ADB

Technical Assistance Consultant's Report

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Integrated High Impact Innovation in Sustainable Energy Technology – Prefeasibility Analysis for Carbon Capture, Utilization and Storage (Subproject 2)

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For ADB Energy Sector Group

Asian Development Bank

Technical Assistance Consultant's Report

Project Number: TA-9686 REG

Integrated High Impact Innovation in Sustainable Energy Technology - Prefeasibility Analysis for Carbon Capture, Utilization and Storage (Subproject 2)

Prefeasibility Study on Carbon Capture and Utilization Cement Industry of India

REVISED REPORT

October 2021

Asian Development Bank

ABBREVIATIONS AND NOTES

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ADB	Asian Development Bank
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CCUS	Carbon Capture Utilization and Storage
CAPEX	Capital expenditure
CIF	Cost, Insurance and Freight
CO_2	Carbon dioxide
CSI	Cement Sustainability Initiative
CUP	CO_2 Utilization Plant
DAC	Direct air capture
DBL	Dalmia Bharat Limited
DCBL	Dalmia Cement (Bharat) Limited
EA	Executing Agency
EOR	Enhanced oil Recovery
EGR	Enhanced gas Recovery
ECBM	Enhanced coal bed methane
FOB	Free on Board
FY	Financial Year
H_2	Hydrogen
IA	Implementing Agency
INDC	Intended Nationally Determined Contributions
IRR	Internal Rate of Return
MCA	Multi Criteria Analysis
MIRR	Modified Internal Rate of Return
MTPA	Million Tonnes Per Annum
NPV	Net Present Value
OPEX	Operating expenditure
SPV	Special Purpose Vehicle

TA	Technical Assistance
tpa	tonnes per annum
TRL	Technology readiness level
VGF	Viability Gap Funding
WACC	Weighted Average Cost of Capital
WDV	Written Down Value

NOTES

(i) The fiscal year (FY) of the Government and its agencies ends on March 31.

(ii)In this report, "$" refers to US dollars, unless otherwise stated.

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Executive Summary

Background

Cement industry contributes to about 8 per cent of global CO_2 emissions, and it has been considered, along with iron/steel, as the hard-to-abate sector. Unlike other manufacturing sectors where CO_2 emissions are mostly from energy usage, significant proportion of CO_2 emissions from cement industry are process centric. Without practical alternatives, the sector needs carbon capture, utilization and storage (CCUS) to achieve its climate change goals.

Dalmia Cement (Bharat) Limited('DCBL'), one of the leading cement companies in India, has announced to become carbon negative by 2040. Carbon capture and Utilisation (CCU) is one of the key levers identified by the company to achieve its goal, considering 55-60% GHG emissions in cement plant are attributable to cement process. The company is exploring the feasibility of building a large-scale demonstration CCU plant in its Ariyalur cement facility.

This study is being commissioned to assess the techno-economic pre-feasibility of the CCUS options in the Ariyalur cement factory with support from Asian Development Bank (ADB). Key findings of this study are presented below.

Capture CO_2 from a cement plant

Despite a lack of commercial CCUS projects in the cement sector, there are numerous demonstration and pilot CCUS projects at cement plants around the world. Most applicable CO_2 capture technologies (commercially applied in other industries) for cement industry are post combustion and oxy-fuel combustion technologies. Post-combustion technologies are preferred as it is commercially available and applied to other dilute CO_2 streams (power stations) and it does not interfere with the operation of cement production.

It is technologically feasible to build and operate a 500,000 tonnes per year CO_2 capture plant at the Ariyalur plant, using chemical absorption with amine-based solvents. A conceptual design for an amine-based solvent carbon capture plant was completed with major equipment sizing and costing.

Process emissions (kiln stack flue gas) is the preferred stream for capture due to higher CO_2 concentrations. However, the flue gas does contain relatively high levels of NOx and SOx, which can lead to faster amine degradation and increase operational costs. Water consumption at the capture plant could be substantial and proper management is required, which may include heat recovery and integration between the capture process (reboiler steam generation), cement production process and CO_2 utilization process.

In line with Dalmia Cement's long-term decarbonisation strategy, more sustainable alternatives to produce steam for the capture plant reboiler should be considered and evaluated. Those measures may include system heat recovery from flue gas, biomass fuel, fuel switch (biomass), and renewable energy powered electric steam generator.

Utilization of captured CO_2

CO_2 utilization review

CO_2 utilization is recognized as one of the key levers for making the cement industry carbon negative. There are multiple pathways for utilization of CO_2. This study carried out an extensive overview of CO_2 utilization landscape. The review included market demand, Technology Readiness Level (TRL) and relevance of the technology for implementation in cement industry.

CO_2 utilisation screening methodology

A quantitative *Multi Criteria Analysis* (MCA) methodology has been developed to assess various CO_2 utilization options. This methodology may be used by other cement producers when evaluating their CCUS routes. Key parameters for the methodology include Technology Readiness Level (TRL), CAPEX, OPEX, Payback period, Market demand, Energy consumption, CO_2 avoidance.

Employing this methodology, detailed MCA analysis was then performed for six products: urea, soda ash, mineralization, methanol, algae for feed and algae for oil with the results below:

Product	Urea	Soda Ash	Mineralization	Methanol	Algae feed	Algal Oil
TRL	9	9	8 to 9	7 to 9	5 to 7	5 to 7
Overall Score *	89	79	87	79	69	75

Overall score Includes scores for all the 8 parameters listed earlier. (details in the utilization section)

The above analysis provides directional guidance towards shortlisting a product for the prefeasibility study. It is noted that, when applying this methodology, other project implementation related factors (besides those considered for MCA) may need to be taken into consideration while deciding a final CO_2 derived product.

According to MCA screening scores, urea and mineralization are the top-ranking options. Though the mineralization is recognised as one of the most promising CO_2 utilization options in developed countries, it emerged out during the discussions that the CO2 derived cement requires more than 5 to 6 years in technical approval. Hence, the option was dropped.

Soda ash and methanol emerged out as the next best options. The project team expressed the view that the soda ash has limited market.

Methanol has a great potential for CO_2 utilization as a long-term solution, particularly in view of the continual fall in the cost of renewable electricity and traction that is getting from the government and research institutes for the hydrogen economy.

Based discussions with the officials of DCBL, after considering all the possible factors and organizational priorities, urea was selected for the prefeasibility study.

Urea production

For the prefeasibility study, a process based on ammonia stripping has been considered. Urea production is a mature and commercial technology and large plants have the benefits of economies of scale. For the prefeasibility study, two cases have been considered:

- Base case: 0.5 million tpa of CO_2 utilization
- Advanced case: 1.0 million tpa of CO_2 utilization

In case of integrated urea plants, ammonia is an intermediate product made out of fossil fuel, while in case of standalone urea plant for CO_2 utilization, ammonia would need to be purchased.

Environmental impact and CO_2 emissions analysis of CCU chain

Based on data available, the preliminary environment impact assessment (EIA) identifies no significant adverse environmental impacts for the proposed project. Overall, the proposed project would not cause air, water, or soil to be contaminated with waste (assuming best operation and maintenance practices) to a degree that would pose a threat to human or ecological health and safety.

This study calculated CO_2 abatement potential for several scenarios, based on a 0.5 mpta carbon capture plant and corresponding urea plant. Key results are listed in Table below:

Scenario	Total emissions, mpta	Emissions reductions, mtpa
Baseline (cement and urea business as usual without CCU)	2.18	N/A
CO_2 capture from cement plant and ammonia as well as steam from fossil fuel	2.04	0.14
CCU with green ammonia and steam from fossil fuel	1.36	0.82
CCU with biomass boiler and ammonia from fossil fuel	1.47	0.71
CCU with biomass boiler and green ammonia	0.81	1.38

By employing biomass boilers to generate steam for both capture and utilization plant, Scope 1 CO_2 emissions can be reduced by 0.71 mpta. Other measures, if adopted, may also make an material contribution on emissions reduction:

- Use green ammonia produced onsite or outsourced.

  It should be noted that currently green ammonia has much higher costs to produce or procure (in some circumstances, cost of green ammonia more than double the prevailing market price). Based literature and simple calculations, more than USD2 billion CAPEX may needed to build a green ammonia plant sufficient for the conversion of 0.5 mpta CO_2(as shown in table below). Such high CAPEX and OPEX would make urea production cost prohibitively high under the current market conditions. However, with technology progress and market conditions change, future projects planning may look at the viability at the time of investment decision.

Items	Amount
Ammonia production capacity , tpa	386,364
Estimated cost of the plant	USD2.9 billion
CO_2 saved per annum	664,669

- Waste heat recovery and system optimization of the CCU facility.

Commercial viability

A financial model was constructed to perform financial assessment for the carbon capture and utilization(urea) project. Assumptions of key parameters are based on current commercial conditions in India.

For the Base Case where 0.5 million tonnes of CO_2 is converted into of 680,000 tonnes of urea, its Capital Expenditure (CAPEX) is estimated at **\$365.43 million (INR 26,417.98 million)**, which translates to CAPEX of \$730.86 (INR 52,835.96) per tonne of CO_2 for conversion into urea. Operational Expenditure (OPEX) for the conversion is determined as \$167.35 million (INR12,098.23 million) which translates to **\$316.34 (INR 22,869.17)** per tonne of CO_2 converted to urea. The capture cost is \$55.65 per tonne. Key parameters listed in the summary table below.

Summary of Base Case (0.5mpta CO_2)

Item	Quantity
Debt/Equity Ratio	70:30
Weighted Average Cost of Capital (WACC)	12.30%
Electricity price, USD (INR) /kWh	0.09 / 6.35
Steam price, USD per tonne (urea plant)	23.50
Urea sale price, USD(INR) per tonne	270 (19,519.06)
Carbon price, USD per tonne	0
CAPEX	US$365.43 million(INR26,417.98 million)
OPEX(per annum)	US$167.35 million(INR12,098.23 million)
Revenue, USD (INR) per annum	183.60 million(INR13,272.96 million)
NPV	Negative
IRR	0.01%
Carbon credit needed(biomass case), USD per tonne	85.80

The study also looked at an advanced case where a 1 Mtpa CO_2 is captured and utilized. The advanced case benefited from economies of scale and yielded slightly better NPV and IRR (2.09%).

Based on above analysis, the study identified several key parameters which impact on project financial viability (parameters listed in table below).

Parameter	Range (base case)
Urea price, US$ per tonne	270 – 310 (270)
Carbon credit value, US$ per tonne	10 - 50(0)
Ammonia price, US$ per tonne	270 -320 (300)
Electricity Tariff, $ per kWh	0.04 – 0.07 (0.09)
Cost of CO_2 capture, USD per tonne	50.08 -60.67 (55.65)
Steam cost, US$ per tonne	22-25 (23.5)
CAPEX, variation	-20% - 20% (0)
Rate of Inflation	2% - 6% (4%)
Construction period, year	3-5 (3)

Sensitivity analysis of key parameters was performed, including urea price, cost of CO_2 (capture cost), electricity tariff, rate of inflation, construction period, and carbon credits. As expected, lower cost of CO_2, lower electricity tariff, higher rate of inflation, and higher urea price would result in more positive financial feasibility. Construction time overrun has insignificant impact on project returns partially due to the long operating period of the CCU project. Wherever applicable, some form of carbon credits may significantly improve project bankability. With a credit price of US$50 per tonne, the project IRR is 8.24%. Additionally, to achieve more emission reductions for the CCU plant, biomass (a carbon neutral energy source) is recommended for steam boilers. Biomass is more expensive than coal boilers which results steam cost increase. With the inclusion of biomass boilers for the Base Case, a per tonne carbon credit of **US$85.80** and **US$58.00** are needed for the 0.5mtpa plant and 1.0 mtpa plant respectively to achieve an IRR of 20%.

Under the standard conditions assumed, financial assessment indicated low return on investment. With the steep increase in urea price in Indian market and the availability of low cost onsite electricity, the project may yield positive NPV and an IRR more than 20%.

In consultation with DCBL, this study also looked at Viability Gap Funding required to reach an Equity IRR of 20% (a typical return on investment in Indian cement sector). At a **urea price of**

US$325 per tonne and an **electricity tariff of INR3/kWh**, no VGF is required, and the project can achieve a NPV of US$112.32 million and an IRR of 20.33%. VGF funding will be required when urea price is lower than US$325 per tonne.

Conclusions and suggestions

Based on the preliminary technology and economic assessment, it is found that a large CCU project (0.5-1.0 mpta) can be implemented with commercially available technologies at an Indian cement plant.

However, there are a few challenges and opportunities to the commercial viability of such project. Urea price (greater than US$325 per tonne) is critical to the bankability of the project. Operational costs (electricity, steam, CO_2 capture etc) need to be reduced compared with the Base Case. Biomass-based boilers and renewable electricity can substantially increase carbon abatement.

Therefore, the project team would make the following tentative suggestions:

- To achieve long term climate change targets, cement companies should invest in emissions reduction technologies to reduce costs for carbon capture technology and CO_2 utilization technology and build up expertise in CCUS.
- Cement sector should look at various pathways and carbon-neutral energy sources which align with the net zero trajectory.
- Cement sector may explore policy incentives or carbon market incentives to support their investment in emissions reductions if the current price poses challenges to financial viability of the project.

I. Introduction

Global cement sector emits around 7-8% of the global total emissions. Cement production process emissions have few clear alternatives, and this sector is considered as one of the hard-to-abate sectors. It is widely acknowledged that CCUS technology has an essential role in reducing process emissions from cement production.

Dalmia Cement (Bharat) Limited, one of the leading cement companies in India, has announced to become carbon negative by 2040. Carbon capture and Utilisation (CCU) is one of the key lever identified by the organisation to reach towards this goal considering 55-60% GHG emissions in cement plant are attributable to cement process. The company is willing to set-up a large scale demonstration CCU plant in its Ariyalur cement facility. This study is being commissioned to assess the techno-economic evaluation of the CCUS options in the Ariyalur cement factory of Dalmia Cement with support from Asian Development Bank (ADB)

The Project commenced on 6th November 2020. The final completion date is set as 1st March 2021 and has since been extended 15 June 2021.

This project conducted a techno-economic evaluation of CCU options in the Ariyalur cement factory of Dalmia Cement. A final report has been prepared on the prefeasibility of deploying CCU at the Ariyalur cement factory.

