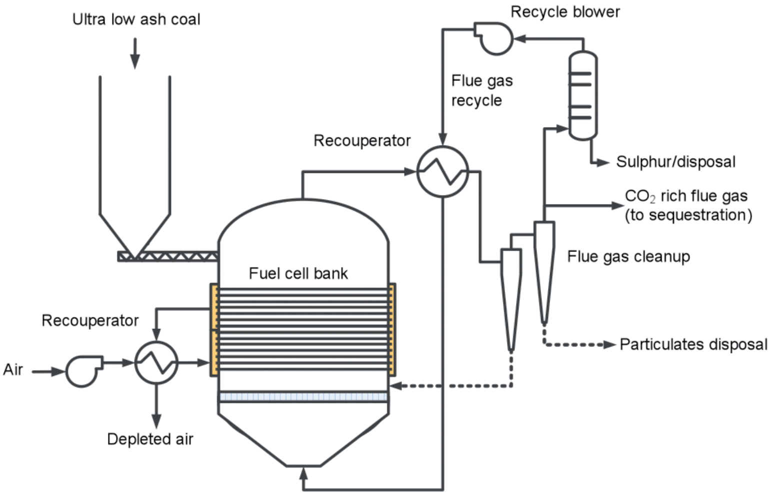

Figure 4 *Example schematic for a direct carbon fuel cell generator*

Making a current versus future technology comparison, if the delivered efficiency were increased to 45%, then the amount of CO_2 to be stored would decrease to 600 kg/MWh (a 40% reduction for black coal, and a 62% reduction for brown coal). If a delivered efficiency of 65% could be achieved, this would reduce the amount of storage required for black coal by 62%, and by around 76% for brown coal.

These higher delivered efficiencies would markedly reduce the aquifer volume required for CCS. As an example, to store the CO_2 from NSW's current coal plants would require injecting liquid CO_2 into around 8000 m^3 of reservoir pore volume every hour. Using nominal Department of Primary Industries values for aquifer porosity and the effectiveness factor, this means that around 1 000 000 m^3 of reservoir aquifer will be filled every hour. The higher efficiency value would reduce this to around 380 000 m^3 per hour for black coal.

As the cost of CO_2 mitigation per unit of power will also decrease in the same proportion, anything which can increase the system efficiency, and reduce the amount of CO_2 required to be stored, will be valued much more highly in the future.

THE ALTERNATIVE PATHWAY

The alternative pathway being proposed by CSIRO has different priorities to those of the current clean coal approach:

- Achieving the highest possible efficiency for coal-based generation at smaller scale,
- Using the advantages of higher efficiency, smaller coal plants to underpin a high penetration of renewables, thereby giving more cost-effective renewables and a proportional reduction in CO_2 intensity of the system, and
- Using niche (rather than major) CO_2 capture and storage as the last step in meeting emissions targets.

So while current clean coal technologies are based on large-scale centralised plants with major CO_2 capture and storage – the alternative pathway is about smaller, more efficient plants that underpin renewables, and using niche capture as a last step.

MAXIMISING THERMAL EFFICIENCY

Figure 3 compares the thermal efficiency (from delivered fuel to delivered electricity – without capture) for a range of technologies. Size-for-size, the most efficient means of converting fuel energy to electricity is by using large diesel engines or direct carbon fuel cells (not yet commercially available, though the high efficiency has been demonstrated in the laboratory).

Coal could achieve a much higher efficiency if these technologies could somehow be used, enabling a delivered efficiency of around 50% from a direct injection coal engine (DICE) in the short-medium term, and at least 65% in the longer-term future from the direct carbon fuel cell (DCFC). Both could be achieved at a smaller scale than for conventional coal technologies – an attribute that could give a number of other important advantages associated with more decentralised electricity generation, including a reduction in transmission losses (electricity transmission losses are almost always significantly higher than those from the transport of fuel).

Although DICE and the DCFC require ultra low ash coals (say below 2% ash), technologies already exist to produce suitable fuels from coals (including from Victorian brown coals).

