International Journal of Research in Engineering Technology -– Volume 2 Issue 6, Sep - Oct 2017

RESEARCH ARTICLE OPEN ACCESS

Carbon Capture, Utilization and Storage: A Review

Shivam Paneri[1], Dr. Dipak Ranjan Jana[2]

[1,2](Department of Mechanical Engineering, Poornima College of Engineering, Jaipur)

Abstract:

Carbon Capture, Utilization, and Storage (CCUS) technology deals with capturing of carbon in form of CO_2, its utilization and storage. The objective of this study is to simply capture the CO_2 to utilize and store it. As CO_2 is one of the gases causing global warming. For sustainable development of society there is need to use some preventive measures, one of them is CCUS. In this paper the methods of capturing CO_2 from power plants and industries has been studied with an aim to capture it for Carbon utilization and storage .Carbon utilization and storage option includes injecting it to mature oil and coal wells for enhancing oil or natural gases recovery or storing it in empty oil and gas wells, in saline aquifers and under oceans. The resulting environmental effects are also studied in this paper.

Keywords — **Carbon Capture, Carbon Utilization, Carbon Storage, Sequestration, Pollution control.**

I. INTRODUCTION

This Green house gas emission, global climate change we are all facing the same problems and need to work together to develop solution Carbon Dioxide or CO_2 comes from many sources the decay of plant and animal matter, fires and volcanoes even our breathing emits CO_2. The way we live has a cumulative impact on our environment. Every time we drive a car or turn on the lights most of us are using energy that comes from fossil fuels. Burning fossil fuels create emission including CO_2. Industrialization and rising population around the world has increased demand for energy and needing that demand increases the emission release into the atmosphere. CO_2 is one of the many green house gases being ignited into the air from both natural sources and human activity. Solar, wind and other renewable energy resource will play a more important role in our burdeous energy future but they can't completely replace oil and gas so we must develop our fossil fuels in a cleaner, more environmentally responsible way.

The only way of doing this is Carbon Capture, Utilization and Storage. This technology is also known as CCUS. This technology is outlined in 2008 "Climate Change Strategy" as most effective way to help our burden meet emission reduction goals. In this the CO_2 is captured, transported and stored. This is a tested and proven technology. Its capability to reduce carbon emission is recognized around the world by groups such as International Energy Agency and United Nations Inter Governmental Panel on Climate Change.

CO_2 collected during the Carbon Capture and Storage process can be pumped into an oil reservoir to help increase production. They can also be pumped kilometres deep below the earth surface where it would be permanently sealed. In case of Carbon Capture and Utilization the captured CO_2 is used to generate energy. There are three ways of conversion as:-

- Pre-conversion
- Post-conversion
- Oxy fuel combustion

II. LITERATURE REVIEW

Global emission CO_2 from fossil fuels have been increasing by 2.7% annually over the past decade and are now 60% above 1990 levels, the reference year for the Kyoto Protocol [1]. However, CCS faces a number of technical and economic barriers that must be overcome before it can be deployed on a large scale. One of the main economic obstacles is the fact that it is an unprofitable activity that requires large capital investment [5]. In the UK, for example, there are no incentives or subsidies for

CCS which is going to make its development and deployment difficult. On the technical side, CO_2 leakage rates are uncertain and in some countries CCS is not a viable option as their geological storage capacity is limited or in some cases only available offshore, thus increasing transportation and injection costs [5,6]. This is the case with the UK, Norway, Singapore, Brazil and India [5,6].

III. OVERVIEW OF CCS AND CCU TECHNOLOGIES

CCS and CCU aim to capture CO_2 emissions from point sources such as power plants and industrial processes, to prevent the release into the atmosphere [9]. The difference between CCS and CCU is in the final destination of the captured CO_2. In CCS, captured CO_2 is transferred to a suitable site for long-term storage [9–15], while in CCU, captured CO_2 is converted into commercial products [5,9].