This final report covers the following topics:

- Carbon capture technology review and development trend analysis
- Carbon capture plant conceptual design and assessment
- CO2 Utilization technology review and development trend analysis
- CO_2 utilization conceptual design and assessment
- Civil engineering design
- Environment assessment
- Financial assessment
- Conclusion

II. Carbon capture review and conceptual design

Prepared by Devika Wattal and Guido Magneschi

Section outline

1. Review of carbon capture technologies in cement industry

1.1 CO_2 Emissions in the cement industry

The global production of cement reached 4.2Gt in 2019 (Edwards, December 2019). India is the second largest cement producer in the world after China and accounts for over 8 per cent of the global installed cement capacity as of 2019. In India, cement production reached 334.48 million tonnes (MT) in FY20 and is expected to rise between 5-7 per cent in FY20, amounting to 550 MT per annum, due to increase in demands for roads, housing, commercial and industrial construction (IBEF, 2020).

The Cement industry contributes to about 8% of the global CO_2 emissions. With increase in concerns regarding global warming and the availability of CO_2 emissions from the cement industry the need for lowering the cement industry footprint has led to exploration of various CO_2 capture processes that will be specific to cement industry.

1.2 Status of CO_2 capture in Indian cement industry

In 2018, World Business Council for Sustainable Development (WBCSD)'s Cement Sustainability Initiative (CSI) in India launched its "**Low Carbon Roadmap for Indian Cement Industry**". And the results from this Status report shows a 5% reduction in direct CO_2 emission intensity and 6.8% reduction in CO_2 emission intensity including onsite or captive power plant (CPP) power generation in comparison to the 2010 baseline. Furthermore, alternative fuel use reflected by Thermal Substitution Rate (TSR) has increased by 5 times from 2010 to 2017 and more than 1.2 million tonnes of alternative fuels were consumed by cement sector in 2017 ((CSI) W. C., n.d.). These encouraging results are credited to the increased use of alternative fuel and blended cement production, coupled with a reduction in clinker replacement factor. However, the study also shows that significant efforts will be needed to meet the 2050 objectives of 40% reduction.

Looking at the performance of India's cement industry between 2010 and 2017 with respect to emission reduction measures, the country currently demonstrates a promising low-carbon future for the cement industry. From improving energy consumption patterns during the production process to increasing use of alternative fuels through recovering energy from a range of waste streams, the Indian cement industry is gradually positioning itself to be at the heart of a circular economy. But this is not all, over the last couple of years India's is also keen on implementation of Carbon Capture and Storage (CCS) and Carbon Capture, Utilisation and Storage (CCUS) to promote industrial CCS and CCUS projects. It is pertinent to note that such ambitions are attainable only with CCS/CCUS technologies (with high Technology Readiness Level (TRL) of 8 or above), a supportive policy framework and appropriate financial resources invested over the long term. ***To achieve the levels of efficiency improvements and emissions reduction set in the roadmap to 2050, government, industry and the finance community must take collaborative actions.***

This chapter evaluates the state of the existing technologies currently being deployed for CCS by the cement industry all over the world. Data from various research papers and patent sources is collected and assessed specifically for the cement industry.

1.3 Importance of CCS in cement industry

CCS/CCUS is becoming an emerging approach for CO_2 abatement, i.e., the CO_2 from combustion of fuels and from the treatment of raw materials is captured and stored or captured and utilised. Due to the size and inherent characteristics for cement production process, the cement sector is a main source for anthropogenic CO_2 that accounts for 8% of global emissions (4). About 65% of the direct CO_2 emissions are process-related and the rest are related to fuel combustion (5).

In general CO_2 emissions from any cement plant are attributed to the following components:

1. Limestone decomposition where calcium carbonate is calcined (heated) to CaO.
2. Energy (about 5 million BTU/metric ton of cement) is needed to heat (drive) the endothermic limestone decomposition.
3. Electrical energy needed for driving process equipment such as the rotary calciner and milling equipment.

Hence, for every ton of cement produced, 1.08 tons of carbon dioxide is generated. The actual carbon footprint depends on the ratio of the clinker to cement, the manufacturing processes (dry or wet method), the level of heat recovery, electricity consumed, the fuel used, the moisture content of the raw materials, and the capacity of the plant, among other factors (6).

According to new research by Swiss Federal Institute of Technology (ETH Zurich) and the Ecole Polytechnique de Lausanne (EPFL), "The construction sector can reduce polluting emissions by applying efficiency measures along the whole value chain, combined with CCS can bring down emissions to net-zero by 2050 (7). In relation to deployment of CCS and the reduction of CO_2 emissions in the cement sector, the current practices in energy efficiency improvement, alternative fuel/raw material use, and clinker substitution are already under consideration and is being deployed in various cement plants across Europe, US, Canada, Australia and China (8).

India realises the potential of CCS in cement industry for future CO_2 reduction and shows its willingness to apply these technologies. The increase in R&D activities and pilot/demonstrations for different CCS technologies all over the world illustrates promising results but, it is still limited to some globally operating companies. As the decisions in favour of CCS are governed by technical and economic feasibility, uncertainties originating from current legal framework and political developments. Hence, the application of CCS will make sense when challenges related to suitable storage sites, the transportation of CO_2, and the legal and political framework supporting CCS are in place (9).

1.4 State-of-art of CO_2 capture technologies

Carbon dioxide (CO_2) capture technologies are classified into three major categories:

- Post-combustion,
- Pre-combustion, and
- Oxy-combustion.

Figure 1 illustrates a snapshot of capture approaches, critical challenges, and developmental state of these technologies.

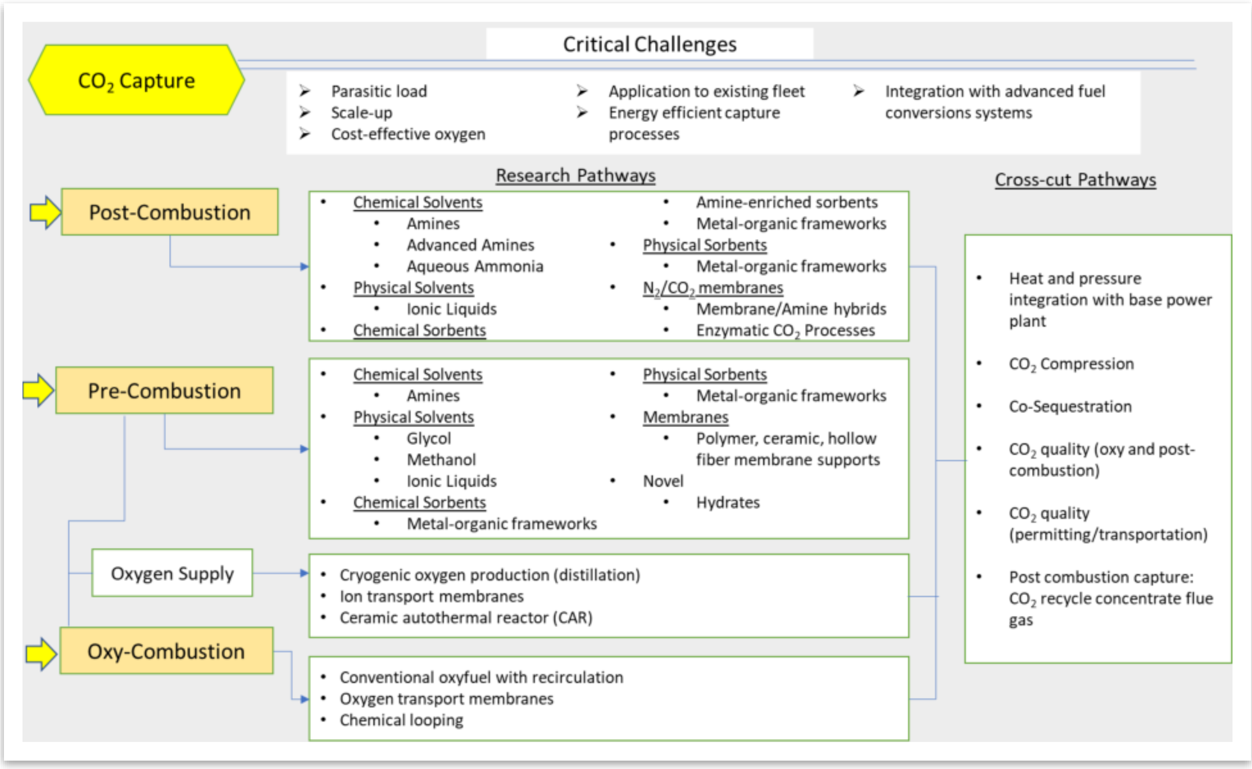

Figure 1: CO_2 Capture Approaches, challenges, and developmental progress. (NET)

Post-combustion Capture systems separate CO_2 from the flue gas stream produced by conventional fossil fuel-fired power plants after fuel combustion in air. In this approach, CO_2 is separated from nitrogen (N_2), the primary constituent of the flue gas. R&D efforts in post-combustion technologies are focused on advanced solvent, sorbent, membranes and calcium looping systems, as well as novel concepts (such as hybrid systems that efficiently combine attributes from multiple key technologies) that have the potential to provide step-change reductions in both cost and energy penalties compared to currently available technologies (NETL Website, n.d.). Chemical solvents (amines) have reached commercial stage for post-combustion capture technologies and are demonstrated at two large scale projects in North America. Chemical sorbents have also reached commercial scale with one proposed plant in Colorado (USA) while membranes are being evaluated at lab to pilot for different flue gas compositions.

Pre-Combustion capture systems are designed to separate CO_2 and hydrogen (H_2) from the syngas stream produced by the gasifier in integrated gasification combined cycle (IGCC) power plants. To facilitate carbon capture and increase the hydrogen production, the syngas is shifted in a water-gas-shift (WGS) reaction to produce additional hydrogen and convert the carbon monoxide into CO_2. Pre-combustion R&D efforts are focused on advanced solvents, solid sorbents, and membrane systems for the separation of H_2 and CO_2, with specific emphasis on high-temperature/novel materials, process intensification, and nanomaterials (NETL Pre-Combustion, n.d.). Chemical and physical solvents have reached commercial stage for pre-combustion capture technologies whereas sorbents and membranes are still being evaluated at lab to pilot scale.

Oxy-Combustion/Oxyfuel combustion is one of the leading technologies considered for capturing CO_2 from power plants with CCS. This involves the process of burning the fuel with nearly pure oxygen instead of air. Conventional oxyfuel with recirculation is already proven at commercial scale and is demonstrated at one plant in Germany.

Another form of CCS that is gaining acceptance is Direct Air Capture (DAC), it focuses on capturing CO_2 directly from ambient air. And the CO_2 is either permanently stored in deep geological formations or used in the production of fuels, chemicals, building materials and other products containing CO_2. Even though this technology is not specifically relevant to CO_2 capture in the cement industry, but it may become useful in case retrofitting plants are not possible in a particular location. There are currently 15 direct air capture plants operating worldwide, capturing more than 9000 tCO_2/year. R&D in DAC is focussed on refining this technology with development of new materials as well as structured adsorbents further to reduce capture costs (Capture).

Several types of post-combustion CO_2 capture technologies have been developed and deployed commercially in the refinery and chemical industries. The main technologies used in post combustion as explained in Figure 1 and are further classified into sub-categories in Figure 2. Absorption technology with chemical and physical solvents, membrane technology with inorganic/polymeric/hybrid membranes, adsorption with chemical and physical sorbents, and chemical looping. These post-combustion capture route Sub-categories are highlighted in the Figure 2 below.

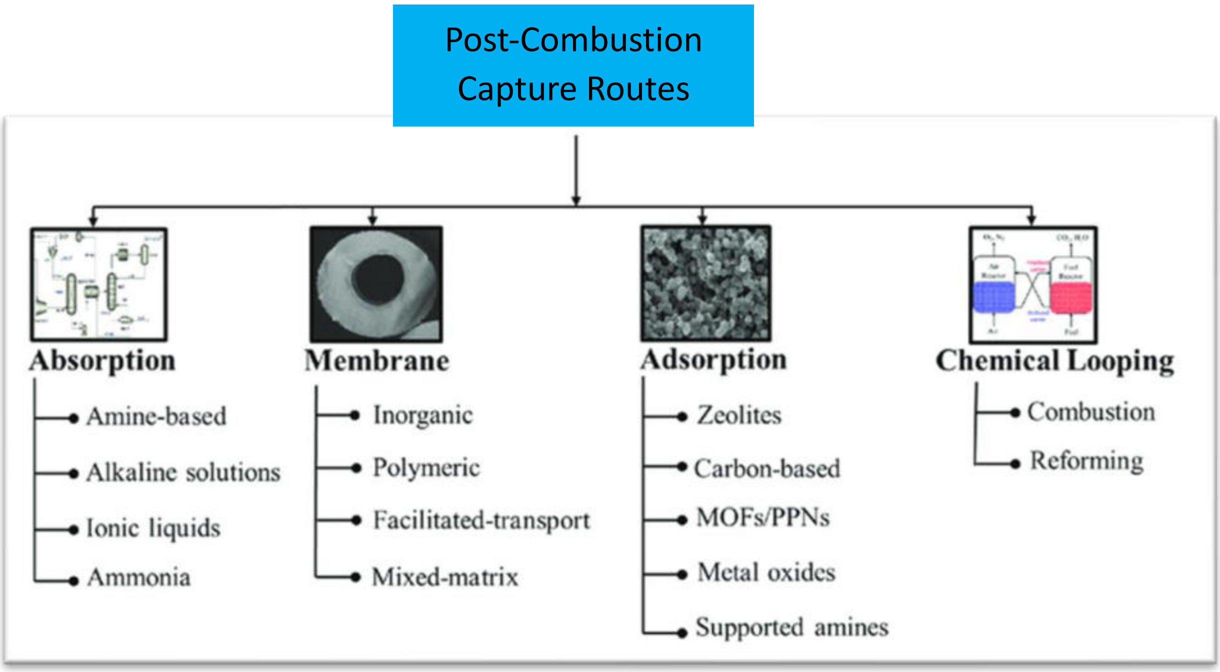

Figure 2 : Overview of CO_2 Capture Routes for Post-Combustion (Ahmen Al-Mamoori, 2017)

Table 1 summarizes CO_2 capture technologies with their associated challenges and opportunities (Ahmen Al-Mamoori, 2017).

