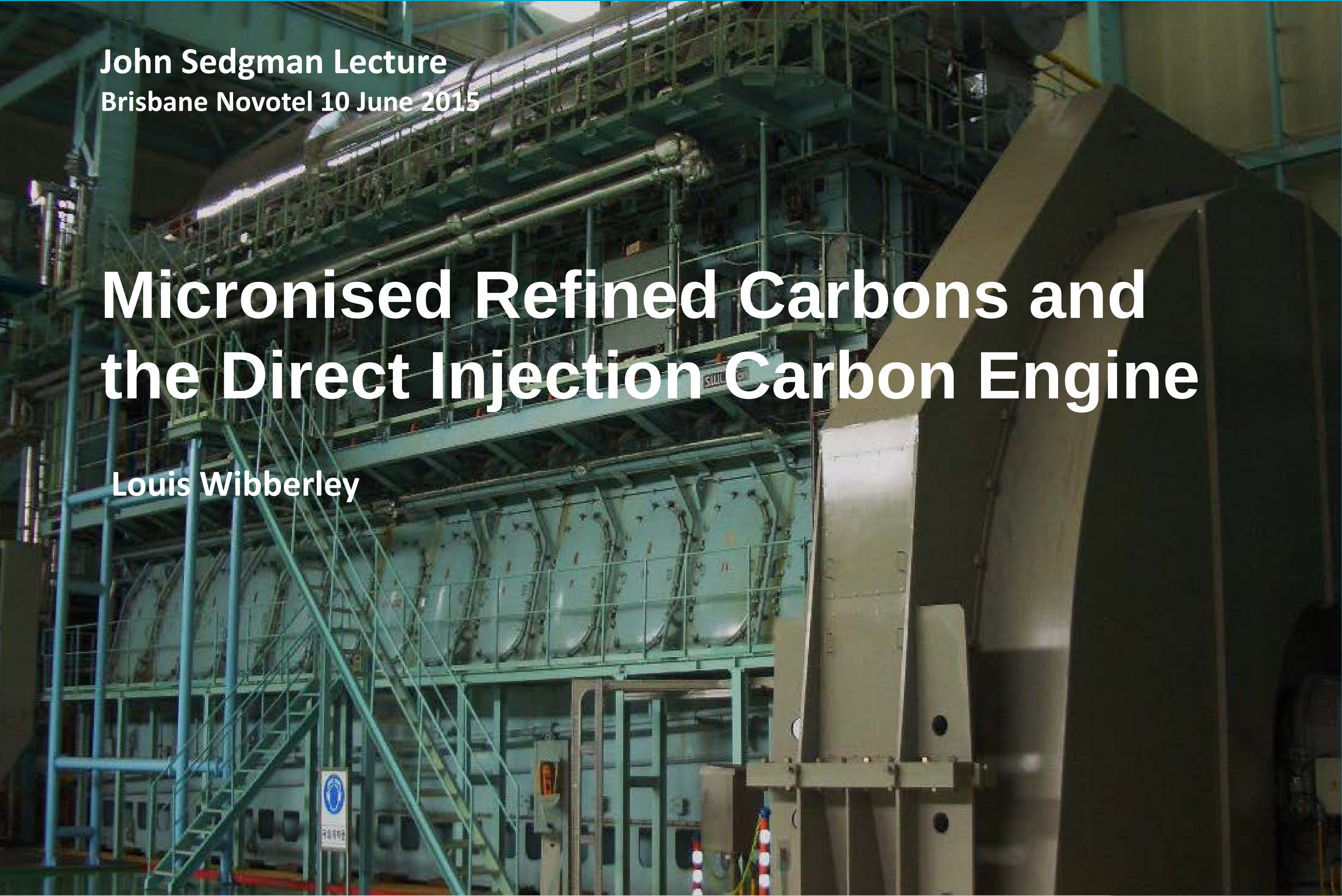
John Sedgman Lecture

Brisbane Novotel 10 June 2015



Micronised Refined Carbons and the Direct Injection Carbon Engine

Louis Wibberley

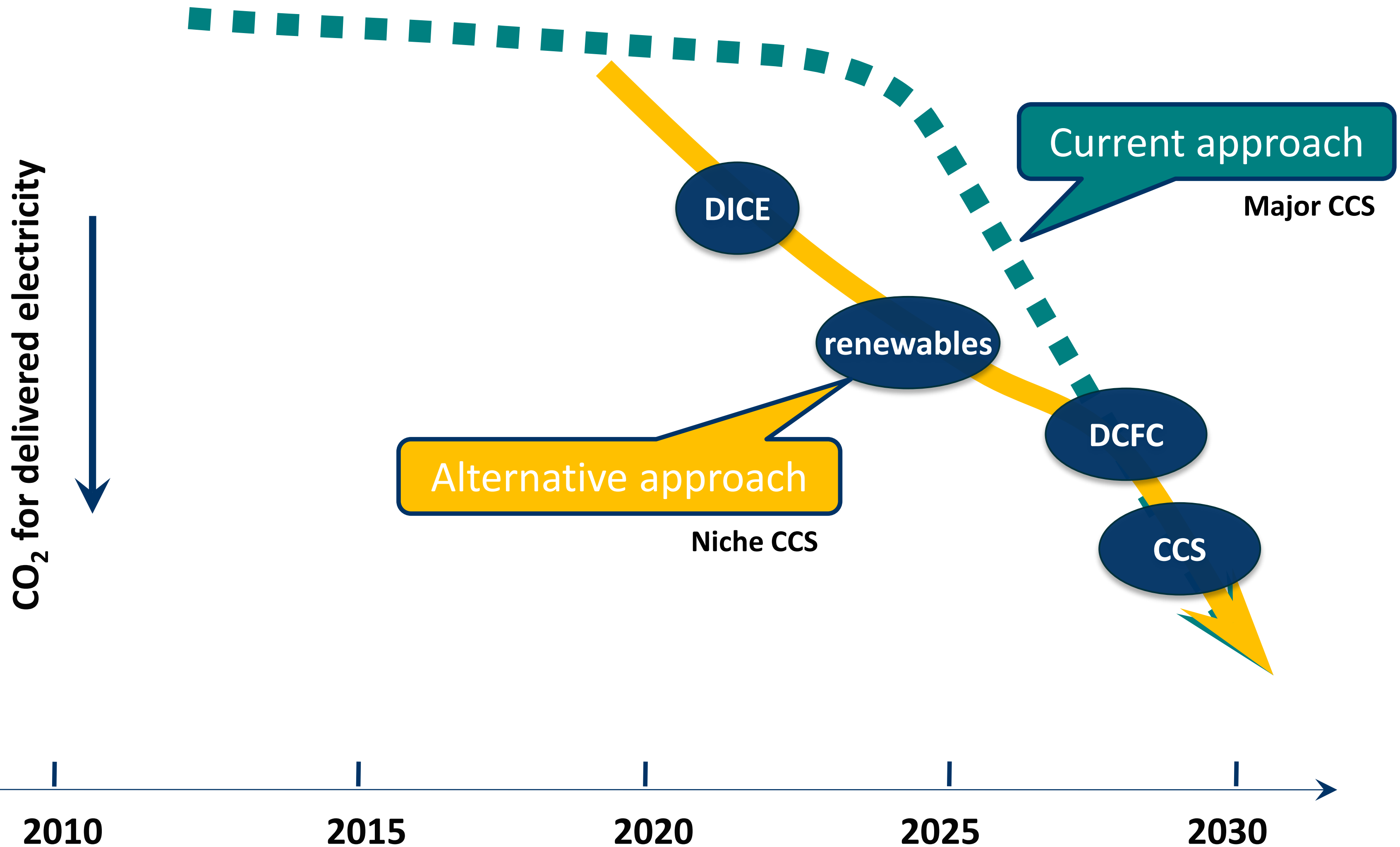
Key messages

1. Combining the low cost and availability of coal with the superior thermal efficiency, flexibility and lower capital cost of the diesel engine provides a step change technology for coal
   – this requires ultra low ash coal

2. Ultra low ash (and other premium coals) can be economically produced from a wide range of coal sources, including tailings - using conventional equipment
   … but this requires a change in philosophy

Why? … provides an alternative LE pathway

Philosophy: higher efficiency + underpinning renewables + niche CCS



MRC-DICE fuel cycle

Carbons

Premium water-based slurry fuel

micronised refined carbons (MRC)

Ultra efficient diesel engine generation

direct injection carbon engine (DICE)

MRC – the most efficient way of converting carbons into liquid fuels

MRC from Victorian brown coal