DIRECT INJECTION COAL ENGINE

Although never commercialised, the coal engine is not new, being the subject of a number of development programs over the last century (with key programs every 20 years approximately). The early work was led by Diesel and then co-worker Padowski, with engines running for many years on everything from lignite dust to coke. However, the most comprehensive test program was undertaken by the US Department of Energy (DOE) over the period 1978 to 1992, mostly for transportation applications. This included adapting and testing engines ranging from a 2MW single cylinder test engine (90 rpm), a 2MW locomotive (1000 rpm), and an 800 kW haul truck engine (1900 rpm). The most successful demonstrations used ultra low ash coal water fuels which were injected using modified conventional direct injection (i.e. solid injection) systems. Although the technical issues were overcome for the direct injection coal engine, with combustion efficiencies of over 99% being achieved at up to 1900 rpm, and with thermal efficiency equal to diesel fuel, the program was eventually terminated due to persistently low oil prices and before a commercial engine was developed.

WHAT'S CHANGED?

In revisiting this technology, it is important to consider a number of different drivers: the impending cost of CO_2 abatement, cooling water availability, the need to support a step increase in renewables, energy security and changes to the structure of the electricity supply industry.

DICE would have a number of advantages, including being implemented with smaller capital steps, and would be suitable for baseload, peaking and providing grid security or ancillary services. DICE would also be capable of cofiring of biomass fuels (char, crude bio-oils and algae soups), which could enable biomass to be utilised at double the efficiency of current biomass plants. Also, as waste heat is at sufficient temperature to provide the low temperature heat energy needed for CO_2 capture, this could be added with a smaller cost and energy penalty than for current clean coal technologies (instead of converting this energy to electricity with very small and inefficient turbo machinery).

In addition, there have been a number of key technology changes, including developments in coal cleaning, micronising, engine technology/materials/size and costs (about the same as for pf), which are all likely to further increase the viability of the coal engine over that in previous development programs, and reduce the time required for adoption of the technology. Currently, under the European HERCULES Project, new engine technologies are being developed which will increase the efficiency of large engines to over 60% (LHV, mech).

DIRECT CARBON FUEL CELL

The ultimate in thermal efficiency from coal could be achieved by using ultra low ash coals in direct carbon fuel cells. The DCFC works similarly to the hydrogen fuel cell, but is superior in terms of thermal efficiency, with over 75% being achieved in US laboratories for a range of carbon types, including a sample of ultra low ash coal produced by UCC Energy. There are a number of possible configurations being developed. An example schematic arrangement is shown in Figure 4, which comprises a solid oxide fuel cell bank, and a flue gas split (capture is not required) for CO_2 sequestration.

The DCFC is being commercialised for small applications (e.g. the US Army are funding the development of a unit to convert ration pack wrappers to electricity for field use), and current projections from US developers are that it will be available for large-scale commercial electricity production from around 2030. Development is also expected to piggy-back on technologies being developed for the hydrogen fuel cell.

From a system perspective, the DCFC would be highly advantageous, as the technology would be suitable for baseload and peaking duties, is highly suitable for biomass char, and as it produces essentially pure CO_2, it would have a smaller efficiency and cost penalty for CO_2 capture and storage. In the alternative pathway, it is envisaged that DICE power plants would ultimately be converted to DCFC, say post 2030.

In Australia, the DCFC is being researched for coal applications by the CSIRO, and the Universities of Newcastle and Queensland.