Capture Technology	Challenges	Opportunites
Absorption	• Equipment corrosion • Amine degradation • High regeneration energy required • High overall energy penalty • Environmental Impact	• Technology is mature and tested at a plant scale • Improvement in commercially availableabsorption technologies • Use of Ionic liquids • Use of advance amines
Adsorption	• Longterm stability to moisture and impurities • Thermal management • Pressure drop and adsorbent attrition	• Composite adsorbents • Structured adsorbents • Rapid swing cycles • Hybrid membrane-PSA processes
Membrane	• Energy intensive for post combustion applications • High fabrication cost of novel membranes • Not suitable for high temperature applications • Trade-off between purity and recovery • Low selectivity	• Composite hollow fibre membranes • Mixed Matrix Mambranes (MMM) • Hybrid membrane-cyrogenic processes
Calcium Looping	• High pressure operation • Efficient and stable oxygen-carrier materials	• Composite oxides as oxygen carriers • Process-design modifications
Direct Air Capture	• Ultradilute CO2 content • Energy Intensive • Developemnt of durable materials	• Geographically agnostic • DAC coupled with renewable energy sources • Structured adsorbents
Hybrid Capture Processes	• Less Studied • Enhancement of synergy and process optimisation • Developemnt of hybrid materials	• Membrane-distillation • Membrane-PSA • Pressure-Temperature Swing Adsorption (PTSA)

Even with plethora of CO_2 capture technologies available today i.e. post-combustion (including amines, carbonates, chilled ammonia, membranes etc.), pre-combustion, oxy-fuel combustion and direct air capture, post-combustion technologies are the most studied and explored options for CCS technologies. Considering the type of predominant emissions in a cement plant, post combustion and oxyfuel combustion technologies for CO_2 capture are relevant to use and is evident from the research activities, pilot/demonstration plants and patent filings every year. The post-combustion technologies, particularly the reference technology MEA are assessed as an easier retrofit than other integrated technologies due to the main advantage of low impact on the cement production process and the flexibility in placing new equipment at the cement plant. The oxy-fuel and integrated CaL are more integrated with the cement plant hence are more challenging to retrofit (M. Voldsund, 2019).

One major challenge for carbon capture deployment is its relatively high cost for dilute CO_2 emissions. Governments and industry around the world have been supporting R&D in capture technology to reduce costs. 787 research papers were identified in literature for the last 10 years related to CO_2 capture in cement industry. Figure 3 gives the country-wise document count of research papers published in the last 10 years. The research initiatives are highly concentrated in US and UK, followed by China, Germany, and Australia.

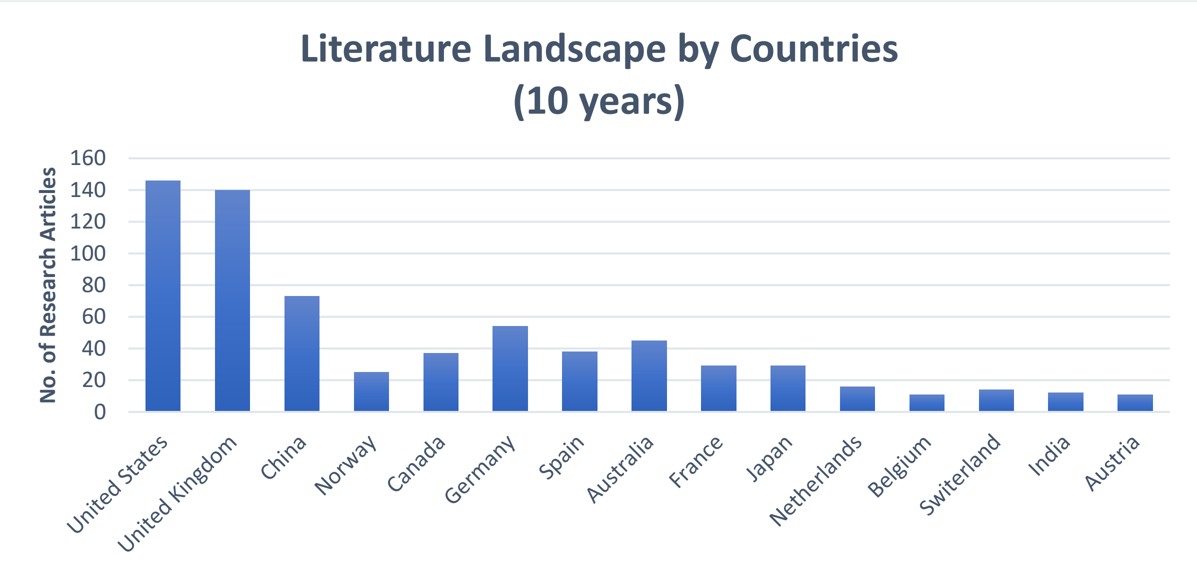

Figure 3: Literature Landscape over 10 years - Country-wise

Most relevant papers found in literature for application of CCS technologies in the cement industry are summarised in Table 2 below.

Table 1: Relevant Research Papers for CO_2 Capture in Cement Industry

Year	Technology	Reference
2014	Four carbon capture technologies (Amine-based chemical absorption, temperature swing adsorption, membrane, and regenerative calcium cycle)	Bjerge and Brevik (Bjerge L-M, 2014)
2016	Post-combustion and Oxy-fuel combustion	Zhou et al. (W. Zhou, 2016)
2017	Post-combustion and Oxy-fuel combustion	Roussanaly et al. (S. Roussanaly, 2017)
2017	Hollow fiber membrane-based processes	Hagg et al. (M. B. Hagg, 2018)
2018	Amine absorption process	Nwaoha et al. (C. Nwaoha, 2018)
2018	Chemical absorption	Dubois and Thomas (L. Dubois, 2018)
2019	Post-combustion MEA absorption CCUS in cement industry	Markewitz et al. (Peter Markewitz, 2019)
2020	Post-combustion (absorption, membranes, adsorption, calcium looping), oxyfuel and direct separation.	Plaza et al. (Marta G. Plaza, 2020)

Similarly, around 743 patents were analysed specific to CO_2 capture in cement for the last 20 years (1 Jan 2001 to 13 Jan 2021) using various patent search engines (such as USPTO, WIPO, googlepatents, espacenet and lens.org) for this evaluation. Figure 4 below gives patents filed as per jurisdiction, with USA being the top jurisdiction followed by Europe, Australia, China and Taiwan.

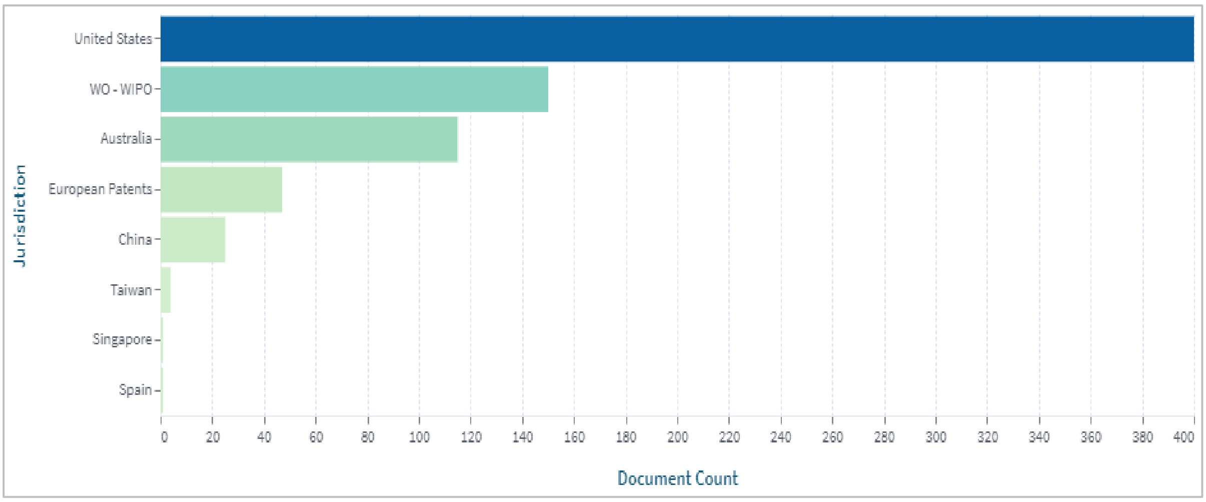

Figure 4: Patent filing as per jurisdiction over the last 20 years

Figure 5 provides an overview of patent filing for CO_2 capture in cement industry for the last 10 years. It is evident that there was a steep increase in patenting activity from 2008 to 2014 with most of the patents related to process efficiency by reducing CO_2 emissions at source and use of post combustion/oxy-fuel combustion technologies for CO_2 capture in cement industry.

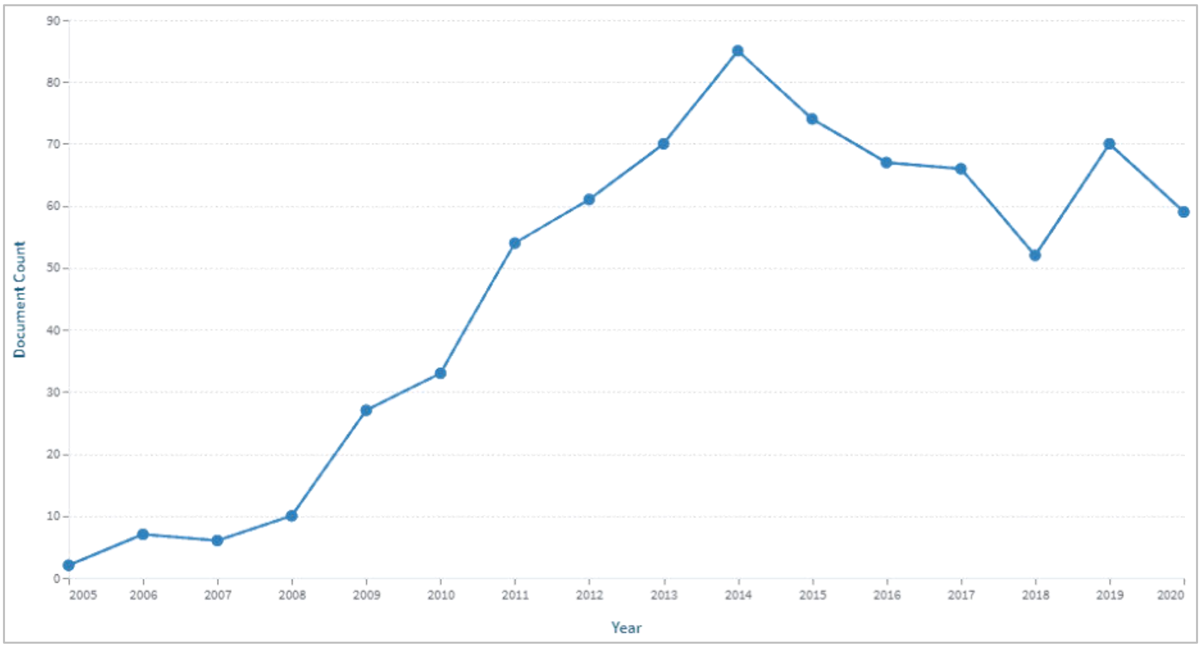

Figure 5: Patent Trends for CO_2 Capture in cement for the last 20 years

There is a decline in the patenting activity after 2014 that picks up again in 2018. This is a result of an increased interest in CCUS technologies and various breakthrough/emerging technologies like new materials for adsorbents including MOFs, fuel cells, CO_2 mineralisation etc.

As per the patents analysed the major players are Exxon Mobil, Air Liquide, Commonwealth Scientific Industrial Research Organisation (CSIRO), Alstom, Aker solutions, Skyonic, ITRI, GE and Anhui Conch Group Co. Ltd. (Forbestechcouncil/2019/11/15, n.d.).

Table 3 shows the most relevant patents for CO_2 capture in cement industry. In the patenting landscape, it is evident that there are two set of patents: one from CO_2 capture companies that claim their technology can be used for cement industry flue gas and one set of patents for the process related patents that aim to reduce CO_2 emission in the cement making process itself.

Table 2: Relevant Patents for CO_2 capture in cement industry

Patent or Application Number	Year of publication	Title and Abstract	Assignee
US 10434469	October 8, 2019	Method for capturing carbon dioxide..	General Electric Technology GmbH
US 8178332 US 7998714	May 15, 2012 August 16, 2011	Process for accelerated capture of carbon dioxide	Akermin, Inc. (St. Louis, MO)
US 10307711 US 10130912	Jan 17, 2019 Mar 9, 2017	Cement kiln exhaust gas pollution reduction	Mercury Capture Intellectual Property, LLC
US 10066834	Dec 17, 2015	Sulphur-assisted carbon capture and storage (CCS) processes and systems	Wojak; Bogdan Vancouver, CA
9808759	Dec 3, 2015	Carbon capture system and method for capturing carbon dioxide.	General Electric Technology GmbH (Baden, CH)
WO2013042088	March 28, 2013	Heat Integration of a cement manufacturing plant with an absorption based CO_2 capture process	Alstom Technology Ltd.
CA2705857C	August 30, 2016	Systems and methods for capture and sequestration of gases and compositions derived therefrom	Rutgers State University of New Jersey

Both the research and patent landscapes are focused on ***amine-based CO_2 capture, followed by fewer studies on calcium looping, oxyfuel, membrane-based technologies and direct-air separation capture.*** Other than these majority of patenting activity also focus on process improvement in a cement plant illustrating reduction of CO_2 emissions at the source by improvement in clinker substitution, use of alternative fuels and kiln electrification. Over the years research and industry are trying to reduce cost of CO_2 capture so that it can be implemented at all levels.

1.5 Existing demonstration plants for CO_2 capture in cement industry

Plaza et al summarizes relevant information of the CO_2 capture technologies that have been evaluated in the cement sector and the ones that are under planning stage in the last 7 years. It needs to be noted that the difference in energy consumption and cost between various technologies could be due to the different assumptions of the technology developers. ***Costs depend strongly on factors such as the geographical location, the steam source, the electricity mix, the electricity price, the fuel price, and the plant specific characteristics***. However, cost is not the only factor to consider for the retrofit of a cement plant with CO_2 capture. ***The other important factors that need to be considered are***

technology maturity, possible effects over product quality, space requirements, and the need for utilities. Furthermore, introducing a carbon tax in various countries around the world point to change in commercial viability.

Table 2,3 and 4 provides a summary of the existing CCS technologies at different levels of research including bench scale, pilot scale and commercial demonstration scale in the cement industry. Some of pilot and bench scale studies are conducted for evaluating various solvents, integrated processes, and technologies. It also summarizes the current TRL of CO_2 capture technologies in the cement sector: chemical adsorption with TRL 8, followed by CaL (calcium looping) with TRL 7, and TRL 6 for adsorption, oxyfuel, and direct separator; and membranes with the lowest TRL 4.

Amine absorption has reached commercial scale demonstration in the industry and power sector, and hence is considered the most mature technology available. Chemical absorption with liquid solvents in cement sector have also reached the largest demonstration scale in the cement sector, with the SkyMine™ process at the top, with 75,000 t CO_2/y, followed by amine-based Anhui Conch's project, with 50,000 t CO_2/y (Marta G. Plaza, 2020). Table 2 provides the list of commercially demonstrated CO_2 capture plants in the cement industry. It also includes the proposed plants such as Norway's full chain CCS at Norcem's cement plant, Brevik, Norway using Aker Solutions (Knudsen, 2019); LafargeHolcim Cement Carbon Capture at Holcim Portland cement plant, Colorado, USA using Svante's Veloxotherm™ (Svante, n.d.); and LEILAC 2 at Heidelberg cement plant in Western Europe using Calix's Direct CO_2 separation technology (T. P. Hills, 2017).

