ACBCCU 2018

Workshop on Awareness and Capacity Building Carbon Capture and Utilization

August 29-September 1, 2018, New Delhi

Organized by

Climate Change Research Institute

Pre-Workshop Bulletin of Lecture Notes

Workshop Highlights

- Carbon Capture and Sequestration: Overview
- Recent Advances in CO_2 Capture Technologies
- Carbon-Utilization and Value Addition
- Sectoral Applications in Oil Refineries,Minerals and Agriculture
- *Round Table* – CCS in Power sector, pros & cons and Issues in environmental norms

Workshop Theme

Recent Advances in CO_2 Capture Technology and Its Sectoral Application'

Convener / Organizing Secretary:

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IITRAM, Ahmedabad

Supported by

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Ministry of Earth Sciences & Department of Biotechnology Government of India

Awareness and Capacity Building in Carbon Capture and Storage and Utilization

(ACBCCU-2018)

India International Centre, August 29th – September 1st, 2018

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Convener

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Chief Executive, Climate Change Research Institute and Former Adviser & Emeritus Scientist, Ministry of Science & Technology, New Delhi

Awareness and Capacity Building in Carbon Capture and Utilization (ACBCCU-2018)

August 29th – September 1st, 2018 at IIC, New Delhi

PREFACE

The Climate Change Research Institute has been organizing Capacity Building workshops to address critical challenges of carbon capture, storage and utilization for the benefit of youth in the country. Pre-workshop lecture notes for the fourth edition of the workshop on ACBCCU-2018 being organized from August 29th to September 1st, 2018 at India International Centre, New Delhi provide glimpses of proposed deliberations. The aim is to discuss advances in CO_2 capture technologies and to widen the scope of application in sectors other than Power. A Roundtable discussion on relevance of CCU to Power Sector and new Environment Norms is also proposed.

On this occasion I place on record my sincere thanks to Prof. D.P. Agrawal, Chairman, National Advisory Board as well as the Members for their support and encouragement. I feel indebted to Chairman and Members of National organizing Committee for their advice. We are grateful to eminent experts and delegates from various institutions and industry across the country for their keen interest. The support from Ministry of Earth Sciences, Government of India for this capacity building workshop is thankfully acknowledged.

Dr. (Mrs.) Malti Goel
Convener, ACBCCU 2018
Chief Executive, Climate Change Research Institute

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MESSAGE

I am glad that a national level ACBCCU-2018 workshop on **Recent Advances in CO_2 Capture Technology and Its Sectoral Application** has been organized by Climate Change Research Institute from August 29th – September 1st, 2018 at India International Centre, New Delhi.

India being a coal-dominant economy, Carbon capture, Storage and Utilization (CCSU) is a complex set of technologies, emerging as an important option for sustainable growth. The CCSU methodologies are getting acceptance as environment friendly approach. It can make an important contribution towards low carbon growth strategy, both in power and industry sectors. A renewed thrust is being given to Carbon Capture Innovations with substantial increase in R&D investments by 2020 under the international Mission Innovation (MI) in which India is a partner country.

I am happy that ACBCCU-2018 is a Capacity Building programme for students and researchers with a focused goal and provides an opportunity for them to interact with the experts, and have exposure on recent developments in CO_2 capture technology, as well as research being conducted in India for its sectoral applications. Intangible benefits can be expected in terms of regional knowledge sharing, awareness creation and strengthening capacity through science & technology solutions.

I wish the workshop a great success and look forward to the deliberations.

(M. Rajeevan)

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ACBCCU- 2018
Awareness and Capacity Building Workshop on
'Recent Advances in CO_2 Capture Technology and Its Sectoral Application'

Pre Workshop Lecture Notes

CONTENTS

Overview of CCS Technologies and Experimental report on Post Combustion Carbon Capture

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Extended Summary

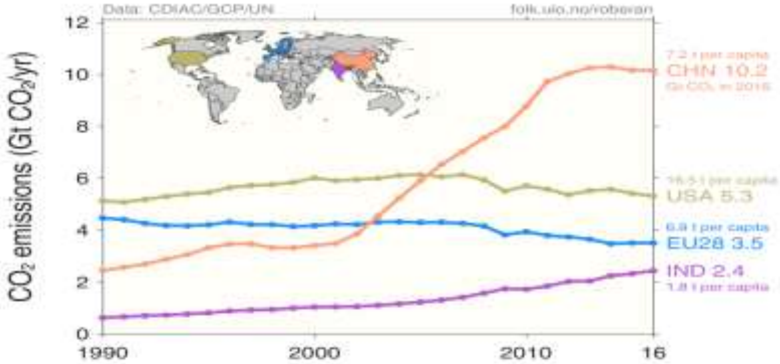
Current Scenario and need for CCS

Rapid economic growth has contributed to today's ever-increasing demand for energy. An obvious consequence of this is an increase in the use of fuels, particularly conventional fossil fuels (i.e. coal, oil and Natural gas) that have become key energy source since the industrial revolution. However, the abundant use of fossil fuels has become a cause of concern due to their adverse effects on the environment, particularly related to the emission of carbon dioxide (CO_2), a major anthropogenic greenhouse gas (GHG).

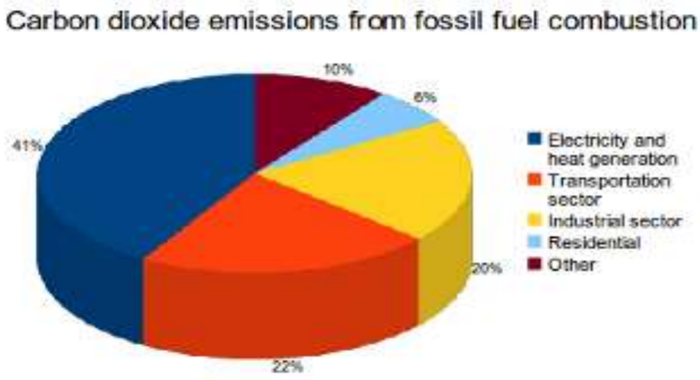
According to the Emission Database for Global Atmospheric Research, global emission of CO_2 was 33.4 billion tonnes in 2011, which is 48% more than that of two decades ago. Over the past century, atmospheric CO_2 level has increased more than 39%, from 280 ppm during pre-industrial time to the record high level of 400 ppm in May 2013 with a corresponding increase in global surface temperature of about 0.81ºC. Without climate change mitigation policiesit is estimated that global GHG emission in 2030 will increase by 25 – 90% over the year 2000 level, with CO_2 -equivalent concentrations in the atmosphere Growing to as much as 600 –1550 ppm.Global warming and climate change concerns have triggered global efforts to reduce the concentration of atmospheric carbon dioxide (CO_2).Carbon dioxide capture and storage (CCS) is considered a crucial strategy for meeting CO_2 emission reduction targets.

Indian Scenario

India's pledge under the Paris Agreement is to reduce the carbon intensity of its economy by 33-35% by 2030, compared to 2005 levels.



India has the world's fourth highest CO_2 emissions, but its emissions per person are very low. World-average per capita emissions were 4.2 tonnes in 2016. Source: CDIAC, Global Carbon Project, and UN.



Source: CO2 Emissions from Fuel Combustion (2012), International Energy Agency.

The total vehicle population in 2001 and 2015 was 55 and 210 million respectively. It comprised of 73.5% two wheelers, 13.6% cars, jeeps and taxis, 1% buses, 4.4% goods vehicle and 7.5% other vehicles. As compared to the year 2001, the share of two wheelers changed by 3.40%, the share of cars, jeeps and taxis changed by 0.80%, the share of buses changed by -0.2%, the share of goods vehicle changed by -1% and the share of other vehicles changed by -3%.(Community.data.gov.in). The revenue received by the government of India during 2013-14 financial year was around 133840 crores(mospi). With the above statistics, it is essential to take necessary steps to control CO_2 emissions from the automobile vehicles.

Approaches to mitigate global climate change

- Improve energy efficiency and promote energy conservation;
- Increase usage of low carbon fuels, including natural gas, hydrogen or nuclear power;
- Deploy renewable energy, such as solar, wind, hydropower and bioenergy;
- Apply geoengineering approaches, e.g. afforestation and reforestation;
- CO_2 capture and storage (CCS)

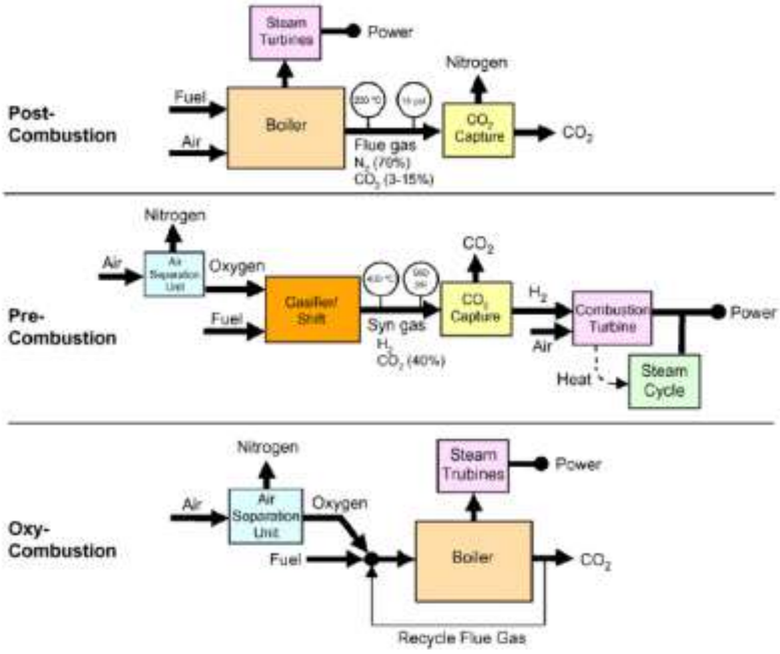
CO_2 capture technologies

There are threemainCO_2 capture systems associated with different combustion processes, namely

There are three main CO_2 capture systems associated with different combustion processes, namely,

- post-combustion,

- pre-combustion
- Oxyfuel combustion



1. In post-combustion capture, the CO_2 isseparated from other flue gas constituents either originallypresent in the air or produced by combustion.
2. In pre-combustioncapture, carbon is removed from the fuel beforecombustion,
3. In oxy-combustion, the fuel is burned in anoxygen stream that contains little or no nitrogen

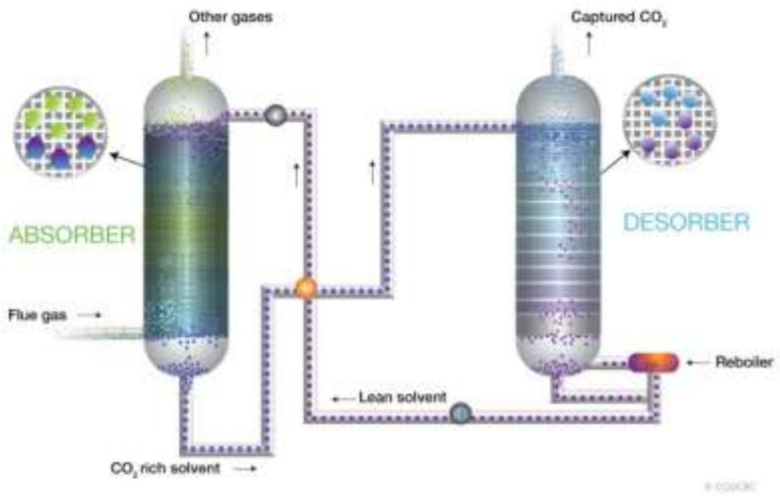
Table 1 – Advantages and disadvantages of different CO_2 capture approaches

	Advantages	Barriers to implementation
Post-combustion	• Applicable to the majority of existing coal-fired power plants • Retrofit technology option	Flue gas is ... • Dilute in CO_2 • At ambient pressure ... resulting in ... • Low CO_2 partial pressure • Significantly higher performance or circulation volume required for high capture levels • CO_2 produced at low pressure compared to sequestration requirements
Pre-combustion	Synthesis gas is ... • Concentrated in CO_2 • High pressure ... resulting in ... • High CO_2 partial pressure • Increased driving force for separation • More technologies available for separation • Potential for reduction in compression costs/loads	• Applicable mainly to new plants, as few gasification plants are currently in operation • Barriers to commercial application of gasification are common to pre-combustion capture • Availability • Cost of equipment • Extensive supporting systems requirements
Oxy-combustion	• Very high CO_2 concentration in flue gas • Retrofit and repowering technology option	• Large cryogenic O_2 production requirement may be cost prohibitive • Cooled CO_2 recycle required to maintain temperatures within limits of combustor materials • Decreased process efficiency • Added auxiliary load

Post Combustion CO_2 Capture techniques

ABSORPTION

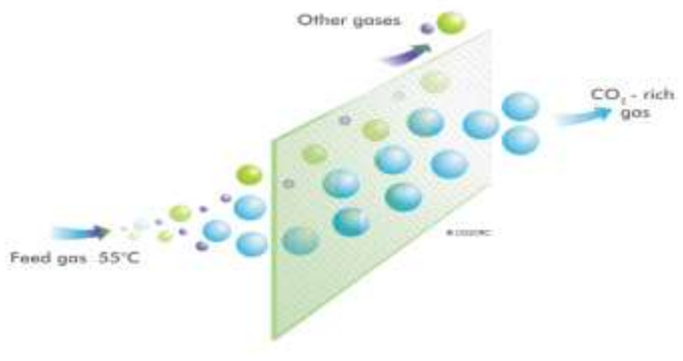
In this method, exhaust gases are first passed through a liquid medium into which the carbon dioxide selectively dissolves. A second step is required to remove the carbon dioxide from the solution. This is generally done by heating the solution to remove the carbon dioxide for capture and storage. This method is commonly used for carbon capture on a small scale and is being adapted for use in large-scale coal-burning electrical-power operations (Global CCS Institute, 2011).



PrincipleAbsorption Technique

Membrane separation:

- In this process, CO_2 is separated from the other exhaust gases using a semipermeable membrane that allows CO_2 to pass through more easily than other gases in the exhaust stream.
- The separated CO_2 is then captured for later storage. This process requires high pressure to drive the separation.



Membrane separation technique

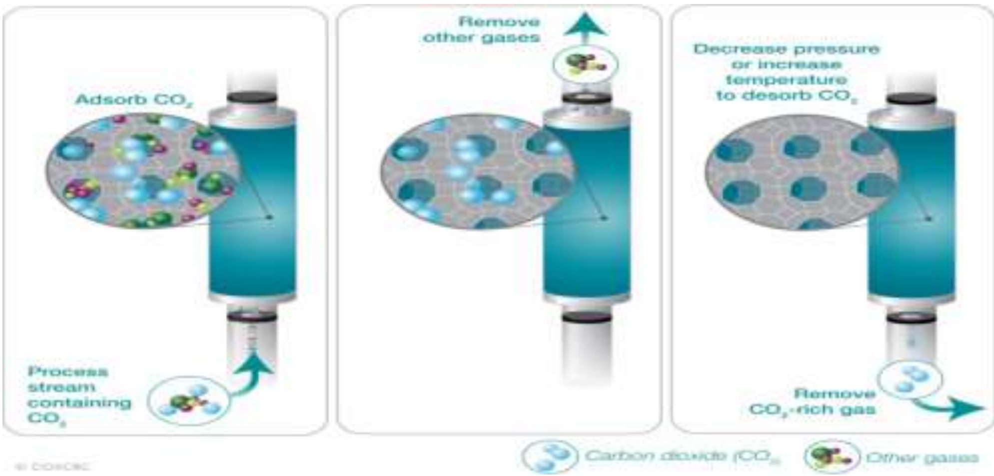
Membranes, which generally consist of thin polymeric films, owe their selectivity to the relative rates at which chemical species permeate. Differences in permeation rates are generally due (in the case of porous membranes) to the relative sizes of the permeating molecules their solubilities and/or diffusion coefficients (i.e., motilities) in the membrane material. Because permeation rates vary inversely with membrane thickness, membranes are made to be as thin as possible without compromising mechanical strength.

