Decarbonization for Oil and Gas Value Chain: An Update Review

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Apart from oil and natural gas conventional reservoirs scarcities, global warming is one of the environmental petroleum industry challenges in the short-medium-long term. This is related to the dramatic growth of greenhouse gases (GHGs) emission in which carbon dioxide (CO₂) produced by the combustion of fossil fuels plays a significant role in atmosphere carbonization. Different technologies or systems for capturing CO₂ are available such as pre-combustion systems, post-combustion systems, oxy-fuel combustion systems and capture from industrial process streams. However, decarbonization involves the removal of greenhouse gases emissions and storing them in geological formation or using them for other sectors of industries including oil production optimization. This process is known as carbon dioxide capture usage and storage (CCUS), a promising method to reduce CO₂ emissions due to increasing energy demand and continued dependency on fossil fuel in the next decades while green energy is still under investigation or is not a mature option yet. Besides the CCUS method, emission reduction can also be achieved by improving energy efficiency or shifting to green energy. Therefore, Oil and gas (O&G) producers need to continue investigating the CCUS as an option that allows using fossil energy sources while the world is moving to transition to other green energies.

years. These emissions are from the consumption of oil, gas and coal for combustion-related activities and natural gas flaring.

1. Introduction

Currently, global warming is the most significant environmental concern. Water vapor, Carbon dioxide (CO₂), methane (CH₄), ozone (O₃), nitrous oxide (N₂O) and some artificial chemicals such as chlorofluorocarbons (CFCs) are the main Greenhouse gases (GHGs) in which carbon emissions present the most challenging global climate change.

The only solution to the climate stabilization is full decarbonization of the energy system. This process is referred to as reducing carbon dioxide (CO₂) emissions resulting from human activity in the atmosphere. According to Beck et al. (2020), 42% of direct and indirect emissions are from the oil and gas industry. Hence, emission reduction can be achieved by switching to renewable energy production and consumption and low carbon energy sources or applying operation systems for capturing and storing the carbon dioxide.

The World Bank encouraged the Governments, oil companies, and development institutions around the world to endorse the “Zero Routine Flaring by 2030”. However, more CO₂ emission reduction policy programs are required for other emissions such as no routine flaring and fugitive emissions.

The Paris Agreement was adopted in December 2015 by consensus of all members of the United Nations Framework Convention on Climate Change (UNFCCC). At this present time, 197 countries have agreed to gradually reduce the use of fossil fuels and CO₂ emissions to reach net carbon neutrality by 2050 and keep global warming below 2 °C by the year 2100.

According to British Petroleum (BP) report (Figure 1), Asia Pacific region recorded the highest CO₂ emissions in last five years (2016 – 2020) with 48.4%, 48.9%, 49.2%, 50.1% and 52.0% respectively in total emissions of 33726.9, 34351.1, 34356.6, 32284.1 million tons. South and Central America, and Africa reported the least CO₂ emissions during the last five

Figure 1: Worldwide CO₂ fossil fuels emissions. Adapted from bp.com/statistical review

Angola is a country currently committed to the Zero Routine Flaring. The country has implemented new projects such as Angola LNG Plant that helps in working on efficient use of natural gas to reduce greenhouse gases and improve the country's energy system. However, according to the data, the world meter report shows an increase of Angola fossil CO₂ emissions from the year of 1971 to 2016 (Figure 2).

Figure 2: Fossil carbon dioxide emissions of Angola. Adapted from <https://www.worldometers.info/co2-emissions/angola-co2-emissions/>

The Angola fossil CO₂ emissions were also reported by sector for the year 2016 as shown in Figure 3.

The fossil CO₂ emissions reported according to Figure 3 was 30566933 tons in which non-combustion and transport are the most polluted with 33.9% and 30.2% respectively. Important to recall that greenhouse gas emissions are measured in tons of carbon dioxide-equivalents (CO₂e).

Figure 3: Fossil CO₂ by sector in Angola for year 2016. Adapted from [Angola CO₂ Emissions - Worldometer \(worldometers.info\)](https://www.worldometers.info/co2-emissions/angola-co2-emissions/)

Emission reduction requires capturing and storing CO₂ produced by combustion of fossil fuels which causes a greenhouse gas (GHG) potential for by-product end-use in the industrial and energy production sectors. Using CO₂ as a by-product would have both economic benefit and simultaneously mitigate global climate change concerns (Figueroa et al., 2008). The capturing and storage technique could reduce 33% of global CO₂ emissions in 2050 compared to today's emission levels (Bellona Foundation, 2007, Al Wahedi and Dadach, 2013).