Table 3 provides a snapshot of various bench/pilot scale plants for CO_2 capture in cement industry with details. This includes major projects like Norcem CO_2 capture, MemCCC, CEMCAP, CO2MENT, ITRI's Calcium looping and CLEANKER.

Table 4 provides testing and R&D for CO_2 capture, but some have not been tested with actual cement flue gas and are ready to be demonstrated at higher scale. These include chilled ammonia process testing at GE's Technology Centre in Vaxjo, Sweden; Svante's technology and process for CO2MENT project, oxyfuel combustion at ECRA's CCS project, and LEILAC in Belgium.

Table 3: Demonstration Scale Plants in the cement Industry

Process	Technology	TRL	Project	Test Location	Operation	Scale of Field Test	Type	CO_2 Capture Efficiency	Cost
SkyMine®	Chemical absorption using NaOH solution	8	SkyMine® Beneficial CO_2 Use Project	Capitol Aggregates' San Antonio cement plant, Texas, United States of America	2015–	76,488 t CO_2/y	CCU	>90%	$125 M (Installation cost)
Amine Scrubbing	Chemical Absorption with amines	8	Anhui Conch Cement project	Anhui Conch's cement plant in Wuhu, China	2018–	50,000 t CO_2/y	CCU	>90%	$10M
Aker Solution's ACC™	Chemical Absorption with amines	8	Proposed Norway's full chain CCS	Norcem's cement plant, Brevik, Norway	2023–	400,000 t CO_2/y	CCS	>85%	NA
Svante's Veloxotherm ™	Temperature Swing Adsorption using proprietary process cycle design	6	Proposed LafargeHolcim Cement Carbon Capture	Holcim Portland cement plant, Colorado, United States of America	2023–	2,000,000 t CO_2/y	CCUS (EOR)	>90%	$150 M $50/t CO_2
Calix's Direct CO_2 separation Technology	Direct separator	6 to 7	LEILAC 2	Heidelberg cement plant in Western Europe	2020–2024	100,000 t CO_2/y	NA	NA	NA

Table 4: Bench/Pilot scale plants for CO_2 capture in Cement Industry

Process	**Technology**	**TRL**	**Project**	**Test Location**	**Operation**	**Scale of Field Test**	**Type of test**	**CO_2 Capture Efficiency**
Aker Solution's ACC™	Chemical absorption using advanced amine (S26)	8	Norcem CO_2 capture project	Mobile Test Unit at Brevik, Norway	2014–2015	450 Nm^3/h kiln flue gas 140–250 kg CO_2/h	Capture	>85%
Membranes	Polyvinylamine based fixed-site carrier membrane	4	Norcem CO_2 capture project	Pilot Brevik, Norway	2014	NA	Capture with Membranes	>85%
Membranes	AirProduct's hollow fiber membrane with Polyvinylamine based fixed-site carrier membrane	4	MemCCC project	Norcem's cement plant, Brevik, Norway	2016	37 Nm^3/h kiln flue gas	Capture with Membranes	>85%
MAL	Perfluoropolymer and PEBAX-based membranes	4	CEMCAP	TNO, Eindhoven, Netherlands and SINTEF Energy Research, Trondheim, Norway	2015–2018	- Tests conducted for N2/CO2 mixtures	Individual components tested separately: membranes and liquefaction	Yet to be established for kiln flue gas
RTI (Research Triangle Institute) solid sorbent technology	Chemical Adsorption with polyethyleneimine loaded on silica in a Temperature Swing Adsorption process	6	Norcem CO_2 capture project	Automated Sorbent Test Rig at Norcem's cement plant, Brevik, Norway	2016	NA	Capture	>85%

Process	**Technology**	**TRL**	**Project**	**Test Location**	**Operation**	**Scale of Field Test**	**Type of test**	**CO_2 Capture Efficiency**
Svante's Veloxotherm ™	Temperature Swing Adsorption using proprietary process cycle design	6	CO2MENT	Lafarge's Richmond British Columbia cement plant, Canada	2019–2022	1 t CO_2/d	CCU	
Industrial Technology Research Institute (ITRI) 's HECLOT	Calcium Looping	7	ITRI's Calcium Looping Pilot	Ho Ping Cement plant, Taiwan	2013-	1 t CO_2/h	CCS	>85%
CaL (fludized bed)	Calcium Looping	7	CEMCAP	200 kW_{th} rig at IFK, Stuttgart University, Germany 30 kW_{th} pilot at INCAR-CSIC, Spain	2015–2018	-	-	98%
Entrained CaL	Calcium Looping	8	CLEANKER	Buzzi Unicem Vernasca cement plant, Italy	2019–2021	1000 Nm^3/h kiln flue gas	capture and mineralization testing	>90%
Oxyfuel combustion	Oxyfuel combustion	6	CEMCAP	HeidelbergCement plant, Hannover	2015–2018	-	oxyfuel prototype testing: clinker cooler and burner	>90%

Table 5: Testing and R&D for CO_2 capture but some have not been tested with actual cement flue gas and are ready to be demonstrated at higher scale.

Process	Technology	TRL	Project	Test Location	Operation	Scale of Field Test	Type of Test	CO_2 Capture Efficiency
Chilled Ammonia Process (CAP)	Chilled Ammonia Process	6	CEMCAP	GE's Technology Center in Växjö, Sweden	2015–2018	-	1) effect of high CO_2 concentration in the absorber 2) Combined DCC and SO_2 absorber 3) Flue gas water wash (but not tested for cement flue gas)	Up to 98%
Svante's Veloxotherm ™	Temperature Swing Adsorption using proprietary process cycle design	6	CO2MENT	DOE-NETL for LafargeHolcim's Portland Cement Plant, Colorado, USA	2020	1 t CO_2/d	Capture with material agnostic process	-
Oxyfuel combustion	Oxyfuel combustion	7 to 8	European Cement Research Academy (ECRA)'s CCS project	HeidelbergCement plant in Coleferro, Italy Lafarge Holcim plant in Retznei, Austria	NA	NA	NA	NA

Process	Technology	TRL	Project	Test Location	Operation	Scale of Field Test	Type of Test	CO_2 Capture Efficiency
Calix's Direct CO_2 separation Technology	Direct separator	6 to 7	LEILAC (Low Emissions Intensity Lime and Cement)	Lixhe, Belgium	2020	25,000 t CO_2/y	NA	NA

As per the statistics collected, it is evident that CO_2 capture in the cement sector is closer to commercial demonstration. Currently, three large scale projects at different stages of development are being evaluated. These are Norway's Longship Project, which proposes to use amine-based Aker solutions' ACC™ technology to capture 0.4 Mt CO_2/y by 2023; Lafarge Holcim cement carbon capture, which uses of the Svante's adsorption-based Veloxotherm™ process to capture up to 2 Mt CO_2/y; and TCC (Taiwan Cement company) (CN, 2019) is developing HECLOT technology to capture 0.45 M tCO_2 by 2025. In addition to these, Calix's direct CO_2 separator implemented in (Low Emissions Intensity Lime and Cement) LEILAC 2 project will also demonstrate direct CO_2 capture at the significant scale of 0.1 Mt CO_2/y by 2024.

While direct separator and oxy-calcination are promising technologies that have great potential to be implemented in new cement plants, the prospects for their use in the retrofitting of existing plants is less likely; considering the age of a cement plant is about 30-50 years (Marta G. Plaza, 2020). Thus, Post-combustion CO_2 capture technologies are the preferred option to retrofit in existing facilities as CO_2 can be captured from the exhaust gas of the cement plant without affecting the existing cement production process provided that enough space is available. Among the available post-combustion technologies, chemical absorption with liquid solvents is the most mature technology till date and has reached the largest demonstration scale at cement plants. Therefore, it seems to be the least risky pathway for the retrofitting of existing facilities (Marta G. Plaza, 2020). Moreover, research in developing new solvent and process development is expected to lead to further cost reductions as the technology deploys in the cement sector, like the technology developments in the power sector.

On the other hand, although with a lesser technology readiness level (TRLs), solid sorbents based post-combustion CO_2 capture processes also show great promise. Svante's adsorption and HECLOT technologies are already on commercial scale development. Further research and development are required to reduce the cost of the capture and hence increase the TRL of emerging technologies to make CCS an economically viable and safer option for cement producers to make net-zero emissions a possibility.

1.6 Technology Providers for CO_2 Capture

Table 7 summarises the salient features of some of the technology providers with cost (it should be noted that these costs are provided by the technology providers) and demonstration scale.

Table 7: Technology providers with Salient Features

Key Players	Capture Technology	Salient Features	Capture Efficiency	Cost	Demonstration Plants
Skyonic Corporation (Texas, US)	Absorption with chemical solvents	• Solvent used is NaOH • CO_2 captured to form sodium bicarbonate	>90%	$125 M (Installation cost for 76,488t CO_2/y)	SkyMine® Beneficial CO_2 Use Project
Aker Solutions (Norway)	Absorption with chemical solvents	• Propriety solvent	>85%	NA	Norcem CO_2 capture project

RTI (Research Triangle Institute) (North Carolina, US)	Adsorption with solid adsorbents	• Non-Aqueous Solvent (NAS)technology • Low solvent regeneration energy requirement • 25% lower CO_2 capture cost than conventional amines	>90%	38.6 €/t CO_2	Norcem's cement plant
Svante (formerly Inventys) Burnaby, BC Canada	Adsorption with solid adsorbents	• Structured adsorbent bed	>90%	$50/t CO_2 for 2,000,000 tCO_2/y	Project CO2MENT demonstrates Svante's CO_2 Capture System and a selection of CO_2 utilization technologies at Lafarge's Richmond, BC, cement plant.
Carbon Clean Solutions Ltd. Mumbai	Absorption using Amine promoted buffer salt (APBS) solvent	• Novel solvent • Demonstration plants in India for CCUS	>90%	$30/tonne cost of CO_2 capture	Plant in Tuticorin Alkali Chemical and Fertilizers Ltd., near Chennai, India
Industrial Technology Research Institute (ITRI) 's HECLOT (Taiwan)	Calcium Looping	• Perfect for cement plants • 75% plant size reduction	>90%	30$/tCO2 (integrated process) for 1t CO_2/y	Y
Calix's Direct Separator	Direct Separator	• Allows for the direct separation of CO2 • Uses Nano active particles with high levels of reactivity	95%	NA	LEILAC – 25,000 – 100,000 tCO_2/yr

For the CO_2 capture, the above list of technology providers may already have partnering companies for EPC or may prefer Dalmia to use their own fabrication/construction partners for the final installation.

It is equally important to consider the supply chain related requirements for raw material a) Flue gas (13.15% CO_2) via pipeline from kiln stack to direct contact cooling tower, b) solvent (either provided by the technology provider or bought locally), and finished product (CO_2 purity of 99.9%) via pipeline to the CO_2 utilization plant. The other important aspects would be infrastructure and logistics cost for the CO_2 capture plant.

1.7 Conclusions and future of CO_2 capture in cement industry

Our findings from this work:

- CO_2 emissions are quite significant in the cement industry.
- Most applicable CO_2 capture technologies for cement industry are post combustion and oxy-fuel combustion technologies (Marta G. Plaza, 2020) (IEAGHG, 2013).
- Post combustion technologies are a preferred option to retrofit into an existing facility. These technologies are most mature and popular choice for CO_2 capture in cement industry around the world as it evident from the large-scale demonstration plants as discussed above.
- Among the post combustion technologies, most mature and demonstrated technologies are amines (absorption with chemical solvents) with TRL of 8, followed by adsorbents with TRL 6, then calcium looping with TRL 7 and lastly membranes with TRL of 4.
- With a lot of research and patenting activity in adsorbents materials (such as amine-based adsorbents, activated carbon, microporous organic polymers, metal-organic frameworks, zeolites, alkali metal carbonates, layered double hydroxides and calcium-based adsorbents etc.) and improved adsorption processes like TSA, PSA, vacuum and temperature swing adsorption or (VTSA), vacuum and pressure swing adsorption (VPSA) and hybrid processes. So, even with lower TRLs of sorbents, it shows great promise with new research initiatives that would lead to better capture efficiency and lower cost in the next 5-10 years.
- Direct capture for CO_2 from air is an emerging technology that shows potential for implementation as it is geographically agnostic and hence can be used in the cement industry in case no other retrofit technologies can be used. As the technology matures and integration with renewable sources are introduced, this might be the future of CO_2 capture in cement industry in the next 10-15 years. However, the cost of this technology will be a challenge in India.

As the technologies mature further resulting in new innovations and process developments, the cost of CO_2 capture will see a cost reduction. And as more and more demonstration plants share their success stories it will motivate others to do the same providing them an added benefit for lowering their carbon footprint.

According to Climate-Neutral Industry summary provided by Agora Energiewende (Institute, 2019), the cement industry will witness an increased interest in CCS (post-combustion and oxyfuel combustion) and CCUS (new binders and value added chemicals) in the coming years from 2025 to 2050. However, CCS and CCUS will still be limited to major players and developed nations. The coming years will witness increase in developing low cost CCS technologies and performance improvement of the current process. We also need to keep in mind that these technologies will be site specific depending on the flue gas quality, regulatory framework, space availability, utilities available, local area characteristics (such as flue gas composition, electricity availability and cost), carbon credits, and the utilisation path for CO_2 captured. In addition, it should be noted that cement plants vary significantly from each other in terms if CO_2 concentration in the flue gas, cost of electricity, availability of waste heat or possibilities for importing steam from external producer. The variability of these conditions will also have a strong impact on the economic performance of CO_2 capture technologies, indicating that the best CO_2 capture option in one cement plant might not be the best in another (S. O. Gardarsdottir, 2019).

As per our evaluation of the different types of CCS technologies, only post-combustion and oxyfuel combustion technologies show great potential for CO_2 capture in cement industry (ECRA, 2018). Even though, the use of amines (chemical absorption) is a well know process that is proven at the largest demonstration scale industrially for CO_2 capture, it has its limitations in terms of energy requirement and solvent degradation/regeneration. Further research in new improved solvents specially the use of Ionic Liquids (ILs) mixed with traditional amines is gaining a lot of interest recently and is evident from the literature. However, this technology is only proven at lab-scale and in with new advances it will be used in membranes and amines, hopefully in the next 10 years.