As is true of membrane-based filtration and desalting of water, membrane-based gas separation is a well-established, mature technology. Many large plants are operating worldwide to recover oxygen and/or nitrogen from air, carbon dioxide from natural gas, and hydrogen from a variety of process streams. As is the case with true of absorption and adsorption, economic considerations dictate that membrane systems recover CO_2 from flue gas selectively.

Membrane permeation is generally pressure-driven – i.e., the feed gas is compressed and/or the permeate channel operates under vacuum and/or a sweep gas is employed. Due to the low partial pressure of CO_2 in the flue gas, this constitutes a major challenge for the membrane-based compared to liquid absorbents or solid adsorbents that are thermally regenerated (i.e., heated to strip the captured CO_2).

ADSORPTION

- In this process, CO_2 first selectively adheres to the surface of a material without forming a chemical bond while other gases pass through. This is done under either increased pressure or decreased temperature.
- In a second phase, the CO_2 is separated by reducing the pressure and/or increasing the temperature, allowing the CO_2 to be drawn off.



Adsorption technique

Comparison of different separation technologies.

Technology	Advantage	Disadvantage
Absorption	– High absorption efficiency (> 90%). – Sorbents can be regenerated by heating and/or depressurization. – Most mature process for CO_2 separation.	– Absorption efficiency depends on CO_2 concentration. – Significant amounts of heat for absorbent regeneration are required. – Environmental impacts related to sorbent degradation have to be understood.
Adsorption	– Process is reversible and the absorbent can be recycled. – High adsorption efficiency achievable (> 85%).	– Require high temperature adsorbent. – High energy required for CO_2 desorption.
Chemical looping combustion	– CO_2 is the main combustion product, which remains unmixed with N_2, thus avoiding energy intensive air separation.	– Process is still under development and there is no large scale operation experience.
Membrane separation	– Process has been adopted for separation of other gases. – High separation efficiency achievable (> 80%).	– Operational problems include low fluxes and fouling.
Hydrate-based separation	– Small energy penalty.	– New technology and more research and development is required.
Cryogenic distillation	– Mature technology. – Adopted for many years in industry for CO_2 recovery.	– Only viable for very high CO_2 concentration > 90% v/v. – Should be conducted at very low temperature. – Process is very energy intensive.

Experimentation on CO_2 Capture

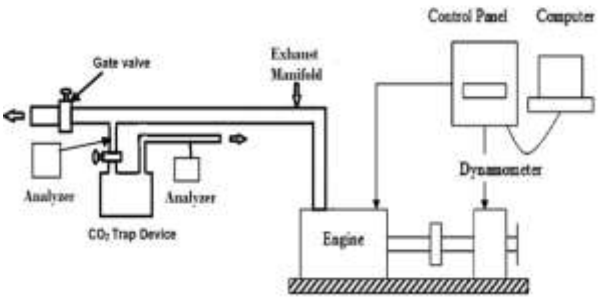
The state-of-the-art technology for CO_2 capture is solvent absorption in which an aqueous solution of alkanol amine serving as an absorbent reacts chemically with CO_2 to form soluble carbamates and/or bicarbonates. This process has already been in commercial use; however, this technology requires an inhibitively high amount of regeneration energy, because CO_2 can only be released at quite high temperatures, owing to the strong interactions of CO_2 with such absorbents. In order to identify cost-effective approaches for CO_2 capture, new materials and techniques have been studied.

In particular, phase change solvents, a new class of solvents, have emerged and been developed into one of the most promising technologies for CO_2 capture. Several experimental studies with absorbents that exhibit phase-change features during the absorption or desorption of CO_2 have shown promise to reduce solvent regeneration energy. Such phase change technology removes CO_2 from power plant flue gases using a solvent that, when it reacts with CO_2, rapidly forms two distinct phases: a CO_2 -rich phase and a CO_2 -lean phase. Only the CO_2 -rich phase will then undergo regeneration. By regenerating only the CO_2 -rich phase, significantly less energy may be needed for the whole process.

The current phase change solvents, which often require organic solvents, may form liquid–liquid phases or liquid–solid phases upon CO_2 absorption. Phase change solvents that form two liquid phases after CO_2 absorption include the mixed amine systems and DMXTM process which can be separated based on differences in density. Certain blends of2-(Diethylamino) ethanol/3-(Methylamino)propylamine couldform two liquid phases after CO_2 absorption and the cyclic loading could be significantly higher than that of monoethnolamine (MEA). Phase change solvents that form a liquid phase and a solid phase (due to precipitation during CO_2 absorption) can be found in systems such as alkanolamine/ionic liquids, chilled ammonia, and triethylenetetramine/ethanol solutions.

Independent of the precipitate type, the formation of a solid reaction product during absorption and its removal from the solution phase by precipitation may shift the reaction equilibrium toward the production of more products (carbamate or bicarbonate). Amino acids are of great interest as potential solvents and sorbents for CO_2 capture because they are environmentally friendly, are naturally present in the environment, and have low volatility (due to their ionic nature). In this study, we report, for the first time, the development of phase change solvents based on amino acid salts to convert CO_2 emissions into regenerablecarbamateand bicarbonate, and we identified a unique phase change amino acid salt which reacted with CO_2 and underwent a self-concentrating process to form a CO_2 -lean phase and a CO_2 -rich phase. The CO_2 -lean phase could be reused and the CO_2 -rich phase could be regenerated.

Schematic Experimental set up :



Experimental Results :

Effect on CO_2 Reduction (USING SINGLE ADSORBENT)

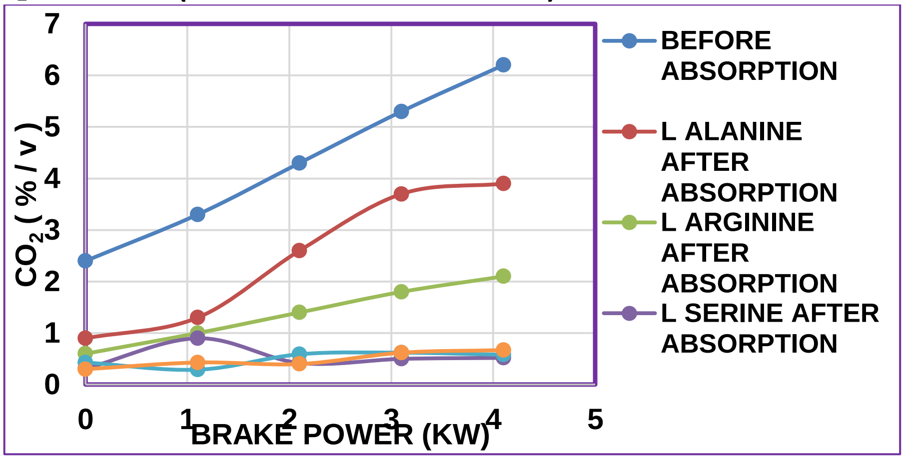


Figure shows the variation of Carbon dioxide emission with brake power for various Amino acids

The above figure shows variation of CO_2 emission of L Alanine, L Arginine, L Serine, L Lysine and L Aspartic acid i.e., Amino acid. Before absorption of amino acids the carbon dioxide emission is very high as compare to the after absorption. Before absorption at low load condition the CO_2 emission is 2.4 % per volume, Which is 60% of CO_2 emission reduced by the various absorbents. The L Serine, L Lysine and L Aspartic acid are very sensitive absorbents it is absorbs 80% of CO_2 emissions from the exhaust at low load conditions due to the amino acids are base material it is absorbs the acidic gases.

At high load condition very high amount of CO_2 emission is coming from the engine due to high temperature and more oxygen in the combustion chamber which results in complete combustion. At high load condition more amount of CO_2 emission are reduced by the L Serine, L Lysine and L Aspartic acid as compare to the L Alanine and L Arginine. The L Alanine absorbent is 48% of CO_2 emission are absorbed due to very less molecular weight and less boiling temperature as compare to the other Amino acid absorbent, By the L arginine absorbent CO_2 emission is further reduced which is show in this figure. The L serine is very good absorbent because of at high load condition 90% of CO_2 emission are reduced due to the higher molecular weight. At all load condition the L Serine, L Lysine monohydrochloride and L Aspartic acid absorbents are more amount of Carbon dioxide emission is reduced.

CARBON DIOXIDE EMISSION (USING ADSORBENT MIXTURES)

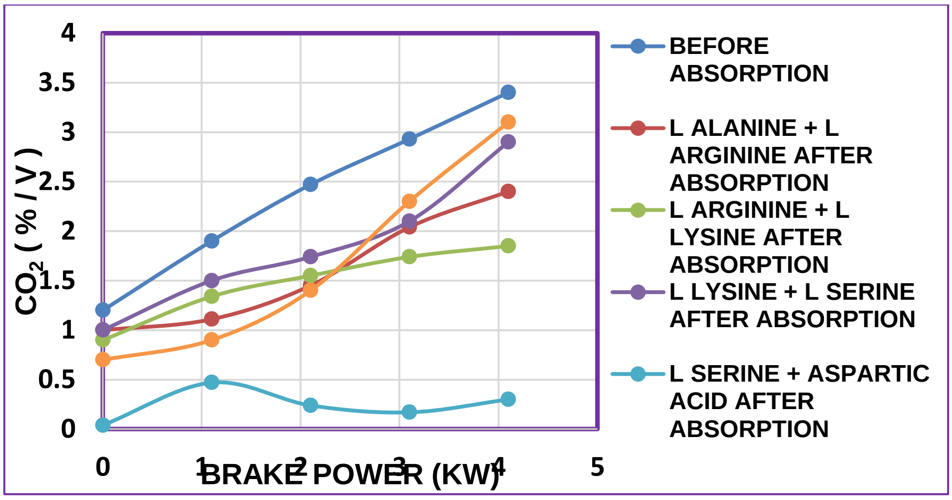


Figure shows the variation of Carbon dioxide emission with brake power for various Amino acid combinations.

The above figure shows variation of CO_2 emission of various combination of amino acids like L Alanine + L Arginine, L Arginine + L Serine, L Serine + L Lysine, L Lysine + L Aspartic acid and L Aspartic acid + L Alanine. Before absorption of amino acids the carbon dioxide emission is very high as compare to the after absorption. Before absorption at low load condition the CO_2 emission is 1.2 % per volume, Which is 30 % of CO_2 emission reduced by the various absorbents. The L Serine + L Aspartic acid is very sensitive absorbents it is absorbs 90% of CO_2 emissions from the exhaust at low load conditions due to the amino acids are basic material it is absorbs the acidic gases and also L Serine + L Aspartic acid having higher molecular weight as compare to the other combination.

At high load condition very high amount of CO_2 emission is coming from the engine due to high temperature and more oxygen in the combustion chamber which results in complete combustion. At high load condition more amount of CO_2 emission are reduced by the L Serine + L Aspartic acid as compare to the L Alanine + L Arginine, L Arginine + L Serine, L Serine + L Lysine, and L Aspartic acid + L Alanine. The L Alanine + L Aspartic acid absorbent is 90% of CO_2 emission are absorbed due to very high molecular weight and boiling temperature as compare to the other Amino acid absorbent. By the L Aspartic acid + L Alanine 0.5 percentage per volume of carbon dioxide emission are reduced from before absorption. Further 25% of CO_2 emission is reduced by the L Alanine + L Arginine and L Lysine + L serine combination. The L Aspartic acid + L Alanine absorbent is more amount of CO_2 emission are reduced at low load condition but at high load condition very less amount of CO_2 emission only reduced. So that which is very effective at high load condition. From the results the L Aspartic acid + L Alanine is best combination as compare to the other combinations.

CONCLUSION

In this research work various amino acids L Alanine, L Arginine, L Serine, L Lysine and L Aspartic acid were used to capture the carbon dioxide emission from the single cylinder four stroke diesel engine. Some of the important inference is furnished below after the investigation of the experimental results.

The L Aspartic acid is very good absorbent because at high load condition 90% of CO_2 emission are reduced due to the higher molecular weight. At low load conditions the 2.45 percentage by volume of CO_2 emission reduced and At high load conditions 5.88 percentage by volume of CO_2 emission reduced.

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Capture of CO_2 from biogas and production of industry worthy CO_2 and compressed biomethane.

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Extended Summary

Carbon dioxide (CO_2), a significant greenhouse gas, is one of the most important gases of Earth's atmosphere. Burning of carbon-based fossil fuels and land use changes have rapidly increased its concentration in the atmosphere, leading to global warming. Admitting that being harsh to the atmosphere, CO_2 is indispensable requirement in various industrial applications. Natural degradation of biomass leads to production of biogas, where as an anaerobic digestion of waste biomass can produce better quality biogas, which can substitute fossil fuels.

At IIT Delhi we are vehemently working on development of technologies for better utilization of biogas in various industrial applications. A water scrubbing based technology is developed for production of BioCH4 with above 95% CH4 content from Biogas. BioCH4 is used for running a CNG vehicle as a substitute of natural gas. IIT-D has received a patent for this system in 2017. Based on our thorough performance analysis and comparisons of the emissions of vehicle fuelled with BioCH4, Bureau of Indian Standards formulated "Indian Biomethane Standards - 16087" for application of biomethane in stationary and automotive engines.We have also developed a system for recovery of BioCO_2 with 99.9% purity from biogas upgradation plant as a green byproduct. A patent has been applied for the same. We are developing technologies for efficient utilization of BioCO_2 an excellent alternative to synthetic CO_2 and chemicals. For example as a fumigant for pest control and as a refrigerant. BioCO_2 is absolutely safe, cost effective, non-hazardous and does not produce harmful residues or fumes in comparison to chemicals which are highly toxic for humans, spur environmental side effects like thinning of ozone layer and contaminate soil and water ways.

Apart from fossil fuels, renewable gas like biogas which is primarily a gas mixture of methane (CH_4 (55%–65%)) andCO2 (CO_2 (35%–45%)) can be a competent source ofCO_2. CO_2 production and recovery can be combined with bio-energy conversion processes like biogas upgradation as well. One of the interesting features of biogas upgradation process is that the separation of CO_2 is already an intrinsic step. Consequently, the incremental costs of additional CO_2 production or capturing would not be incurred. Recently Zhang et al. 2014 estimated that the energy consumption of CO_2 separation from flue gas is the highest and that from biogas upgradation process is the lowest.

CO_2 in raw biogas not only lowers the energy content per unit mass/volume but also limits its compressibility and utility to applications like heat and electricity production. The bulk separation of CO_2 from biogas to obtain biomethane with enhanced energy content and to overcome storage and transportation problems has driven the development of CO_2 separation technologies. Upgraded biogas (biomethane) has properties similar to fossil based natural gas and can substitute it in much wider and higher value applications. Biomethane with CH_4 content above 90% can be either injected in the natural gas grid or can be directly used as vehicle fuel. Different types of upgrading technologies which separate $CO_2$from biogas include water scrubbing, pressure swing absorption, chemical and physical absorption, membrane and cryogenic separation.