Micronised refined carbon (MRC) has been produced from a range of sources

- desanded and hydrothermally treated low rank coals
- deashed black coals (including tailings)
- chars and algal matter (blended)

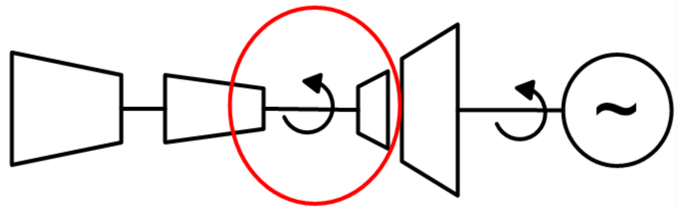
Fuel choice determines carbon footprint

Process has very high energy conversion efficiency >97% (LCA basis)

Diesel engine – efficient, flexible and fuel tolerant
(but some adaptation required for coal)

Gas turbine

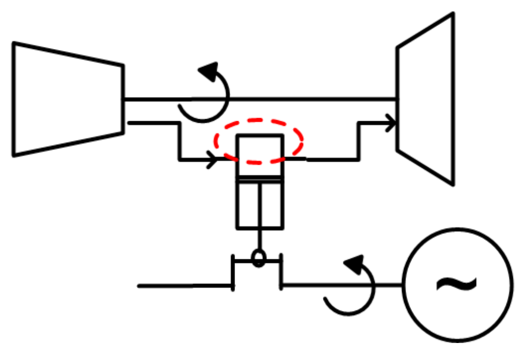
Continuous combustion - hot section is exposed continuously to 1450-1500°C gas at 2-4 MPa
Exotic alloys, hot strength, oxidation
Fouling issues for impure fuels



Turbocharged diesel engine

Higher "Carnot" efficiency
Cyclic hot space allows dirtier fuel without fouling or the need for exotic alloys
Large expansion ratio = smaller waste heat recovery

Batch combustion - hot section hot for <10% of the time, cyclic @ 1-5 Hz (larger engines)
Higher T & P possible and without fouling, >1500°C, 15-25 MPa



Cycle comparisons – too much water?

