Carbon Capture & Storage – CO_2 mineralisation via fuel cells

innovative chemistry to generate zero-carbon electricity & construction materials at global scale

Cleanpower 2010 (http://bit.ly/cleanpower)
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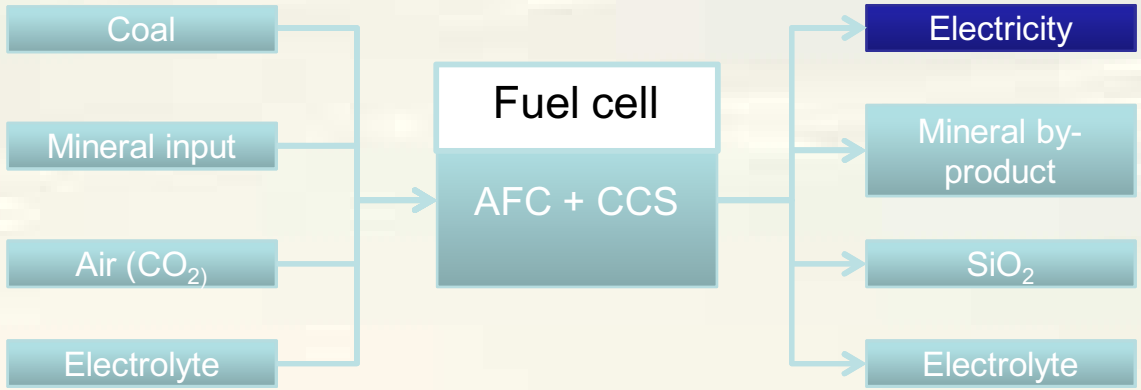
Summary

- Cambridge Carbon Capture – Who we are
- Conventional CCGS – economic challenge
- CCS mineralisation – What, How & Why
- CCC's unique chemistry using fuel cells
- Markets for mineralisation