Also, research and patent trends for the last 10 years show an interest towards solid adsorbent-based technologies that might become mature in the next 5 -10 years. With a great deal of work happening all over the world in developing novel adsorbents, patent filing for adsorbents has also seen a rise in last 5 years. Furthermore, with the rise in global emissions every year direct air capture has gained a lot of momentum for CO_2 capture all over the world. So, direct air capture is a promising technology even though the installation cost is higher as of today but new research methods of using the energy from renewable sources might help in bringing down the cost in future.

Information from various webinars and literature also identifies a couple of emerging technologies that are still in lab-scale such as, electrochemical methods of CO_2 capture, integrated power generation and carbon capture using fuel cells, and CO_2 capture and conversion using solar energy. In comparison to conventional approaches, electrochemical methods might help open new opportunities and low-cost solutions without regeneration challenges while enhancing the extend of CO_2 capture from the atmosphere.

Currently in India, there are no demonstration plants specifically for CO_2 capture in cement industry and Dalmia will be the first to lead such an initiative. Only one successful installation of CCUS by Carbon Clean Solutions Limited in Tuticorin for a Chlor Alkali plant for CO_2 capture and soda ash production.

1.8 Recommendations

While being mindful of the fact that CO_2 capture depends on various factors such as quality and source of emissions, limitations/challenges of the technology selected, status of the plant (new plant or an old plant), local infrastructure (electricity, utilities), and waste generation etc. It is recommended to conduct a consistent technical evaluation of CO_2 capture technologies focussing on emission abatement and energy performance for retrofit in the cement industry.

To choose the best available technology for a specific plant, specific technical and economic evaluations need to be performed. In addition to ***techno-economic evaluation, plant-specific evaluation of more practical properties such as available space, capacity in local power grid and options for steam supply should also be considered.***

We recommend the following retrofit CO_2 capture technologies for a 500,000 t CO_2/year to Dalmia cement:

- Amine based absorption technologies.
- Adsorbent based Technologies

More data should be requested from various technology providers to conduct a site-specific evaluation for retrofitting these technologies and will be evaluated further.

2. Conceptual Design of the CO_2 capture plant

This chapter is divided into three parts:

Part 1: Technical analysis and characteristics of exhaust/flue gas streams

Part 2: Conceptual process design

Part 3: Technology risk assessment and risk mitigation measures

2.1 Part 1: Technical analysis and characteristics of exhaust/flue gas streams

For the technical assessment of the CO_2 emissions from the Ariyalur Cement plant, it is imperative to understand their cement process. Ariyalur Cement Plant of Dalmia Cement was commissioned during the years 2009-2010 and is located in Govindapuram Village, Ariyalur, Tamil Nadu. The total plant area is 112.06 hectares. This cement plant has a single kiln with a five-stage preheater and inline calciner, with an installed capacity of 2.0 MTPA clinker and 3.0 MTPA cement. A captive power plant of 27 MWe capacity is also operated at the site to cater the electrical needs of the plant. It manufactures Ordinary Portland Cement (OPC-43 Grade and OPC-53 Grade) and Portland Pozzolana Cement as per demand though consented for 20% OPC and 80% PPC productions.

Ariyalur cement plant process details

The three major unit operations of cement manufacturing are:

1. Raw milling: the preparation of the kiln feed
2. Calcining and burning or clinkering: the conversion process that takes place within the cement kiln and associated equipment
3. Finish milling: the grinding of clinker to produce cement

Figure 6 illustrates the process flow diagram of a cement plant including the unit operations for milling, calcining, clinkering, and finishing mill.

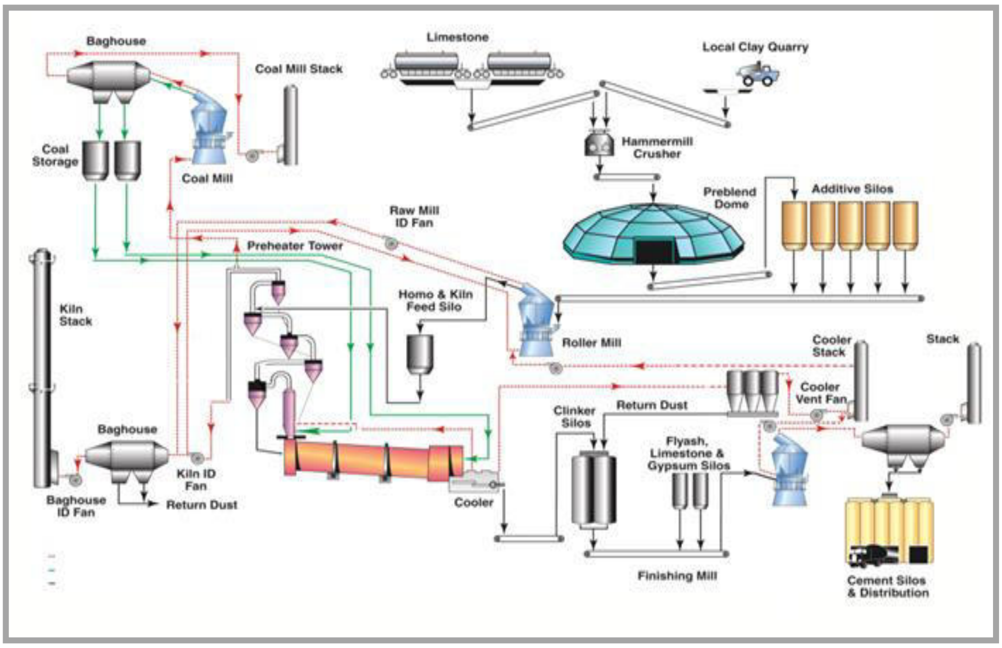

Figure 6 - Cement Process Flow Diagram (source: Dalmia)

Raw milling

The three major components required to produce cement are raw materials, fuel, and power. As raw material, limestone needed to produce clinker is extracted from the four mines of Dalmiapuram through geological research and chemical analysis in specific quantities and proportions. After through a mining process, it is transported to the Ariyalur plant using tipper trucks and crushed in a crusher. Fly ash which is required for producing PPC cement is received from a nearby thermal power plant in the form of dry & wet fly ash as well as from the captive power plant. The major portion of fuel is imported. The distance between port and the plant is 110 km and it is transported by truck. At present, fuel used for producing clinker on heat basis is 95% pet coke/imported coal/lignite and the remaining 5% is alternative fuel such as solid waste mix, spent wash, paper & plastic waste, tyre chips, resin waste, paint sludge, oil rags etc. Other additives required for maintaining the cement quality such as fire clay, blue metal, slag, gypsum etc. are being procured from nearby sources and transported through tipper trucks.

Calcining and burning or clinkering

Burning of the raw mix in a kiln to form clinker involves a four-stage process of evaporation and preheating, calcining, clinkering, and cooling. Evaporation and preheating remove moisture and raise the temperature of the raw mix preparatory to calcining. Calcining takes place at 800 - 900°C and breaks the calcium carbonate down into calcium oxide and carbon dioxide. Clinkering completes the calcination stage and fuses the calcined raw mix into hard nodules resembling small grey pebbles. Kiln temperatures in the burning zone range from 1350 - 1450°C.

Finishing mill

In the finishing mill clinker is ground along with gypsum to produce a fine grey powder called cement. The gypsum controls the rate of hydration of the cement in the cement-setting process. The finer the grind, the more reactive is the finished cement. Rapid-setting cements have smaller particle size than the less reactive, low heat hydration cements. Cement can absorb moisture from the environment leading to some degree of pre-hydration.

Emission sources for Ariyalur cement plant

The Ariyalur plant produces about 1.41 Mton CO_2 per annum. Around 60% (0.84 Mton per annum) of GHG emissions are process related, i.e. due to calcination of limestone 27% (0.38 Mton CO_2 per annum) of GHG emissions attribute to burning of fossil fuels in kilns and calciners and the remaining 13 % (0.18 Mton CO_2 per annum) GHG emissions come from electricity and about 1% GHG emissions come from the fuel use in the cement plant, mining equipment, and on-site equipment/vehicular movement.

The details of total CO_2 emissions from the Ariyalur plant are summarized in table 8 for the last two years as provided by them. It includes the CO_2 emissions from raw materials, kiln fuels (including drying of fuels and raw materials), non-kiln fuels, external power generation, and combustion of biomass.

Exhaust/Flue gas composition and concentration for Ariyalur plant

As discussed above the main sources of CO_2 emissions are the kiln main stack and exhaust from the captive power plant. Tables 8 and 9 provide the detailed composition and concentration of each stream along with temperature, pressure, and flowrates.

Table 8 - Raw Mill/ Kiln Main Stack Flue Gas Characteristics

Raw mill/Kiln Main Stack				
S. No	**Parameters**	**Units**	**Direct (Raw mill stop condition)**	**Indirect (Both raw mill & kiln running)**
1	Oxygen (O_2)	%v/v	13.15	13.60
2	Carbon Dioxide (CO_2)	%v/v	13.20	12.75
3	Nitrogen (N_2)	%v/v	71.15	70.65
4	Carbon Monoxide (CO)	ppm	160.00	139.00
5	Sulphur Dioxide (SO_2)	ppm	8.00	3.00
6	Oxides of Nitrogen (NO_x)	ppm	170.00	161.00
7	Temperature	K	385	357
8	Pressure	mmHg	748	748
9	Moisture	%v/v	2.5	3
10	Flow rate	Nm^3/hr	635,292	685,119

The exhaust/flue gas shows CO_2 concentration to be between 12-13% in kiln main stack. Typical CO_2 concentrations in the flue gas of a cement plant range from 14% to 33 % (GCCSI, 2016); in this respect the Ariyalur plant shows a relatively low CO_2 concentration. This is due to the mixing with other gas streams with lower CO_2 content (eg. from the raw milling section).

It is to be noted that for any solvent-based CO_2 capture process, the current NO_x concentration is high at 160 to 170 ppm, resulting in degradation of the solvent used for capture process. Therefore, it is recommended to reduce it (ideally below 20 ppm) for any solvent based capture process.

Table 9 provides the composition and concentration for the captive power plant exhaust/flue gas.

Table 9 - Captive Power Plant Flue Gas Characteristics

Captive Power Plant			
S. No	**Parameters**	**Units**	**CPP Boiler**
1	Oxygen (O_2)	%v/v	10.86
2	Carbon Dioxide (CO_2)	%v/v	7.11
3	Nitrogen (N_2)	%v/v	80.07
4	Carbon Monoxide (CO)	ppm	36.00
5	Sulphur Dioxide (SO_2)	mg/Nm^3	404.00
6	Oxides of Nitrogen (NO_x)	mg/Nm^3	216.00
7	Temperature	K	378
8	Pressure	mmHg	752
9	Moisture	%v/v	1.96
10	Flow rate	Nm^3/hr	341,509

The exhaust/flue gas shows CO_2 concentration is 7% in captive power plant at 378 K (i.e. 105 °C). The SO_2 and NO_x concentration in the exhaust stream is 154 ppm and 115 ppm respectively.

The next part will discuss the conceptual design for an amine-based system for CO_2 capture at the Ariyalur cement plant.

2.2 Part 2: Conceptual CO_2 Capture Plant Design

2.2.1 Basis of capture plant design

As discussed in the previous chapter, although several technologies exist for CO_2 capture at cement plants, amine-based chemical absorption is today the preferred choice for large scale post combustion capture projects, because of the higher level of maturity of this technology and the availability of different commercial providers. Oxy-combustion (indirect calciner) could also be technically feasible, however its retrofitting would require major (invasive) interventions to the existing cement plant, and for this reason it is not considered a viable option for this project. On the basis of this, the conceptual design of Ariyalur CO_2 capture plant considers the application of an amine-based chemical absorption process.

Selection of CO_2 capture technology

The family of amine-based processes include two options:

1) The so-called "standard" process based on mono-ethanol-amine (MEA) solvent, which is widely applied in industry and often referred to as the baseline reference process, and

2) The proprietary processes developed by vendors, which use a proprietary solvent and might somehow differ from the standard process in terms of configuration and performance.

The standard amine-based solvent used for CO_2 removal from flue gas is a mix of water and mono-ethanol-amine (MEA), typically in the proportion of 30%wt MEA and 70%wt water. MEA is commercially available on the market from various producers and it is not subjected to licensing.

Since the CO_2 capture process provider is not yet defined at this project stage, the conceptual design will be based on a standard process using 30%wt MEA solvent.

Sizing of the capture plant

The CO_2 capture for Dalmia's Ariyalur cement plant shall be preliminarily designed for a capture capacity of 500 kton of CO_2 per year. Although the total plant direct CO_2 emission is higher than 1,500 kton/y, it is decided to aim for a lower capture capacity taking into account the possible limitations in the downstream utilization system of the CO_2.

Flue gas supply to the capture plant

As the flue gas emitted through the kiln stack (i.e. main stack) is the one with the higher flow and the highest CO_2 concentration, the kiln stack is chosen as the flue gas source for the capture plant. The characteristics of this flue gas are summarized in table 9. For the design the characteristics of the direct flue gas, when the raw mill is not in use, are used as a reference.

Spare utilities are available on site

Typically, a capture plant requires utilities such as electricity, cooling water, process steam, demineralized water, and compressed air. From preliminary interviews with plant engineers, it is understood that cooling water and process steam are not available on site. It is assumed that the available plant utilities have spare capacity on site to supply electricity, demineralized water, and compressed air to the capture plant.

Site weather conditions

Typical average, min and max temperatures in Ariyalur are based on weather reports collected during 2005–2015 for Tiruchchirapalli, located 58 km from Ariyalur. [1]

From figure 7, the Max temp is 39°C, the Min is 21°C and the yearly average is 30°C.

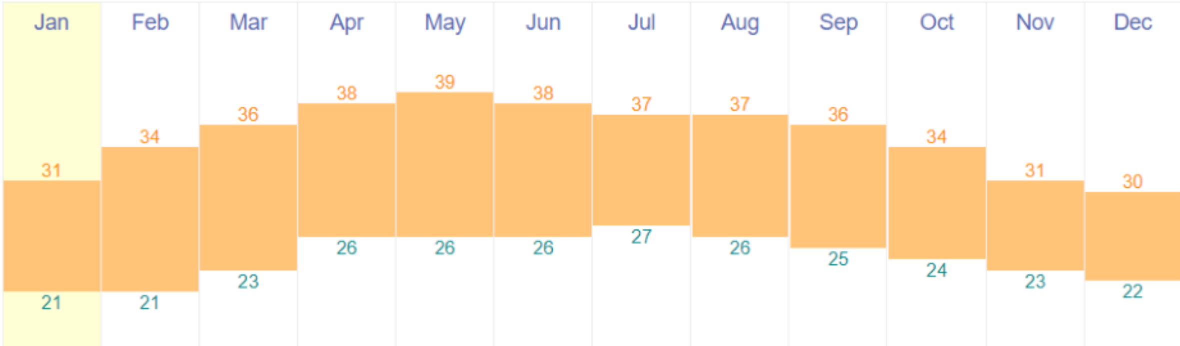

Figure 7 - Typical Temperature Profile for Tiruchchirapalli over a year[2]

Space availability at the site

The total space available for the proposed CO_2 capture and utilization unit is around 100 x 100 m^2 plot, located on the west side of the Cement Mill MCC room as shown in the site layout. Please refer to the civil section of the report for further details.

