

# Comments on the DECC Carbon Capture & Sequestration Roadmap

A submission prepared for the Advanced Power Generation Technology Forum by the IChemE Energy Conversion Technology Subject Group

IChemE welcomes the opportunity to comment upon the DECC roadmap for CCS. In general, the priorities for research are well thought out. We particularly support the short term emphasis on getting working systems demonstrated at utility scale, which is a pressing problem if we are to begin significant full scale rollout in anything approximating 2020.

Our major recommendation is that significant effort must be devoted to the life cycle analysis and health and safety implications of the various technologies as a very high priority item.

A good deal of understanding of the viability of novel technologies can be gained by carrying out basic calculations at an early stage of development. These can give orders of magnitude figures for total inventories of chemicals, reactor sizes and energy costs for most of the technologies discussed in the roadmap. Some preliminary calculations have been used to support the comments made in this response. Spending public money supporting the development of technologies which could well be shown to be unviable - for example, by simple Life Cycle Assessment (LCA) must be strongly discouraged. Many technologies, described as novel, often have viable alternatives which are currently available, particularly those described as energy storage mechanisms. The LCA should be carried out by an independent agency (or grouping), with sufficient input from industry, academe and the learned societies to ensure that nothing is overlooked.

It is challenging for industry and academia to develop research priorities without sufficient engagement. It is a recommendation that in order to enhance this engagement, workshops be set up on technologies about which industry desires to learn more, technologies about which academia would like industry to learn more, and critically *understand what makes, or has the potential to make a technology attractive to industry.*

IChemE offers the following views on specific headings within the Roadmap:

## 1. WHOLE SYSTEMS

*Perform complete HSE, LCA **and operability** analysis of individual sections and full CCS chain (currently medium priority, short term). (Our insertion in bold).*

It is our belief that the LCA and operability analysis should be upgraded to high priority, since LCA forms the basis under which the benefits of CCS to the climate can be unambiguously demonstrated. This ensures that the carbon cost of e.g. raw materials can be properly included.

The merits of "Utilisation of CO<sub>2</sub> for fuels, products etc, and the impact on capture and transport" (currently medium term, low priority) are highly debatable. After all, we burn carbonaceous fuels for the energy within them – the first and second laws of thermodynamics are clearly opposed to the use of CO<sub>2</sub> as a fuel. The IChemE would **remove the production of fuels in its entirety from the matrix – there are many more pressing research needs.** The use of CO<sub>2</sub> in the production of plastics, etc, is a

reasonable idea in theory. However, the market for such plastics is currently around 230 Mt / year<sup>1</sup>, so unlikely to impact very significantly upon the 13,466 Mt / year emitted by the top 8,000 stationary sources <sup>2</sup> unless very significant new roles for plastics emerge.

The often-made claim that “spare” renewable energy can be used to produce significant amounts of fuel should always be examined critically in comparison to other energy storage vectors such as pumped hydro. So-called “spare” electricity can be stored in such a form and used to power an electric vehicle with chain efficiency (from the starting point of the electricity being available, i.e. not including generation efficiency) of around 60 %. In contrast, the chain efficiency for producing and using liquid fuels by hydrolysis of water, reaction of the produced H<sub>2</sub> with CO<sub>2</sub> to form methanol and final use in a standard internal combustion engine is around 12 %. On the grounds of **security of supply**, we should not be choosing to research areas which require **five times** more secondary energy (electricity). The merit of such technologies should first be assessed under the LCA discussed above. Furthermore, the operability of any chemical plant relying on highly intermittent energy sources and primary feedstocks (in this case CO<sub>2</sub>) should be carefully examined, with due consideration of the availability of the overall plant and the consequent return on capital.

## 2. CAPTURE OVERVIEW

Definitions of 2<sup>nd</sup> and 3<sup>rd</sup> generation technologies.