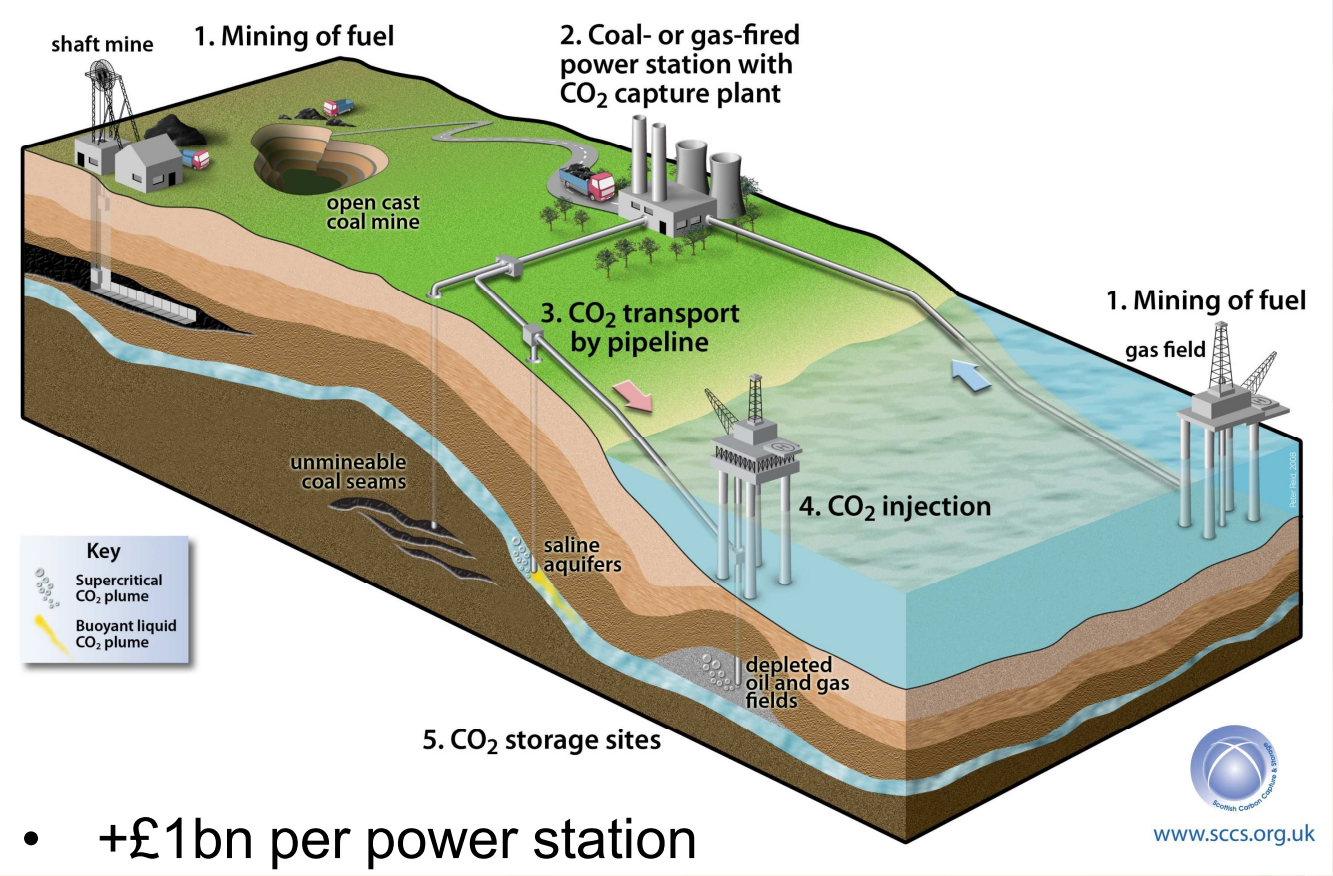
Cambridge Carbon Capture

- new 2010 venture
- developer of innovative CCS chemistry – ***to make CCS profitable***
- unique IP: fuel cells (CO_2 capture) + mineralisation (CO_2 sequestration)



- located at Hauser Forum & Dept. Materials
- Team: Department of Materials; Judge Business School; Nottingham CICCS; Cambridge Enterprise; TSB; EEDA; Renewables East

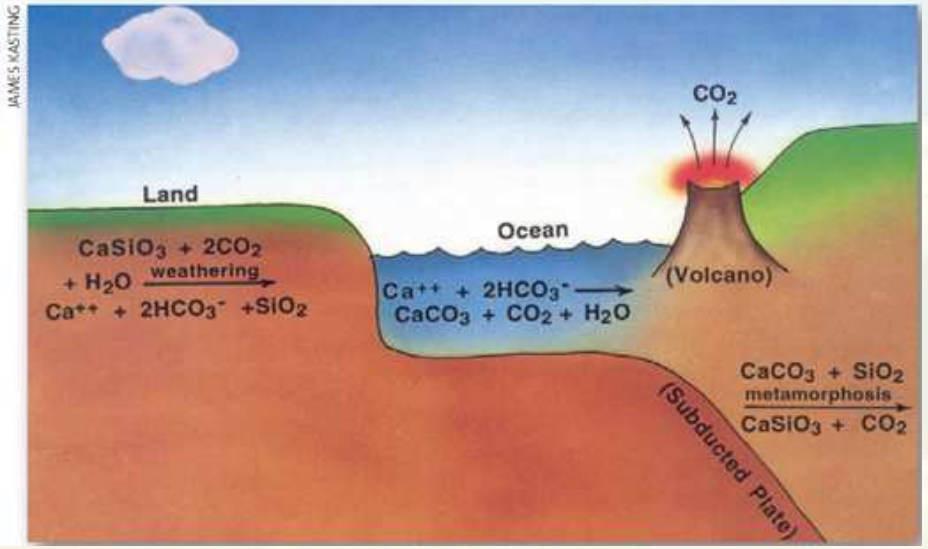
CCGS – economically unfeasible?



- +£1bn per power station
- ~30% parasitic energy; ~30% electricity cost increase
- £/MWh CCS coal > £MWh nuclear & onshore wind
- ~€40-90/tonne CCS >> €15/tonne ETS price

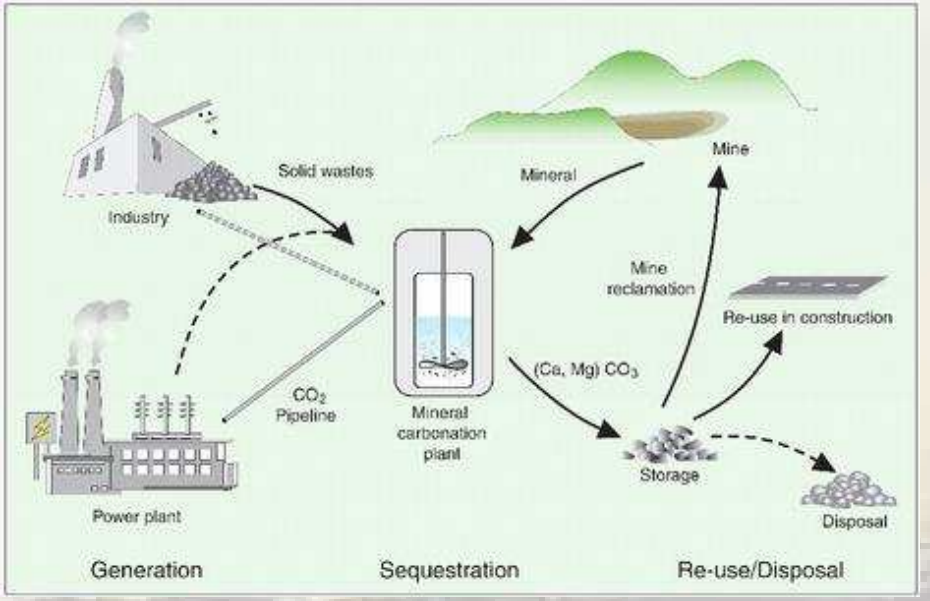
- Will CCS costs fall fast enough?
- When will ETS price > costs?
- Decades until CCS investable?
- CO_2 storage fees?
- Will the public accept CO_2?
- Utilities have other options.
- China will not let CCS risk growth.