Power plants, oil refineries, biogas sweetening as well as production of ammonia, ethylene oxide, cement and iron and steel are the main industrial sources of CO_2 [5,9]. For example, over 40% of the worldwide CO_2 emissions are caused by electricity generation in fossil-fuel power plants [9]. Therefore, these sources are the main candidates for a potential application of CCS or CCU. There is a wide variety of CO_2 capturing systems, to ensure compatibility with the specific industry. However, the level of maturity among different capturing systems varies across industries. For example, power plants and oil refineries are getting closer to implementing CO_2 capturing systems at a large-scale, while the cement and the iron and steel industry will still have to overcome the transition from small-scale demonstration plants to industrial deployment [18]. The CO_2 capture options can be classified as post-conversion, pre-conversion and oxy-fuel combustion [18–20].

A. Post-conversion capture

Post-conversion capture involves separation of CO_2 from waste gas streams after the conversion of the carbon source to CO_2. It can be used to remove CO_2 from various industries, including power plants, production of ethylene oxide, cement, fuels, iron and steel as well as biogas sweetening [10,21]. When used in power plants, post-conversion capture is also known as post-combustion capture [19]. Post-conversion capture methods include absorption in solvents, adsorption by solid sorbents, including porous organic frameworks, membranes and cryogenic separation as well as pressure and vacuum swing adsorption [9,16,22–24]. Among these, absorption by mono-ethanolamine (MEA) is most commonly used [16,25]. However, this method is not economically viable for all industries as MEA regeneration has high heat consumption. For example, MEA absorption of CO_2 in a cement plant is less well suited than in a combined heat and power R.M. Cue´llar-Franca, A. Azapagic / Journal of CO_2 Utilization 9 (2015) 82–102 83plant as the former lacks recoverable heat, incurring additional energy costs [16]. The energy penalty also applies to the other post-conversion technologies, either through the direct energy costs or through a reduced energy efficiency associated with their operation [9,16].

B. Pre-conversion capture

Pre-conversion capture refers to capturing CO_2 generated as an undesired co-product of an intermediate reaction of a conversion process [18]. Some examples include the production of ammonia and coal gasification in power plants [10,19,26]. In ammonia production, CO_2 that is co-produced with hydrogen during steam reforming must be removed before the ammonia synthesis can take place – absorption in MEA is commonly used for these purposes [10,27]. Similarly, in an integrated gasification combined cycle (IGCC) power plant, CO_2 must be separated from hydrogen. This is typically achieved using physical solvents such as selexol and rectisol [19,26,28,29]. Porous organic framework membranes can also be used for CO_2 capture owing to their high CO_2 selectivity and uptake; however, no applications have been reported to date [30]. Note that, when applied in power plants, pre-conversion capture is also referred to as pre-combustion capture [19]. Like post-conversion, pre-conversion capture also incurs energy penalties for regeneration of chemical solvents (e.g. MEA); these are lower for the physical solvents as they are regenerated by reducing pressure rather than by heat. Physical solvents are, therefore, more suitable for applications with high operating pressure; they are also more efficient for concentrated CO_2 streams [9].

C. Oxy-fuel combustion capture

As the name would suggests, oxy-fuel combustion can only be applied to processes involving combustion, such as power generation in fossil-fuelled plants, cement production and the iron and steel industry. Here, fuel is burned with pure oxygen to produce flue gas with high CO_2 concentrations and free from nitrogen and its compounds such as NO and NO_2. While this avoids the need for chemicals or other means of CO_2 separation from the flue gas, a disadvantage is that oxygen is expensive and the environmental impacts, including CO_2 emissions, associated with its production are high because of the energy intensive air-separation processes [31]. The alternatives to the oxy-fuel process are chemical looping combustion (CLC) and chemical looping reforming (CLR). Both use a metal oxide to transfer oxygen selectively from an air reactor to a fuel combustor. In CLR, a sub-stoichiometric amount of oxygen is used, leading to the production of syngas, thus making it suitable for syngas generation or upgrading [32]. Some of the advantages of CLR include lower steam demand, higher fuel conversion efficiencies and better sulphur tolerance [32]; it can also handle dilute CO_2 streams [33]. However, a challenge is to operate the system under the high pressure needed to achieve efficiencies equivalent to that of the state-of-the-art oxy-fuel process or post-combustion capture. For CLC, one of the challenges is application to solid fuels and ash handling [32]. Neither of the oxy-fuel technologies is expected to be fully deployed before 2030 [18].