The “3<sup>rd</sup> Generation” technologies discussed are actually at vastly different technology readiness levels – high temperature carbonate looping cycles are currently being demonstrated at 2 MWth<sup>3</sup> and 1 MWth<sup>4</sup> scales – an order of magnitude bigger than the chemical looping and adsorption technologies, which are shown as medium priority medium impact later in the table – we would promote carbonate looping cycles from long term research to medium term and suggest that carbonate looping being promoted to a “second generation” technology. In fact, we would advocate an independent technology assessment be conducted, including a carbon LCA, with input from industry and academia into the advantages and disadvantages of the different CCS technologies and their current TRLs globally as a high priority, short term piece of work.

It is the opinion of the IChemE that mineralisation of CO<sub>2</sub> is almost certainly **not** a technology which should be pursued (currently long term, low priority). The requirements to mine more than 4 times as much stone as coal for each kg of coal burned, the huge reactor sizes required to effect reactions taking 2 – 3 hours with the stone, and the massive inventories of acid and stone required (rough calculations indicate that thousands of tonnes of rock would need to be crushed to less than 100 microns and be in a chemical reactor at any time, with tens to hundreds of tonnes of acid to take up the CO<sub>2</sub> from a medium sized power station). Preliminary LCA analysis at Imperial College<sup>5</sup> indicates that the work

---

<sup>1</sup> <http://www.waste-management-world.com/index/display/article-display/7224523870/articles/waste-management-world/volume-11/issue-6/features/how-the-european-plastics-sector-will-bounce-back.html>

<sup>2</sup> B.Metz, O. Davidson, H. C. de Coninck, M. Loos and L. A. Meyer, IPCC, 2006: IPCC Special Report of Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2005.

<sup>3</sup> Sanchez, A. (2011). EU Caoling website. [www.caoling.eu](http://www.caoling.eu). Accessed 18/04/2011.

<sup>4</sup> Epple, B. (2011). <http://www.est.tu-darmstadt.de/index.php/en/co2-versuchsfeld> accessed 18/04/2011.

<sup>5</sup> Strubing, MSc, Imperial College, 2007.

required for grinding makes this a very high cost option. Again, prior to support, LCA should be conducted as well as hazard assessment – such technologies would certainly require the plants concerned to become Top Tier COMAH Establishments.

The capture of CO<sub>2</sub> from the atmosphere is at first sight attractive. However, capital costs, space and raw materials utilisation would appear to indicate that it is unlikely to be competitive with CCS or biomass-enhanced CCS for “negative” CO<sub>2</sub> emissions. The costs of bringing diverse quantities of low pressure CO<sub>2</sub> together and compressing it to a pressure suitable for geological storage at a central but remote location have the potential to make this amongst the more expensive CO<sub>2</sub> reduction options. Careful LCA is required, together with assessment of the risks associated with the proposed widespread use of (for example) artificial “trees”, which may use caustic chemicals such as sodium hydroxide in large quantities<sup>6</sup> and on sites which would of necessity (owing to their highly dispersed nature) be accessible to the general public. We would recommend that such an LCA is carried out as a medium priority in order either to eliminate this as a viable technology or to encourage its development to prototype level.

### 3. POST-COMBUSTION CAPTURE

*Assessment of environmental options for treatment of spent solvent and effects on environment/ humans. (Short term, high impact).*

We welcome this work, but note that this is part of the wider LCA and H&S analysis which we are suggesting.

*R&D on improvements to 1st Generation capture options and 2nd Generation capture technologies (membranes for air separation, advanced compression, pressure/temperature/electrical swing adsorptions etc). (Medium term, Medium priority).*

No technology should automatically be considered first, second, or third generation within this roadmap until a more careful analysis has been made of the global status of each technology. For example, electrical swing adsorption has to be more than twice as efficient chemically to make up for the requirement to make the electricity for desorption as a thermal system. The authors are unaware of any large scale trials of this technology.

*R&D on 3rd Generation capture options (ionic liquids, chemical looping, solid sorbents, high temperature carbonate cycles, precipitating systems, metal organic frameworks, gas hydrate crystallisation, bio-capture, advanced membranes, etc) (long term, low priority).*

*(Under oxyfuel) Further develop Chemical Looping Combustion (medium term, medium priority).*

*Investigate and develop chemical looping combustion (short term, medium priority)*

*Develop novel options for oxygen separation (membranes, **absorbents**, ion transport etc) (medium term, medium priority).*

Chemical looping is shown as long term, low priority, medium term, medium priority and short term, medium priority. This is inconsistent.