The first oil in Angola is from 1955 and many fields are producing below the bubble point with most of them maturing allowing excessive gas production. In addition, the country has more than 250 production platforms including compliant towers, wellhead jackets, jack-up, tension leg platform (TLP), floating production storage and offloading (FPSO), floating storage and offloading (FSO) which requires efficient use of CO₂ value chain for the purpose of reducing its emission.

2. Carbon Dioxide (CO₂) Value Chain

The proposed CO₂ value chain is divided into four sections (Figure 4): (1) first section composed of CO₂ emissions, (2) the second section for capture, conditioning, and compression; (3) the third section for CO₂ transportation; and (4) the fourth section composed of CO₂ utilization and storage or sequestration. The framework of the CO₂ value chain is debatable. Each of the elements is described in the succinct form in the next sections.

Figure 4: Proposed carbon dioxide (CO₂) value chain. Adapted from Ansaloni et al., 2020.

2.1 Oil and Gas (O&G) industry emissions

Beck et al. (2020), in their work state that the oil and gas (O&G) industry accounts for 42% of direct and indirect global emissions, which are 16 percent less than the emissions from non-O&G emissions. From the O&G emissions, nine percent of the industry's operations of all human-made GHGs emissions where eight percent and one percent are direct and indirect emissions from O&G operations, respectively, and 33 percent emissions from the O&G value chain.

Within the O&G value chain, for the upstream, midstream, and downstream sectors, the CO₂ emissions are grouped in those with energy

related, not energy related, and non-CO₂ related. Cases of not energy related are attributed to 10% of extraction and drilling operations for upstream section, 5% for crude transport and 20% for refinery heat and power systems in mid/downstream sections (Beck et al., 2020). Carbon dioxide energy related emission is a consequence of 5% of flaring for upstream section and 3% hydrogen production, fluid catalytic converter (FCC) for mid/downstream section. Emissions for non-CO₂ related are 47% of fugitive emissions and venting of methane (CH₄) for upstream section and 10% for mid/downstream section (Beck et al., 2020).

The main challenge is the climate policies, emissions reduction, and mitigation plans. The mitigation plan for O&G sector requires a reduction by at list 3,4 gigatons of carbon dioxide (CO₂) equivalent (GtCO₂e) a year by 2050 compared with current planned policies or technologies – a 90 percent reduction in current emissions Beck et al. (2020). Two-thirds of the emissions account for upstream operations and the remaining one third for midstream and downstream operations (Beck et al., 2020).

2.2. CO₂ Capture, Conditioning and Compression

A physical process to capture manmade carbon dioxide (CO₂) and storing it before its release to the atmosphere is known as carbon capture and storage (or sequestration) or CCS (Folger, 2014). The CCS is one of the processes that could be used to reduce the amount of CO₂ emitted to the atmosphere from the continued use of fossil fuels at power plants and other large, industrial facilities. CCS technology is conceptually similar to strategies used to lower SO₂, NO_x, particulates, and other pollutant emissions. The only difference is that the volume of CO₂ generated is much greater than these other emissions.

Folger published a work in 2014 and states that an integrated CCS system includes three main steps: (1) capturing CO₂ at its source and separating it from other gases; (2) purifying, compressing, and transporting the captured CO₂ to the sequestration site; and (3) injecting the CO₂ into subsurface geological reservoirs. The process requires leakage monitoring to verify and assure if the CO₂ remains in the target geological reservoir (Zahra, 2013).

Carbon capture comes from three potential sources: (1) several industrial processes - produce highly concentrated streams of CO₂ as a byproduct, (2) power plants - emit more than one-third of the CO₂ emissions worldwide, making them a prime candidate for carbon capture, (3) future opportunities for CO₂ sequestration - may arise from producing hydrogen fuels from carbon-rich feedstocks, such as natural gas, coal, and biomass (Zahra, 2013).

There are four basic systems for capturing CO₂ from both the power generation and industrial sectors (Figueroa et al., 2013, Zahra, 2013, Al Wahedi and Dadach, 2013):

- Oxy-fuel combustion systems - uses oxygen instead of air for combustion, producing a flue gas that is mainly H₂O and CO₂ and which is readily captured. The advantage is a very high CO₂ concentration of flue gas and retrofit and repowering technology option. The disadvantage is large cryogenic O₂ production requirements may be cost-prohibitive. Cooled CO₂ required to maintain temperatures within limits of combustor materials during the recycling, decrease process efficiency and added auxiliary load (Figure 5).