	External cycle				Power cycle				
Cycle-fuel $P/T_1/T_2$[1]	Fuel (dry t)	Water (t)	Air (t)	η (%HHV)	Fuel (dry t)	Water (t)	Air (t)	η (%HHV)	η sent out (%HHV)
Steam-black 250/650/650	1	0.1	11	88%		12		48%	42%
Steam-brown 250/650/650	1	2.2	10	73%		11		48%	35%
Steam-CWM 250/650/650	1	0.7	11	84%		11.5		48%	40%
Diesel-HFO 200/1500					1	0-1	15	54%	52%
DICE-MRC 200/1450					**1**	**1**	**15**	**51%**	**49%**

[1] *bar/°C/°C*

DICE offers game-changing attributes in 5-6 years

1. Match and compete with natural gas; rapid start/stop and load following capability
   – excellent match to electricity grid with high intermittent renewables
2. Step reduction in carbon emissions for electricity generation without CCS
   – 20-35% reduction in carbon emissions versus current black coal
   – 35-50% reduction in carbon emissions versus current brown coal (in Victoria)
3. Cost competitive with new conventional coal

… not possible with other coal technology

4. Small capital investment steps
   – can achieve large power plant size incrementally using 20-100 MW units
   – shorter construction time
5. No cooling water
6. Can be used for various biomasses
7. Capture ready/capture efficient
   – 30-40% lower cost of CO_2 abatement over conventional coal
8. Short path to commercialisation
   – adaptation of current large engines, short cycle time to implement changes, relatively low development cost

ability for commercial-scale demonstration at a small scale (say 30 MW)

What about USC? … development opportunities restricted and costly

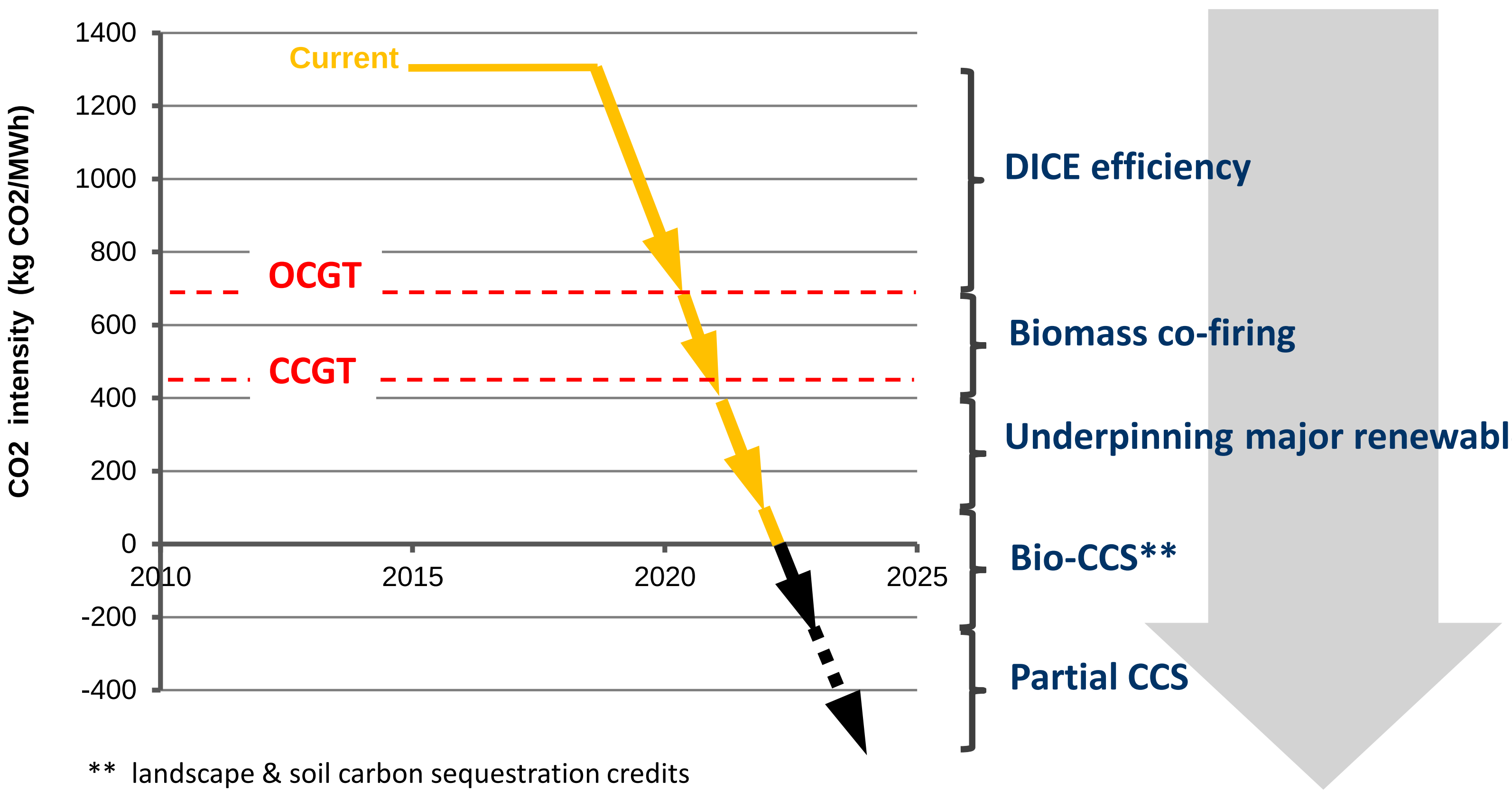
- Thermodynamic efficiency of pf generation is severely limited by the availability of materials that can operate at these conditions for practical service lifetimes
  - EU, USA, Japan, India and China all have extensive material research programs aiming for steam temperatures of 700°C (advanced ultra-supercritical)
  - development cost of billions of $ and long lead times (creep testing)
  - anticipated that a commercial unit could be brought on-line in 2031 (IEACCC/229)
  - high capital cost of advanced ultra-supercritical is of particular concern (high pressure steam pipes currently 80% of the boiler cost)
- While the combustion conditions in the diesel engine are more extreme, the diesel cycle is a batch process
  - high temperature conditions are present for less than 10% of the time, which avoids the need for major exotic alloys

A pathway to net negative CO_2 emissions?