---

<sup>6</sup> Graves, C., S.D. Ebbesen, M. Mogensen, and K.S. Lackner, *Sustainable hydrocarbon fuels by recycling CO<sub>2</sub> and H<sub>2</sub>O with renewable or nuclear energy*. Renewable and Sustainable Energy Reviews, 2011. 15(1): p. 1-23.

*Develop novel process options (sorbent-enhanced water-gas-shift, hydrogen membrane reformers, sorption-enhanced reforming, steam and auto thermal chemical looping reforming) (medium term, low priority).*

Sorbent-enhanced Water Gas Shift (WGS) is a subset of “high temperature carbonate cycles” (*R&D options, third gen capture options*), using very similar CO<sub>2</sub> capture technology (at a base level, CaO from limestone). If high temperature carbonate cycles is long term, so is sorbent enhanced WGS. By comparison with the TRLs of other technologies, we would suggest that this research is medium term, medium priority.

#### **4. INDUSTRIAL CCS**

*2016: Demonstration of capture from a less concentrated industrial source of CO<sub>2</sub> (oil refinery, cement works, blast furnace etc).*

Table 2.3<sup>7</sup> shows the approximate concentration of CO<sub>2</sub> in the flue gas from various sources. Cement clearly has a higher flue gas concentration than all power-related sources shown. The other sources described as “low concentration” are high in concentration compared to GT exhaust.

---

<sup>7</sup> IPCC, *IPCC Special Report on Carbon Dioxide Capture and Storage*, B. Metz, et al., Editors. 2005, IPCC: Geneva, Switzerland. p 81.

Table 2.3 Profile of worldwide large CO<sub>2</sub> stationary sources emitting more than 0.1 Mt CO<sub>2</sub> per year (Source: IEA GHG, 2002a).

Process	CO <sub>2</sub> concentration in gas stream % by vol.	Number of sources	Emissions (MtCO <sub>2</sub> )	% of total CO <sub>2</sub> emissions	Cumulative total CO <sub>2</sub> emissions (%)	Average emissions/source (MtCO <sub>2</sub> per source)
<b>CO<sub>2</sub> from fossil fuels or minerals</b>						
<b>Power</b>						
Coal	12 to 15	2,025	7,984	59.69	59.69	3.94
Natural gas	3	985	759	5.68	65.37	0.77
Natural gas	7 to 10	743	752	5.62	70.99	1.01
Fuel oil	8	515	654	4.89	75.88	1.27
Fuel oil	3	593	326	2.43	78.31	0.55
Other fuels <sup>a</sup>	NA	79	61	0.45	78.77	0.77
Hydrogen	NA	2	3	0.02	78.79	1.27
<b>Natural-gas sweetening</b>						
	NA <sup>b</sup>	NA	50 <sup>c</sup>	0.37	79.16	
<b>Cement production</b>						
Combined	20	1175	932	6.97	86.13	0.79
<b>Refineries</b>						
	3 to 13	638	798	5.97	92.09	1.25
<b>Iron and steel industry</b>						
Integrated steel mills	15	180	630 <sup>d</sup>	4.71	96.81	3.50
Other processes <sup>d</sup>	NA	89	16	0.12	96.92	0.17
<b>Petrochemical industry</b>						
Ethylene	12	240	258	1.93	98.85	1.08
Ammonia: process	100	194	113	0.84	99.70	0.58
Ammonia: fuel combustion	8	19	5	0.04	99.73	0.26
Ethylene oxide	100	17	3	0.02	99.75	0.15
<b>Other sources</b>						
Non-specified	NA	90	33	0.25	100.00	0.37
		<b>7,584</b>	<b>13,375</b>	<b>100</b>		<b>1.76</b>
<b>CO<sub>2</sub> from biomass<sup>e</sup></b>						
Bioenergy	3 to 8	213	73			0.34
Fermentation	100	90	17.6			<b>0.2</b>

<sup>a</sup> Other gas, other oil, digester gas, landfill gas.