Among all the commercially available technologies for separation of CO_2 from biogas, water scrubbing is the simplest, environmentally benign, cost effective and widely implemented method for biogas upgrading. It has widespread commercial applicability for biogas upgradation with nearly 41% market share among more than 500 bio-methane plants worldwide. This method takes the advantage of higher water solubility of CO_2 compared to CH_4. During the process of biogas upgradation using water scrubbing technology, raw biogas is split in two major gas streams, CH4 rich biomethane stream and CO_2 rich off gas stream. The biomethane stream is used as a substitute of natural gas. The second CO_2 rich off gas stream is usually emitted into the atmosphere as a waste product, causing a detrimental effect to the environment. Instead of emitting the CO_2, it can be used as a valuable green product, BioCO_2, which can be sold as an additional commercial product by the biogas producer. BioCO_2 could be utilized for chemical production (calcium carbonate, potassium carbonate, etc.), algae cultivation, and welding purposes. BioCO_2 can be used to produce dry-ice for refrigeration of dairy products like milk, curd, cheese etc. in rural areas. It can be also used to enhance crop production in greenhouses. BioCO_2 is an excellent alternative to synthetic CO_2 and chemicals being used as fumigants for pest control. It is absolutely safe, cost effective, non-hazardous and does not produce harmful residues in grain storages in comparison to chemicals used for long-term storage of grains like methyl bromide and phosphine. Although chemical fumigants like methyl bromide and phosphine are very effective in pest control but these are highly toxic for humans, spur environmental side effects like thinning of ozone layer and contaminate soil and water ways. BioCO_2 produced from biogas is of biogenic origin. Its recovery from biogas and utilization in different applications makes the complete process carbon negative (CO_2 fixed during photosynthesis in biomass – biogas production – biogas upgradation – bioCO_2 recovery - utilization).

An Assessment of CO_2 Reduction Potential from Carbon capture vs Renewable Energy Targets in India

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Extended Summary

Introduction

> "The potential market for products made from carbon dioxide could be as much as $1.1 trillion by 2030"
>
> *--- I. Dainanieh, Global CO_2 Initiative*

Energy is the backbone of the economy of a nation. Share of fossil fuels in world energy continue to dominate giving rise to CO_2 emissions from anthropogenic, yet developmental activities. According to Shell, 80% of world energy was derived from fossil fuel in 2017. CO_2 sequestration strategies are suggested as a clear path in mitigating global warning and climate change, by neutralizing excess CO_2 in the atmosphere by chemical, physical or biological processes. Carbon capture and utilization (CCU) has the potential to strengthen business models for industrial emissions reduction according to a study in European Union.

Pathways for CO_2 mitigation in the atmosphere include; (i) Increasing use of renewable energy; (ii) Improving energy efficiency in supply and demand sides; (iii) Use of low carbon fuel from coal to oil to Natural gas to Hydrogen; (iv) CO_2 capture, storage and utilization. Since its inception Carbon Capture and Storage has not been fully accepted, through R & D has been significant. It is seen as a 'Band Aid' approach to emission already in the atmosphere and as a means to preserve fossil fuel based infrastructure for growth.

International Policy Scenario

In 2003 Department of Energy, USA launched Carbon Sequestration Leadership Forum (CSLF), a Ministerial level multi-country science diplomacy initiative to promote collaborative R&D in CCS. India became a founder member to CSLF. The CSLF recognized collaborative projects aimed at mid-range of research activities in CCS technology. United Nations Framework Convention on Climate Change (UNFCCC) in its 21st meeting of Conference of Parties evoked Paris Agreement on Climate Change and assigned targets to limit rise in global temperature caused by anthropogenic emissions to 2^{o}C, with on ambitious target of reaching 1.5^{o}C. The Agreement has been ratified on 4th November 2016 and 150 signatory Countries are committed to take CO_2 limitation actions under their Nationally Determined Contributions. Internationally carbon utilization research investments are being made by the governments. A Carbon XPrize of $20 million has been announced for breakthrough innovations in carbon utilization.

Mission Innovation

Another important international milestone during COP-21 in Paris was launch of Mission Innovation (MI) to invigorate and accelerate public and private global clean energy Innovation towards clean energy security. There are 23 Countries participating in the Mission Innovation one of them is EU. It is pledged to double Government funded clean energy research and development old 5 years, starting from 2015 as base year, so as to achieve international engagement on clean energy R & D for deployment on a very large commercial scale. 'Carbon Capture Innovation challenge' is one of the shortlisted and agreed seven innovation challenges. India is a partner country to MI. A renewed thrust to R&D in Carbon Capture and Utilization is expected under Mission Innovation (MI).

India's Energy Policy Scene

India as a coal dominate economy, has adopted a policy of intensifying R & D in carbon sequestration, but has not promoted large scale demonstration due to both technology and economic considerations, seeing the complexity of processes involved in carbon capture, carbon transport, storage & injection as well as carbon utilization. According to Central Electricity Authority the Indian states have divided into four zones i.e., East, West, North and South with the currently operated and future installation of the power plants. Different plants use different grades of coal. The CO_2 emissions are estimated based on the carbon content as obtained from the elemental analysis of the coal and the excess air used at the power plants. The growth profile of CO_2 emissions from thermal power generation during 2001-2010 is depicted in Fig. 1.

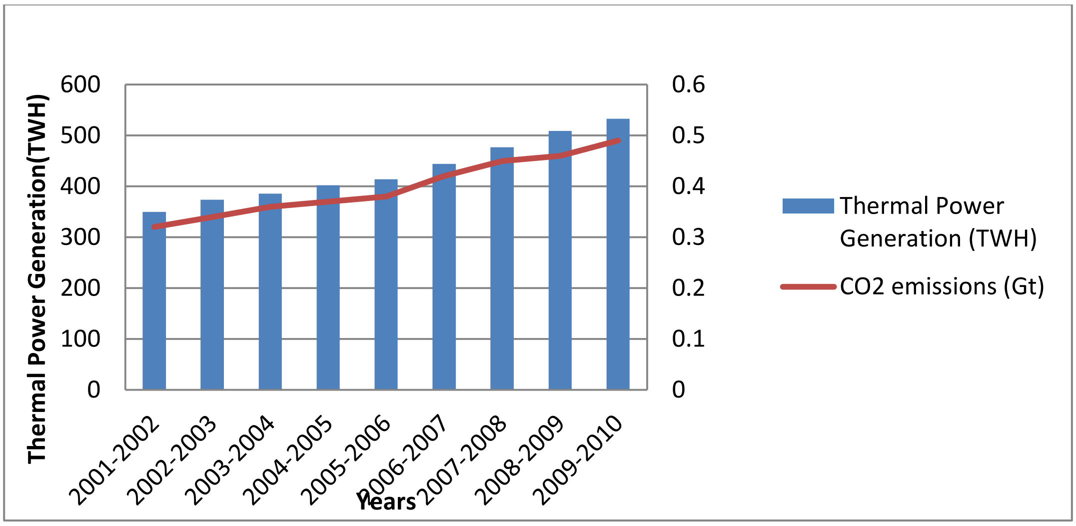

Fig. 1 CO_2 Emissions from thermal power generation (data source https://www3.epa.gov/ttnchie1/conference/ei20/session5/mmittal.pdf

In the total CO_2 emissions, approximately 20-25% emissions are from industrial sources, mainly cement production plants (~7% of the total emission), oil refineries (`~6%) and iron and steel industry (~ 5%).

Status of CCSU in India

In 2007 Department of Science and Technology intensified R&D support and founded 'Indian CO_2 Sequestration and Applied Research Network' in order to coordinate CCS research and development activities within the country (Goel, 2009). The National Action Plan on Climate Change (NAPCC) announced in 2008 comprised of eight mission areas prioritizing both climate change mitigation and adaptation. In the same year the Government emphasized to make CCS technology as a pre -requisite in India, only after technology maturity is achieved as well as cost reduction and safety issues are resolved (Viebhan et al, 2012). A ninth mission was also proposed on clean coal technology and research for development of advanced ultra-supercritical technology was intensified in 2012.

Emerging out of recommendations of a study conducted by the Department of Science and Technology, Government of India, Bharat Heavy Electrical Ltd. (BHEL) in 2009 established Centre for Excellence in Coal Research. A roadmap for Oxyfuel combustion research was elaborated. The BHEL collaborated with TREC-STEP (Tiruchi Regional Engineering College – Science and Technology Entrepreneurs Park) to implement a set of initiatives in CCT and CCS, as part of a three year EU funded project TREC-STEP. It organized two EU-funded training programmes on 'Introduction to CCS and CCT' in December 2011, and 'Skill Leverage Programme on CCT-CCS Technologies' in January 2012.

The CO_2 capture and Utilization R&D took shape in CSIR laboratories and stakeholder public sector industry for development of new absorbents and adsorbent materials, and feasibility of storage processes as EOR and ECBM. Several studies have been conducted for assessment of CO_2 storage potential in India and it was reported from a study conducted at Central Fuel Research Institute, Dhanbad that storage potential exists mostly in peninsular India (Fig. 2). From academic sector large number of universities took part in research projects. The Indian Institute of Petroleum (IIP) Dehradun has been working on developing novel amine based adsorbents, and pressure swing absorption for post-combustion CO_2 capture. It collaborated with Norway on Metal Organic Frameworks. Under the Agreement of Cooperation in Science & Technology concluded between Government of India and the Government of Norway, the DST and the Research Council of Norway (RCN) began a programme for joint funding of Indian-Norwegian joint research projects in climate research, including carbon capture and storage.

A large number of groups in academic sector have taken initiatives in R&D. Energy industry in India has invested not only in research, but also targeting business models in carbon management through carbon capture and utilization.

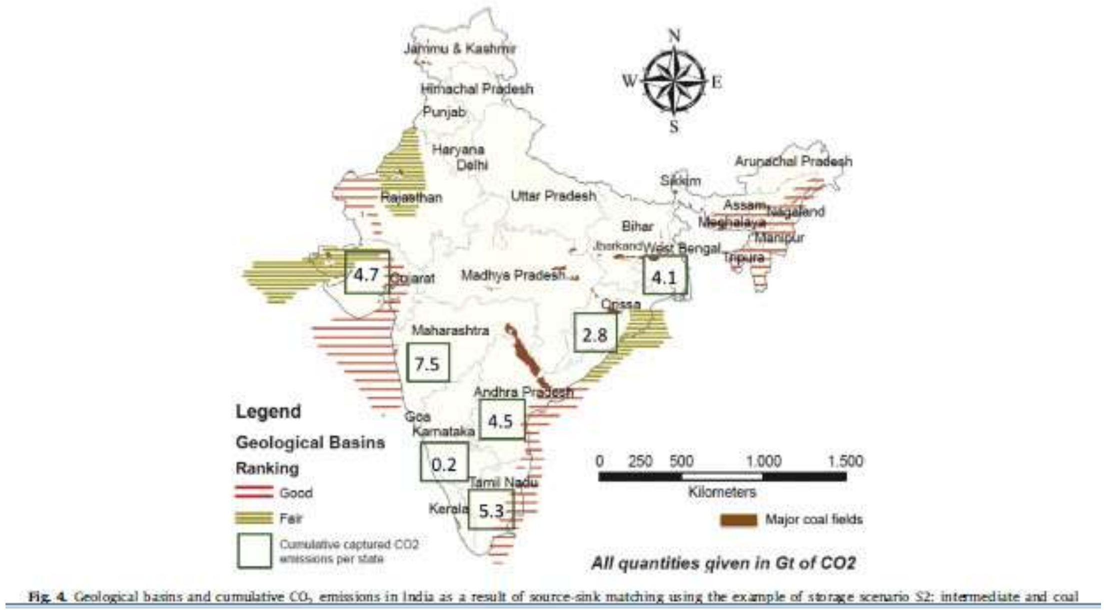

Fig. 2 Locations of geological basins ranking for CO_2 storage (

India's Policy Plan in Renewable Energy

In India the new targets for renewable energy (RE) are to achieve 175 GW of installed capacity by 2022. In this the target is to install 100 GW of solar energy capacity, 40 GW from wind energy and remaining from Biofuels, Geothermal and Waste utilization etc. Of the Solar; 40 GW would be the share of grid connected solar PV rooftop. Projected growth of renewable energy is enthusiastic as well as challenging. In response to RE Plan the status of solar parks across the country are indicated in Fig. 3. Total capacity addition from these parks is approximately 26,500 MW.

Adoption of renewable energy 100% by the year 2051 can be seen as a strategy to mitigate CO_2 emissions to bring down projected CO_2 emissions from 11.2 Gt to 0.40 Gt from energy systems (TERI, 2014). It was pointed out that whole range of energy transformations would be needed in growth sectors of economy to achieve these targets. It concluded that international cooperation and accelerated technological advancement of technologies under R&D stage can only achieve this.

Fig. 3 Solar Parks Locations across India

Conclusions

In many countries rapid innovations are taking place in carbon capture and utilization technologies aimed at cost reduction by energy saving and materials savings. India is on a path of accelerated renewable energy growth in installed capacity. However a clear policy strategy on coal use which is currently a dominant source of energy and is being used almost 100% in industry is lacking. Adoption of renewable energy for power and industry sectors as well as for energy supply in CCU operations would continue to be challenging for both policy makers and industry. In this paper a preliminary assessment of CO_2 reduction scenario in both coal based and renewable energy scenario would be presented.

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CO_2 Sequestration through Phytoremediation Techniques with Special Emphasis on Urban Bio

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Extended Summary

Preamble

Anthropogenic activities particularly the burning of fossil fuels such as coal, oil, and gas, have caused a rapid increase in the concentration of carbon di oxide in the atmosphere. Technically and economically feasible strategies are needed to mitigate the consequences of increased atmospheric CO_2. We focus on an emerging concept "Phytoremediation" the use of plants to assimilate more CO_2 towards mitigating climate change impact. The term CO_2 sequestration is the process of removing carbon from the atmosphere and depositing it in reservoirs. Plants can play important roles as CO_2 sinks. By capturing atmospheric CO_2 through photosynthesis plants store large amounts of CO_2 in above- and below ground biomass. This study emphasis on developing green belt model in urban forestry.

Carbon dioxide Sequestration

Carbon dioxide circulates through, and accumulates in, the atmosphere, the oceans, and the land; these CO_2 pools are a natural part of the carbon cycle. Unfortunately, the natural land and ocean pools are unable to absorb all of the anthropogenic CO_2 currently being emitted; Carbon dioxide capture and storage (CCS) is a process consisting of the separation of CO_2 from industrial and energy-related sources, transport to a storage location and long-term isolation from the atmosphere. By improved management practices, the amount of carbon stored in soils and plants can be increased. Storing carbon in this way is referred to as terrestrial sequestration. The terrestrial sequestration has the advantage that it can be quickly instituted and restores degraded soils, enhances biomass production, purifies surface and ground waters.

Phytoremediation

Phytoremediation is a method to use of plants to assimilate more CO_2 towards mitigating climate change impact. It introduces plants into an environment and allows them to assimilate the contaminants into their roots and leaves. Such a process has been used to clean up greenhouse gases, heavy metals, pesticides, xenobiotics, organic compounds, toxic aromatic pollutants and acid mine drainage. By growing plants over a number of years, the aim is to either remove the pollutant from the contaminated matrix or to alter the chemical and physical nature of the contaminant within the soil to that it no longer presents a risk to human health and the environment. With this approach we can develop a suitable site specific greenbelt with variety of plants including economical benefits. So it is a multipurpose technique available in nature could be designed with scientific findings would be appropriate and benefit to the environment.