(DICE efficiency first, then high penetration renewables with bio-CCS and lastly partial CCS)

Example: Victorian generation

Carbon management sequence



** landscape & soil carbon sequestration credits

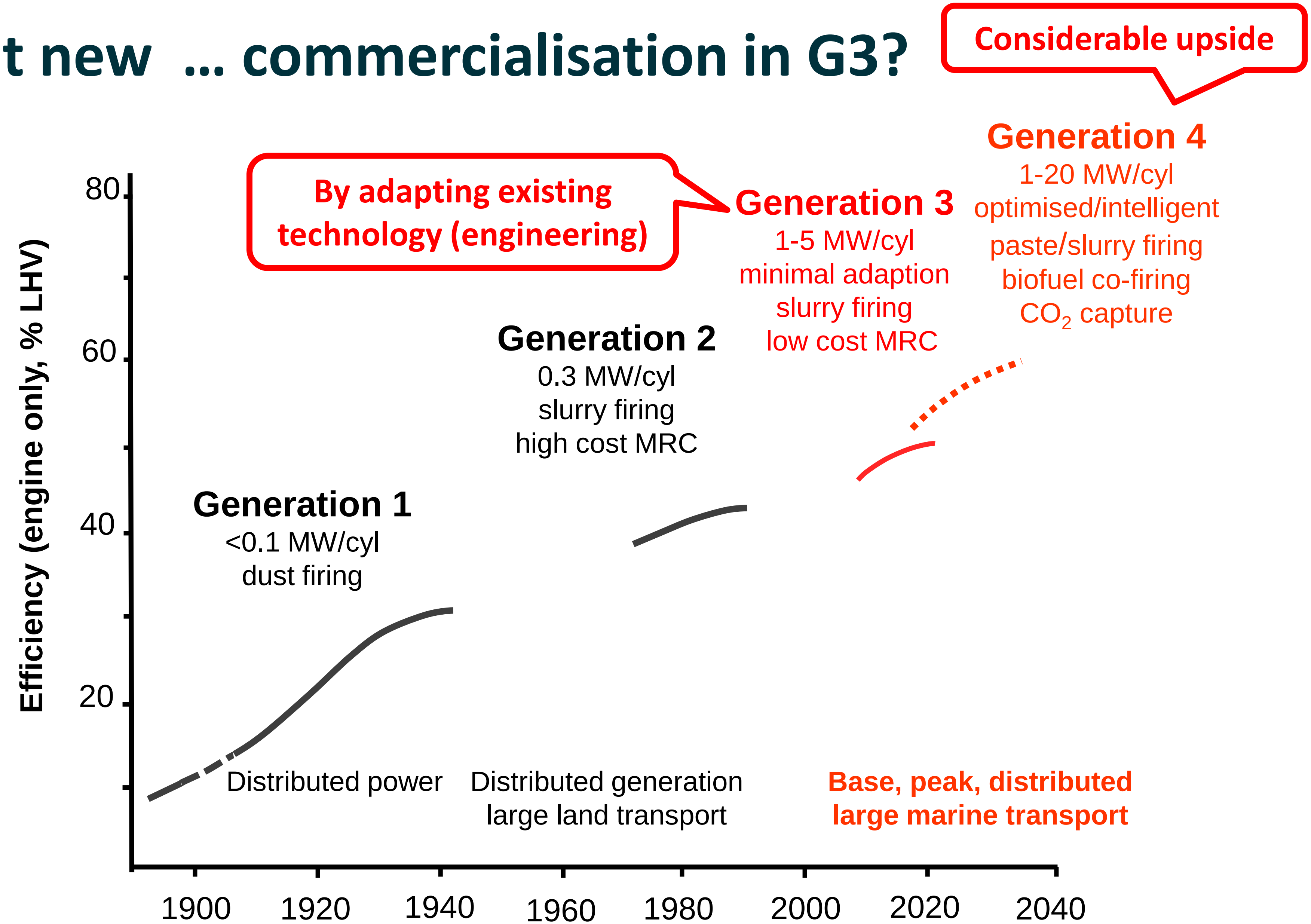
If successful DICE could address many aspects of the coal dilemma

Including:

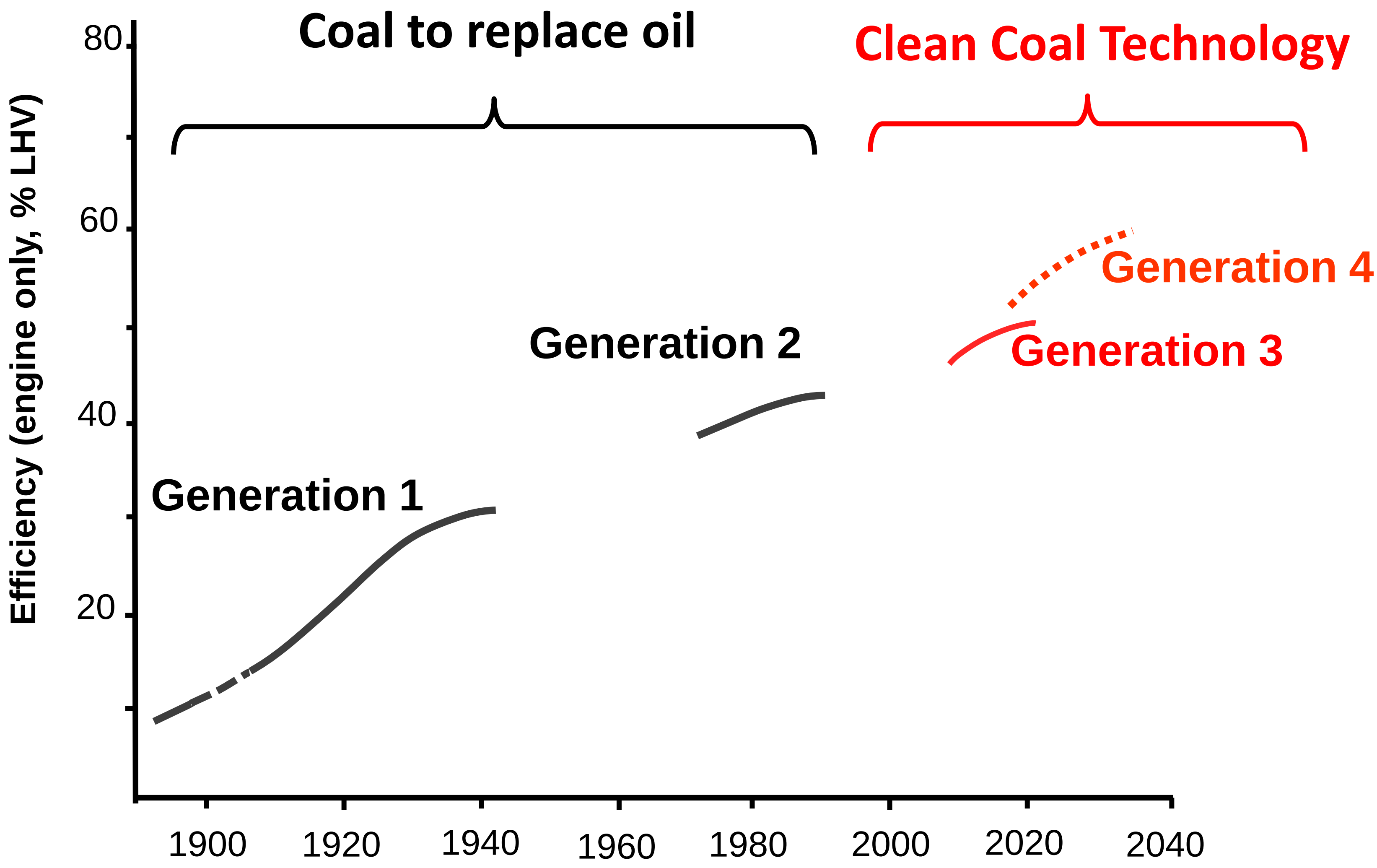
- that large centralised plants are needed for efficiency
- the nexus between water/CO_2 and cost (dry cooling)
- technology development by a fragment of generation industry
- inefficient (even if cheap) is no longer acceptable
- very poor image of low rank coals
- poor project economics from long development times
- the higher flexibility needed for current and future electricity markets

Could DICE become the benchmark coal generation technology?

Not new ... commercialisation in G3?



… with a changed philosophy



The fuel side … towards commercial production of MRC

Coal water fuel in China – stepping stone to MRC?

Coal water mixtures for boilers

~40 Mtpa in China
5-8% ash, d90 ~150µm
typically 70% coal
2000 mPa.s @ 100/s

Micronise and float

MRC for DICE

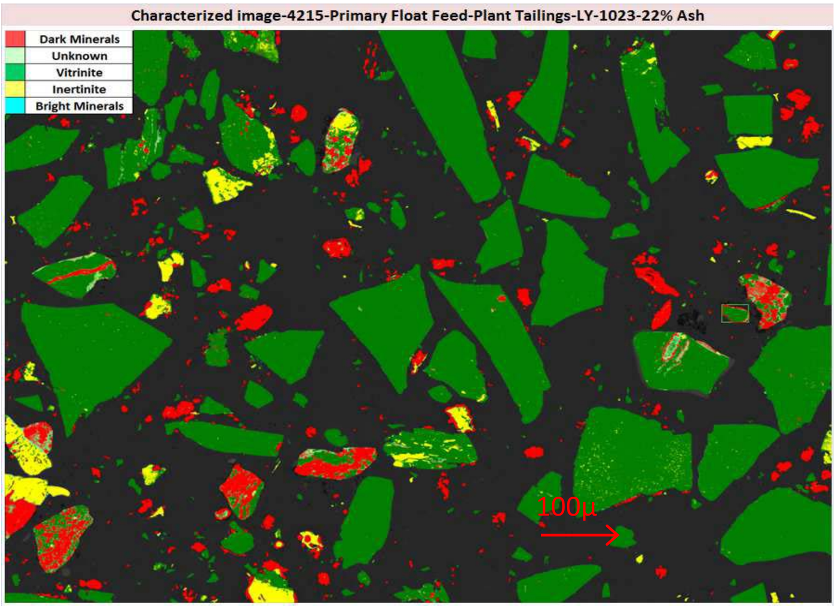
nominal specifications
1-2% ash, d90 ~40µm
typically 55% coal
<300 mPa.s @ >200,000/s