Figure 5: Block diagrams illustrating oxy-combustion systems. Adapted from Figueroa et al., 2008.

Pre-combustion systems - process the primary fuel in a reactor to produce separate streams of CO₂ for storage and H₂ which is used as a fuel. The vantage is synthesis gas is concentrated in CO₂, high pressure and resulting in high CO₂ partial pressure (increased driving force for separation, more technologies available for separation) and potential for reducing the cost of compression for sequestration. The disadvantages are applicable mainly to new plants as few gasification plants that are currently in operation, are adaptable to commercial application of gasification common to pre-combustion capture, availability, cost of equipment and extensive supporting systems requirements (Figure 6).

Figure 6: Block diagrams illustrating post-combustion systems. Adapted from Figueroa et al., 2008.

- Post-combustion systems - Involves the removal of CO₂ from the flue gas produced by combustion of fossil fuel. The advantage is this method is applicable to any kind of existing coal-fired power plants and has the greatest near-term potential for reducing CO₂ emissions. The disadvantages of this method are the system flue gas is dilute in CO₂, at ambient pressure and low CO₂ partial pressure compared to sequestration requirements (Figure 5).

Figure 7: Block diagrams illustrating post-combustion systems. Adapted from Figueroa et al., 2008.

- Capture from industrial process streams - other industrial processes such as Iron and steel, non-metallic minerals and chemicals and petrochemical industries, including processes to produce low-carbon or carbon-free fuels, employ one or more of these same basic capture methods.

Nowadays, there are a wide range of technologies for separation and capture of CO₂ from gas streams in existence. These technologies are based on different physical and chemical processes including absorption, adsorption, membranes, and cryogenics as illustrated in Table 2 in appendix. Table 2 summarizes the current and future trends of each carbon dioxide capturing technology. The current capturing technologies can be improved according to the principles of separation. For example, the current chemical solvents of post-combustion separation technology require an improved process design, improved solvents, or novel contacting equipment.

The monitoring, risk and legal aspects associated with CO₂ capture systems appear to present no new challenges, as they are all elements of long-standing health, safety, and environmental control practice in industry. Due to the global warming, the continued use of fossil energy depends on CO₂ capture and sequestration.

2.2.1 CO₂ Conditioning and Compression

One of the important steps in any CCUS project is the CO₂ compression. Significant power is required to boost the pressure of CO₂ from the atmospheric pressure of the stripping column up to a pressure suitable for injection. However, before compression CO₂ is treated or purified, known as the conditioning process.

With traditional technology, CO₂ is compressed at an initial pressure ranging from 15 psi (1.034 bar) to 100 psi (6.895 bar) to a final pressure of 2.200 PSI (151.685 bar). At this point, a multiple stage process of compression is required. New concepts with part compression followed by liquefaction and pumping can be utilized for high-pressure applications depending on the specific characteristics of the injection process.

Positive displacement compressors (rotary or screw) may also be used for pressures below 550 psi (37.921). However, more stages are required because these machines are pressure ratio limited. Centrifugal compressors need also be considered because of their ability to process large volumes of gas at both low and high pressures.

2.3 Carbon Dioxide Transportation

The three ways of transporting CO₂ are via pipeline, road, and railway. According to a study conducted by Norisor et al. (2012), the pipeline transport way could be rentable compared with other ways for a plant's life more than 23 years. The other hindrance is the source surface facility of CO₂ to a storage site. The cost of very long pipelines appears to be prohibitive. It has been proposed that 500 km might be the maximum distance (Recht, 1984).

The transport of captured CO₂ via pipeline requires it to be compressed and cooled at a liquid state due to the transport of gaseous CO₂ (at lower densities) is inefficient because of the low density of the CO₂ and relatively high-pressure drop per unit length.

Corrosion in pipeline is an action to be considered at a pressure level around and above the critical point. Temperature level above 90°C is one of the requirements to prevent liquid building during decompression (e.g., sealing elements and packing of the compressor). CO₂ transportation can produce water vapor and it can precipitate to a liquid or solid phase when the compressed gas is cooled in the pipeline. Liquid water accelerates corrosion, and ice or solid hydrates can plug valves, fittings, and even the pipeline. Treating CO₂ at the source is crucial to avoid pipeline and additional cost to a CCS plant (Al Wahedi and Dadach, 2013).