Green belt Model

Plants are identified and grown around the industrial area in the form of Greenbelt to reduce the air pollution. It acts as a wind breaker to minimize the transportation of air pollutants. The plants involved in more CO_2 assimilation is identified by various characteristics such as tree height, diameter at breast height, stomatal density, conductance, total chlorophyll, carotenoid, ascorbic acid, relative water content, pH of leaf, leaf structure, leaf size and rubisco content. Also, the rate of CO_2 assimilation in plants is measured by portable photosynthetic gas exchange system. The identified plants to be suggested as wind breakers show monopodial branching pattern and should have dense foliage with thick cuticle and linear leaves. The plants with above said characters will reduce the velocity of wind and allow the dust laden wind to pass through their dense foliage. Moreover, the stomatal apertures should be more in number and they should be in lower epidermis of leaves. Otherwise, dust particles will clog the stomatal apertures. With these, trees can trap the dust particles from the wind to reduce velocity for which they should have compound leaves with thick epidermis and waxy cuticle. *Polyalthialongifolia*Sonn., *Casuarineequisetifolia*, *Bambusaarundinacea* and *Eucalyptus* hybrid species were added as wind breakers, *Bougunvilleaspectabillis* species can be grown within the greenbelt to maintain the soil moisture and air quality. Among those species where involved for analysis *Mangiferaindica* is the most tolerant to grow around the thermal power station followed by *Mimusopselengi*, *Ficusbenghalensis*, *AnacardiumOccidentale*, *Manilkarazapota*, *Ficusreligiosa* and *Artocarpusheterophyllus*is assessed to be very good performer.

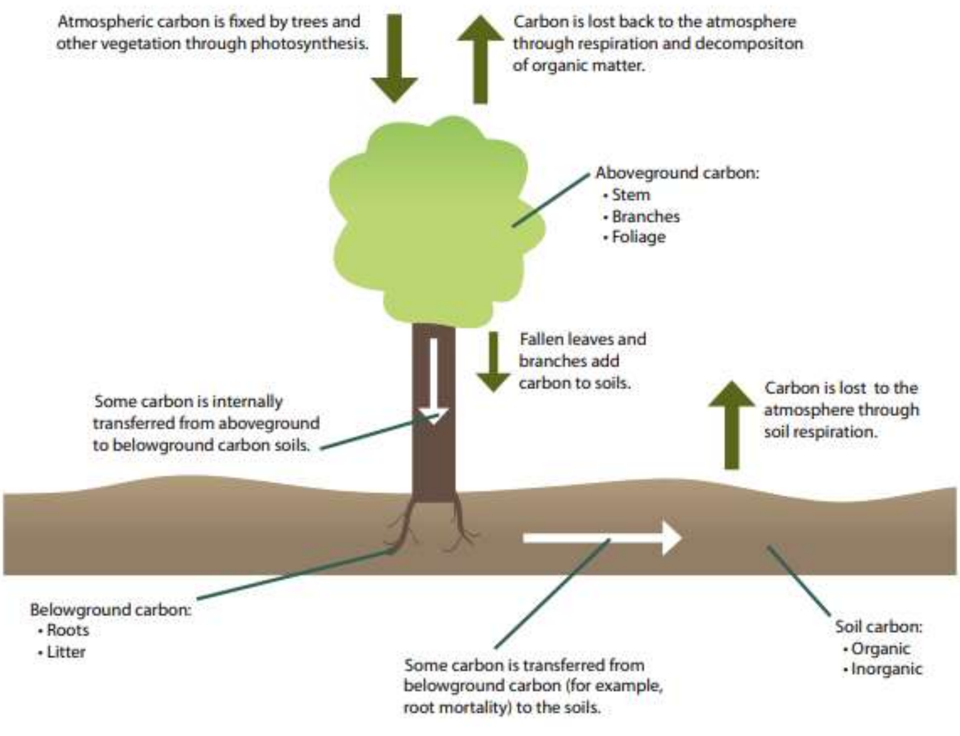
Urban forestry

The ‘Urban forest’- the collection of trees, shrubs and green space that grow within and around cities and towns. Green belt model can be implemented in urban forestry. CO_2 emission by vehicles, urbanization and other sources can be controlled by planting CO_2 assimilating trees suggested in green belt model. The benefits of developing this model will improve micro climate of the urban area and increasing urban biodiversity. It plays a vital role in making livable places by i) improving local food and nutrition security, ii) providing cool and clean air iii) filtering urban pollutants and fine particulates, iv) regulating water flow and play a key role in preventing floods and reducing the risk of natural disasters, v) helping to conserve energy.

Role of Agriculture in CO_2 Sequestration

All crops absorb CO_2 for the photosynthesis. The goal of agricultural carbon removal is to use the crop and its relation to the carbon cycle to permanently sequester carbon within the soil. This is done by selecting farming methods that return biomass to the soil and enhance the conditions in which the carbon within the plants will be reduced to its elemental nature and stored in a stable state. Methods for accomplishing this include:

- Use cover crops such as grasses and weeds as temporary cover between planting seasons.
- Concentrate livestock in small paddocks for days at a time so they graze lightly but evenly. This encourages roots to grow deeper into the soil. Stock also till the soil with their hooves, grinding old grass and manures into the soil.
- Cover bare paddocks with hay or dead vegetation. This protects soil from the sun and allows the soil to hold more water and be more attractive to carbon-capturing microbes.
- Restore degraded land, which slows carbon release while returning the land to agriculture or other use.



Summary

All crops absorb CO_2 during growth and release it after harvest. The carbon dioxide sequestration in trees is achieved by several ways such as mixed planted for exotic and native trees, fast-growing hardy species for waste land afforestation/reforestation, softwood species for agri-silvicultural practice, native trees, gardening, parks etc. In our case study *Mangiferaindica, Mimusopselengi* has been shown to be good performer in CO_2 assimilation. Hence, we suggest that the plants can be identified with CO_2 assimilating characters and grown around the urban area in the form of Greenbelt. The benefits of developing this model will improve micro climate of the urban area and increasing urban biodiversity by carbon sequestration.

Case study-1: The amount of carbon dioxide is stored in trees is estimated by two ways destruction method and non-destruction method. In non-destruction method carbon storage is estimated by allometric equations that use several parameters to calculate tree biomass: diameter at breast height, tree height, tree condition, wood density and moisture content. The amount of carbon dioxide storage is estimated among ten species which are having the above said characteristics. *Tamarindusindica* followed by *Peltophorumafricanum* and *Peltophorumpterocarpum* has more capacity to sequestrate more CO_2. The rate of carbon dioxide sequestration is different between trees based on several factors such as age of tree, soil nutrition, speed of growth, floral diversity composition, type of soil, type of forest, forest elevation, size of tree and root, leaf abscission, climatic factor, etc. The carbon dioxide sequestration in trees is achieved by several ways such as mixed planted for exotic and native trees, fast-growing hardy species for waste land afforestation/reforestation, softwood species for agri-silvicultural practice, native trees, gardening, etc.

Case study-2: Biosolid waste material release of the greenhouse gases such as carbon dioxide, methane, nitrous oxide, etc. The direct emission of gases to the environment causes global warming. Bio-solid waste can produce valuable by-products such as biogas, enzymes and organic acid. Biosolid is a renewable energy and it can be used as substrate for the production of bio-energy, enzymes and organic acids. The research work was carried out in laboratory scale using coffee pulp waste disposed in the road side of nearby coffee estates were used as substrate to generate methane(biogas). Further, it is used for the production of microbial metabolites such as α-amylase and endoglucanase by using *Bacillus amyloliquefaciens* and citric acid by*Aspergillusniger*under solid state fermentation process. The conversion of organic solid waste to energy concept is more useful technique to mitigate climate change impact by reducing the release of GHG into the atmosphere.

Lowering Carbon Footprint through CO_2 Capture and Sequestration: A Refinery Perspective

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Extended Summary

Rising levels of CO_2 in the atmosphere due to burning of fossil fuel have been recognized to be the main contributor of global warming and associated climate change phenomenon. Fossil fuel combustion for power generation is the major source of increased CO_2 levels in the atmosphere. Beside power plants for electricity generation, refineries are also contributing significantly towards CO_2 emission (1,2,3).

It has also been reported that around 4% of CO_2 emissions(4) may be credited to refineries worldwide.India's refining capacity from 2010 to 2017 has grown by 68% indicating proportionally increased CO_2 emission.In a refinery,CO_2 may be emitted from different sources which include furnaces,boilers, catalyst regeneration, and hydrogen manufacturing and its concentration in the off gases may vary from source to source. For instance, around 10–20 vol.% CO_2 is present in catalyst regeneration in fluid catalytic cracking (FCC) (2), and 50–55 vol.% for hydrogen purification plants(5).
Among the different technologies available to capture CO_2, adsorption processes using Pressure or Vacuum Swing Adsorption (PSA/VSA) are attracting interest as energy requirements are lower (6).

Although several adsorbent materials like zeolites and activated carbons have been investigated for CO_2 recovery by PSA/VSA. The general consensus appears to be that Zeolite 13X materials performs better than activated carbons or silica gels (7,8). However, as CO_2 isotherms on zeolites are nonlinear, power requirement during regeneration can be high and there is for this reason a large scope for developing new adsorbents which will show better selectivity and regenerability.

Metal Organic Frameworks (MOF) is a new class of adsorbents attracting interest for selective CO_2 separation (9,10). These are materials in which metal ions or clusters are connected via organic linkers to form highly porous network structures. Several MOF's have been proposed as adsorbents for CO_2 recovery. These include MOF-47 [Vanadium (IV) benzene 1,4 dicarboxylate], MIL-53 [Chromium (III) benzene 1,4 dicarboxylate] and CuBTC [Copper(II) benzene 1,3,5 tri carboxylate]. However, the several studies that have been reported so far on CO_2 adsorption on MOF's have been limited mostly to equilibrium isotherm and diffusion measurements with pure components(11,12). The case study reported includes an experimental study on the separation of CO_2 from a dry as well as moist synthetic feed mixtures using formulated MOF adsorbentin a vacuum swing adsorber operating with a heavy reflux or rinse cycle typically used for recovery of the strong adsorptive (in this case, CO_2) from gas mixtures. The results from single column testing show that the presence of moist in the flue gas reduces the CO_2 working capacity somewhat (around 15%), however, over multiple cycle, an apparent steady state performance is reached in which the CO_2 working capacity still is significant and stable over more than 50 cycles.

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An attempt in mitigating global warming through carbonic anhydrase-mediated carbon sequestration

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Extended Summary

In the early 18th century, industrial revolution took the world by storm. This led to large scale manufacture, which at that time proved to be a major economic boost world over. In the last 300 years, there has been a marked transformation in human life. Due to improved farming practices, food production increased. This along with technological advances in health, communication and transport sectors paved the way towards modern age for human civilization. This modernization led to a heavy toll on 'mother nature'. The concentrations of greenhouse gases are increasing day by day mainly due to anthropogenic activities, of them about two-thirds is contributed by fossil fuels. The burning of fossil fuels resultsin the emission of large quantities of flue gas that contains ~ 71% N_2, 14% CO_2, 1-2% hydrocarbons, carbon monoxide, NO_x, and minor amounts of SO_x. According to IPCC, among all the greenhouse gases, CO_2 isemitted most (65% from fossil fuels and 11% from forestry). Other gases such as methane (16%), nitrous oxide (6%) and fluorinated gases (2%) are emitted in smaller amounts by anthropogenic activities.Cumulative carbon emissions from different sectors have increased by about 40% since 1970s. The concentrations of hazardous gases such as NOx, SOx and methane are well beyond their threshold in many cities all over the world, thus, the Air Quality Index (AQI) is declining. CO_2 levels in the atmosphere have surged past the threshold of 400 ppm and it may not climb down for generations. This 400 ppm benchmark was broken first time in the recorded history 2016. According to World Meteorological Organization (WMO), 2016 would be the first full year to exceed the mark. As per the latest measurement in April 2017, the concentration of CO_2 at present is 406.17ppm. Some of the isolated places (Arctic regions) have already breached this mark in the past few years as recorded in Mouna Loa Observatory (Hawaii) in 2013. Emission Database for Global Atmospheric Research stated that global emission of CO_2 has increased by 48% in the last two decades.The increase in GHG emissions has led to increase in earth's surface temperature by about 2 ºC from pre-industrial times. These conditions have also led to widespread natural calamities and affected the environment adversely. An increase in warm temperature extremes and decrease in cold temperature extremes have been noted in the past few years. This has also led to an impact on the precipitation patterns around the world and disturbed the water cycle. Agricultural production has been affected due to adverse climatic changes. There has been a reduction in crop yields leading to increase in food prices, food shortage and insecurity. These climatic hazards are affecting the lives of people round the world particularly those who are living below the poverty line. Many freshwater, marine and terrestrial species are already on the verge of extinction. A change in the distribution and interaction pattern has been observed in many freshwater and marine phytoplanktons. According to IPCC, the period from 1983 – 2012 were the warmest years.

Air pollution causes various respiratory and cardiac diseases. Tiny particles produced by vehicular engines and industry worsen heart and brain related disorders and increase the risk of stroke. Global warming is taking the earth towards peril and it is essential to tackle this catastrophe for our survival. It is next to impossible for developing and under developed nations to control large scale CO_2 emissions. Nevertheless global warming has to be mitigated. Scientific and global consensus on global warming and climate change has brought the world powers together in order to hunt for new technologies for mitigating the global warming.

The year 2015 ushered in an era of optimism and action with Paris climate change agreement. It also marks a new era of climate change reality with record levels of high greenhouse gases. In order to tackle increasing carbon emissions, carbon trading and taxation have been implemented by various countries. The progress made in developing carbon capture technologies has been reviewed from time to time. IPCC has also published a wholesome review on different CCS technologies providing a precious input for policy makers and researchers in developing schemes for reducing GHG emissions. Some reviews have also outlined various holistic approaches for carbon capture and also described methods for mitigating global warming. Biomimetic approach has been suggested for mitigation of global warming with a special focus on utilising nature's own catalyst, carbonic anhydrase (CA), as the biomimetic carbon sequestering agent.

CO_2 emissions are captured and separated from flue gas, transported via huge pipelines and stored permanently deep underground or reutilized for various applications. Various approaches have been designed for efficient CO_2 capture. These approaches are basically divided into three phases:

- Pre-combustion CO_2 capture
- Post-combustion CO_2 capture
- Oxyfuel combustion

Although, Carbon Capture and Storage (CCS) approaches are quite efficient, they still have certain implications. First of all the cost of the overall process is quite high. It has been estimated that CCS will lead to a rise in power tariff by about 10% in US alone. It also requires a large amount of energy as it consumes 25 percent of the power plant's output capacity.

The process of carbon mineralization occurs in nature which is responsible for the presence of huge amounts of limestone on the surface of Earth. This is called silicate weathering. It traps the atmospheric carbon by reacting with large limestone rocks such as wollastonite ($CaSiO_3$), serpentine ($Mg_3Si_2O_5(OH)_4$) and olivine (Mg_2SiO_4). This process occurs in both salt and fresh waters as CO_2 gets dissolved in water easily and there exists equilibrium between CO_2, HCO_3^-, and CO_3^{2-}. The set of reactions involved in CO_2 mineralization is outlined below:

Gaseous CO_2 dissolves quickly in water and produces a loosely hydrated aqueous form (1).

$CO_2 (g) \rightarrow CO_2 (aq)$ (1)

Then carbonic acid is formed when aqueous CO_2 reacts with water (2).