MRC is based on ultra-fine coal beneficiation

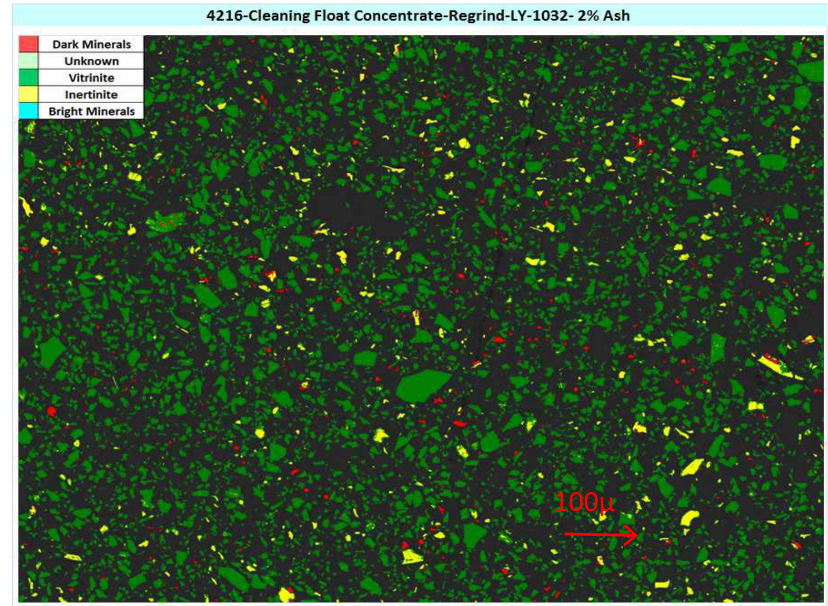
- Physical cleaning – coal structure not changed, but comminution is needed for optimal liberation/improved flotation response
  - potential product <1% ash, including from tailings
- "Old school" thinking typically regards ash contents below 2-3%, as both technically and economically unviable because
  - "inherent ash" of coal is usually regarded as the lowest achievable ash content
  - lower ash requires milling to impractical ultra-fine sizes for liberation
  - … but flotation of ultra-fine coal is problematic requiring higher reagent dosages
  - fine coal concentrates are inevitably high in moisture (> 35%) which means costly dewatering and/or drying to produce saleable products
- All of these factors are incorrect, or at best very misleading, as recent research/pilot plant tests have shown

Excellent liberation by micronising

Feed

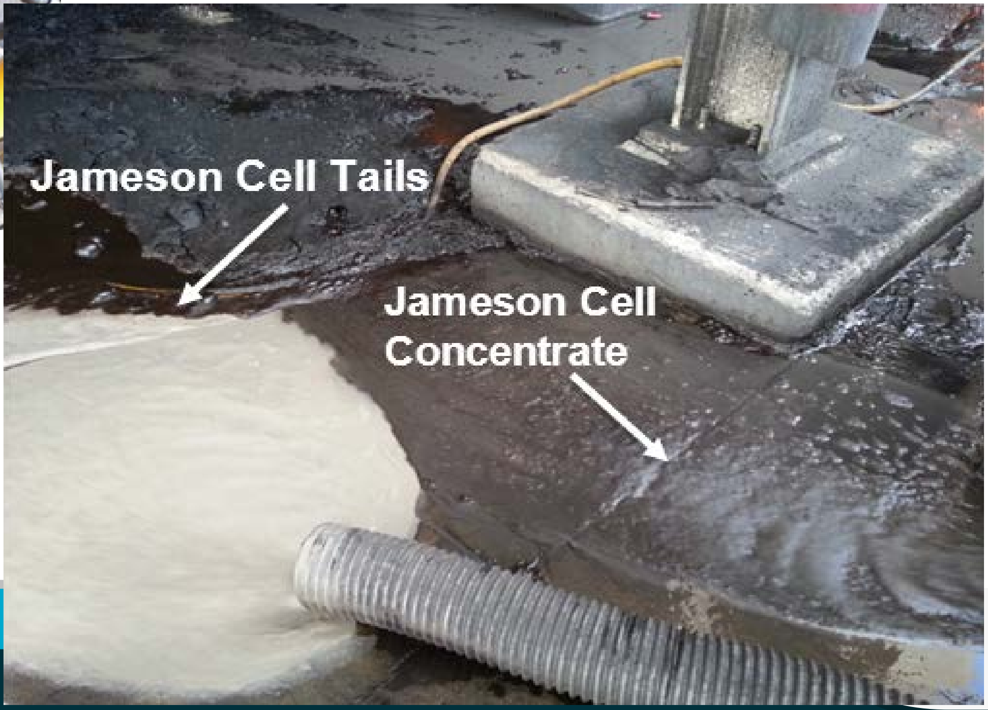


After liberation by milling



Characterised images for raw coal tailings feed compared with final concentrate (QCAT-CSIRO)

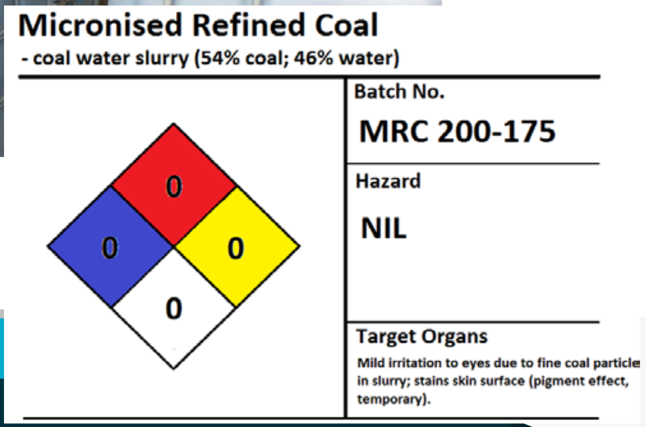
Micronising and sub-50µm coal flotation – excellent separation and recovery