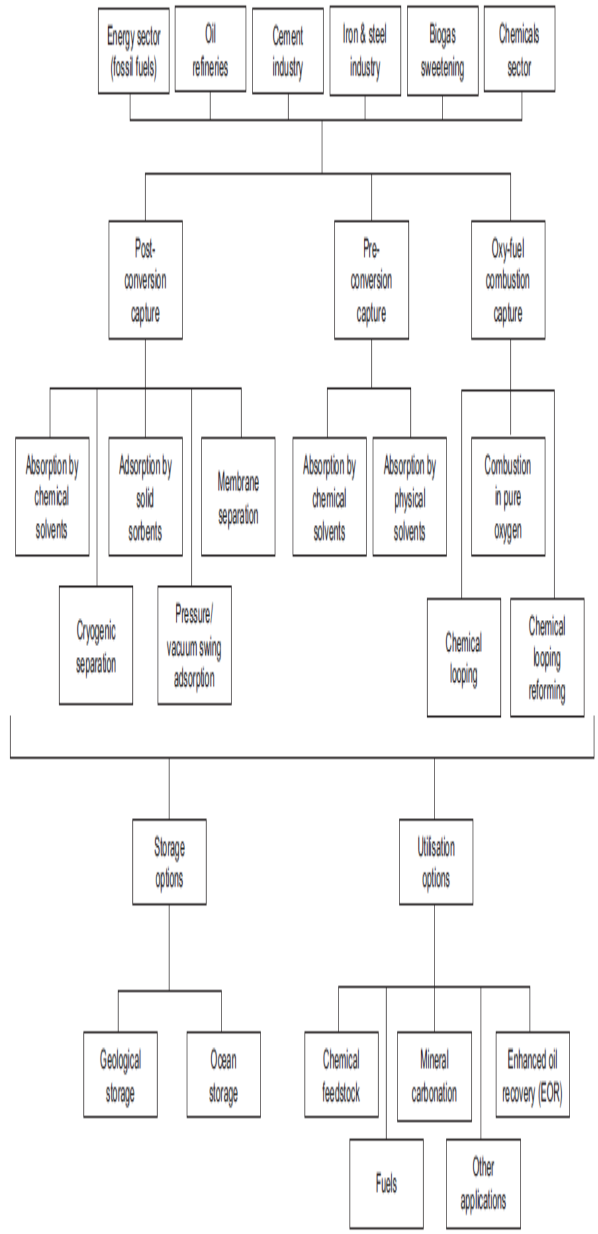

Fig.1-Different CCUS options [51]

TABLE I

Carbon Capture *options, separation technology, method and applications [51]*

Capture Option	Separation Technology	Method	Applications
Post-Conversion	Absorption by chemical solvents	• Amine-based solvent, e.g. monoethanolamine(MEA)[b], dietanolamine(DEA), and hindered amine (KS-1) • Alkaline solvents e.g. NaOH and $Ca(OH)_2$ • Ionic Liquids	Power plants, iron and steel industry, oil refineries, cement industries
	Absorption by solid sorbents	• Amine based solid sorbents • Alkali earth metal based solid sorbents e.g. $CaCO_3$ • Alkali metal carbonate solid sorbents e.g. Na_2CO_3 and K_2CO_3 • Porous organic frameworks - Polymers	No applications reported
	Membrane Separation	• Polymeric membranes e.g. polymeric gas permeation membranes[b] • Inorganic membranes e.g. Zeolites • Hybrid membranes	Power plants, natural gas sweetening
	Cryogenic Separation Pressure/ vacuum swing adsorption	• Cryogenic separation • Zeolites[b] • Activated carbon[b]	Power plants, iron & steel industry
Pre-Conversion	Absorption by physical solvents	• Selexol, rectisol	Power plants(IGCC)
	Absorption by chemical solvents	• Amine-based solvent e.g. monoetanolamine (MEA)	Ammonia production
	Absorption by porous organic frameworks	• Porous organic frameworks membranes	Gas separations
Oxy-fuel Combustion	Separation of oxygen from air	• Oxy-fuel process • Chemical looping combustion • Chemical looping reforming	Power plants, iron & steel industry, cement industries, Syngas production and upgrading