$CO_2 (aq) + OH^- \rightarrow H_2CO_3$ (2)

In the 2nd step, carbonic acid breaks down into carbonate and bicarbonate ions [(3), (4)]

$H_2CO_3 \rightarrow HCO_3^- + H^+$ (3)

$HCO_3^- + OH^- \rightarrow CO_3^{2-} + H_2O$ (4)

The presence of metal ions such as Ca^{2+}, Mg^{2+} and F^{e2+} drives the precipitation of carbonate into mineral carbonates as depicted below (5):

$CO_3^{2-} + Ca^{2+} \rightarrow CaCO_3\downarrow$ (calcite)

$CO_3^{2-} + Mg^{2+} \rightarrow MgCO_3\downarrow$ (magnesite)

$CO_3^{2-} + Ca^{2+} + Mg^{2+} \rightarrow CaMg(CO_3)_2\downarrow$ (dolomite)

$CO_3^{2-} + Fe^{2+} \rightarrow FeCO_3\downarrow$ (siderite)

This process of mineralization of atmospheric carbon is pH dependent. At pH below 8.0, reaction 2 becomes insignificant as OH^- ions are absent. Between pH 8.0 and 10.0, both the reactions (2 and 3) occur, and above pH 10, reaction 2 occurs mainly. Due to abundant supply of OH^- at alkaline pH, mainly HCO_3^- (bicarbonate) and CO_3^- form leading to $CaCO_3$ precipitation. Also at acidic pH, the solubility of carbonate increases. In order to increase carbonate precipitation, it is necessary to make the environment alkaline.

This technique has several advantages over other sequestration based approaches:

1. This process is an environmentally benign and one of the most effective techniques of carbon sequestration, and carbonates produced naturally via mineralization of CO_2 can remain stable for centuries. This process is free from complexities and many researchers have already outlined this process in minute details, hence, easily adaptable.
2. Raw materials for mineralization of CO_2 are in abundance. These minerals comprise a huge CO_2 reservoir having carbon equivalent to about 150,000 **x** 10 metric tons of CO_2. Metal oxides such as MgO and CaO are emitted from the industries as hazardous wastes in the form of fly ash. Mineral carbonation using such wastes will allow their re-utilization in sequestering CO_2. Fly ash was used for mineral carbonation in USA and concentration of CO_2 reduced from 13.0% to 9.6% and SO_2 concentration drastically decreased from 107.8 ppm to 15.1 ppm within 2 minutes.
3. Mineral carbonates formed after sequestration will also provide industrially valuable and useful byproducts such as cements, chemicals, fillers for paper making, white paints and

other construction materials. These mineral carbonates are also used in manufacturing calcium supplements, antacids and tableting the excipient for medical usage as well as remediation of waste feed stocks. Pure silica with a desirable particle size can be used as a material in the construction, plastics, electronics and glass industries.

4. The process is economically viable, since it eliminates the large scale and energy-intensive process of solvent capture of CO_2 from industrial wastes. This process does not require the transportation of supercritical CO_2 into deep underground.

Carbonic anhydrases catalyze CO_2 hydration and HCO_3^-dehydration, in almost all organisms. It (EC No. 4.2.1.1) is a zinc metalloenzyme which is used as a catalyst in living systems for the conversion of carbon dioxide to bicarbonates and vice-versa. It was the first zinc metalloenzyme to be discovered in living systems. Zinc ion complex facilitates carbon dioxide hydration activity. In most of the organisms, CAs are required for rapid processes, particularly transport processes. For example, it is required for the removal of CO_2 from lungs and for synthesis of eye secretions. CAs maintain optimum level of CO_2 and HCO_3^- in the body as they are utilized as substrate for many enzymatic reactions. It maintains acid – base balance in blood and helps in maintaining its physiological pH and also actively participates in ion transport and respiration.

We focused on producing thermo-alkali-stable CA by *B. halodurans* and testing its efficacy in carbon sequestration. The CA encoding gene from *B. halodurans* has been cloned in *Escherichia coli*and *Pichia pastoris* and expressed in active form and purified. The enzyme is active in the temperature and pH ranges of 50 - 60 °C and 6 - 11, respectively. rBhCA has been immobilized successfully on silanized magnetic iron oxide nanoparticles (rBhCA-si-MNPs), which could be used up to 22 cycles with 50 % retention of activity. rBhCA-si-MNPs exhibited significantly higher thermostability. Efficacy of BhCA in mineralization of CO_2 from flue gas has been confirmed by using exhaust fumes of petrol driven car as a source of CO_2. BhCA very efficiently mineralized CO_2 present in the fumes to calcium carbonate.The suitability of immobilized recombinant α-CA of *B. halodurans* for biomimetic carbon sequestration will be discussed.

Further reading

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Climate Resilient Agriculture: Adaptation of Rice Plants to Elevated CO_2 Grown in Free Air Carbondioxide Enrichment (FACE) Facility

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Extended Summary

The concentration of carbondioxide in the post-industrial era has tremendously risen due to high anthropogenic activities and is expected to reach upto 585 μmol mol^{-1} within next 50 years. The impact of elevated [CO_2] (585 μmol mol^{-1}) on chlorophyll a fluorescence, photosynthetic electron transport reactions, CO_2 assimilation rate of Rice was grown inside free air carbon dioxide enrichment (FACE) ring installed on the campus of Jawaharlal Nehru University, New Delhi, India. Rice plants were grown in ambient (400 μmol mol^{-1}) or elevated [CO_2] (585μmol mol^{-1}), in open field conditions. Chl *a* fluorescence measurement revealed that ambient- and elevated-CO_2 -grown plants had almost similar Fo in plants. The Fm was slightly higher (4.7%) in elevated-CO_2-grown rice. The maximum primary photochemical efficiency of PSII, which was measured as Fv/Fm, was slightly higher (3%) in rice grown in elevated CO_2. The electron transport rate (ETR) (μmol electrons m^{-2} s^{-1}) of PS II increased in response to photosynthetic active radiation. The light response curves demonstrate that ETR was higher by 16% in rice grown in elevated [CO_2]. The ETR in ambient- and elevated- CO_2 grown plants saturated at almost similar light intensity. The NPQ was reduced in plants grown in elevated [CO_2] at all light intensities measured. The increase in the ETR and Fv/Fm of leaves suggests that the PS II was modulated by high CO_2.

The diurnal variations of rate of photosynthesis in rice grown in ambient and elevated CO_2 were recorded from 8 AM to 6 PM. Carbon assimilation rate attained maximum value between 10 AM and 3 PM. In rice, the rate of photosynthesis (μmole CO_2 assimilation m^{-2} of leaf area s^{-1}) in high-CO_2-grown plants increased by 29%. Stomatal conductance (g_s) (mmol H_2O m^{-2} s^{-1}) decreased by 20% in high-CO_2- grown rice plants than grown in ambient CO_2. The decreased stomatal conductance resulted in reduced transpiration rate (mmol H_2O m^{-2} s^{-1}) (5%) in high CO_2. The water use efficiency (WUE) (μmol CO_2 m^{-2} s^{-1} / m mol H_2O m^{-2} s^{-1}) increased due to increased photosynthesis and decreased transpiration rates in high CO_2 by 35%. To understand the impact of elevated CO_2 on carbon assimilation and light utilization, the light response of net CO_2 fixation was monitored in attached leaves of rice plants by IRGA. The net photosynthesis rate of high-CO_2-grown plants at saturating light intensity was higher than that of ambient-CO_2-grown cultivars. High-CO_2-grown rice had higher photosynthesis rate than that of ambient-CO_2-grown plants. Photosynthesis rate of rice saturated 95% at ~1000 μmol photons m^{-2} s^{-1}. Our results reveal that not only photosynthesis rate but photosynthesizing surface, i.e., leaf area per plant and leaf area index increased by 50% in high [CO_2] indicating a strong morphogenic effect of CO_2 on leaf initiation. The number of tillers per plant increased by 40% in elevated CO_2. The increased photosynthesis rate coupled with a higher leaf area per plant led to increased biomass under elevated [CO_2] by 40%. Therefore, in the absence of nutrient limitation, rice is highly responsive to elevated CO_2 whose yield potential shall increase in changing climatic conditions.

Heat and Mass transfer modelling of fuel reactor for Chemical Looping Combustion

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Extended Summary

The Chemical Looping Combustion (CLC) concept is based on the transfer of oxygen from the combustion air to the fuel by means of an oxygen carrier in the form of a metal oxide, avoiding the direct contact between fuel and air. The CLC system is made of two interconnected reactors, designated as air and fuel reactors as shown in figure below.

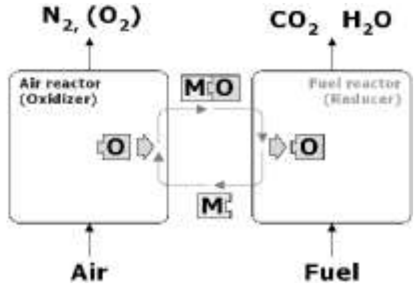

Fig. Conceptual Process Scheme for CLC

In the fuel reactor, the fuel gas is oxidised by a metal oxide through the chemical reaction:

$$CH_4\ (CO, H_2) + MeO \rightarrow CO_2 + H_2O\ (CO_2, H_2O) + Me$$

The exit gas stream from the fuel reactor contains CO_2 and H_2O. After water condensation, almost pure CO_2 can be obtained with little energy lost for component separation. The metal or reduced oxide, Me, is further transferred into the air reactor in which it is regenerated by taking up oxygen from the air.

$$Me + \frac{1}{2}O_2 \rightarrow MeO$$

The flue gas leaving the air reactor contains N2 and unused O_2. The total amount of heat evolved over the two reactors in CLC process is the same as for normal combustion, where the oxygen is in direct contact with the fuel. The significant advantage compared to normal combustion is that the CO_2 is not diluted with N_2. As opposite to other technologies proposed for CO_2 separation, this process has no significant energy penalty for the capture process, and external capture devices are avoided. Thus, the process is expected to be less costly than available technologies for CO_2 separation. Different metal oxides have been proposed as possible candidates for CLC process: CuO, CdO, NiO, Mn_2O_3, Fe_2O_3, and CoO.

The presentation will focus on overview of CLC for carbon capture and CFD multiphase modeling for Heat and Mass transfer analysis of reactors.

CO_2 as Refrigerant in HVAC, Supermarket and Cold-chain Application

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Extended Summary

Present scenario the global warming is the major concern worldwide, due to the continuous increment of CO2 level in the environment. The power plants, chemical, manufacturing industries and the automobile application are the major cause for the same. Now a days, various protocols and norms have been in implementation stage to either reduce the CO2 level or to capture the CO2 produce during the process.

The various research are going on to capturing the CO2, however, the storage of the captured CO2 is the major challenge, which again leaves a question whether the capturing of CO2 with storage is a really a feasible and economical solution than the protection from CO2. At this stage, HVAC sector are in the transition phase due to the enactment of Montreal and Kyoto Protocols to control the ozone depletion and global warming respectively. In other hand, the challenges associated with the storage of CO2 captured from the various sectors, the use of CO2 as a refrigerant in various HVAC applications could be an appreciable solution.

CO2 can be used as natural refrigerants due to its favourable thermo-physical properties and having lowest warming potential (GWP). There are many research going on worldwide for different application in HVAC sector, like Automobile Air Conditioning, Supermarket, Cold chain, industrial application etc. Cold chain is one of the major sector where the use of CO2 as refrigerant can be appreciated, especially for the referred vehicles and cold storage for NH_3 charge reduction. The session will give the glimpse of the present and future status of cold chain infrastructure in India, followed by why CO2 as refrigerant, its technical challenges and opportunities over the existing systems, and the development of CO2 refrigeration systems for the above mention application.

Indian Cold Chain Infrastructure [1]

Cold-chain is an environment controlled logistics chain, ensuring uninterrupted care from source-to-user, consisting only of storage and distribution related activities in which the inventory is maintained within predetermined ambient parameters. Cold chain does not alter the essential characteristics of the produce or product handled.

[1] National Centre for Cold-chain Development (NCCD) Report "All India Cold-chain Infrastructure Capacity (Assessment of Status & Gap)" 2015 prepared by NABARD Building, New Delhi.

As per the data from nation centre for cold chain development (NCCD) India, the status of Cold-chain Infrastructure Gap evaluates into a current gap of 3.28 million tons in cold storage space (Bulk & Hub). The gap for other types of infrastructure is based on available information of existing assets from the line departments and market estimates Table 1. The data clearly indicate the huge scope and demand of HVAC for Infrastructure development of India.

Table 1: Infrastructural GAP in India Cold Chain [1]

Type of Infrastructure	Infrastructure Requirement	Infrastructure Created	All India Gap
Reefer Vehicles	61,826	9,000	52,826
Cold Storage (Bulk)	341,64,411 MT		
Cold Storage (Hub)	9,36,251 MT	318,23,700 MT	32,76,962 MT
Pack-house	70,080	249	69,831
Ripening Chamber	9,131 nos.	812 nos.	8,319 nos.

Why CO_2 as refrigerant

CO_2 has favourable and excellent thermo-physical properties and it is most suitable as lowest GWP. The detail comparison of properties with different refrigerants are shown in table 2. It is being already in use as refrigerant in the colder climate countries like northern Europe, Canada, some part of USA, etc. especially, for the heating application.

Table 2. Environmental, Thermo physical and safety Standard for Refrigerants (UNEP 2014b)[2]

Refrigerant	GWP	ODP	Critical Point	Safety
R22	1780	0.04	96.1	A1
R134a	1360	0	101.1	A1
R32	704	0	78.1	A2L
R152a	0	148	113.3	A2
R1234yf	0	<1	94.7	A2L
R1234ze	0	<1	109.4	A2L
R407C	0	1600	86.0	A1
R290	0	20	96.7	A3
R600a	0	20	134.6	A3
R1270	0	20	91.1	A3
R717	0	<1	132.3	B2L
R744 (CO_2)	0	1	31.1	A1

[2]*UNEP, Report of Refrigeration Air conditioning and Heat pump technical option committee assessment UNEP 2014b*

However, warmer climatic conditions, like in Middle East, including India, where the majority of the application is in cooling has its own challenges. Therefore, present focus of the research is on warm climatic conditions. Many modified and up gradation on the system has already been proposed to make this system useful in the warm climatic conditions. The application of CO_2 systems are mainly on commercial refrigeration like display cabinet, standalone unit , bottle cooler water cooler, visi cooler, Ice cream cabinet etc. In addition to that it is also suitable for mobile air conditioning (car, bus, truck, train etc.).

<u>Technical challenges and opportunities</u>

In spite of the most favourable thermo physical properties and its eco-friendly nature, there are many technical challenges associated with the CO_2 system. The main drawback of the CO_2 is its lower critical temperature (31.1^{o}C), because of that, while operating the system in warm climatic conditions, it has to be operated in super critical region. The whole cycle operates between the subcritical and supercritical region, therefore the cycle is called as trans-critical cycle. The basic cycle of CO_2 refrigeration system is shown is Fig.1.

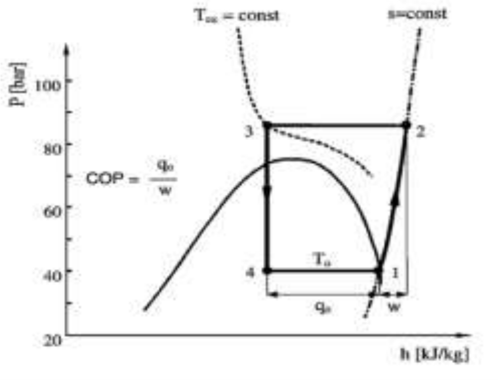

Fig. 1: Trans-critical Cycle for CO_2

The technological development in present scenario for making the system possible to operate in Trans-critical range, the component has been designed based on the requirement. However, using this system have still lower performance compared to the existing system, especially in warm climatic conditions. Therefore, systems need to be tuned based on the application wise. Subsequently, various modified cycles have been proposed. In the following sectionthe development of the CO2 refrigeration system is discussed.