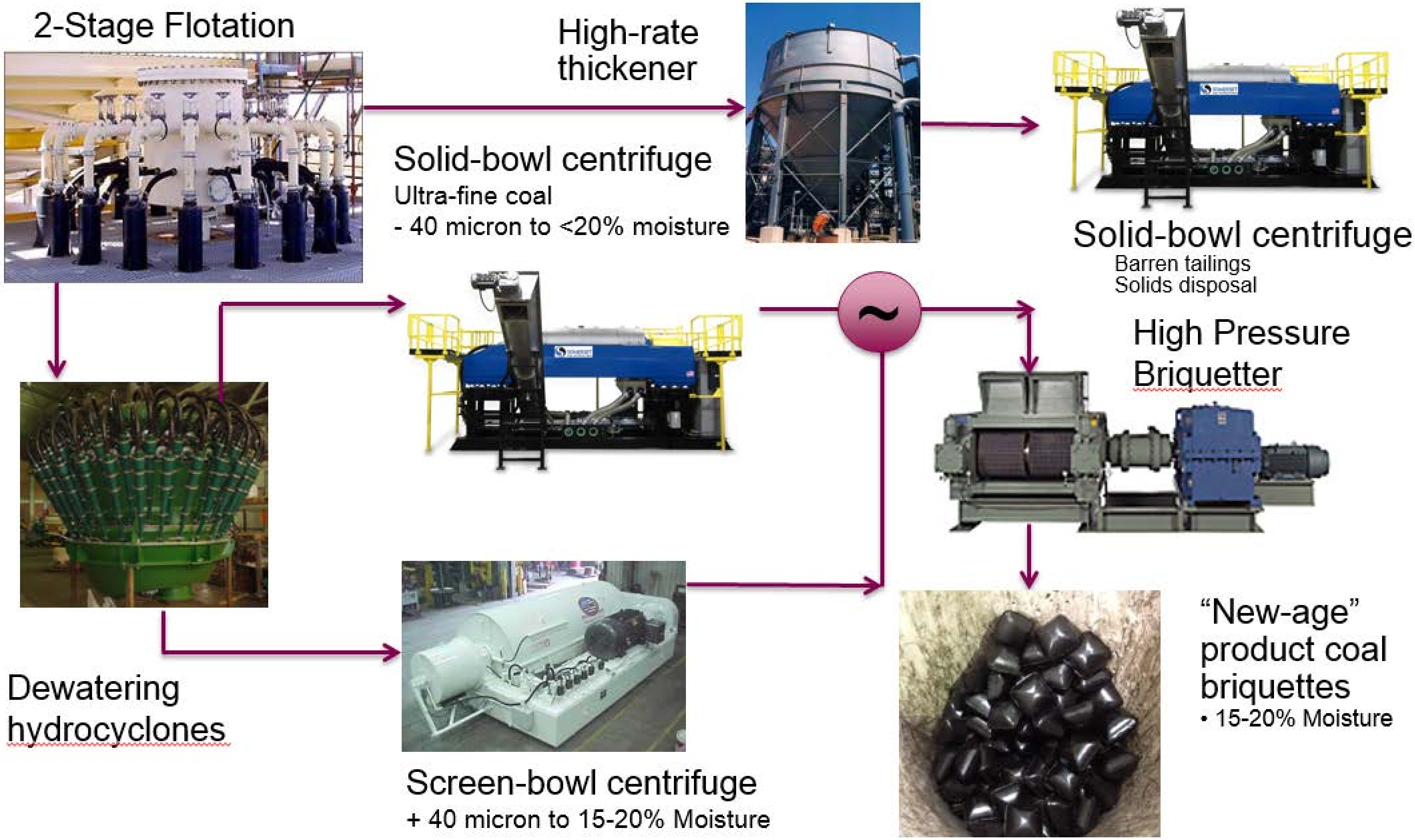
Courtesy Glencore Technology

Pilot scale production of MRC for MAN Diesel & Turbo

1. MRC cake production at Bulga Pilot Plant *(Glencore)*
2. Formulation & rheology trim *(CSIRO)*
3. Certification *(ALS)*



MRC … strategic part of a bigger picture of “Premium Coal Products”



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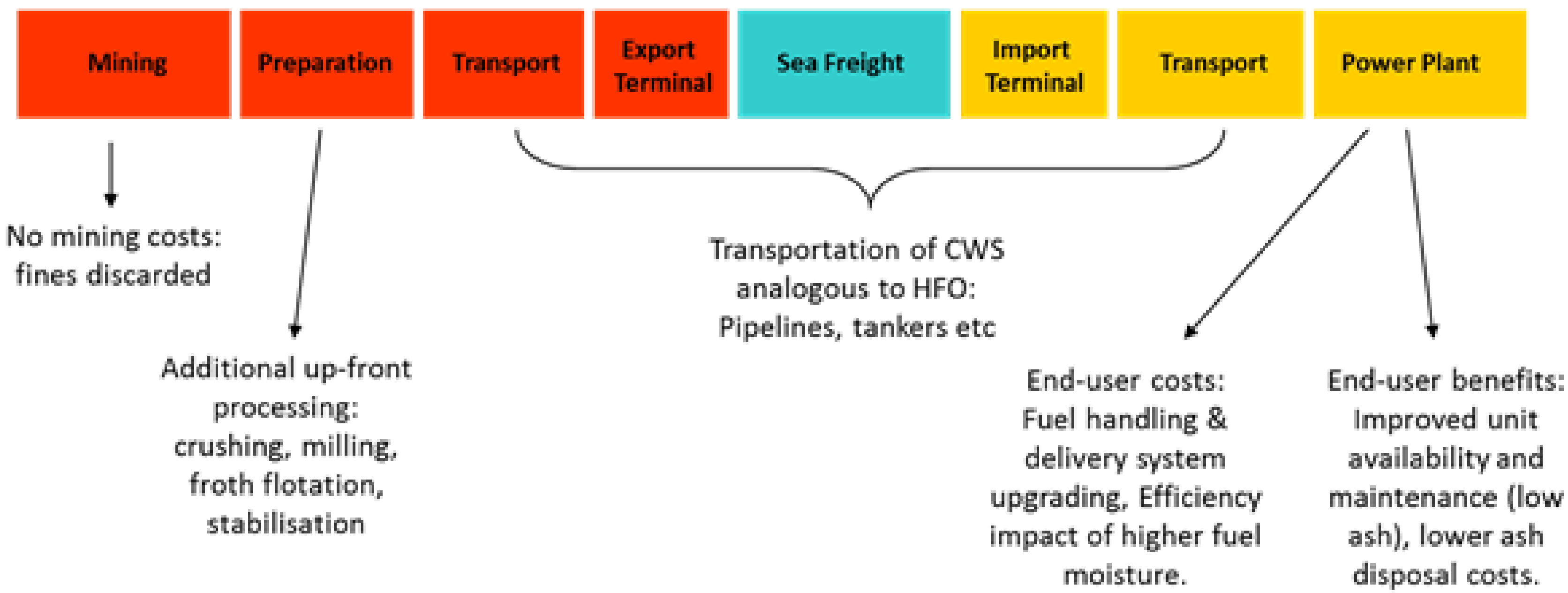
Context