2.2.2 General description of the CO_2 capture process

The CO_2 capture process is based on a regenerative absorption-desorption cycle as shown in figure 8. The flue gas enters the direct contact cooler and is cooled down in direct contact with cooling water to about 40-50°C. Subsequently, the flue gas is transported to the absorber where it flows upwards, in counter current with the MEA solvent, the carbon dioxide binds chemically with the solvent in an exothermic reaction. Downstream of the absorber, the CO_2-lean flue gas enters a water washer to remove MEA vapor and droplets. The treated gas is then emitted to the atmosphere.

The rich solvent containing chemically bound CO_2 is pumped to the top of a stripper via lean/rich cross heat exchanger in which the rich solvent is heated to a temperature close to the stripper temperature (110-120 °C) and the lean solvent is cooled. The solvent is "regenerated" in the stripper by heating it up to temperature of 110-130 °C at a pressure slightly higher than atmospheric. Heat is supplied to the solvent by the reboiler that is usually heated with low pressure steam.

The CO_2 leaving the top of the stripper is then cooled and passed through a separator where the condensed water is collected and returned to the stripper. The CO_2 leaving the separator is then sent to the utilization unit with a booster fan, after passing through a dehumidification unit to reach a CO_2 purity above 99%.

[1] https://www.timeanddate.com/weather/india/ariyalur/climate

[2] https://www.timeanddate.com/weather/india/ariyalur/climate

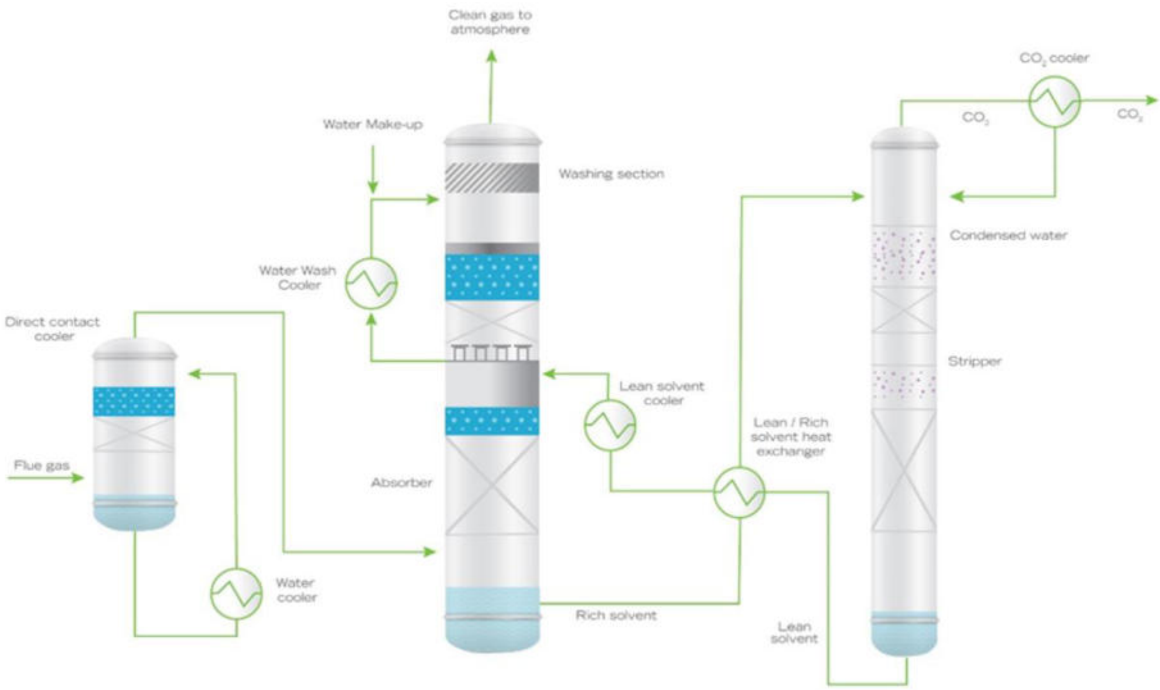

Figure 8 - Scheme of a chemical absorption/desorption process (Source: Global CCS Institute)

Flue gas connection

Flue gas for the capture plant should be preferably sourced from the duct between the electrostatic precipitator and the kiln stack of the cement plant. The flue gas extraction point is connected to the inlet of the direct contact cooler. The connection should include a shutter to stop the flue gas flow in case of emergency or if the capture unit is not in use.

Concerns regarding SO_x and NO_x emissions in the flue gas

The presence of relatively high SO_x and NO_x levels as in Ariyalur flue gas can be of concern in the CO_2 capture plant as they degrade the solvents. This not only hampers CO_2 removal capacity but can also lead to operational problems such as foaming, corrosion, high solution viscosity, fouling and decreased plant and equipment life. Moreover, some of these degradation products have high volatility and can be emitted to the atmosphere both in the vapor and droplet phases and thus could potentially affect the environment adversely. (Source: CSIRO Report, 2012)
The adoption of additional flue gas cleaning measures for the Ariyalur plant has not been considered in the scopes of this study.

Direct contact cooler (DCC)

The DCC (or pre-scrubber) has the main function to cool down the inlet flue gas to the required temperature for the absorber, typically around 40-50 °C. Due to the hot (112 °C) and dry condition of the flue gas entering the DCC, substantial evaporation is expected in the DCC, requiring a continuous make-up of fresh water. To reduce this make-up requirement, recovery options to reduce the temperature of the flue gas at the inlet of the DCC should be considered.

Flue gas fan

A centrifugal flue gas fan shall be included in the system to ensure that the required volume of flue gas is extracted and that sufficient head is provided to overcome the pressure drop along the flue gas pipe, the capture process equipment and the pipe returning the cleaned flue gas to the main stack. The fan shall be either placed at the inlet of the DCC or on the duct connecting the DCC outlet and the absorber inlet.

Absorber

In the absorber the solvent gets in contact with the flue gas and it binds chemically with the CO_2 molecules. The solvent/gas contact area is enhanced using structured packings (e.g. Mellapack M250X) together with proper liquid and gas distributors. A scheme of the absorber, including two washing sections (described in the next paragraph), is shown in figure 9 below.

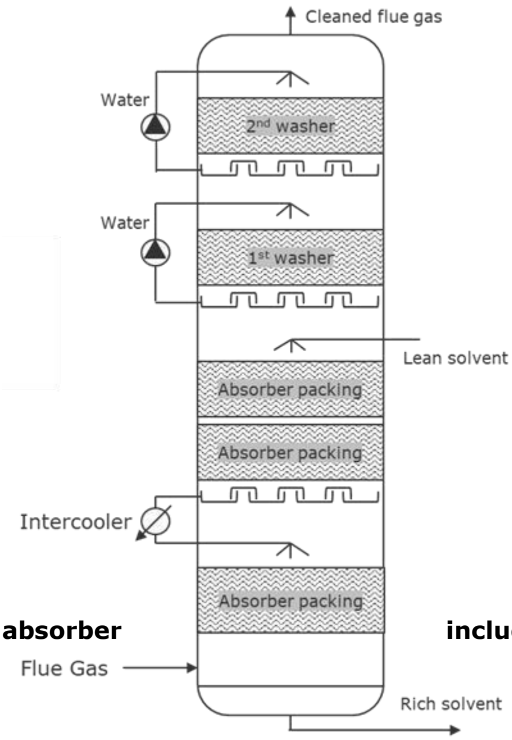

Figure 9 - Scheme of absorber including two washing sections (source: DNV)

Water-washing section

The exhaust gas (CO_2 lean flue gas) leaving the top of the absorber needs to undergo a washing process with water to condense the water and solvent vapour and trap the suspended solvent droplets. This is necessary to avoid that too much solvent, and solvent degradation products, are emitted to the atmosphere. The washing sections basically cools the flue gas through direct contact with the washing water that flows in counter current with the flue gas and has a cooler temperature. The cooling effect makes the solvent vapours condense onto condensation droplets or dissolve into the washing water, therefore reducing the amines molecules dispersed in the gas flow, consequently reducing the emission of amines solvent and amine degradation products.

More than one washing section could be included considered depending on the emission limits as well as proprietary design choices of the technology provider. Typically, one washing sections is sufficient but the final decision depends on the local emission regulations, the quality of the flue gas and the solvent employed; a detailed estimation of the expected emission has not included in this study. A demister shall be installed at the outlet of the upper washing section to remove liquid droplets entrained in the gas stream.

Desorber

In the desorber (or stripper) the rich solvent is heated up to around 120-125°C to release the CO_2 and therefore reduce the loading of the solvent before it is circulated back to the absorber. The desorber is basically a 1-stage distillation column with structured packing. The rich solvent is injected above the packing and flows downwards counter-current with the hot vapour rising from the bottom of the desorber. The structured packing, together with proper liquid and gas distributors maximizes the contact surface between the gas and the liquid.

The lean solvent leaves the bottom of the packing and it is collected to the sump of the desorber. From there the lean solvent is recirculated back to the absorber. Heat in the desorber is provided through a reboiler that in most cases is a kettle type heat exchanger heated by condensing low pressure steam. The lean solvent liquid is circulated through the reboiler and returned to the desorber as vapour. Typically, the reboiler employed in this kind of plant is a shell and tube exchanger of the kettle type.

The CO_2 gas leaving the top of the desorber is cooled in the overhead condenser to condensate most of its water vapour. The CO_2 and the condensate are separated in a separation vessel (ie. overhead condenser) and the water is returned to the desorber.

CO_2 compression & purification

As the CO_2 will be transported via pipeline to the nearby utilization plant, the capture does not include a CO_2 compressor although a boosting fan might be required to overcome the pressure losses in the CO_2 duct between the capture plant and the utilization plant.

The purity above 99% required by the utilization route can be achieved by removing water through an additional refrigeration and/or glycol dehydration after the CO_2 overhead condenser.

Cooling system

Cooling water is required to provide the necessary cooling duty for multiple coolers in the capture plant (see Figure 9). Since cooling water will not be available on site for direct cooling, the plant will be served by an indirect air-cooling system.

The recommended design is a closed cooling water loop, cooled by a single, centralized, dry-air cooling tower. Each single cooler in the process is cooled with the water circulating in the loop, which is then collected and sent to the cooling tower. In this way, it is not necessary to install single air coolers for each process coolers, which is less cost effective.

The limit of such system is the temperature achievable by the cooling system in the summer. In Ariyalur, the temperature in the summer can reach up to 39 °C. This could be a limit for the process requirements, for the water washer's cooler that, depending on the design condition, may require low temperatures (e.g. 20 °C). This limitation shall be accounted during the detailed design to ensure that the capture plant performances are met also during summer months.

Reclaimer

A reclaimer has the function to separate the solvent from the Heat Stable Salts (HSS) that are formed during operation, for instance by reaction of the solvent with SO_2. This is accomplished by boiling the solvent at a temperature around 150 °C and in the presence of caustic soda (NaOH). Reclaimer can be operated continuously or intermittently (e.g. 3 times a year). The sludge remaining at the end of the reclaiming must be removed and disposed or treated as chemical waste.

The reclaimer is typically a thermal reclaimer type, connected to the desorber column. A small slip stream of the lean amine solvent is continuously routed to the reclaimer in regular reclaiming campaigns. NaOH is injected in stoichiometric amounts to react with heat stable salts (HSS), and hence recover molecular amines, which are liberated by boiling the solution and returned to the desorber. The frequency of reclaiming, or the size of the slip stream, depends on the rate of degradation of the solvent. For a flue gas like the one of Ariyalur, with relatively high content of SOx and NO_x, a high level of reclaiming is expected.

Steam generator

Since process steam is not available on site, a steam generator must be added in the plant design to guarantee sufficient steam supply to the reboiler of the capture plant. Typically, the reboiler is designed to use the latent heat of steam condensation, for this reason the steam generator must be designed to supply saturated steam for reboiler in the range 130-140 °C. If a reclaimer is used, the steam generator should also be able to supply saturated steam in the range 180-190 °C during reboiler operation.

It is assumed in this study for simplicity that the steam generator will be fuelled with coal, since alternative options have not been assessed and the extraction of steam from the captive plant is not feasible due to its limited capacity. As the use of coal is counterproductive for the objectives of the power plant, in the next project phase (feasibility study) more sustainable alternatives shall be assessed, among the others: integration with cement plant process, biomass fuel, gas fuel, electric steam generator.

Demineralized water generator

If demineralized (demi) water supply from the cement plant utilities is not feasible, the capture plant shall include a demineralized water generator. The main following uses of demi-water are expected in the capture plant, the actual consumption will depend on the contractor's design and the mode of operation:

- Solvent dilution during first fill-up of the system and solvent make-up
- Water for water washing sections
- Water for rinsing the process equipment after regular cleaning or maintenance work

Solvent storage tank

A storage tank shall be included with enough capacity to hold the volume of solvent required for an initial fill, which is about 3 tons of pure MEA solvent for a 500 kton/yr capture plant. Such amount requires a storage volume of about 5 m^3 indicatively.

2.2.3 Energy & Mass balance

Preliminary dimensioning of the capture unit has been carried out and the main results are presented in the following sections.

Flue gas flow

Flue gas is extracted from the duct of the raw mill/kiln flue gas, between the Electrostatic Precipitator (ESP) and the stack. The flue gas composition used for the dimensioning is given in Table 10.

Table 10 – Flue gas composition

Flue gas composition	value	unit
O_2	13.15	% vol
CO_2	13.2	% vol
N_2	71.15	% vol
Moisture	2.5	% vol

In order to reach about 0.5 Mt of CO_2 captured per year, assuming 90% capture efficiency, a flue gas volume flow of 290,000 Nm^3/h is required.

Main process parameters and assumptions

For the conceptual design and preliminary dimensioning of the capture plant, the process parameters indicated in Table 11 are used.

Table 11 – Flue gas composition

Process parameters	value	unit
Flue gas flow (inlet DCC)	290,000	Nm^3/h
Capture rate	90	%
MEA concentration	30	%wt
Lean solvent loading	0.22	mol CO_2/ mol MEA
Rich solvent loading	0.48	mol CO_2/ mol MEA
Desorption pressure	1.5	bara
Reboiler duty	3.5	MJ/kg_{CO2}
CO_2 purity	>99	%wt
CO_2 delivery pressure	1.5	bara

Mass balance

The characteristic and composition of the main inlet and outlet streams of the capture unit are summarized in tables 12 and 13, the stream numbers are indicated in the process flow diagram depicted in Figure 10.