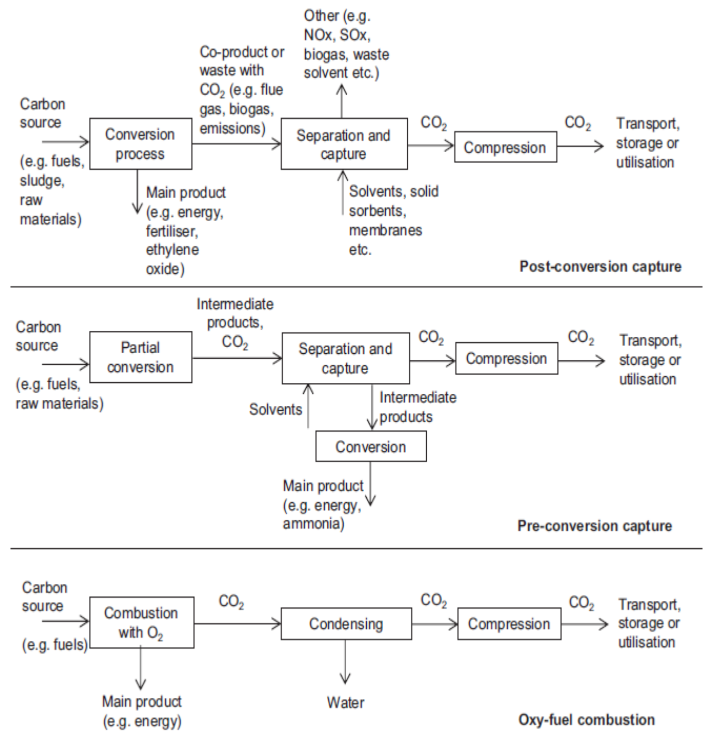

Fig.2 Carbon Capture Options [51]

IV. CO_2 STORAGE OPTIONS

Once captured, CO_2 is compressed and shipped or pipelined to be stored either in the ground, ocean or as a mineral carbonate [10,13,25]. The first option, known as geological storage, involves injecting CO_2 into geological formations such as depleted oil and gas reservoirs, deep saline aquifers and coal bed formations, at depths between 800 and 1000 m [10,13].Carbon dioxide is stored by using different mechanism including impermeable layer of stones, mud and rock which trap CO_2 underneath as well as in situ fluids and organic matter where CO_2 is dissolved or adsorbed [10].

V. CO_2 UTILISATION OPTIONS

As mentioned earlier, as an alternative to storage, captured CO_2 can be used as a commercial product, either directly or after conversion. Examples of direct utilisation include its use in the food and drink industry and for EOR; CO_2 can also be converted into chemicals or fuels.

A. Direct utilisation of CO_2

Several industries utilise CO_2 directly. For example, in the food and drink industry, CO_2 is commonly used as a carbonating agent (e.g. Cold drinks), preservative, packaging gas and as a solvent for the extraction of flavours and in the decaffeination process [42].CO_2 is also use to produce dry ice. Other applications can be found in the pharmaceutical industry where CO_2 can be used as a respiratory stimulant or as an intermediate in the synthesis of drugs [7,42].

B. Enhanced oil and coal-bed methane recovery

EOR and ECBM are other examples of direct utilisation of CO_2 where it is used to extract crude oil from an oil field or natural gas from unmineable coal deposits, respectively. It is Injected under supercritical conditions, it mixes well with the oil to decrease its viscosity, thus helping to increase the extraction yields [45].

C. Conversion of CO_2

Into chemicals and fuels CO_2 can also be utilised by processing and converting it into chemicals and fuels. This can be achieved through carboxylation reactions where the C=O bonds are broken to produce chemicals such as methane, methanol, syngas, urea and formic acid [5,7,9,41]. Furthermore, CO_2 can be used as a feedstock to produce fuels, for example, in the Fischer–Tropsch process [46].