Coal products	Conventional	Steaming
		Coking
	"Premium" (<3% ash)	Coal water fuel
		Electrode carbon
		Micronised refined carbons for DICE (MRC)
Electricity generation	Conventional	Pf
	Alternative	IGCC
	Emerging	**Direct injection carbon engine (DICE)**
	Novel	Direct carbon fuel cell (DCFC)

… and an alternative Coal Supply Chain

- Current Coal Supply Chain hampered by an inability to dewater and efficiently transport fine coal
- Innovative approach - recover and use all the ultra-fines as coal water slurry thereby recovering potential “lost coal” creating higher yield and lower cost/tonne



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The engine side … towards commercial DICE

Recent developments

www.dice-net.org

- CSIRO DICE program since 2008
  - **de-risking based R&D** program (Yancoal, Exergen, Newcrest/JGC, BCIA, Ignite Energy Resources, Xstrata)
- **MAN Diesel & Turbo** have taken a lead position in DICE development
- Umbrella organisation established to facilitate DICE development internationally
  - 17 participants includes MAN, RWE (Germany), JGC (Japan), Sinarmas (Indonesia), Exergen, Ignite Energy Resources, BCIA, Energy Aust, AGL, Newcrest, Yancoal, Worley Parsons, GHD, ACALET and CSIRO
- Recent interest from groups in Korea and China

Stage-gated development

Joint funding with BCIA, ANLEC, CSIRO and industry

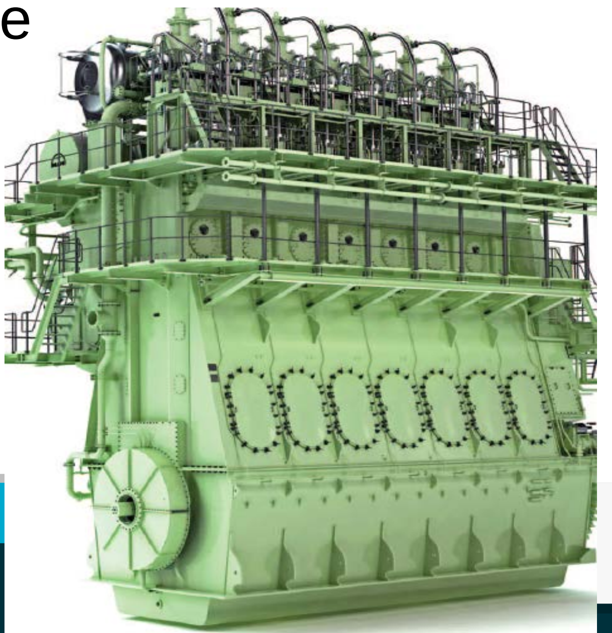
2014-16 Small scale demonstration, initial demonstration/validation DICE,1MW single cylinder (brown and black coals)

2016-17* Development/design of components for prototype engine

2017-19* Full scale demonstration MRC production with a 12-30 MW prototype engine for 8000h campaign

2020*- First commercial DICE power plant [$1.4-2 M/MW] possible given appropriate funding support

***** based on MAN D&T estimates of 3-5 years for engine dev***



DICE deployment strategy

DICE favoured when natural gas price >$6-7/GJ forecast to occur by 2020 for most countries

- Australia; $5-6/GJ; forecast >$8.50/GJ in 2020
- China (import); $13.70/GJ; forecast >$10/GJ in 2020
- Europe; $10.80-12.20/GJ; forecast >$8.80/GJ in 2020
- UK; $10-14.60/GJ; forecast >$10/GJ in 2020
- Japan/Korea; $14.20-16/GJ; forecast >$13/GJ in 2020
- Limited incentives in USA (low cost gas,1100 lb CO_2/MWh regulations)

DICE suitable for new coal capacity, and to replace old capacity nearing the end of its economic life (or as it becomes socially unacceptable)

Final comments

1. DICE could provide coals with a innovative step technology to increase its cost competitiveness and environmental acceptance
2. Barriers to commercialisation are <u>mostly engineering</u>
   - adaptation of commercial process & engine technologies
3. Rapid development possible - can be demonstrated at commercial scale at a relatively small cost
   - <u>short lead time</u> between technology development & implement
4. Logistical barriers to commercialisation of the fuel cycle needs broad intra-industry support
   - <u>as part of premium coal products for maximum benefit</u>

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