CCS Mineralisation – what is it?



- CCS Mineralisation is a very fast version of natural mountain weathering & marine sedimentation processes
  - $CO_2 + H_2O$ + Ca/Mg silicates = limestone
  - >99% world's carbon reservoir is locked in limestone & dolomite

- Known deposits serpentine & olivine > amount needed to sequester known coal reserves
- Challenge is to develop a practicable industrial process
  - reaction kinetics
  - capture ratio (tonnes CO_2 per tonne feedstock)
  - energy & cost
  - materials logistics



CCS Mineralisation – how to do it?

- IPCC & IEA review reports examine range of chemistry options & costs (+10yrs of research):
  - many process papers & patents; little data on energy consumption
  - milling to <75um, heating ~650C and/or acid/base digestion (~100C) required to activate serpentine for carbonation
  - aqueous phase chemistries better than gas-solid; serpentine carbonation at ~80-150C & ambient to high-pressure
  - watching brief with scope for new, cheaper chemical processes
  - continuing progress in low-energy pre-treatment of serpentine (olivine, wollastonite & industrial wastes also offer low-energy routes)
- wide range of feedstock mineral/waste options – any Ca or Mg ions
- e.g. closed-cycle, pH-swing ammonium bisulphate digestion at 80C & carbonation to convert asbestos ($Mg_3Si_2O_5(OH)_4$) waste to high-purity $MgCO_3$, SiO_2 & Fe
- e.g. mine tailings study at four Canadian & Australian sites: 1-50 kt/CO_2/yr per mine site (CO_2 from atmosphere) – rate-limited by silicate mineral dissolution & depends on local climate [Dipple, 2009]

CCS Mineralisation – why do it?

- huge capacity (of feedstock minerals) globally distributed >> conventional CCS
- option where no suitable underground oil/gas/aquifer space exists
- geologically stable CO_2 storage as limestone – avoids environmental, safety & legacy concerns of conventional CCS – i.e. higher public acceptability v. "toxic" CO_2
- higher density CO2 storage (1.6tonnes CO_2/m^3 for $MgCO_3$) >2X supercritical CO_2
- endothermic process, in principle (not yet in practice); faster, lower-energy chemistries available
- ***materials product value makes mineralisation cheaper than conventional CCS***
  - ***JBS economic modelling "CCC best case" electricity is cheaper than unabated coal***
- sequestered carbonate matches scale of market for aggregates & fillers in global construction industry
  - global ~5bn tonnes/year CO_2 from coal-fired power generation
  - 100% mineralisation would generate ~20bn tonnes/yr solid carbonates
  - global ~25bn tonnes construction aggregates (of which cement ~3bn tonnes)
- potential by-product materials & process values:
  - recovery of residual metals (Fe, Co, Ni, rare-earths, precious metals)
  - high-purity silica, bicarbonate chemicals
  - cementitious phase carbonates to substitute Portland & pozzolanic cements
  - remediation value from carbonation of landfill wastes, mine tailings & hazardous wastes
  - CO_2 credits from displaced quarrying & cement processes

CCS Mineralisation – Why isn't industry doing it?