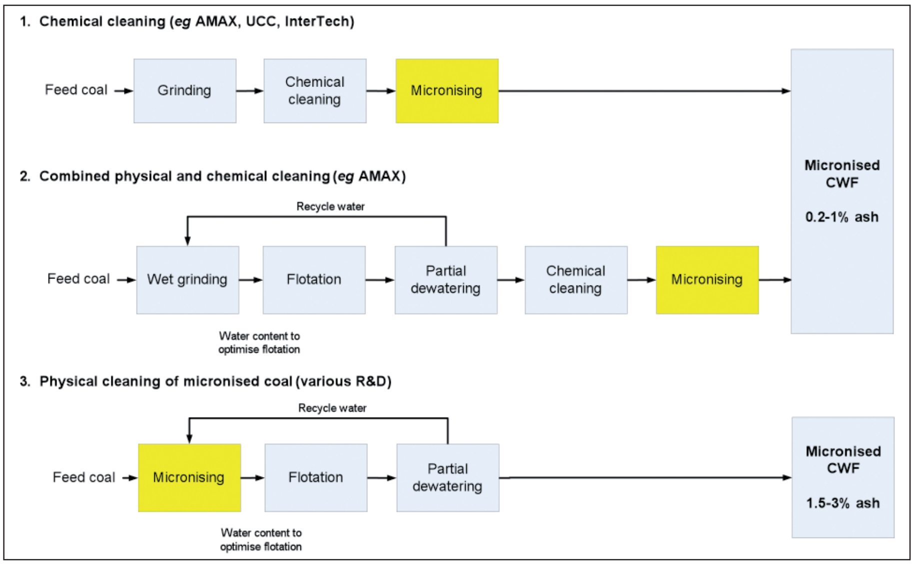

Figure 5 *Main coal cleaning processes (3) for production of engine grade CWF from bituminous coal*

ULTRA LOW ASH COAL

The alternative pathway depends entirely on cost-effective production of ultra low ash coals. Although the cleaner the better, detailed coal specifications for both large diesel engines and the DCFC remain unclear. The DOE work in the 1980s and early 1990s concluded that up to 2% ash is suitable for DICE, and this could be produced from chemical and physical coal cleaning processes.

The DOE studies showed that the most suitable method for fuel delivery was direct injection of micronised coal water fuel or CWF (so drying is not required after cleaning). Depending on engine size and operating speed, the micronised coal should have a top size of 20–30 μm, and a coal concentration of around 45%. This gives a CWF viscosity of around 300–500 mPa.s (at 100/s) which is sufficient to enable effective atomisation.

Although there are a number of methods of utilising CWF in the DCFC (including integrated flash drying and partial gasification combinations), it is expected that a similar quality coal would be required.

There are three main process types for cleaning coal and producing an engine grade CWF from bituminous coals, as shown in Figure 5. These involve either removing mineral matter from the coal, or the coal from the mineral matter. None of these processes are currently commercial, but have been operated at up to pilot scale.

CHEMICALLY CLEANING LOW ASH FEED COAL

The first process involves chemically cleaning a relatively low ash feed coal, producing a coal water slurry, and then micronising to produce an engine grade CWF. Examples are the AMAX and UCC processes which use a combination of caustic and acid treatments to dissolve away the ash and InterTech which does a similar thing using hydrofluoric acid.

FINE COAL PROCESSING

The second approach uses fine coal processing to remove as much of the ash as possible by conventional flotation, then uses chemical cleaning to remove the remaining ash, followed by slurrying and micronising to produce a CWF for an engine. This was developed by AMAX in the 1980s. However, as there are limitations on how much grinding can be tolerated without compromising the materials handling in the chemical cleaning process, the ability of the pre-cleaning step to reduce ash levels significantly (below that of normal coal preparation techniques) will be highly coal dependent.

ULTRA FINE COAL PROCESSING

The third approach involves slurrying and micronising the coal first (not last), and then using ultra fine flotation or selective agglomeration to remove the ash. Although several previous studies have shown that this process is technically feasible, the results obtained in the past have been highly variable, especially with respect to coal recovery rates. However, recent test work with a range of Australian coals (including tailings) has shown that if coal is ground finely enough, a consistent and low ash product is possible with very high coal recovery. As the micronised raw coal slurry has the appearance of crude oil prior to refining, this process has been termed micronised coal refining, and the product micronised refined coal (MRC).

As there is a trade-off between product ash and (nominal) processing costs (see Figure 6), the most suitable cleaning process will depend on the target application. In particular, there is likely to be a significant increase in production cost with ash contents below around 1.5–2%, because chemical cleaning is then required for most coals. For this reason, chemically cleaned coals at 0.2–1% ash are likely to be cost competitive with natural gas.

Continued page 8 ▶

Continued from page 7

Coal at around 2% ash would be cost competitive with thermal coals used in conventional coal power plants.

ULTRA LOW ASH COAL PROJECTS

Over the last few years there has been a steady increase in efforts to produce ultra low ash coals. By far the most advanced is the process being developed by UCC Energy, which is aiming to demonstrate the production of ultra clean coal (UCC) with ash contents down to 0.2%. This very low level is achieved by chemical cleaning. Although originally developed for gas turbines, UCC Energy is now aiming to optimise the process to produce a higher ash specification fuel for a wide range of diesel engines in applications that could replace natural gas/LNG turbines. It is projected that the revised process will give a step reduction in processing costs and CO_2 emissions from coal processing. A small-scale demonstration is presently being undertaken as part of the Asia Pacific Clean Fossil Fuel program (a component of the Asia-Pacific Partnership on Clean Development and Climate).