D. Mineral carbonation

Mineral carbonation is a chemical process in which CO_2 reacts with a metal oxide such as magnesium or calcium to form carbonates [10,25]. Magnesium and calcium are normally found in nature in the form of silicate minerals such as serpentine, olivine and wollastonite [10,47].

$$Mg_3Si_2O_5(OH)_4 + 3CO_2 = 3MgCO_3 + 2SiO_2 + 2H_2O$$

E. Biofuels from microalgae

CO_2 can be used to cultivate microalgae used for the production of biofuels [5,48,49]. Micro-algae have the ability to fix CO_2 directly from waste streams such as flue gas as well as using nitrogen from the gas as a nutrient [5,50]

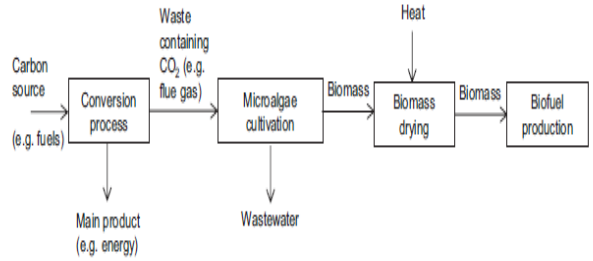

Fig.3 Utilisation of CO_2 to produce biofuels from microalgae[51]

VI. RESULTED ENVIRONMENTAL IMPACTS OF CCUS

Over the past decade, several studies have evaluated the life cycle environmental impacts of CCS technologies for power plants, considering pulverised coal (PC), integrated coal gasification combined cycle (IGCC) and combined cycle gas turbine (CCGT) plants [19,26,28,29,37,40,52-56]. Viebahn et al. [29] also compared the environmental performance of CCS against those from renewable energy technologies such as wind and solar thermal. The rest of the studies assessed the environmental impacts of fossil-fuel based power plants with and without CCS technologies [26,28,37,40,52–54,56].

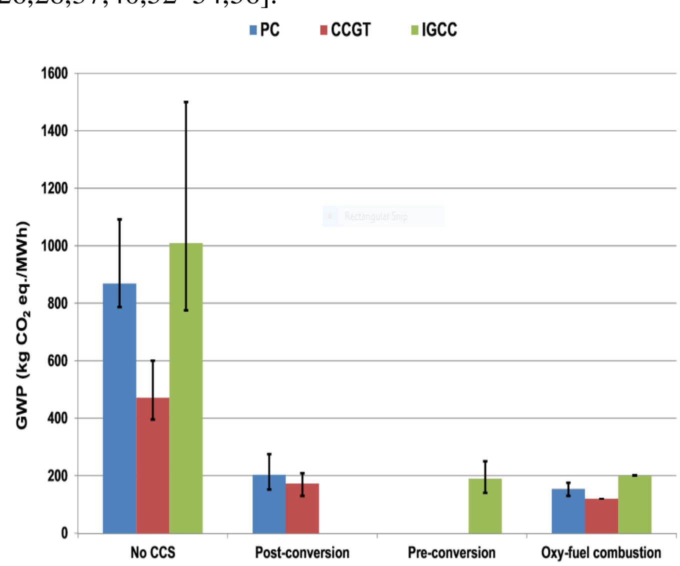

Fig. 4 Global warming potential of CCS options for PC, pulverised coal; CCGT, combined cycle gas turbine; IGCC, integrated coal gasification combined cycle.[51]

VII. CONCLUSION

This paper has analysed the environmental impacts of various CCS and CCU options for the capture, storage and/or utilisation of CO_2 emitted by power plants and other industrial sources. The main CO_2 capture options are post- conversion, pre-conversion capture and oxy-fuel combustion. Post-conversion capture via chemical absorption using mono-ethanolamine (MEA) is the most mature and widely used technique, especially in the power generation sector. However, the use and regeneration of MEA is a significant contributor to the emissions of CO_2 and related global warming potential (GWP), so that the development of more environmentally sustainable sorbents is one of the challenges for both CCS and CCU.

The captured CO_2 can be stored in geological formations, also known as geological storage, or in the oceans. In particular, it is not clear how disposal in the oceans would affect the acidity and marine species. Besides storage, CO_2 can be used directly in different industrial sectors, including the food and beverage as well as pharmaceutical industry. It can also be converted into high-demand products such as urea, methanol and biofuels.