2.4 Carbon Dioxide Utilization and Storage

Most chemical processes using CO₂ require relatively small amounts. Hence, CO₂ is used (1) in beverages (carbonated beverages) to give them effervescence, (2) in fire extinguishers during fires to isolate oxygen from the fuel, (3) on rollers for Paintball practice (3) in aquarium hobby in regulating the pH of water, (4) in medicine 30 to 40% of CO₂ concentration can be used with oxygen gas to produce anesthetic effect in small animals, (5) in polymer, pharmaceutical, and chemical industry, CO₂ can be used for the synthesis of dimethyl carbonate, a versatile compound in these sectors. Synthetic fuels are produced by chemical processes from combination of hydrogen gas and CO₂.

Carbon Dioxide commercial usage in large-scale applications is limited. To improve oil and gas recovery process, CO₂ can be injected into geological formations for enhanced oil recovery (EOR) projects to recover the remaining hydrocarbon left by the conventional type of recovery. This type of EOR process can be miscible or immiscible CO₂ techniques which can contribute to CO₂ sequestration for both oil production and CO₂ storage optimization. EOR planning strategy and screening criteria were

published by Ramos and Akanji (2017); Ramos et al. (2020); Ramos and Yates (2021).

2.4.1 Carbon Dioxide (CO₂) Storage or Sequestration

Large quantities of captured CO₂ could be stored in geological formations and the deep ocean (Table 1). The two main worldwide capacity of potential CO₂ storage are the ocean and land-based sites. Deep saline formations, depleted oil and gas reservoirs, and unmineable coal seams are known as Geological sinks for CO₂.

Table 1: The worldwide capacity of potential CO₂ storage reservoirs. GtC (thousands of gigatons of carbon) = 1 billion metric tons of carbon equivalent. Adapted from Zahra, 2013.

Storage Option	Worldwide capacity
Ocean	1000s GtC
Deep saline formations	100s-1000s GtC
Depleted oil and gas reservoirs	100s GtC
Coal seams	10s – 100s GtC
Terrestrial	10s GtC
Utilization	< 1 GtC/yr

The storage reservoir must be effective, safe, and environmentally suitable. In geological storage, CO₂ reacts underground to form carbon minerals. Hence safety is more of a concern than environmental impact. The mechanism for potential leaks must be understood and avoided.

For oceanic storage of CO₂, 15 – 20% of injected CO₂ will escape over a period of a hundred years with the rest remaining in the ocean. During oceanic storage, pH drops because of the reaction of CO₂ with seawater. This is an environmental concern that can be avoided or controlled if the injection technique disperses the CO₂ as it dissolves into seawater.

3. Carbon Dioxide Emission Mitigation Plan

Angola has huge infrastructures such as support bases, yards, production platforms, and drilling rigs which produce a considerable amount of greenhouse gases emission requiring decarbonization of this sector or appropriate climate policies and emissions-reduction plans.

Sonangol EP, operating companies, service companies and providers monitored by Ministry of Mineral Resources, Oil and Gas and Ministry of Culture, Tourism and Environment, and Angola's National Oil, Gas and Biofuel's Agency (ANPG) can work out local climate policies and emissions-reduction plans. This cannot fall out of the quality, safety, health, and environment procedures required for good practices in O&G operations.

Some essential required technologies to mitigate the climate change through CO₂ reduction or to stabilize the CO₂ concentration in the atmosphere are (1) conservation and energy efficiency (2) renewable energy (3) nuclear energy (4) replacing coal energy by gas, (5) carbon capture, transport, utilization, and storage (CCUS) (Zahra, 2013), and (6) reforestation.

Around 2.4 billion tons of CO₂ a year is sequestered by reforestation (plants and trees). Green cities as well as planting trees would help to create carbon sink in the planet. The Italian Energy company (ENI) has planned to plant 20 million acres of forest in Africa (Beck et al., 2020). Angolan Government, led by Vice-President, is planning to plant 1 million mangroves as one of the country's contributions to protect the ecosystem in which Sonangol has joined the program.

Mangroves are natural tropical ecosystems, composed of plant species that tolerate salt water generally located in coastal areas. Mangroves are considered "blue carbon ecosystems", as well as seagrasses and salt marshes, because they are 10 times more efficient at absorbing and

storing large amounts of carbon over the long term, compared to terrestrial ecosystems.