<u>Development of the CO2 system</u>

The major modification on the system have been discussed as booster system, and sub cooling system. The main application is on the supermarkets, and industrial application.

CO2 booster system [3]

The performance of five CO2 booster refrigeration systems is analysed and compared forsupermarketapplication.The investigated configurations include a standard booster system, (BC1), booster system with parallel compressor (BC2), booster system with flooded low temperature evaporator (BC3), booster system with work recovery expander (BC4) and a booster with parallel compressor along with flooded low temperature evaporator and work recovery expander (BC5).

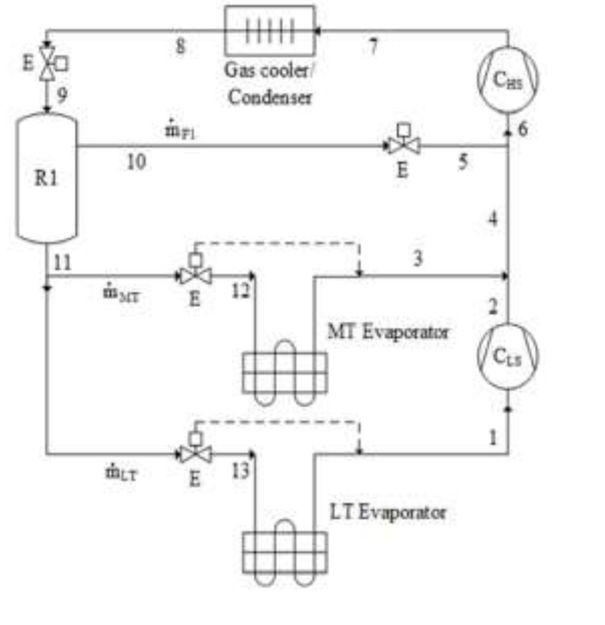

Fig.2: Standard CO2 booster system (BC1)

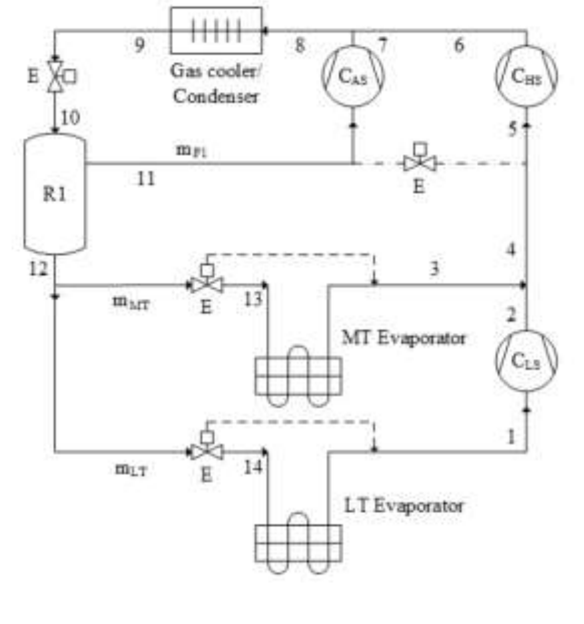

Fig.3: CO2 booster system with parallel compression (BC2).

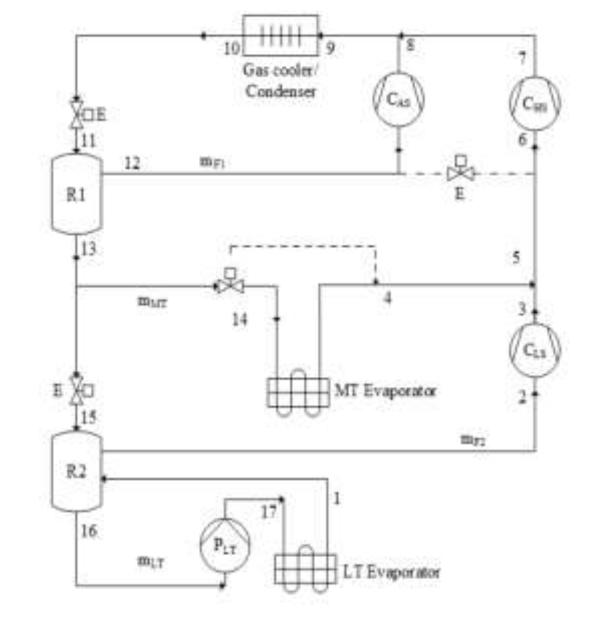

Fig. 4: CO2 booster system with flooded LT evaporator (BC3).

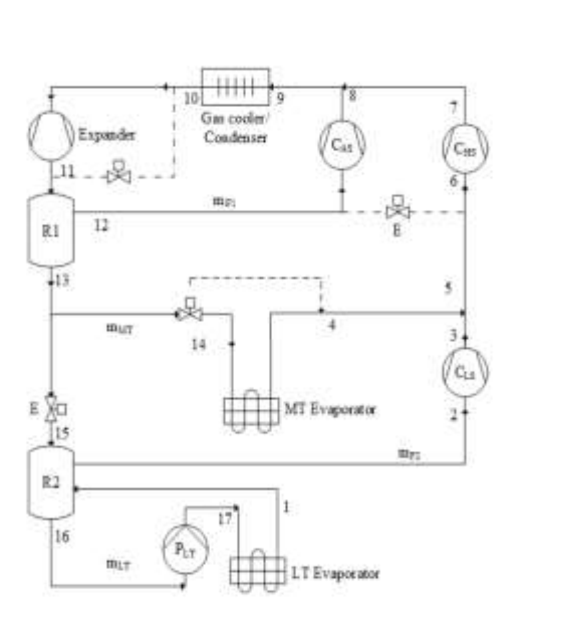

Fig. 5:CO2 booster system with work recovery expander (BC4).

[3]Nilesh Purohi, Dileep Kumar Gupta and M. S. Dasgupta; Energetic and economic analysis of trans-critical CO2 booster system for refrigeration in warm climatic condition; International Journal of Refrigeration; Vol. 80 (2017), Pages 182-196.

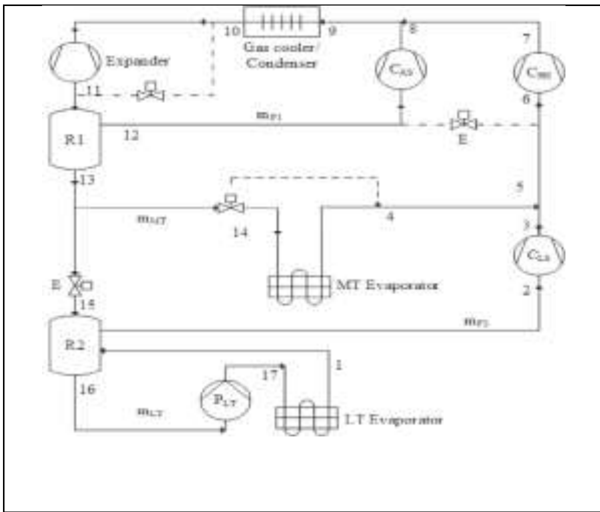

Fig.6: CO2 booster system with parallel compression along with flooded LT evaporator and work recovery expander (BC5).

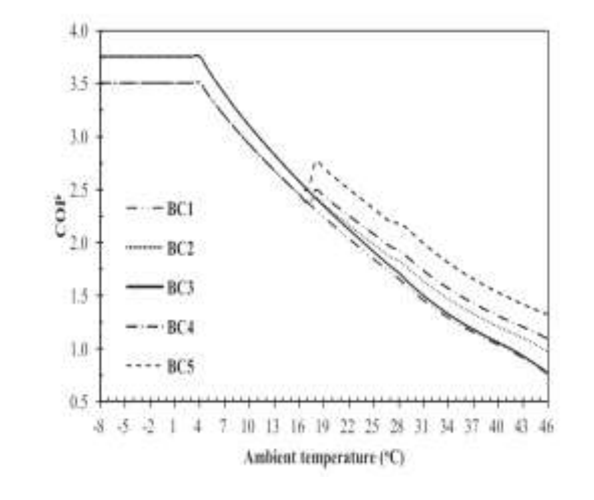

Fig. 7: COP of the investigated systems at various ambient temperatures.

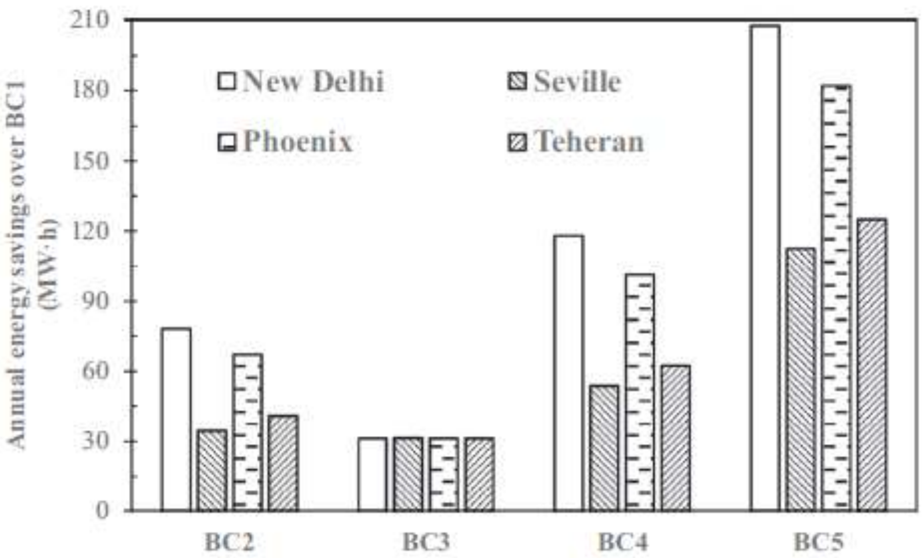

Fig. 8: Annual Energy Saving over the standard Booster System

Annual hourly averaged temperature variations at four prominent cities across the world are taken as case study. Simulation indicates advantage of the proposed system BC5 over BC1 configuration. Work recovery unit is found to have the highest potential in the annual energy savings in BC5, followed by parallel compressor and flooded evaporator. The maximum annual energy savings is found to be 22.16% for BC5 in New Delhi. Economic analysis reveals recovery time of less than four years for the additional investment made in BC5.The slope of recovery time is found steeper at lower tariff compared to that at higher tariff.

CO2 refrigeration system with dedicated mechanical sub-cooling [4]

CO2 transcritical refrigeration cycles require optimization to reach the performance of conventional solutions at high ambient temperatures. The studies demonstrated that the combination of a transcritical cycle with a mechanical subcooling cycle improves its performance.

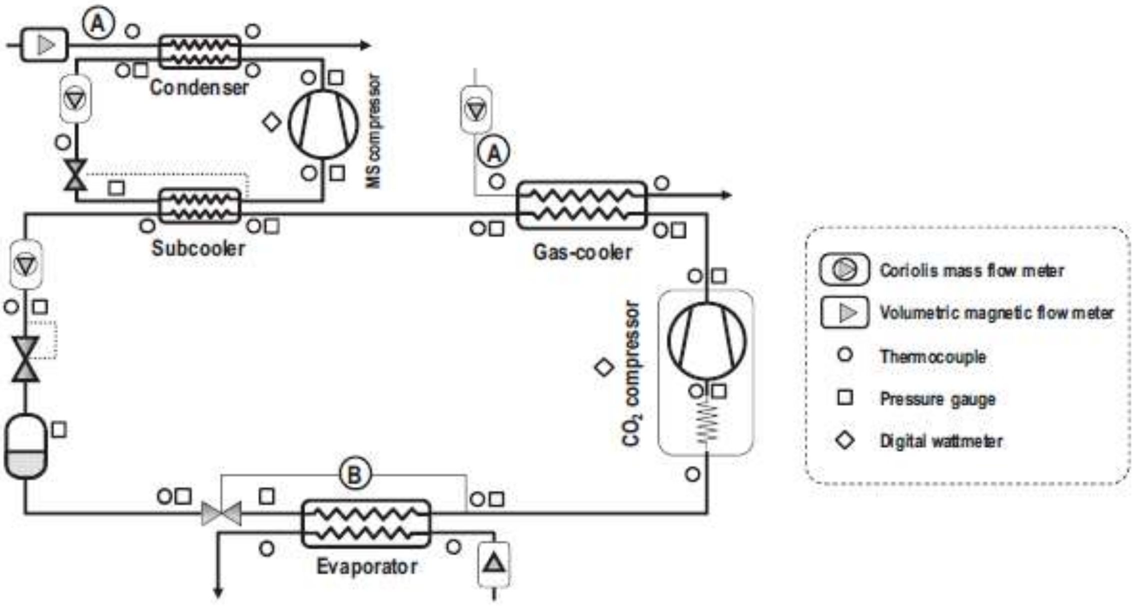

Fig. 9: Schematic Diagram of Mechanical Subcooling System

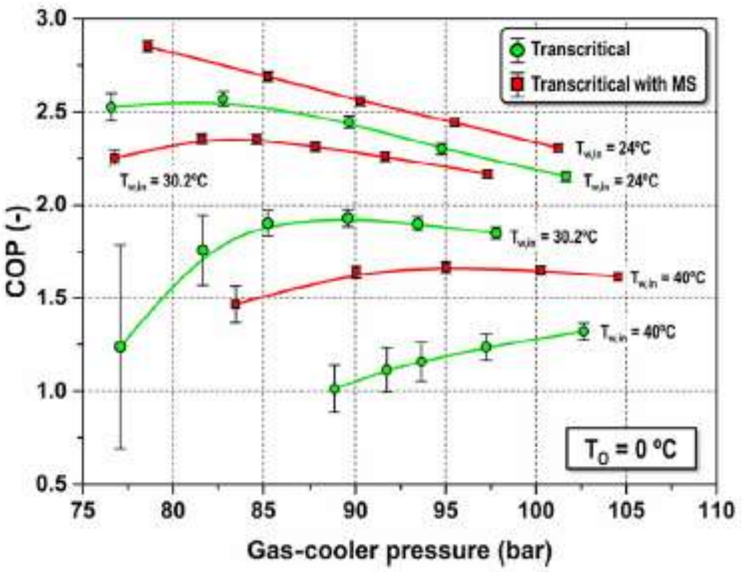

Fig. 10: Performance of Mechanical Subcooling System

[4]*Rodrigo Llopis, Laura Nebot-Andrés, Ramón Cabello, Daniel Sánchez, Jesús Catalán-Gil. Experimental evaluation of a CO2 transcritical refrigeration plant with dedicated mechanical subcooling. International journal of refrigeration 69 (2016) 361–368.*

The combination is evaluated at two evaporating levels of the CO2 cycle (0 and −10 °C) and three heat rejection temperatures (24, 30 and 40 °C). The optimum operating conditions and capacity and COP improvements are analysed with maximum increments on capacity of 55.7% and 30.3% on COP.The result indicate that the performance of the overall system has more improvement in high climatic temperature zones. Hence it can be consider as an opportunities in warm climatic conditions.

Conclusions

CO_2may be consider as an ecologically safe and natural refrigerant for the next generation of HVAC industries. It can also be considered as a utilization of captured CO2 from the different sources. There are challenges and opportunities associated with the CO_2 refrigeration system, therefore, many research groups are actively working on this systems to make itfeasible. Still many more application of CO_2as refrigerant is to be explored in future for Indian HVAC industries.

References

[1] National Centre for Cold-chain Development (NCCD) Report "All India Cold-chain Infrastructure Capacity (Assessment of Status & Gap)" 2015 prepared by NABARD Building, New Delhi.