The overall study shows that by use of CCU and CCS technology there is decrease in Global Warming Potential in world. Leading to reduce the effect of global warming and directs to a sustainable future. With reduction in global warming potential the technology also solves other two major problems that include pollution and climate change. The stored CO_2 can be utilised as discussed in paper. Thus we are generating best out of waste in terms of money, energy and products or goods. Though the implementation of this technology proves out to costly but we need to find economical way of implementing this technology. The newly developed system must be economical as well as fully integrated also, one which can be built into new power plants and can be mounted on the existing ones.

ACKNOWLEDGMENT

The author takes the opportunity to express immense gratitude to my supervisor **Dr. Dipak Ranjan Jana,** Professor of Mechanical Engineering Department, Poornima College of Engineering, Jaipur for his guidance, encouragement and motivation towards real-time review work right from the beginning. I have taken efforts in this project work report. I would like to extend my sincere thanks to Sir. I would like to thank those persons whose name could not figure here, once again for their valuable guidance, support and kind attention given to me throughout the project work.

Finally I bow to my parents, my all-family members, well-wishers for their blessing.

Shivam Paneri, (Mechanical Engineering Department, Poornima College of Engineering, Jaipur.)

REFERENCES

[1] C. Le Que´ re´ , G.P. Peters, R.J. Andres, R.M. Andrew, T. Boden, P. Ciais, P. Friedling-stein, R.A. Houghton, G. Marland, R. Moriarty, S. Sitch, P. Tans, A. Arneth, A. Arvanitis, D.C.E. Bakker, L. Bopp, J.G. Canadell, L.P. Chini, S.C. Doney, A. Harper, I. Harris, J.I. House, A.K. Jain, S.D. Jones, E. Kato, R.F. Keeling, K. Klein Goldewijk, A. Ko¨ rtzinger, C. Koven, N. Lefe` vre, A. Omar, T. Ono, G.H. Park, B. Pfeil, B. Poulter, M.R. Raupach, P. Regnier, C. Ro¨denbeck, S. Saito, J. Schwinger, J. Segschneider, B.D. Stocker, B. Tilbrook, S. van Heuven, N. Viovy, R. Wanninkhof, A. Wiltshire, S. Zaehle, C. Yue, Earth Syst. Sci. Data Discuss. 6 (2) (2013) 689–760.

[2] IPCC, Climate Change 2013: The Physical Science Basis, Intergovernmental Panel on Climate Change, 2013 available at: https://www.ipcc.ch/report/ar5/wg1/.

[3] DECC, CCS Roadmap Storage Strategy, Department of Energy and Climate Change, 2012 available at: https://www.gov.uk/government/uploads/system/uploads/ attachment_data/file/48320/4904-ccs-roadmap–storage-strategy.pdf.

[4] IEA, Technology Roadmap Carbon Capture and Storage, Organisation for Economic Development & International Energy Agency, Paris, France, 2013, available at: http://www.iea.org/publications/freepublications/pu