Another mitigation plan is decarbonizing each section O&G chain value. From upstream section of the O&G chain value this requires (IEA, 2018 and Beck et al., 2020) (1) Changing power sources by using renewable-power generation on-site. For example, replacing generators with a solar photovoltaic (PV) and battery setup which can reduce emissions and investments. (2) Reducing fugitive emissions (Methane is a powerful GHG) by improving leak detection and repair (LDAR), installing vapor recovery units (VRU) or applying other available techniques such as double mechanical seals on pumps, dry gas seals on compressors and carbon packing ring sets on valve. Preventive and predictive maintenance of equipment and pipelines and repair system at compression stations are also method to be adopted for fugitive emissions avoidance. (3) Upgrading electrifying equipment by replacing gas boilers with electric steam-production systems. This includes high-pressure storage for nighttime steam to support separation units. (4) Reducing no routine flaring through improved reliability is one of the actions that can reduce the emissions and raise the production. The studies show that 70% of all flaring is from no routine flaring as a result of poor reliability. Predictive maintenance and replacing equipment can be applied to improve reliability. (5) Reducing routine flaring through improved additional gas processing and infrastructure are a requirement to reduce the routine flaring. Angola LNG is one of the infrastructure that successfully reduces routine flaring through increased efficiency in their additional gas processing. (6) Construction of carbon capture, use, and storage (CCUS) plants with the purpose to capture and store CO₂. Small CCUS units can be adapted for the new generation production platforms. The CO₂ captured and stored is then used for EOR projects. (7) extracting and drilling requires CCUS system and use of the captured CO₂ for EOR projects as well as energy efficiency and electrification are some emissions mitigation strategies. (8) Rebalancing the portfolios in which the reservoir engineers and geoscientists need to evaluate the upstream projects including the type of reservoirs available. Complex reservoirs may become unattractive to develop in future. This includes the highly viscous in deep or ultra deep water, or high pressure and temperature.

In the mid/Downstream requires thorough planning and extra investments but in future will not only reduce the emissions but also reduce the cost (IEA, 2018 and Beck et al., 2020) (1) Energy efficiency by reducing the primary energy used in distillation by using waste-heat-recovery technology and medium-temperature heat pumps in refineries. (2) Green hydrogen (renewable energy) can be used rather than steam methane reforming (SMR) to power the electrolysis as a way to reduce emissions in refineries. (3) High temperature electric cracking by replacing fuel gas by electric coils to provide heats to refineries. (4) Greener feedstocks by replacing the conventional oil feedstocks with biomass feedstocks or recycled plastics materials.

4. Cost of CO₂ capture

Gas natural extraction to meet commercial specifications is required to reduce its CO₂ contaminants from about 9% to 2.5% (Herzog, 2001). Hence, the CO₂ removed from natural gas or other emissions can be captured, stored and used for commercial purposes.

The main contributor to the cost of the complete CCUS value chain is the CO₂ capture. Besides the continued usage of fossil fuels, one of the motivations of CCUS projects is implementing the offshore/onshore carbon tax incentive. For example, Norwegian offshore carbon tax was lowered to \$38/ton of CO₂ in January 2001 with previous value of \$50/ton in 1991 (Herzog, 2001).

The capture cost depends on technical, economic and financial factors. The technical factors are related to plant design and operation such as plant size, net efficiency, fuel properties and loading factor. Whereas economic and financial factors such as fuel cost, interest rate and plant life are different assumptions for the estimation of CO₂ capture cost (Zhara, 2013).

The cost varies widely depending on CCUS plant location, timeframe and finance, the emitting plant and the technology and energy used. Since the capture process involves conditioning (separation and purifying) and compression which is an energy-intensive process. (IPCC, 2005, Zhara, 2013). Hence, for the coal or gas power plant there is a 40 – 90% increase in the leveled cost of electricity (LCOE) of CCUS for each fossil fuel power plant as compared to the cement and steel industry where the application is estimated to 50% and 12%, respectively (Zhara, 2013).

5. Conclusions

The synergy between carbon dioxide captures, storage, and usage (CCUS), energy efficiency and demand management play an important role in stabilizing the CO₂ in the atmosphere. Several companies have adopted techniques that can substantially decarbonize the O&G operations such as improving the maintenance routines to reduce intermittent flaring and vapor-recovery units to reduce methane leaks among others. The CCUS is an important area of research, particularly because it extends the energy transition period and continues the usage of fossil fuels for the countries that rely on fossil fuels. This will save energy and CO₂ emissions to prevent global warming and climate change. Tax incentives and other incentives are needed to lower the cost of the CCUS projects or investments.