[2] UNEP, Report of Refrigeration Air conditioning and Heat pump technical option committee assessment UNEP 2014b

[3] Nilesh Purohi, Dileep Kumar Gupta and M. S. Dasgupta; Energetic and economic analysis of trans-critical CO2 booster system for refrigeration in warm climatic condition; International Journal of Refrigeration; Vol. 80 (2017), Pages 182-196.

[4] Rodrigo Llopis , Laura Nebot-Andrés, Ramón Cabello, Daniel Sánchez, Jesús Catalán-Gil. Experimental evaluation of a CO2 transcritical refrigeration plant with dedicated mechanical subcooling. International journal of refrigeration 69 (2016) 361–368.

Aluminium & Green House Gases: Mitigation & Capture

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Extended Summary

The production of primary aluminium has been there since 1950s, is one of the world's most energy-intensive industries with traces of gases having high global warming potentials. Challenged by growing environmental concerns, the primary aluminium industry has undergone major changes over the last two decades to become a much more efficient industry with lower energy-intensity and GHG emissions during the smelting process.

Smelters with old technologies like Soderberg, Side work Prebaked etc. with low energy efficiency have been phased out, amperage of cells have increased, alumina refining processes have been improved, and better control systems introduced to either eliminate or limit the so-called "anode effect". All is being done to improve the energy efficiency leading to lower GHG emissions. The energy intensity has been steadily decreased over period of time, from 17,000 kWh/t Al in 1980 to 13,500 kWh/t Al in 2017. From a lifecycle perspective, GHG emissions in terms of CO_2 equivalent range from 15- 17 t/t Al mainly carbon dioxide and fluorinated gases.

As a very energy-intensive sector, the aluminium industry has a substantial impact on GHG emissions (mainly CO_2 and PFC), not only directly from the process of reducing alumina into liquid aluminium, but also indirectly from the entire production process starting with bauxite mining up to ingot casting.

The primary aluminium production process consists of diverse set of emission sources and the numbers of potential mitigation options are very large. There are options to improve upon the existing Hall-Heroult process like retrofitting the older ones, implementing advance cell technologies, increase recycling, invest into alternatives to Hall-Heroult process like carbothermic reduction, inert anodes etc. Carbon capture is still at trial stage as far as aluminium industry is concerned.

Effective Utilization of Carbon dioxide from Thermal Power Plants Exhaust Adapting Bio- Carbon Capture and Storage Technology

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Extended Summary

The increase of CO_2 level in the atmosphere have caused alarming changes in the climate such as global warming, extreme weather conditions, sea level rise and shrinking of glaciers etc., which have great implications on global food security and economics. The UNFCCC (United Nation Framework on Convention of Climate change) have addressed the issues that strong desirable and achievable commitments are necessary to race against climate change by developed and developing nations. The fossil fuels burning add to ~ 80 % of CO_2 in the atmosphere, and is the principal cause of CO_2 built up.

The "micro-algae based technology" (Biological carbon sequestration) is a new, might be the most promising, environmentally friendly and cost-effective means of reducing CO_2 emissions in the energy sector. The most common microalgae species are Spirulina spa., Chlorella spa., Haematococcus spa. and Dunaliella spa., etc. These species have more important characteristics apart from carbon dioxide sequestration such as high biomass yield per unit of light and algal pond area.

The aim of the proposed study is to develop a commercial scale technology by using flue gas CO_2 from thermal power stations for biomass production. The methodology include: Strain selection; Optimization of culture conditions to enhance the biomass production and CO_2 sequestration; Design and construction of bio-plant capable of CO_2 utilization; and user friendly and economically feasible model for culture harvesting. This project targets on the implementation of algae based methodology able to capture, utilize and recycle the CO_2 from thermal power plants and demonstrate its commercial viability. The process is based on the ability of micro-algae to capture CO_2 via photosynthesis in the presence of sunlight. The CO_2 absorbed is then converted into biomass in a algae Pond, using the digestate as nutrients source. The wet micro-algae biomass obtained is then harvested and dried with solar heat energy to minimize the energy requirements. The dried algal biomass obtained can be used as bio-fertilizer and/ or for bio-diesel production.

The R&D studies will comprise: Strain selection; Optimization of culture conditions; and Design of culture system for biomass production. The Pilot scale study shall comprise: Erection of algal pond; Development of photo-bioreactor for circulation of flue gas CO_2 after

scrubbing; Culturing of algal species; Drying of algae using solar energy and developing use of algae as fertilizer and biomass for diesel and animal food production.

The design and development parameters of a pilot scale plant at Thermal power station, optimized from the laboratory based studies towards flue gas CO_2 utilization for biomass production and approach towards its commercialization will be presented and discussed.

Prospects and Limitations in Establishing Integrated Carbon Capture and Wastewater Treatment Facility using Algal and Bacterial Consortia

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Extended Summary

Carbon-dioxide (CO_2), the most important greenhouse gas produced by combustion of fuels, has become a cause of global panic as its concentration in the Earth's atmosphere has been rising alarmingly. Human activity generates about 37 Gigatons of CO_2 emissions each year, with over 24 Gigatonscoming from direct combustion of carbon for energy production. India's percapita emission during 2016 was 1.7 ton CO_2, well below the global per capita average of 4.3 ton CO_2. However, high coal consumption at existing and new capacities has been tipped to pose challenges to this. Therefore, many research and technologies propel CO_2 management (capture, storage and sequestration) to the centre stage.

In spite of enormous government support and private participation, according to an estimate, out of 13468 MLD of wastewater generated by industries in India only 60% is treated. Though research is being conducted on applications of biotechnological processes on the treatment of industrial effluents like paper and pulp industry, electroplating, distillery, tannery, textile dye and refineries, widespread implementation of different biotechnological process developed in the laboratories are lacking.

Carbon sequestration (storage and conversion) is either the prevention of release of CO_2 onto the atmosphere – removal of CO_2 from industrial flue gas or any such major sources by a gas separation process prior to release to the atmosphere or capture CO_2 from theatmosphere – sequester through biological process such as afforestation, biomass conversion in order to avoid continued build up of CO_2 in the atmosphere. Biological sequestration of CO_2 by algae (micro or macro)takes advantage of the photosynthetic machinery of the aquatic species since they are the most efficient organisms for CO_2 mitigation.This is gaining importance as an alternative process to reduce CO_2 emissions from various industrial manufacturing sectors, by incorporating this gaseous pollutant into biomass. Algae have the ability to absorb more CO_2 gas per hectare than land-based plants and it is estimated that about 1.83 tons of CO_2 gets converted to 1 ton of dry algal biomass under ideal conditions including continuous feeding of CO_2 during daylight hours. Several microalgae that were studied for CO_2 sequestration are *Aphanothece*sp., *Botryococcusbraunii*, *Chlorellakessleri*, *Chlorococcumlittorale*, *Chlamydomonasreinhardtii*, *Chlorella vulgaris*, *Dunaliella*sp., *Euglena gracilis*, *Isochrysis*sp.,*Nannochloropsis*sp., *Neochloris*sp., *Phaeodactylum*sp., *Scenedesmusobliquus*, *Scenedesmusdimorphus*, *Spirulina*sp. etc. These microalgal species have been studied widely because they are not only useful in CO_2 capture but also biosynthesize a wide range of metabolites with various

bioactive properties such as polysaccharides, fatty acids, essential amino acids, polypeptides, pigments, vitamins and minerals, which find various applications.

As the first and very vital step in Algal Biotechnology, selection of microalgal strain determines the usefulness of that particular microalga for a specific application. The selection process can also be determined by the alga's ability to be mass–cultured, ruggedness to withstand the existing environmental conditions, possess high growth rate with high biomass productivity and easy to harvest. For example, in many studies related to CO_2 bio-mitigation and biodiesel production, *Chlorella* sp.and *Botryococcusbraunii*were found to be ideal. Some species of microalgae show high growth rates as well as ability to thrive in harsh environments such as seawater (salinity ~35 g L^{-1}), alkaline lakes (pH ≥ 8.5) and even in certain industrial wastewaters. Their entrained lipids offer several different types of biofuel production options including *trans*-esterified biodiesel, fermented bioethanol, photo-biological hydrogen, and hydrocarbon biofuels for replacements of gasoline, diesel, jet fuel and anaerobically generated methane. They also serve as raw materials for fish and animal feed or for high-quality applications such as medicines or a source of omega-3 fatty acids.

Some of the important factors that either influence or act as limitations for CO_2 uptake include (i) mode of growth of microalgae – phototrophy, heterotrophy or mixotrophy, (ii) nutrient sufficiency and deficiency, (iii) inorganic carbon source, (iv) composition of other gases in flue gas, (v) temperature, (vi) CO_2sparging and mixing mechanism, and (vii) method of cultivation – open raceway ponds or closed photo bioreactor. Among these factors, the most practical difficulty experienced is with the method of cultivation; the key challenge to generate algal biomass at large scale is availability of huge volumes of water. For cultivation in open ponds, algae require as high as 11–13 million litres of water per hectare in addition to macronutrients (N & P), which accounts for 10–20% of the total cost for algal production.Given the huge requirement of water and nutrients for algal cultivation at large-scale, wastewaters rich in organic and inorganic components are tried and tested as substitutes for freshwater and fertilizers.Organic substances such as carbon, nitrogen & phosphorus and inorganic salts available in the effluents act as nutritive substrate for micro algal growth. Due to the nutrient removal efficiency, microalgae provide an additional advantage of wastewater treatment by reducing the requirement for huge amounts of toxic chemicals normally used in the conventional processes. In contrast to the conventional effluent treatment process using only bacteria, microalgae offer an efficient method to consume nutrients and provide space for the aerobic bacteria (that co-exist) with the required O_2 through the photosynthesis process. Many studies in the recent past have demonstrated the cultivation of various microalgae in different wastewaters such as municipal sewage, dairy, poultry, swine, aquaculture, paper and pulp, palm oil, agricultural run-off etc. by assimilating carbon, nitrogen and phosphorus and other chemical compounds.

Preliminary studies conducted over seven years by Murugappa Chettiar Research Centre (MCRC) using an alga, *Scenedesmus*, for treating sugar mill effluents at EID Parry (I) Ltd., Nellikuppam as a step towards combating both air and water pollution have shown promising results in stabilizing the pH to neutral and increasing the Dissolved Oxygen, optimizing the Electrical Conductivity, Salinity and Total Dissolved Solids (50–60%), and reducing the Sugar content and Chemical Oxygen Demand (80–85%). This pilot scale facility aims at combining the two systems viz., CO_2, a gaseous waste from distillery and the liquid effluent from sugar generates 0.3–0.5 kg (dry wt.) algal biomass per m^3 every day utilizing 6000 m^3 CO_2. The biomass production range will be between 9.6 and 42.0 tons/ha/year based on the environment, water quality, availability of CO_2 and rainfall patterns as the studies were conducted in open environment with the potential to sequester 322 ton C/ha /yr. Intensification of the same process might lead to the production of biomass upto 100 tons/ha/year to sequester 1500 ton C/ha/year. Moreover, the biomass generated could be used in many ways including food, fuel (biogas generation and biochar production), and fertilizer (soil conditioner), and extraction of value added compounds.

The way forward for sustainability in environmental, social and economicaspects is to couple the CO_2 sequestration and wastewater bioremediation processesthat will have serious positive impact on the environment, but will largely depend on conceiving, establishing and demonstrating an Integrated Approach considering all prevailing parameters in a particular industrial environment to arrive at customized viable solutions.

Emission Control Strategy for Coal Fired Thermal Power Plants emphasizing the Roles of R&D: A Policy Analysis under Indian Regulatory Framework

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Extended Summary

Abstract

The stack emission standards are promulgated for Indian coal fired thermal power plants (TPPs) for Sulfur Dioxide (SO_2), Oxides of Nitrogen (NO_x) and Mercury (Hg) in December 2015 by the Ministry of Environment, Forest and Climate Change (MoEFCC), Government of India (GoI), besides tightening of particulate matter (PM) emission standard. Limestone based wet flue gas desulphurization (FGD) technology has so far been recommended by different governmental agencies and by a non-governmental organization for removing only SO_2 and other options for rest of the pollutants. A single technology, such as the Multi Pollutants Control Technology (MPCT), developed recently elsewhere in the world for removing all the pollutants from the TPP, could be more economic than introducing separate technology for removing each pollutant. The MPCT technology offers lower carbon and water footprints following the Sustainable Development Goals. Conscientious efforts on R&D could be undertaken immediately by the user ministries to explore indigenize MPCT in India under the aegis of "Swachh Bharat Mission" so that Indian TPPs would have a chance to commission a comprehensive emission control technology for plurality of pollutants with user friendly products suitable for the country. In the light of these observations, this article aims to assess the emission control strategy for the coal fired TPPs emphasizing the roles of R&D under Indian regulatory framework and to recommend policy options for strengthening the Indian decision support system. The R&D efforts made on CO_2 capture or removal in India is also critically examined from the standpoint of emission control strategy for coal fired TPPs under the premise of the newly promulgated emission standards.

Key words: coal combustion; emission standard; multi pollutants capture; thermal power plant;

Introduction

The stack emission standards are promulgated for Indian coal fired thermal power plants (TPPs) for Sulfur Dioxide (SO_2), Oxides of Nitrogen (NO_x) and Mercury (Hg) in December 2015 by the Ministry of Environment, Forest and Climate Change (MoEFCC), Government of India (GoI) and are summarized in Table–1 (MoEFCC, 2015). Additionally, the emission standard for Particulate Matter (PM) has been tightened.

Table -1. Promulgated Stack Emission Standards for TPPs Notified by MoEFCC, GoI on 07.12.2015

Parameters	All values are in mg/Nm^3		
	TPPs installed		TPPs to be installed
	Before 31.12.2003	01.01.2004 to 31.12.2016	After 01.01.2017
PM	100	50	30
SO_2	600 (< 500 MW) 200 (≥ 500 MW)	600 (< 500 MW) 200 (≥ 500 MW)	100
NO_x	600	300	100
Hg	0.03 (≥ 500 MW)	0.03	0.03
TPPs (units) shall meet the limits within two years from date of publication of this notification			

The Ozone Monitoring Instrument observed total SO_2 and annual average SO_2 concentrations for the Indian coal fired TPPs were reported (Lu et al., 2013) to increase by more than 60% between 2005 and 2012 in contrast to the gradual decreasing trend of national mean SO_2 concentrations reported by the Central Pollution Control Board (CPCB). Reportedly, it was suggested that the air quality monitoring network generating such data by the CPCB required to be optimized to reflect the true SO_2 profile in Indian air. The Centre for Science and Environment (CSE) (an NGO), referred (Bhati and Ramanathan, 2016) the findings of Lu et al. (2013) while discussing the need of SO_2 emission standard for Indian coal fired TPPs.

The CSE has framed almost the entire policy to meet the new emission standards. Briefly, the policy recommendations flown from a national workshop held on September 07, 2016 organized by CSE (CSE, 2016) were (i) MoEF should survey the implementation status of power plants, (ii) CEA (Central Electricity Authority) should act as the key technical advisor and prepare a 'Technology Guidelines', (iii) CERC (Central Electricity Regulatory Commission) should prepare a simplified tariff application, (iv) CEA and CPCB should develop a monitoring mechanism, and (v) CEA and POSOCO (Power System Operation Corporation) Limited need to prepare a scheduled shut-down plan. In the "Policy Brief" (Bhati, 2017), CSE further recommends utilization of a part of the National Clean Energy Fund (NCEF) for installation of emission control technologies to the TPPs. The CSE has recommended (Bhati and Ramanathan, 2016) the limestone based wet Flue Gas Desulfurization (FGD) for controlling SO_2 emission from Indian coal fired TPPs to meet the newly promulgated SO_2 emission standard besides other options for other pollutants. Interestingly, CPCB (Paliwal, 2016) and CEA (CEA, 2017a) have also recommended limestone based wet FGD. The CEA further clarified "*that presently CEA has come up with standard technical specifications for wet FGD, however, this is only advisory in nature and power producers have liberty to choose any suitable technology for reducing SOx.*" (CEA, 2017a).