- CCS industry has so-far largely dismissed mineralisation on basis that is more energy intensive, costly & logistically difficult than conventional CCGS:
  - cost & energy of intense natural mineral pre-treatments (Mg-extraction)
  - still have energy & capital costs of CO_2 capture (most expensive part of CCS)
  - millions tonnes of mineral feedstocks to be mined & transported & process inputs
  - millions tonnes of waste carbonate or bicarbonate solids to store or dispose of
  - overall cost ~€30-100/tonne v. €30-45/t in 2030 (€60-90/t in 2015) for CCGS
- CCS industry is focussed on government-funded delivery of power-station-scale demonstrations of EOR-proven CO_2 separation, compression & underground storage
- But… industries, governments, researchers, companies & investors are increasingly looking at feasibility & re-evaluating economics:
  - ETI - £1m 2011 paper study launched on "mineralisation opportunities" (Shell, Caterpillar, BGS, CICCS) – UK mineral distribution + techno-economic viability
  - Australia – Latrobe valley; NSW (GreenMag-U.Newcastle)
  - USDoE CO2 Mineral Seqstr. WG (ARU, ASU, LANL, NETL, PSU, SAIC, UU)
  - CCC, Calera, ICS, Novacem, Carbon8, Calix, Oxford Geo-Engineering, Skyonic

CCC's Unique Technology

- Oxidation of carbon to solid carbonate (~470kJ/mole) releases ~15% more energy than oxidation (~400kJ/mole) to CO_2
- (hydro)carbons can be efficiently, cleanly & cheaply converted to electricity via direct electro-chemical oxidation in an alkaline fuel cell
  - at high efficiency >50% (+ le Chatelier) & with low-cost base-metal electrodes
  - currently using methanol (for proof of principle); low-rank coals feasible
- Aqueous KOH/K2CO3/KHCO3 & ammonia-based solutions
  - CCS-proven fast capture & conversion medium for CO_2 to (bi)carbonate;
  - is an excellent electrolyte & existing component of alkaline fuel cell systems
  - after carbonation, can be regenerated by reaction with Mg^{2+} & Ca^{2+} ions from abundant silicate minerals and alkaline industrial wastes & slags.
  - OH^- and ammonium salt digestion reported for serpentine
- Process chemistry can also be used for point-source CO2 sequestration
- Carbonate mineral precipitates can be consolidated to building materials & aggregates and cementitious phases can replace high value cements & displace additional CO_2

CCC Process

$$C + O_2 + 2OH^- \xrightarrow[\sim pH14]{KOH} CO_3^{2-} + H_2O \xrightarrow[\sim pH9 - 13]{Ca^{2+},\ Mg^{2+}} CaCO_3 + 2OH^- \quad dG = -ve$$

0.9 million tonnes/yr coal
fossil fuel
air

3.3 million tonnes/yr CO_2
OR (no AFC):
flue-gas CO_2

integrated or distant: Mg^{2+} & Ca^{2+} from olivine, serpentines, industrial wastes, mine & quarry fines, oil drilling cuttings & combustion ash etc.

>5.2 million tonnes/yr forsterite

500 MWe power plant

conventional alkaline fuel cell using base-metal electrodes and

re-circulating KOH/K_2CO_3 (aq) electrolyte (NH_3 & molten salt options)

5-30% of energy output

~500MW electricity
CO_2-free electricity
water

100% CO2 capture feasible
exhaust gas: CO_2-free air

>6.3 million tonnes/yr carbonate products
solid Mg & Ca carbonate mineral phases (for sales into cement, concrete, aggregate, bricks etc)

~4.5 million tonnes/yr SiO_2
silica powders

metals (Fe, Ni, Co)
~12,000 tonnes/yr Ni

£ waste remediation & CO_2 abatement value

Markets for CCC's Process

- £330 billion/yr – global market for carbonate materials produced by CCC process
- £3300 bn (period 2010-2050) – global spend on CCS technology (IEA estimate)
- £300 billion/yr – ~7.5TWh coal-fired electricity @ £40/MWh wholesale
- £130 billion/yr (~10bn tonnes CO_2 @ £13/tonne)
- global power growth ~2.5% + ~2% replacement

- Early-stage opportunities
  - Minerals & mining industry: recovery of high-value metals & chemicals; on-site clean electricity;
  - Industrial waste processing industry: stabilisation process profitable via avoidance of landfill taxes
  - Industrial AFC industry: improve the business case for fuel cells

- Later-stage opportunities
  - Utilities: £/MWh coal+MinCCS < £/MWh coal+€15/t
  - Cement & concrete industry: low-CO_2 manufacturing process
  - Construction sector: low-embodied carbon building materials
  - CO2 credits & CDM (credit for saving CO2 overseas)
  - optimisation of mineralisation chemistry to maximise value of materials throughput
  - continuous improvement in serpentine activation processes driven by market demand

Conclusions

- ***Mineralisation offers a highly profitable & fully scalable approach to CCS for a ~$1 trillion/year market***
- ***Technology is at least as proven as CCGS***
- ***Commercial deployment doesn't depend on learning curves, carbon pricing or CO_2 pipeline infrastructure***
- ***Can start small-scale and build from there***
- ***…and it's only just coming onto the CCS radar screen***

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