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Conflict of interest

The author declares that there is no conflict of interest regarding the publication of this manuscript.

References

- Ansaroni, L., Alcock, B., & Peters, T. A. (2020). Effects of CO₂ on polymeric materials in the CO₂ transport chain: A review. *International Journal of Greenhouse Gas Control*, 94, 102930.
- Al Wahedi, F. and Dadach, Z. (2013). Cost Effective Strategies to Reduce CO₂ Emissions in the UAE: A Literature Review. *Ind Eng Manage*, 1(116), 2169-0316.

- Beck, C., Rashidbeigi, S., Roelofsen, O., and Speelman, E. (2020). The future is now: How oil and gas companies can decarbonize. *Oil and Gas Practice*, McKinsey & Company.

- Bringing carbon capture & storage to Market, Schlumberger, SBC Energy Institute. Available from <http://www.sbc.slb.com/SBCInstitute/Publications/CCSRoadmap.pdf>

- Figuerola, J. D., Fout, T., Plasynski, S., McIlvried, H., & Srivastava, R. D. (2008). Advances in CO₂ capture technology—the US Department of Energy's Carbon Sequestration Program. *International journal of greenhouse gas control*, 2(1), 9-20.

- Folger, P. F. (2014). Carbon Capture and Sequestration: Research, Development, and Demonstration at the US Department of Energy.

- Herzog, H. J. (2001). What future for carbon capture and sequestration? *Environmental Science and Technology*. Vol 35, pp.148 A – 153 A.

- IEA, International Energy Agency, *World Energy Outlook 2018*, November 2018. << <https://www.iea.org/reports/world-energy-outlook-2018>>>. Accessed on July 18, 2021.

- IPCC, 2005. Carbon dioxide capture and storage. Cambridge university press.

- Norişor, M., Badea, A., & Dincă, C. (2012). Economical and technical analysis of CO₂ transport ways. *UPB Sci Bull*, 74(1), 303-308.

- Ramos, G. A. R., & Yates, K. (2021). Enhanced Oil Recovery: Projects Planning Strategy in Angolan Oilfields. *Angolan Mineral, Oil & Gas Journal*, 2(2), 1-11.

- Ramos, G. A., & Akanji, L. (2017). Data analysis and neuro-fuzzy technique for EOR screening: Application in Angolan oilfields. *Energies*, 10(7), 837.

- Ramos, G. A., Elias, B., & Yates, K. (2020). Screening Reservoir Candidates for Enhanced Oil Recovery (EOR) in Angolan Offshore Projects. *Angolan Mineral, Oil & Gas Journal*, 1(1), 6-10.

- Recht, D. L. (1984). Design considerations for carbon dioxide pipe lines. *Pipe Line Ind. (United States)*, 61(4).

- The Bellona Foundation (2007) fact sheet: CO₂ capture and storage.

- Zahra, M. A. (2013). Carbon captures technologies overview, assessment and potential development and deployment in the ESCWA region.

Appendix

Table 2: Carbon dioxide capturing technology. Adapted from Zahara, 2013.

Principles of separation	Oxy-fuel combustion (O ₂ /N ₂)		Pre-combustion (CO ₂ /H ₂)		Post-combustion (CO ₂ /N ₂)	
	Current	Future	Current	Future	Current	Future
Solvents/Absorption	NA	Bio-mimetic solvents	Chemical solvents, Physical solvents	Improved process design, Improved solvents, Novel contacting equipment	Chemical solvents	Improved process design, Improved solvents, Novel contacting equipment
Membranes	Polymeric	Ion-transport facilitated transport	Polymeric	Ceramic, Palladium, Reactors, Contactors	Polymeric	Ceramic facilitated transport, Carbon molecular sieve.
Solid Sorbents	Zeolites, Activated carbon	Carbonates, Hydrotalcites, Silicates	Zeolites, Activated carbon, Alumina	Dolomites, Hydrotalcites, Zirconates	Zeolites, Activated carbon	Carbonates, Carbon based solvents
Cryogenic	Distillation	Improved distillation	Liquefaction	Hybrid process	Liquefaction	Hybrid process, Anti-sublimation
Biotechnology		Bio-mimetic solvents		High pressure		Algae production