MICRONISED REFINED COAL

To compete with black coal pf plants, CSIRO, TUNRA Clean Coal, the University of Newcastle and Xstrata Technology are collaborating to investigate the use of new developments in milling and ultra fine coal cleaning to produce low-cost micronised refined coal (MRC) suitable for very large diesel engines. The process involves micronising run of mine coal to a d90 of <20 µm using an Isamill, and then physical cleaning and partial dewatering using advanced ultra fine coal flotation.

Cost estimates show that MRC could be produced at substantially lower costs than for processes using chemicals, which should enable MRC-DICE technology with the largest engines (mostly likely to be able to cope with higher residual mineral matter and other ash forming material in the fuel) to compete favourably with pf plants for CO_2 costs above $30/t.

To date, very promising results have been achieved using an Isamill to efficiently micronise the coal before flotation using TUNRA or Jameson cells. As an example, the Isamill-TUNRA Clean Coal technology combination has produced:

- 1.6% ash MRC from a 27% ash Queensland coal with a combustibles recovery of 94%,
- 2.8–3% ash MRC from a 14% Hunter Valley coal with a combustibles recovery of 90%, and
- 3% ash MRC from 52% ash Hunter Valley tailings with a combustibles recovery of 85%.

Similar results have been obtained by the University of Newcastle using alternative flotation techniques.

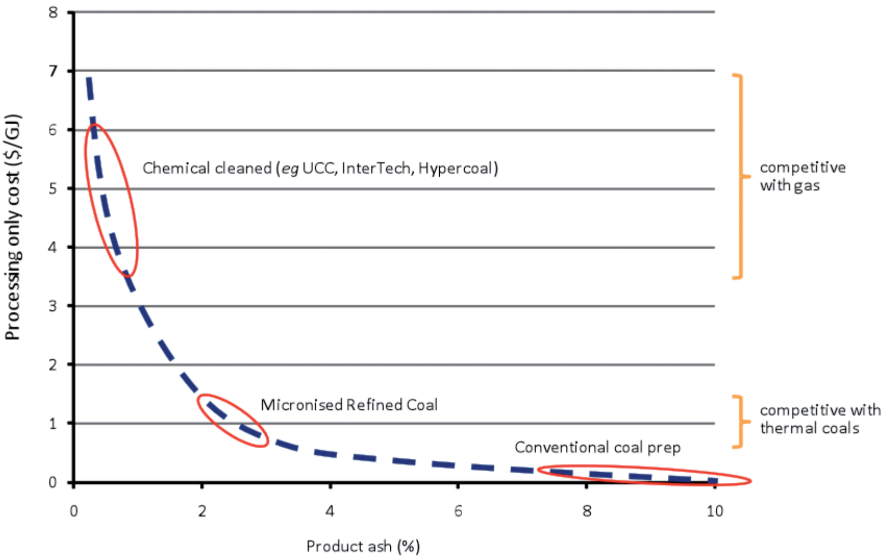

Figure 6 *Nominal processing only cost vs product ash*

Another interesting development is that TUNRA Clean Coal have dewatered MRC to 12% total moisture using selective agglomeration (at very low levels of organic additions). MRC is produced as a dry prill, which would give the option of transporting and storing MRC in solid form.

While most effort is on bituminous coals, Exergen are developing a diesel engine fuel from Victorian brown coal and lignites. As the ash content of these coals is already low, fuel production is focused on producing a suitable CWF by upgrading these coals by hydrothermal treatment.

MICRONISING

Efficient micronising of coal is essential for either coal engine or fuel cell applications. Conventional pf mills are totally unsuitable for producing the ultra fine particle size which is thought to be required for diesel engines (d50 of <10 µm and a top size of 30 µm). Conventional mills are even less suitable when treating higher ash coals. Since the extensive coal engine R&D for the DOE in the 1980s, new large mills have been developed for the minerals industry, routinely milling up to 10 000 tonnes of hard rock per day to sizes below 10 µm (e.g. see photograph of a typical Isamill in Figure 7). Preliminary studies by CSIRO have shown that coal can be micronised by an Isamill suitable for producing engine grade fuel with a projected energy consumption of around 60 kWh/t.