<sup>b</sup> A relatively small fraction of these sources has a high concentration of CO<sub>2</sub>. In Canada, only two plants out of a total of 24 have high CO<sub>2</sub> concentrations.

<sup>c</sup> Based on an estimate that about half of the annual worldwide natural-gas production contains CO<sub>2</sub> at concentrations of about 4% mol and that this CO<sub>2</sub> content is normally reduced from 4% to 2% mol (see Section 3.2.2).

<sup>d</sup> This amount corresponds to the emissions of those sources that have been individually identified in the reference database. The worldwide CO<sub>2</sub> emissions, estimated by a top-down approach, are larger than this amount and exceed 1 Gt (Gielen and Moriguchi, 2003).

<sup>e</sup> For North America and Brazil only. All numbers are for 2003, except for power generation from biomass and waste in North America, which is for 2000.

*Investigate the extent to which CCS technologies could apply to industrial applications. In particular, iron and steel (post-combustion and oxy-fuel), cement (oxyfuel and chemical looping), refineries – oil, gas and biofuels – and aluminium (short term, high priority).*

High temperature carbonate looping cycles, which have a very clear synergy with cement manufacture<sup>8 9 10</sup> owing to the use of spent sorbent directly in the cement kiln in place of the main feedstock for cement manufacture, CaCO<sub>3</sub>, must be included in this investigation.

<sup>8</sup> Dean, C.C., J. Blamey, N.H. Florin, M.J. Al-Jeboori, and P.S. Fennell, *The calcium looping cycle for CO<sub>2</sub> capture from power generation, cement manufacture and hydrogen production*. Chemical Engineering Research and Design. **In Press, Corrected Proof**.

<sup>9</sup> <http://blogs.rsc.org/ee/2011/04/21/putting-the-cement-industry-in-the-calcium-loop/>

<sup>10</sup> Dean, C.C., D. Dugwell, and P.S. Fennell, *Investigation into potential synergy between power generation, cement manufacture and CO<sub>2</sub> abatement using the calcium looping cycle*. Energy & Environmental Science, 2011.

Research into this technology is currently being funded by major cement manufacturers. The authors can provide details if required.

There is also scope to include pre-combustion CCS for steelworks: post combustion CO<sub>2</sub> removal is made more difficult than for power generation by the low partial pressure of CO<sub>2</sub> and the high amount of nitrogen in the exhaust gases. Again, the authors can provide more details (on a confidential basis) if required. Given the amount of CO<sub>2</sub> produced by steelmaking (approximately 1.9 tonnes CO<sub>2</sub>/tonne of rolled product<sup>11</sup>) this should be high priority, short term.

Aluminium and other smelting processes also produce significant amounts of CO<sub>2</sub> (typically 0.45 – 0.6 tonnes CO<sub>2</sub>/tonne of finished aluminium slab, excluding electricity generation<sup>12</sup>), and we would like to see research carried out into minimising this.

## **5. TRANSPORT**

*Reduce power and cost of compression (and drying, where required)* (short term, medium priority)

This might be linked with the aim of developing solvents, etc, capable of regeneration at higher pressure. It might be more sensible to move this line item to “capture overview”, as it is crosscutting.

## **6. STORAGE**

Not commented on as outside the knowledge base of the authors and outside of the core competences of IChemE’s Energy Conversion Technology Subject Group.

---

For further comment and/or supporting information on any of the point raised in this paper, please contact:

Andy Furlong

Director of Policy & Communication  
IChemE  
+44 1788 534484  
afurlong@icheme.org

---

<sup>11</sup> “Reduction of CO<sub>2</sub> emissions in the steel industry based on LCA methodology”, Ana-Maria Losif, Jean-Pierre Birat, Olivier Mirgaux, Denis Ablitzer

<sup>12</sup> <http://www.calsmelt.com/energy-environmental.html>