blication/TechnologyRoad mapCarbonCaptureandStorage.pdf.
[5] P. Styring, D. Jansen, H. de Coninck, H. Reith, K. Armstrong, Carbon Capture and Utilisation in the Green Economy, Centre for Low Carbon Futures, 2011 available at: http://co2chem.co.uk/wp-content/uploads/2012/06/ CCU%20in%20the%20green%20economy%20report.pdf.
[6] H.H. Khoo, J. Bu, R.L. Wong, S.Y. Kuan, P.N. Sharratt, Energy Proc. 4 (2011) 2494–2501.
[7] K.M. Yu, I. Curcic, J. Gabriel, S.C. Tsang, ChemSusChem 1 (11) (2008) 893–899.
[8] PBL and JRC, Trends in Global CO2 Emissions: 2013 Report, PBL Netherlands Environmental Assessment Agency and European Commission Joint Research Cen- tre Institute for Environment and Sustainability, The Hague/Ispra, 2013, available at: http://edgar.jrc.ec.europa.eu/news_docs/pbl-2013-trends-in-global-co2- emissions-2013-report-1148.pdf.
[9] P. Markewitz, W. Kuckshinrichs, W. Leitner, J. Linssen, P. Zapp, R. Bongartz, A. Schreiber, T.E. Mu¨ ller, Energy Environ. Sci. 5 (6) (2012) 7281–7305.
[10] B. Metz, O. Davidson, H. de Coninck, M. Loos, L. Meyer, IPCC Special Report on Carbon Dioxide Capture and Storage, Intergovernmental Panel on Climate Change, 2005 available at: http://www.ipcc.ch/pdf/special-reports/srccs/ srccs_wholereport.pdf.
[11] D. Weisser, Energy 32 (9) (2007) 1543–1559.
[12] E.G. Hertwich, M. Aaberg, B. Singh, A.H. Strømman, Chin. J. Chem. Eng. 16 (3) (2008) 343–353. [13] C. Cooper, A Technical Basis for Carbon Dioxide Storage, CO2 Capture Project, 2009 available at: http://unfccc.int/resource/docs/2011/smsn/ngo/276.pdf.
[14] S. Nagashima, T. Miyagawa, M. Matsumoto, S. Suzuki, H. Komaki, M. Takagi, S. Murai, Life Cycle Assessment Performed on a CCS Model Case in Japan and Evaluation of Improvement Facilitated by Heat Integration, 2011.
[15] P. Zapp, A. Schreiber, J. Marx, M. Haines, J.F. Hake, J. Gale, Int. J. Greenhouse Gas Control 8 (2012) 12–21.
[16] T. Kuramochi, A. Ramı´rez, W. Turkenburg, A. Faaij, Prog. Energy Combust. Sci. 38 (1) (2012) 87–112.
[17] E.S. Rubin, C. Chen, A.B. Rao, Energy Policy 35 (9) (2007) 4444–4454.
[18] UNIDO, Technology Roadmap: Carbon Capture and Storage in Industrial Applica-tions, United Nations Industrial Development Organization, Organisation for Economic Development & International Energy Agency, 2011 available at: http://www.unido.org/fileadmin/user_media/News/ 2011/ CCS_Industry_Roadmap_WEB.pdf.
[19] B. Singh, A.H. Strømman, E.G. Hertwich, Int. J. Greenhouse Gas Control 5 (4) (2011) 911–921.
[20] G.G. Zaimes, V. Khanna, Biotechnol. Biofuels 6 (1) (2013) 88.
[21] M. Aresta, Carbon Dioxide Recovery and Utilization, Kluwer Academics Publish-ers, The Netherlands, 2003.
[22] B.J. Maring, P.A. Webley, Int. J. Greenhouse Gas Control 15 (2013) 16–31.
[23] S. Krishnamurthy, V.R. Rao, S. Guntuka, P. Sharratt, R. Haghpanah, A. Rajendran, M. Amanullah, I.A. Karimi, S. Farooq, AIChE J. 60 (5) (2014) 1830–1842.
[24] S. Sung, M.P. Suh, J. Mater. Chem. A 2 (33) (2014) 13245–13249.
[25] L. Li, N. Zhao, W. Wei, Y. Sun, Fuel 108 (2013) 112–130.
[26] M. Pehnt, J. Henkel, Int. J. Greenhouse Gas Control 3 (1) (2009) 49–66.
[27] J.M. Farla, C. Hendriks, K. Blok, Clim. Change 29 (4) (1995) 439–461.
[28] N. Odeh, T. Cockerill, Energy Policy 36 (1) (2008) 367–380.
[29] P. Viebahn, J. Nitsch, M. Fischedick, A. Esken, D. Schuwer, N. Supersberger, U. Zuberbuhler, O. Edenhofer, Int. J. Greenhouse Gas Control 1 (2007) 121–133.
[30] X. Gao, X. Zou, H. Ma, S. Meng, G. Zhu, Adv. Mater. 26 (22) (2014) 3644–3648.
[31] A. Azapagic, R. Clift, C. Duff, in: A. Azapagic, S. Perdan, R. Clift (Eds.), Sustainable