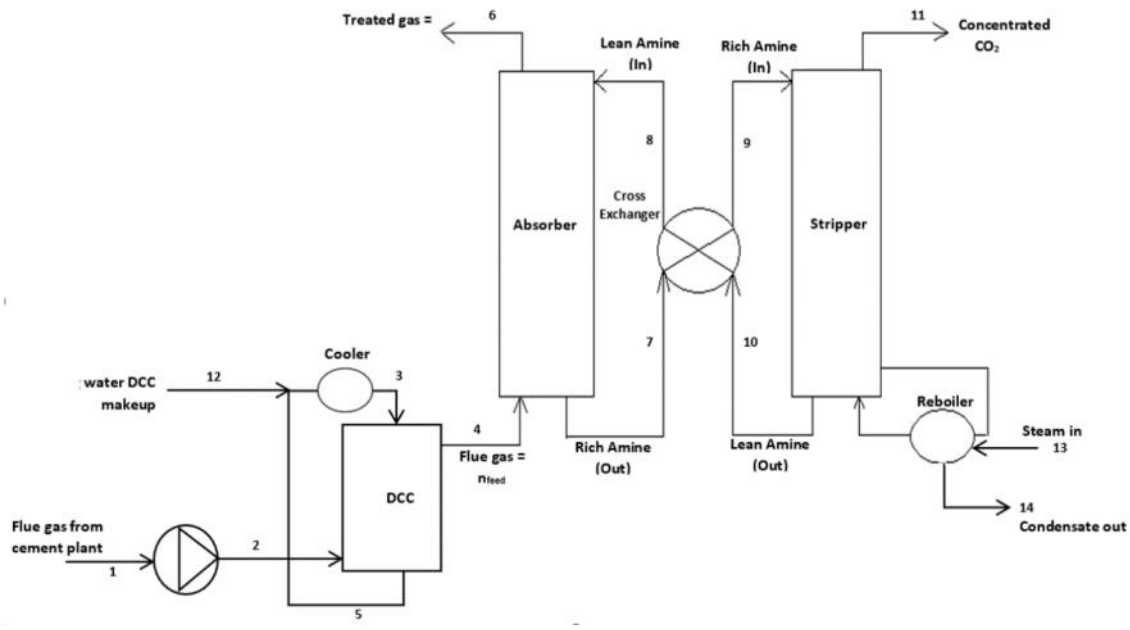

Figure 10 – Process flow diagram of the CO_2 capture process

Table 12 – Inlet streams to CO_2 capture plant

INLET STREAMS

	unit	Flue gas in (1)	Steam in (13)	Cooling water in	Makeup water (12)
Mass flow	kg/h	393,416	107,321	6,316,556	24,535
Volume flow	m³/h	432,788	66,248	6,317	25
Temperature	°C	111.9	140.0	35.0	25.0
Pressure	bar(a)	1.0	3.0	1.0	1.0
Composition					
CO_2	molfrac.	0.13	-	-	-
H_2O	molfrac.	0.03	1	1	1
O_2	molfrac.	0.13	-	-	-
N_2	molfrac.	0.71	-	-	-

Table 13 – Outlet streams from CO_2 capture plant

OUTLET STREAMS

	unit	Cleaned flue gas (6)	Condensate out (14)	Cooling water out	CO_2 product (11)
Mass flow	kg/h	347,571	107,321	6,316,556	70,381
Volume flow	m³/h	338,057	114	6317	39,100
Temperature	°C	50.0	127.0	45.0	40.0
Pressure	bar(a)	1.0	2.5	1.0	1.5
Composition					
CO_2	molfrac.	0.01	-	-	0.99
H_2O	molfrac.	0.12	1	1	0.01
O_2	molfrac.	0.13	-	-	-
N_2	molfrac.	0.73	-	-	-

Reboiler steam supply

For the steam requirement quantification, the steam supply and condensate return conditions are assumed as indicated in table 14. Typical reboiler heat duty for MEA solvent is in the range of 3-4 MJ for every kg of CO_2 captured. Considering an average heat requirement of 3.5 MJ/kg CO_2, the reboiler would require a thermal input of about 66 MW_{th}.

Table 14 – Inlet and outlet stream of the reboiler

	P [bara]	T [°C]
Steam in	3	140
Condensate out	2.5	127

Capacity of the steam generator

With the above steam and condensate condition the steam generator capacity required is about 110,000 kg/h.

Cooling duty

The total duty of the air-cooled system is estimated around 73.5 MW_{th}. The following assumptions for the cooling water temperature: 35 °C for the cold side (yearly average of local air temperature with 5 K temperature difference approach in air cooler) and 45 °C for the warm side.

Power demand

The quantification of the power demand is based on typical requirements for CO_2 capture process using MEA solvents, without CO_2 compression and liquefaction, but including the power to run the air cooler fans. The power demand is estimated to be about 12.5 MW_e.

Make-up water

Due to the hot and dry condition of the inlet flue gas, substantial evaporation occurs in the DCC, requiring a continues make-up of fresh water. The total make-up is estimated to be about 24,500 kg/h. In order to reduce this make-up requirement, the detailed design should consider heat recovery options to reduce the temperature of the flue gas at the inlet of the DCC.

Solvent consumption

Literature indicates for MEA solvent, a loss of 0.45 kg for every ton of CO_2 captured (loss of pure MEA).[3] The loss is due to several factors, including loss to atmosphere, decomposition to ammonia, oxidative degradation, thermal degradation, and reclaiming. For the nominal capture volume at the Ariyalur plant this loss results would result in a yearly make up of about 230 ton/yr of pure MEA solvent.

Dimensions of main equipment

The preliminary estimation of the dimensions of the main equipment leads to the dimension reported in table 15.

Table 15 – dimension of main equipment of the capture plant

Component	Volume (m^3)	Height (m)	Diameter (m)
DCC	193	10	5.0
Absorber (incl. washers)	894	40	5.3
Desorber	357	25	4.3

Plant footprint

The proposed CO_2 capture unit is expected to fit inside an area of 50x100 m^2 (half of the allotted area) on the outer side that is closest to our flue gas source, the main kiln stack. However, the actual footprint will eventually depend on final process layout and eventual spatial restrictions to keep into account during detailed design.

2.3 Part 3: Technology risk assessment and risk mitigation measures

The main goal of the risk assessment is to identify all possible failures of the intended design, so that safeguards and actions required for improving the safety of the process could be considered in the next design stages. The main technology risks associated with solvent based

[3] IEAGHG, 2014. Evaluation of reclaimer sludge disposal from post-combustion CO_2 capture.

CO_2 capture methods are summarized in the in table 16, and possible mitigation actions are suggested.

Table 16 – Summary of main technical risks and mitigation measures

Risk	Mitigation Measures
Variability in the flue gas composition during operation causing process instability	Design capture unit with margins to accommodate possible variations in flue gas composition
High level of impurities (NOx, Sox), dust, aerosols in the flue gas leading to fast solvent degradation	Monitoring flue gas composition and level of impurities through detailed flue gas analysis before detailed design. Understand degradation behavior of the solvent with the given flue gas composition. If necessary, mitigate content of NO_x and SO_x in the flue gas by additional flue gas cleaning.
Emission of amines and amine degradation products to the atmosphere with the treated gas	Use of washing section at the top of the absorber to minimize emissions of amines and amines degradation products to acceptable levels
Significant water losses in DCC due to evaporation	Implement heat recovery option to bring down the temperature of flue gas and reduce the DCC cooling duty (decrease temperature of flue gas at DCC inlet)
Corrosion in major equipment, valves, and pipes if carbon steel is used	Selecting material of construction resistant to corrosion in MEA/CO_2 mixture and acidic gases
Accidental spilling of solvent from piping or equipment	Carbon capture plant to be placed on concrete floor with dedicated drain holes to avoid contamination with soil or rainwater

A comprehensive technology risk assessment and mitigation measures can be conducted by a HAZOP study. But that is out of the scope for this prefeasibility study and can be conducted in detail later by the technology provider.

2.4 Conclusion & recommendations

- A 500 kton/yr CO_2 capture at the Ariyalur plant is technologically feasible using chemical absorption with amine-based solvents.
- The most suitable flue gas source at Ariyalur is the kiln stack flue gas due to the higher CO_2 concentration, although it presents relatively high levels of NO_x and SO_x, which can lead to faster amine degradation. The impact of the solvent degradation and possible ways to reduce it, for instance by the adoption of additional flue gas cleaning measures, shall be further assessed.
- Due to conditions(the high temperature (112 °C) and low dew-point) of the flue gas entering the DCC, substantial evaporation is expected in the DCC, requiring a significant make-up of fresh water. To reduce the water make-up requirement, heat

recovery options to reduce the temperature of the flue gas at the inlet of the DCC should be considered. This include heat recovery and integration with 1) the capture process for reboiler steam generation, 2) with the cement production process and 3) with the CO_2 utilization process.

- As the use of coal is counterproductive for the objectives of the capture plant, more sustainable alternatives to produce steam for the capture plant shall be considered and evaluated, among the others: integration with heat recovery from flue gas, biomass fuel, gas fuel, electric steam generator.

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III. CO_2 Utilization

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Section Outline

Table and Figures

ABBREVIATIONS:

Capital expenditure	CAPEX
Carbon dioxide	CO_2
Carbon capture and storage	CCS
Carbon capture, utilization, and storage	CCUS
Direct air capture	DAC
Enhanced oil Recovery	EOR
Enhanced gas Recovery	EGR
Enhanced coal bed methane	ECBM
Hydrogen	H_2
Operating expenditure	OPEX
Technology readiness level	TRL

Unit	**Abbreviation**
barrel	bbl
British thermal unit	Btu
Celsius (centigrade)	C
kilocalorie	kCal
cubic meter per day	m3/day
hectare	ha
kilogram	kg
kilogram per cubic meter	kg/m3
kilometer	km
kilo ton	kt
kiloton per year	ktpa
kilovolt	kV
kilovolt-ampere	kVA
kilowatt	kW
kilowatt-hour	kWh
liter	L
megawatt	MW
megawatt-hour	MWh
meter	m
metric ton (1000 kg)	t
million tons	Mt
million tons per annum	Mtpa
part per million	ppm
volt	V
volt-ampere	VA
watt	W
year	yr

Section Summary

CO_2 utilization is recognized as one of the key levers for making the cement industry carbon negative. Unlike other manufacturing sectors where CO_2 emissions are mostly from energy usage, major proportion of CO_2 emissions from cement industry are process centric. The mitigation of unavoidable CO_2 emissions, after exhausting all the conventional levers, will need carbon capture, utilization and storage (CCUS) to achieve the goal of making cement industry carbon negative. The fate of the utilized CO_2 and the impact it makes on CO_2 reduction or removal depends on the utilization pathway.

There are multiple pathways for utilization of CO_2. A key challenge is to identify the most sustainable and affordable CO_2 utilization pathway and the product, that is suitable for the particular manufacturing site. The present prefeasibility study assessed various CO_2 Utilization options and followed the quantitative approach of Multi Criteria Analysis (MCA) to arrive at the most techno-economically competitive and environmentally sustainable solution for near term implementation at the Ariyalur cement factory of Dalmia Cement (Bharat) Limited (DBCL). The report provides the methodology for evaluation of various technologies and also provides the medium term and long-term guidance for CO2 utilization, as applicable to Dalmia Cement in particular and the cement industry in general.

The highlights of the study are as follows:

- **CO_2 Utilization Technology overview**

  ADB CO_2 consultants team carried out the extensive overview of CO2 utilization technologies landscape and presented the summary to DCBL.

  - Biological conversion (Fermentation, Photosynthesis): Bio-ethanol, Bio-methanol, Drop-in fuel oil, syngas, methane (to chemicals), algae for Algae for liquid fuel, algae for bio-products. aquafeed
  - Electrochemical conversion: Solar energy + CO2 → Fuel and Chemicals
  - Catalytic / Thermal conversion: Plastics, chemicals, carbonates, Urea
  - Mineralization: Soda ash, cementitious products, sequestration in Basalt rock
  - Use of CO2 without conversion: Beverages, refrigeration, EOR/EGR/ECBM

Technology overview included the technologies with potential for CO2 utilization, market demand of CO_2-derived products, Technology Readiness Level (TRL) and relevance of the technology for implementation in cement industry.

- **Technology Evaluation Criteria and Finalising the product**:

  The multistep method has been used to evaluate promising pathways before arriving at the final product of choice.

  - DCBL provided the MCA parameters and weightage for each parameter.

Parameter	TRL	Capex	Opex	Payback	Market demand	Energy consumption		Capture avoidance	Total
						Electricity	Steam		
Weightage %	40	10	10	10	13	8	4	5	100

Note: Capex, Opex, energy consumption per t of CO2 utilised

- It is worth noting here that the weightage suggested by DBCL to TRL is highest (40%) followed by economic parameters (30 %), totalling 70% weightage towards the overall score.
- TRL is defined on the scale of TRL 1 (Proof of concept) to TRL 9 (Commercial deployment). The time frame required to deploy the technology at commercial scale depends on the TRL. The time frame can be as high as 10 to 20 for TRL 1 to 3 (R&D stage projects) and 7 to 10 years for TRL 4-6 (Development stage projects).
- DCBL indicated the requirement of TRL of 7^{+} for the technology evaluation. That means the technologies which are ready to deploy within 5 years.
- The weightage of over 70% for TRL and economic parameters and minimum requirement of TRL 7 is in line with the intent of implementing the project in near term. It should be also be noted that the technologies which are in development stage with relatively low TRL will get lower ranking in the overall score with the above criteria, even if such technologies may be promising in the medium and long term.
- Taking into account the parameters as proposed by DCBL, ADB consultants developed the detailed methodology for assessing the technologies. Employing this methodology, preliminary screening was done and following options were proposed to DCBL for further consideration:
    - Short term – Soda ash
    - Medium term: Mineralization
    - Long term: Methanol, Methane and Algae
- DCBL suggested to include urea as one of the potential products for further evaluation under short term category. The ranking methodology as developed by ADB consultants was also discussed and agreed upon.
- Detailed MCA analysis has been carried out for six products: Urea, Soda ash, Mineralization, Methanol, Algae for feed and Algae for oil.