In the light of these observations, attempts have been made in this article to assess the emission control strategy for the coal fired TPPs emphasizing the roles of R&D under Indian regulatory framework followed by policy recommendations for strengthening the Indian decision support system. The R&D efforts made on CO_2 capture (removal) in India is also critically examined from the standpoint of emission control strategy for coal fired TPPs under the premise of the newly promulgated emission standards (Bandyopadhyay, 2017a; Bandyopadhyay, 2017b).

Assessing the emission control strategy

In India, six coal fired TPPs operate with FGD in which four plants use sea water and the rest use limestone as summarized in Table–2 (Bhati and Ramanathan, 2016). The region wise capacity of coal fired TPPs requiring FGD installations is presented in Table–3 (CEA, 2017b). A deadline of two years from the date of publication of the notification of the standards (i.e., up to December 06, 2017) has been fixed for compliance. On the other hand, the deadlines for phasing plans for scheduled implementation specified by CEA (2017b) are 30.06.2023 for Northern region, 31.12.2022 for Southern region and 31.12.2023 for both Eastern as well as Western regions. Now, whether limestone based wet FGD would be suited under Indian condition or not is a matter of further deliberation for few reasons – (i) availability of limestone for catering 295 (1,22,672 MW) power generating units (CEA, 2017b) in the country, (ii) disposal of gypsum produced in addition to the existing burden of disposal of fly ash in most of the TPPs, and (iii) selecting the limestone based wet FGD without performing any techno-enviro-economic analysis among other technological options (Bandyopadhyay, 2017b).

Table–2. Status of six Indian operating FGDs (Bhati and Ramanathan, 2016)

	Trombay TPS of Tata Power	Dahanu TPS of Reliance	Mundra Ultra Mega Power Project of Adani	Ratnagiri TPP of JSW	Udupi TPS	NTPC Vindhyachal Stage V
Capacity, MW	750	500	1,980	1,200	1,200	500
Type of FGD	Seawater wet FGD				Limestone-based FGD	
Area of construction, m^2/Acres	7,200	NA	1,500 (scrubber)	NA	10,000	10,000–20,000
Water consumption, $10^{-5}m^3$/year	147.73	876–1051	1.25 –1.40		3.06–3.50	6.13–8.76

Auxiliary power consumption, %	1–1.5	1.25	1.5	0.5–1.5	0.5	1.1
Reagent, kg/ hr	–	–	–	–	–	6,250

NA: Data not available

Table–3. Region wise overall TPP capacity for FGD installation implementation plan as per Central Electricity Authority, India [CEA, 2017b]

Region	**Capacity (in MW)**	**No. of units**
Northern	27,405	70
Southern	20,240	41
Eastern	16,670	39
Western	58,357	145
Total	**1,22,672**	**295**

Carpenter (2013) reported that a legion of new emission standards were being introduced tightening the existing emission standards of coal fired TPPs with the promulgation of emission standards on earlier unregulated pollutants. It was further reported that the new emission standards could be achievable at a significantly lower cost using the recently developed Multi Pollutant Control Technologies (MPCTs) for removing plurality of pollutants in a single system than a series of traditional single pollutant control systems for controlling the same pollutants.

In this present article, four MPCTs amongst others are identified from those summarized by Carpenter (2013). These MPCTs are suitable mainly for Indian demographic condition as well as for producing saleable byproducts, e.g., fertilizers, keeping in view India being an agriculturally developed nation. The limestone based wet FGD technology has been in commercial operation since 1938 utilizing limestone slurry as the absorbent. The three out of four MPCTs such as Airborne® Process (commercialized), SkyMine® as well as SkyScrapper® processes (under commercial demonstration) and NeuStream® process (under commercial demonstration) use a sodium-based (sodium carbonate or sodium hydroxide solution) absorbent. Very high removal efficiencies (99% for SO_2 and NO_x, are 90% for CO_2 and 90 – 99% for Hg) are achievable. Carbon neutral operation is also possible in some cases and CO_2 can be captured for use in the gas phase. These sodium based wet scrubbing processes can produce saleable by-products. Amongst these three processes, NeuStream® process can have amine emission into the atmosphere leading to several environmental problems (Dautzenberg and Bruhn, 2013). In the fourth MPCT, namely ECO®-ECO_2® process (not yet commercially demonstrated), SO_2, NO_x and Hg can be removed at very high removal efficiencies while CO_2 can be recovered in the gas phase for use or geological sequestration.

This process however, suffers from the problem of slippage of ammonia to the atmosphere attracting stringent safety measures. Thus Indian choice rests between Airborne® and SkyMine® / SkyScrapper® processes. These technologies offer lower water- and carbon-footprints meeting the Sustainable Development Goals (SDGs) of UNEP. Also, the developed nations with already installed FGDs could not be able to get this benefit unless existing FGDs are revamped or removed for installing the MPCTs afresh. Clearly, India is in an advantageous position and that is what is exactly pointed out by Sloss (2015) in his report as *"Pollution control technologies are expensive and take time to install. It would therefore make sense for India to coordinate pollution control systems and to focus as much as possible on multi-pollutant control systems which will reduce emissions of several pollutants simultaneously."* Poullikkas (2015) further reported that the emerging technologies for combined control of SO_2 and NOx emissions have the potential to curb these emissions together for less than the combined cost of conventional wet FGD for SO_2 control and selective catalytic reduction (SCR) for NO_x control. Some of these technologies are commercially used on low to medium sulfur coal fired TPPs.

Though there is no emission standard for CO_2 from the Indian coal fired TPPs, the MPCT could be developed analogous to any of the two MPCTs mentioned earlier with or without carbon neutral approach keeping in view that a single technology could be more economic than introducing separate technology for removing each pollutant. Conscientious efforts on R&D could be undertaken immediately by the user ministries to explore indigenize MPCT in India under the aegis of "Swachh Bharat Mission" so that Indian TPPs would have a chance to commission a comprehensive emission control technology for plurality of pollutants with user friendly products suitable for the country. There are multiple benefits once such a technology is installed – (i) reduces SO_2 emission functioning as FGD unit, (ii) reduces NOx emission, (iv) reduces Hg emission, and finally (iii) captures CO_2 (offering GHG emission mitigation option enabling TPPs to earn carbon credits). In contrast, limestone based wet FGD technology recommended by the CPCB, CEA, and CSE as mentioned earlier, will reduce only SO_2 emission resulting into partial cleaning of the flue gas of TPPs, and thereby demanding commissioning of other technologies for the rest of the pollutants and hence, it can not be conducive in achieving better air quality than the MPCT. Recommending a specific stand alone limestone based wet FGD setting aside others and that too with the proposed utilization of a part of the "National Clean Energy Fund" (NCEF) of Government of India in such a situation would raise serious concerns. The MPCTs developed well after the limestone based wet FGD technology may face a challenge in providing approved vendors for installation under Indian condition for catering to a large number of TPPs and in that the said FGD technology may have a better chance, but owing to this lone advantage, it can not be installed forcibly utilizing a part of NCEF sacrificing the Indian environment (Bandyopadhyay, 2017a; Bandyopadhyay, 2017b).

Status of current research on CO_2 capture in India

Legion of R&D projects are being currently funded by various governmental agencies in India towards CO_2 capture from the simulated gas streams by various methods largely ignoring the estimation of the CO_2 generation from the processes developed to capture the CO_2. Also a number of seminars, conferences and workshops are being held throughout the country for the past several years on CO_2 capture followed by its use. In contrast, seminars or even funded R&D projects for SO_2 removal (or FGD) and MPCTs in India are few and far between. The major research areas towards CO_2 capture/removal include – (i) development of membranes (inorganic and organic) for CO_2 capture, (ii) absorption of CO_2 in amine based blended solvents, (iii) removal of CO_2 on synthesized nano-materials as adsorbents. In addition, biological methods are also attempted for CO_2 capture. The main thrust has so far been imparted on the material development for CO_2 capture/ removal from simulated gaseous streams, but a demonstration project commissioned on a slip-stream from the flue gas of an Indian TPP does not seem to have been reported as yet. Further, the presence of other gases and traces of PM has not yet been included in any of the Indian CO_2 capture/removal projects. Thus these projects undertaken so far can not be directly put into practice in any of the TPPs operating in India unless comprehensive studies are being conducted taking into consideration of the plurality of pollutants present in the flue gas emitted from the coal fired TPPs. Finally, the life cycle analysis in the current Indian CO_2 capture/removal projects do not seem to have been reported so far which essentially constitutes an integral approach under the present circumstances.

Policy recommendations

After careful considerations of the conflicting situations elucidated in the previous sections, following recommendations are being put forward for strengthening Indian decision support system (Bandyopadhyay, 2017a):

1. To constitute a Task Force at national level under the aegis of the user governmental agencies such as CEA and MoEFCC.
2. Outlining the proposed *modus operandi* of the Task Force–

(i) To take the stock of the situation towards measures being taken for compliance of the newly promulgated emission standards at 4 (such as Northern, Western, Southern and Eastern) regions of the country by constituting 4 ***Regional Expert Committees*** under the aegis of a ***Central Expert Committee*** constituted by CEA and MoEFCC;

(ii) To consider various MPCTs for selecting appropriate technology for purifying the stack emission from 295 (total capacity of 1,22,672 MW) TPPs for meeting the newly promulgated emission standards, and in order to achieve this, the possibility of development of indigenize MPCT under "Swachh Bharat Mission" should be explored, and simultaneously if needed, dialogue between Indian experts/suppliers and foreign experts/suppliers on MPCT may be made for implementing MPCT at least in some of the Indian TPPs;

(iii) To avoid ignoring CO_2 capture in the MPCT at the first place, though it is not a listed parameter in the newly promulgated stack emission standards for Indian TPPs;

(iv) To consider utilization of captured CO_2 as saleable by-products (e.g., fertilizers) followed by its sequestration as in Carbon Capture and Sequestration (CCS) projects [e.g. Enhanced Coal Bed Methane Recovery (ECBMR) Project];

(v) To consider Zoning for CCS with the assessment of 295 TPPs earmarked by CEA for installation of gas cleaning devices – typical examples are

TPPs located at Durgapur, West Bengal (WB) may have CCS for ECBMR

TPPs located elsewhere, e.g. at Mejia, WB may have MPCT with saleable by-products (avoiding CCS projects here);

(vi) To consider the market potential of the by-products generated from the operation of the MPCTs so that the end-product produced would not cause any disposal problem as in the case of gypsum arising from the limestone based wet FGD technology that may add to the burden of the existing ash disposal problem of many TPPs;

(vii) To consider revamping of ESP for controlling the emission of fly ash for meeting the stringent emission standard for PM;

(viii) To adopt the principle of Charter on Corporate Responsibility of Environmental Protection (CREP) for proposing "Technology Guidelines";

(ix) To consider support for other logistics, if any;

(x) The promulgated emission standards may be reviewed under "Change in Law";

3. To propose Capacity Building Programme on Advanced Emission Control Technology for those TPPs that are required to meet the newly promulgated emission standards.

4. To propose Capacity Building Programme on Advanced Emission Control Technology for the State Pollution Control Boards and Pollution Control Committees in India as well as for the CPCB for the framing of post-implementation strategies.

5. To propose establishment of a ***National Emission Control Technology Research Centre***, that would also include CO_2 Capture Research indicating the role of Indian R&D toward emission control from the TPPs, and that the outcome of such research could be exported to other industrial gas cleaning operations (business to business or multi-sectoral approach) as and whenever, needed. The proposal should also take into account Indian R&D for projects on CO_2 capture with the life-cycle analysis. The approach for the R&D would target lower water- and carbon- footprints in accordance with the SDGs.

6. Indian TPPs utilize electrical, mechanical, and civil engineers on the front line, followed by instrumentation, electronics, and computer science engineers at the next

level. Chemists are utilized in the laboratories for various chemical analyses. The designing, commissioning, operating and trouble shooting of gas cleaning plants require the knowledge of thermodynamics, chemical kinetics and mass transfer (with or without chemical reactions). "***Chemical Engineer****s*" are appropriately equipped with this knowledge. Therefore, Indian TPPs will now require "***Chemical Engineers***" for meeting the challenges of the newly promulgated emission standards for Indian coal fired TPPs. Outsourcing appropriate man-power ("Chemical Engineers") may not be conducive under the present circumstances. Therefore, the "***Chemical Engineering***" curricula must be consolidated at the UG and PG levels in this regard so as to comply with the future demands of industries for improved gas cleaning operations in the country.

7. Submission of recommendations to the Government of India for consideration by the ***Central/Regional Expert Committees***.

Conclusions

The newly promulgated emission standards by the MoEFCC for the Indian coal fired TPPs are concentration based. Thus Indian TPPs are at liberty to commission any technology to meet the emission standards under the provisions of the Air (Prevention and Control of Pollution) Act, 1981 as amended and Environment (Protection) Act, 1986 as amended. However, limestone based FGD technology has been recommended by different governmental agencies (such as CPCB and CEA) and by a non-governmental organization (CSE) for removing only SO_2, though the promulgated standards are neither technology based nor equipment based as in developed nations. A stand alone technological solution (FGD technology) may appear economic to achieve the target however, a need based outlook is more demanding with a techno-enviro-economically feasible solution for cleaning the skies from getting polluted. The user ministries, at least, could have proposed for exploring indigenize MPCT in India under the aegis of "Swachh Bharat Mission" through R&D projects so that Indian TPPs would have a chance to commission a comprehensive emission control technology for plurality of pollutants with user friendly products suitable for the country rather than generating gypsum as solid waste as the additional burden of disposal of fly ash. After promulgating the emission standards, sufficient time should have been allowed for appropriate interactions amongst all stake holders for finding a stable technology fitting into Indian TPPs. As regards to the operation of the gas cleaning plants (FGD technology or MPCT), Chemical Engineers are required since Chemical Engineers are appropriately equipped with the knowledge required for the operation of gas cleaning plants, since Indian TPPs do not recruit Chemical Engineers. Therefore, Indian TPPs will now require Chemical Engineers for meeting the challenges of the newly promulgated emission standards. Furthermore, the "Chemical Engineering" curricula must be consolidated at the UG and PG levels in this regard so as to comply with the future demands of industries for improved gas cleaning operations in the country. The current decision support system seems incoherently weak.

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Acknowledgement:

Author acknowledges the development of the current article using his earlier published article cited in text and in reference section as "**Bandyopadhyay, A.** Assessing the current practice and policy with recommendations for emission control strategy for coal-fired thermal power plants under Indian regulatory framework emphasizing the roles of R&D. Environmental Quality Management. 27, 49–55, 2017b"; https://doi.org/10.1002/tqem.21511

Carbon Cycle Modelling and Measurements - Robust flux estimation

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Extended Summary

The exchange of carbon between the land, atmosphere and the ocean determines the trajectory of its accumulation in the global system. While the atmospheric component can be reasonably well measured in a global scale, considerable uncertainties remain about the land and ocean components. Robust spatial and temporal estimates which are required for compliance with COP 21 accords are even more difficult due to lack of data. In this talk, we will outline the approach in obtaining these estimates as best as we can - by a combination of accurate GHG measurements and their use in an inverse transport model in a Bayesian framework to estimate sources and sinks of carbon. We will give a brief overview of the marine carbon cycle to illustrate its potential for carbon sequestration.

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