Development in Practice: Case Studies for Engineers and Scientists, John Wiley & Sons, Chichester, 2004 (Chapter 3).
[32] T. Pro¨ ll, H. Hofbauer, in: Proceedings of the 9th European Conference on Industrial Furnaces and Boilers (INFUB-9), Estoril, Portugal, 2011, available at: http://www. chemical-looping.at/upload/Publikationen/124_Datei.pdf.
[33] M. Najera, R. Solunke, T. Gardner, G. Veser, Chem. Eng. Res. Des. 89 (9) (2011) 1533–1543.
[34] J. Song, D. Zhang, Environ. Sci. Technol. 47 (1) (2012) 9–22.
[35] W.-W. Liu, B. Zhang, Y.-Z. Li, Y.-M. He, H.-C. Zhang, Appl. Surf. Sci. 292 (0) (2014) 142–148.
[36] Y. Zhang, J. Sunarso, S. Liu, R. Wang, Int. J. Greenhouse Gas Control 12 (0) (2013) 84–107.
[37] H.H. Khoo, R.B.H. Tan, Environ. Sci. Technol. 40 (12) (2006) 4016–4024.
[38] E. Nduagu, J. Bergerson, R. Zevenhoven, Energy Convers. Manage. 55 (2012) 116–126.
[39] B. Singh, A.H. Strømman, E.G. Hertwich, Comparative Impact Assessment of CCS Portfolio: Life Cycle Perspective, 2011.
[40] A. Korre, Z. Nie, S. Durucan, Int. J. Greenhouse Gas Control 4 (2) (2010) 289–300.
[41] N. von der Assen, J. Jung, A. Bardow, Energy Environ. Sci. 6 (9) (2013) 2721–2734.
[42] NETL, Carbon Storage CO2 Utilization Focus Area, 2013 available from: http:// www.netl.doe.gov/technologies/carbon_seq/corerd/ co2utilization.html#cement (cited 05.07.13). [43] NETL, Carbon Dioxide Enhanced Oil Recovery, National Energy Technology Lab-oratory, 2010 available at: http://www.netl.doe.gov/technologies/oil-gas/ publications/EP/CO2_EOR_Primer.pdf. [44] S. Kokal, A. Al-Kaabi, Enhanced Oil Recovery: Challenges and Opportunities, EXPEC Advanced Research Centre, Saudi Aramco, 2010, available at: http:// www.world-petroleum.org/docs/docs/publications/2010yearbook/ P64-69_Kokal-Al_Kaabi.pdf.
[45] Advanced Resources International Inc., Melzer Consulting, Optimization of CO2 Storage in CO2 Enhanced Oil Recovery Projects, Department of Energy & Climate Change (DECC), UK, 2010,available at: https://www.gov.uk/government/uploads/ system/uploads/attachment_data/file/47992/ 1006-optimization-of-co2-storage-in-co2-enhanced-oil-re.pdf.
[46] A. Steynberg, in: A. Steynberg, M.E. Dry (Eds.), Fischer–Tropsch Technology, Elsevier, Amsterdam, 2006, pp. 1–63.
[47] W. Huijgen, Carbon Dioxide Sequestration by Mineral Carbonation, Energy Research Centre of the Netherlands, Wageningen University, The Netherlands, 2007, available at: http://edepot.wur.nl/121870.
[48] L. Brennan, P. Owende, Renew. Sustain. Energy Rev. 14 (2) (2010) 557–577.
[49] Y. Li, M. Horsman, N. Wu, C.Q. Lan, N. Dubois-Calero, Biotechnol. Prog. 24 (4) (2008) 815–820.
[50] P.J.L.B. Williams, L.M.L. Laurens, Energy Environ. Sci. 3 (5) (2010) 554–590.
[51] Rosa M. Cue´ llar-Franca, Adisa Azapagic ,Carbon capture, storage and utilisation technologies: A critical analysis and comparison of their life cycle environmental impacts.
[52] J. Koornneef, T. van Keulen, A. Faaij, W. Turkenburg, Int. J. Greenhouse Gas Control 2 (4) (2008) 448–467.
[53] I.S. Modahl, C.A. Nyland, H.L. Raadal, O. Ka˚ rstad, T.A. Torp, R. Hagemann, in: Proceedings of the Conference: Joint Actions on Climate Change, Aalborg, Den, June 2009, 2009.
[54] A. Schreiber, P. Zapp, W. Kuckshinrichs, Int. J. Life Cycle Assess. 14 (6) (2009) 547–559.
[55] Z. Nie, A. Korre, S. Durucan, Energy Proc. 4 (2011) 2510–2517.
[56] B. Singh, A.H. Strømman, E. Hertwich, Int. J. Greenhouse Gas Control 5 (3) (2011) 457–466.