UNDERPINNING RENEWABLES

The second aspect of the alternative pathway is to use smaller high efficiency coal power plants to provide the grid security necessary to enable a higher penetration of renewables. Coal could have a more important role in underpinning the uptake and development of renewable energy, particularly those which are intermittent – wind and solar of course, but also seasonal biofuels. By doing this, coal

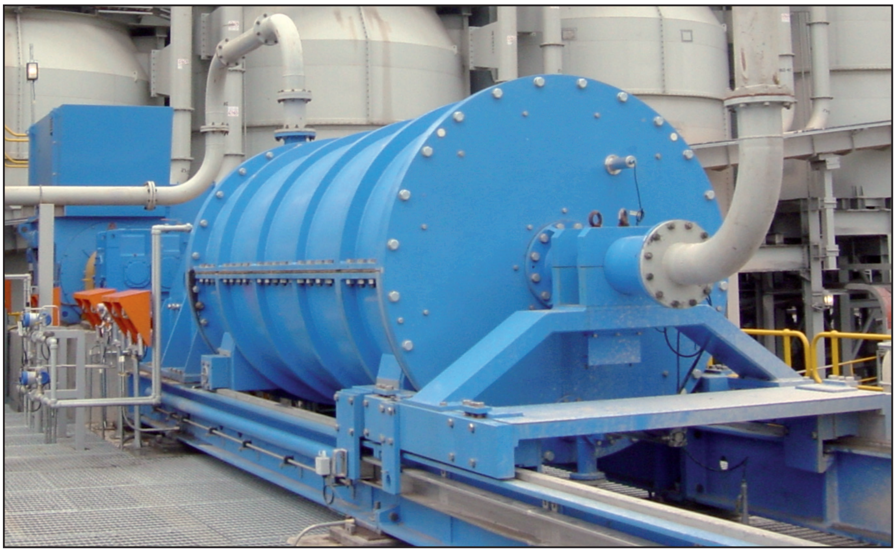

Figure 7 *A 3 MW M10,000 IsaMill™ operating in base metal regrind duty*

effectively reduces its own CO_2 intensity, and supports the transition to more sustainable generation.

Done effectively, this avoids the costs and inefficiency of energy storage or of providing the ancillary services required for a secure grid.

There are at least three ways that coal plants can do this – providing longer-term backup, shorter-term spinning reserve, and efficient utilisation of biofuels.

While the backup and spinning reserve roles are well known, to do this efficiently, without increased CO_2 emissions (especially with a higher penetration of renewables), requires technology which can give higher part-load efficiency and short start times. As large diesel engines have excellent part-load efficiency and also relatively short start times, DICE-based power plants should be better than pf and gas plants for this role.

The ability of DICE to efficiently utilise other biofuels is also likely to greatly assist the development of renewables. These could range from micronised chars, through a wide range of crude bio-oils, to soups of high lipid content algae. Relative to gas turbines, diesel engines are extremely tolerant to alkalis in the fuel, and compared to pf plants have only a marginal penalty for fuel containing up to 60% water. While these attributes are also shared with gasification-based technologies, DICE could do this with a much higher efficiency (8–15 percentage points depending on unit capacity) and remain effective at smaller scale.

CAPTURE AND STORAGE

Even with high efficiency and a high penetration of renewables, some CCS may eventually be required. As yet there appears to have been no R&D specifically undertaken for capture from a coal engine or a direct carbon fuel cell. However, as the coal engine exhaust will have properties between that of pf boilers and NG gas turbines, it should not pose any special difficulty for post-combustion capture. As engines reject their heat at a temperature which is usable for CO_2 stripping, this will greatly reduce the energy penalty for capture – especially if an integrated capture process is used to replace the small turbo machinery normally used to recoup extra exhaust energy.

Capture from a DCFC would be even easier, as the flue gas produced would be similar to that from oxy-pf. Capture would not be required, only dehumidification and liquefaction, giving an energy penalty only one-third that for oxy-pf.

It is likely that either technology has the potential to halve the energy penalty for capture, thereby further reducing the amount of CO_2 that has to be stored.

IMPLICATIONS FOR CO_2 INTENSITY

The diagram in Figure 8 shows the likely reduction in CO_2 intensity of delivered electricity for the current approach based on clean coal technologies with CCS, and that proposed for the alternative pathway. Although both pathways remain unproven, both could achieve a CO_2 intensity of around 100 kg/MWh into the future.

With clean coal technologies only a small reduction in intensity is likely until the rollout of major CCS – which by current projections is unlikely before 2025–2030.

As the alternative pathway can be implemented at smaller unit capacity (60–100 MW), it is proposed that this should result in smaller capital and risk hurdles which could facilitate earlier implementation. This would start with using ultra low ash coals into large diesel engines from 2015 giving a 20% reduction in CO_2 for new plants. These plants could be used to give both direct and indirect support to a high penetration of renewables (say 20%), providing a cumulative reduction in CO_2 intensity of around 40%. DICE plants would be replaced by DCFC/niche CCS as required post 2030 to meet future emission targets, and with a 400% reduction in the amount of CCS required. It is proposed that additional cumulative CO_2 savings could accrue from earlier implementation.

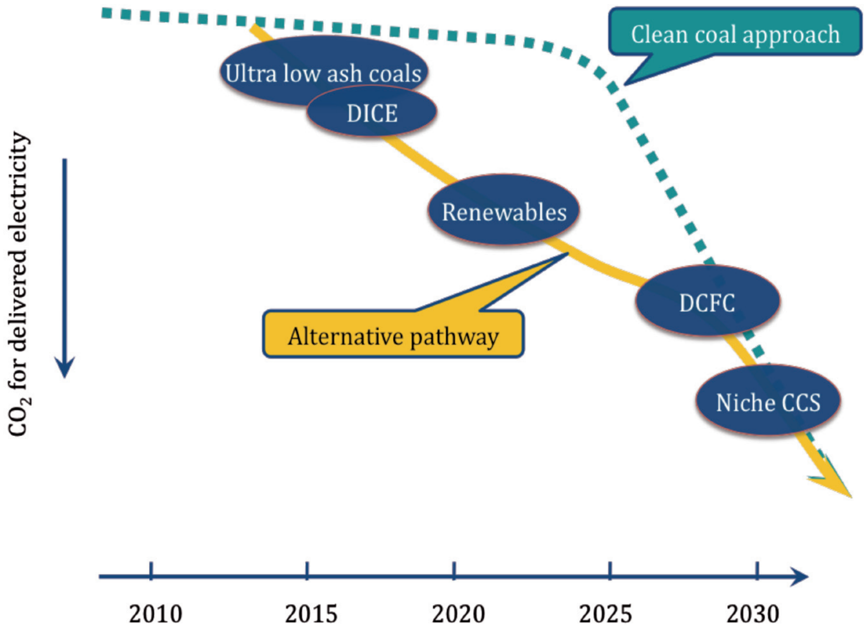

Figure 8 *Possible future CO_2 for delivered electricity*

WHERE TO FROM HERE

It is acknowledged that the proposed alternative pathway needs considerable development and demonstration to match the level of technical development of the clean coal technologies. Despite this, the proposed pathway has strong technical merit because of the ability to carry out a near-commercial scale demonstration at a relatively small scale. This greatly reduces development and commercialisation risk hurdles. In addition, while the overall approach is novel, most of the component technologies are based on adapting commercial and mature processes (and many are Australian). An additional feature is the high degree of flexibility and adaptability of all of the technologies.

A number of proposals are under development to establish small-scale demonstration projects in Australia. These mostly involve a two-stage program starting with pilot testing of fuel production at around 1 t/day for use in a 500 kW pilot engine (or several cylinders of a larger engine), together with engineering for a larger demonstration plant. This would be followed by a 10 000 hour demonstration plant with a 10 MW power plant. Even at this small scale, the demonstration plant would exceed the sent out thermal efficiency of Australia's best pf plants. In addition, this would be sufficient to scale up (through both multiples and scale) to a 100 MW power plant within 5 years.

As the most costly component of the demonstration is expected to be the power plant (around $25M for 10MW), there is considerable scope for cost-sharing this facility between a number of ultra low ash coal projects. Hopefully this could be achieved with strong interest from the large engine manufacturers.

In the meantime, CSIRO, partners and several industry groups continue to undertake research on how best to prepare coal water fuels from different coals/different cleaning technologies, and to better understand coal-engine interactions. Several Chinese groups are also working in this area.