The analysis shows:

Product	Urea	Soda Ash	Mineralization	Methanol	Algae feed	Algal Oil
TRL	9	9	8 to 9	7 to 9	5 to 7	5 to 7
Overall Score *	**89**	79	**87**	79	69	75

* Overall score Includes score for all the 8 parameters listed earlier. (pl refer to details in the report)

- The above analysis provides directional guidance towards shortlisting a product for the prefeasibility study. There are, however other project implementation related factors (besides those considered for MCA) which may need to be taken into consideration while deciding the final CO2 derived product.
- In view of the above, the findings of the screening study were shared with the top management of DCBL. There was a general concurrence on the findings of study carried out by the ADB consultant team and much appreciation for coming out with the pragmatic solutions to the complex issue of shortlisting the product.
- DCBL management suggested ADB team to provide more information on the fate of the carbon for the options evaluated to enable them decide the final product.
- This aspect was addressed appropriately by ADB consultant team and presented the details to DCBL.

- As revealed in the MCA study, urea and mineralization are the top-ranking options as per the criteria considered for the evaluation. Though the mineralization is recognised as one of the most promising CO2 utilization options in developed countries, it emerged out during the discussions that deploying the option of mineralization in India may take longer time in order to complete the necessary testing and meeting the procedural requirements for regulatory compliance.
- Soda ash and methanol emerged out as the next best options. ADB consultant team expressed the view that the soda ash has limited market.
- Methanol has a great potential for CO_2 utilization as a long-term solution, particularly in view of the continual fall in the cost of renewable electricity and traction that is getting from the government and research institutes for the hydrogen economy.

During the discussion, DCBL expressed the view that two options – Urea and Soda ash be considered for the prefeasibility study. **After taking into account all the possible factors and organizational priorities, it has been decided to go for the prefeasibility study of Urea production**.

- **Prefeasibility study of CO2 Utilization for Urea**

Urea (NH_2CONH_2), also known as Carbamide, has 46% nitrogen, the highest available in any solid fertilizer. Besides its major use as a fertilizer, urea has other industrial applications in production of cattle feed, melamine and other chemicals. Recently, the feasibility of using urea to mitigate thermal and shrinkage cracking in concrete has been studied and results are promising.

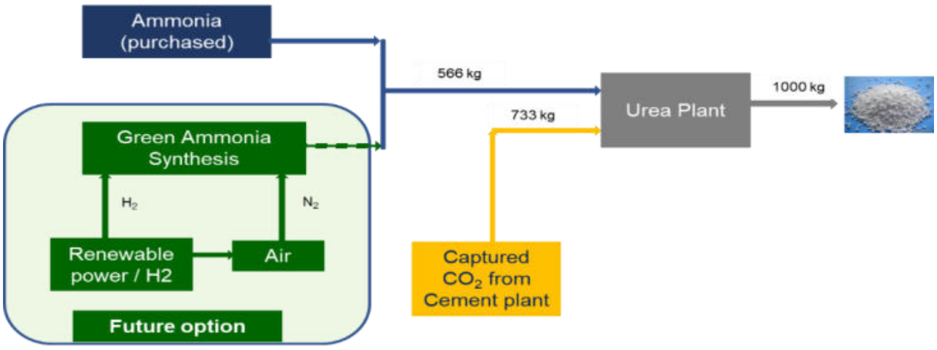
Urea production worldwide is the major utilizer of CO_2 - some 230 mtpa of CO_2 is utilized in 2020 for urea production followed by EOR (130 mtpa). In the years to come, urea market is expected to grow significantly (38% growth between 2019 and 2030). India is one of the biggest importers of urea in the world to meet the domestic demand. In 2019-20, India imported some 11 million tons of urea, which amounts to over 30% of the total requirement. The urea market is ever growing and urea production would remain as one of the high potential options for large scale CO_2 utilization.

Currently, almost all the urea plants worldwide are integrated plants, based on fossil feed (mostly natural gas and coal). The fossil feed is first converted to ammonia. During the production of ammonia, CO2 is generated as a by-product. In the urea section of the integrated urea plant, CO_2 and ammonia react to produce urea:

Reaction 1: $CO_2 + 2\ NH_3 \rightarrow NH_2COONH_4$ (Fast, Exothermic)

Reaction 2: $NH_2COONH_4 \rightarrow NH_2CONH_2 + H_2O$ (Slow, Endothermic)

For the proposed urea plant for the utilization of CO_2 produced at DCBL, purchased ammonia has been considered as an input.



As regards the urea technology, there are mainly three leading licensors: Stamicarbon Netherlands, Saipem Italy and Toyo Engineering Corporation (TEC), Japan. In India, all the three technology providers have reference installations. For the pre-feasibility study, process based on ammonia stripping has been considered. The final selection of a particular technology will be mainly based on its techno-economic competitiveness, as applicable for the project at the time of project implementation.

The urea technology is a matured technology and there is a trend to install the mega size plants to take advantage of a scale. There are plants operating in India and world over, which consume over 1.0 million tons of CO2 per annum. During the screening study, ADB consultant team advised that the CO_2 utilization plant in case of urea be of the capacity which could utilize 1 mtpa of CO_2.

For the prefeasibility study, two cases have been considered:

- **Base case**: 0.5 million tpa of CO2 utilization
- **Advanced case**: 1.0 million tpa of CO2 utilization

The advantage of scale is evident from the following analysis.

Description	Base Case	Advanced Case
CO2 consumption, mtpa	**A = 0.5**	**2 A = 1.0**
Urea production, mtpa	0.682	1.36
Urea plant capacity, tpd @ 8000 hrs/annum	C = 2,050	2 C = 4,100
Opex, $/t of urea	F	0.98 F
Capex, $ m	G = 227	1.54 G = 350

As can be observed, CAPEX only increases around 54 % when doubling the production capacity and maintaining similar OPEX. The cost of purchased ammonia is the determinant towards the total cost of urea. The impact of energy cost (steam and/or electricity) is very less – for example, the increase in steam cost by over 25 % increases the urea cost by less than 2%.

There are urea plants world over, operating as well as in design stage, with a capacity of over 5,000 tpd of urea. As such, there is no technological challenge in designing the plants of required capacity (2,050 tpd or 4,100 tpd). In case of integrated urea plants, ammonia is an intermediate product while in case of standalone urea plant for CO2 utilization, ammonia would need to be purchased. The economics of an integrated plant would be much more competitive as compared to standalone urea plant. Therefore, it is all the more critical to have maximum possible capacity of standalone urea plant using CO_2 as a feedstock from cement industry.

In this context, it should be noted that currently there are five new urea plants (integrated) under implementation in India. Each of these new integrated plants has 3850 tpd capacity. It is advisable to go for such “repeat design” plant which would offer huge advantages of further lowering the overall cost, fast implementation and associated economic benefits. With marginal design changes and performance enhancement of 3,850 tpd plant to 4,100 tpd capacity (8% increase), it would be possible to utilize 1.0 mtpa of CO_2.

All the aspects captured in this executive summary are covered in detail in the report.

1. Introduction

The cement industry is known to have world's one of the most *difficult-to-abate* sources of CO_2 emissions (1, 2, 6). This is mainly due to the fact that 2/3rd of the of the total emissions are raw-material induced process emissions. The cement industry has been working on the roadmaps and strategies to make the industry carbon negative (1, 8, 14, 18). It is now well recognised that the unavoidable CO_2, which remains after exhausting and implementing all the possible conventional CO_2 mitigation measures, will need carbon capture, utilization and storage (CCUS) to achieve the goal of decarbonising the cement sector.

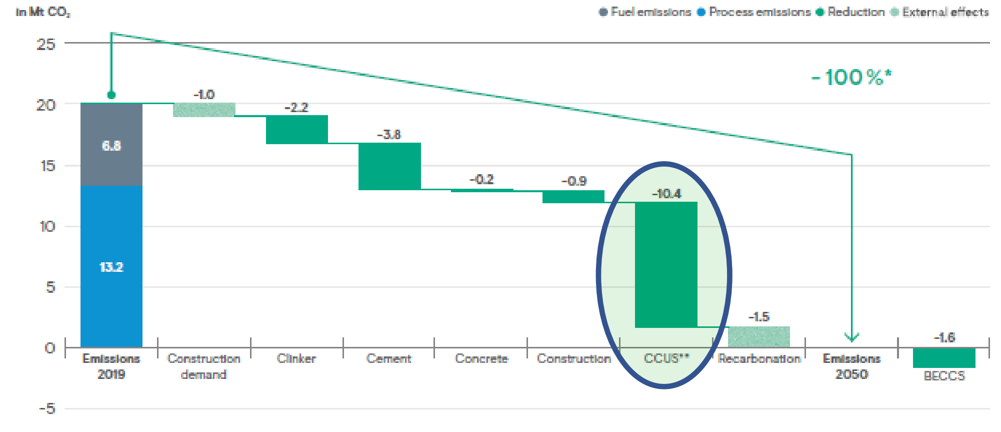


Fig 1: Cement Industry Climate Neutrality Scenario by 2050 (Source: VDZ, Nov 2020, [1])

The present report pertains to carbon utilization part of the CCUS value chain, as applicable to Dalmia Cement Bharat Limited (DCBL) in particular and the cement industry in general.

DCBL is a leading player in the Indian cement Industry and has been in existence since 1939. It is one of the most efficient cement manufacturing companies globally with one of the lowest carbon footprints in cement manufacturing. DCBL is the first heavy-industry sector company in the world to announce 2040 carbon negative commitment in 2018 (20).

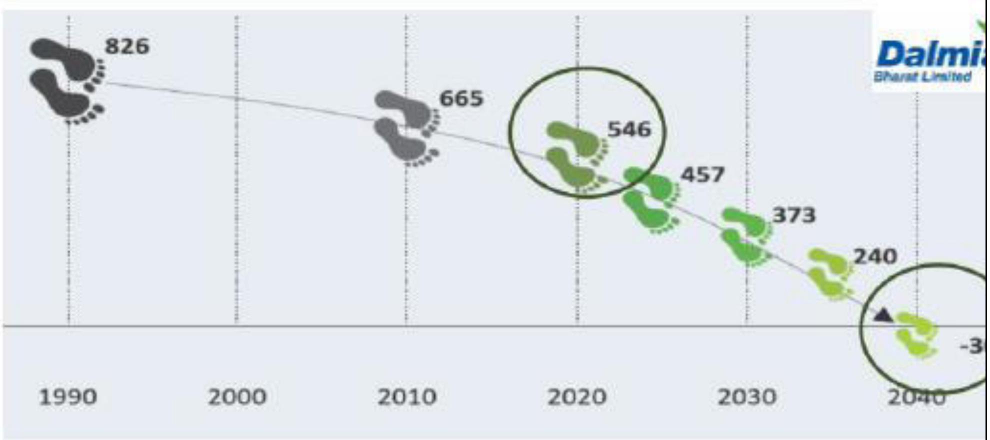


Fig 2: DCBL roadmap for carbon negative scenario (Source: DCBL 2019, [20])

As part of the sustainability initiative, DCBL proposes to set up the carbon capture and utilization (CCU) facility of 500,000 tpa capacity of CO2 (100% purity basis) at Ariyalur Tamil Nadu, India. This capacity is in line with the concept of commercial demonstration plant size plant for new technologies. The commercial scale plants are those with *at least* 500,000 tpa of CO2 capture and utilization (14, 29). The scale of CO2 capture and utilization (as rightly proposed by DBCL) needs to be significantly large to make the meaningful impact on the CO2 mitigation and make the systems affordable for implementation.

Ariyalur Cement Plant of DCBL was commissioned during the Year 2009-10, with an installed capacity of 2.0 million tpa clinker and 3.0 million tpa cement. The plant produces approximately 1.41 million tpa of CO_2 and 60% of this amount is process centric emission due to calcination of limestone. Besides Ariyalur cement plant, DBCL has other 12 cement plants at various locations in India. In year 2019-20, the total cement production from DCBL is reported to be 26.5 million tons. By year 2022, the cement production from all the cement units of DCBL is expected to reach 37.3 million tpa. Global production of cement was 410 million in 2020 (Global cement, Apr 2021).

The CCUS industry is expected to be a multi trillion-dollar economy by 2050, larger than even today's oil industry. There has been growing interest by government, corporates, academia and investors in the development of CCUS technologies. The emerging interest in opportunities for the use of CO2 is driven by several concerns. Key among these is its potential to contribute to climate goals. Other factors include technology leadership, energy security, the anticipated availability of cheap and abundant renewable energy (which could make CO2 conversion routes more economical).

Almost every other day over the last few years, there are thousands of publications claiming the breakthrough in the CCUS technologies. The challenge is to find the most sustainable and affordable technology that is implementable in near term, as suitable for the particular manufacturing site and industry. It is essential to have proper due diligence done of the emerging technologies to validate the claims, for successful implementation at large scale.

The present report is a comprehensive document, covering the review of the CO2 utilization technologies (as on Q1 2021), and prefeasibility analysis of the most suitable carbon utilization pathway, as found through multi-criteria analysis, for implementation at Ariyalur cement plant in near term. The document would also serve as the key information source for developing the holistic CO2 abatement strategy and investment planning at DCBL.

2. Methodology

The multistep method has been used to evaluate promising pathways before arriving at the final product of choice.

- Review of Carbon Utilization Technology
    a. CO_2 Utilization Pathways classification
    b. CO_2 Utilization Potential
    c. Market Potential of CO_2-derived products
    d. Business Potential of CO_2 Utilization
    e. Technology Readiness Levels (TRL) for various technologies
    f. Overview of Potential CO_2 Utilization Pathways
    g. Discussion/interactions with concerned stakeholders.
- Selection of CO_2 Utilization Pathway and Product
    a. Multi Criteria Analysis and Ranking of Technologies to arrive at the most techno-economically competitive and environmentally sustainable solution for near term implementation.
    b. Ranking of CO_2 Utilization Technologies
    c. Discussion and Finalization of CO_2 Utilization Pathway and Product

- Prefeasibility of the final product (Urea in this case)

    a. Background
    b. Design Basis/Assumptions
        i. Plant Location
        ii. Plant Capacity, Annual operating hours
    c. Product specifications
    d. Raw material specifications
    e. Battery limit conditions for feed, products, utilities etc.
    f. Process Chemistry
    g. Process Technology Providers
    h. Process Description
    i. Process Block Diagram
    j. Overall Material and Energy requirement
    k. Off-sites and Utilities
    l. Assessment of operating manpower requirement.
    m. Any other specific requirement to meet the project objective.
    n. Cost estimate and economics:
        i. Capital Expenses (Capex): +/- 30% as applicable for prefeasibility study.
        ii. Operating Expenses (OPEX):
        iii. Revenue: Product revenue and by-product credit
        iv. Preliminary payback calculations (detailed financial analysis of integrated carbon capture and utilization is covered in separate section of the integrated report)

3. Review of Carbon Utilization Technology

It is very pertinent to note that the fate of CO2 utilised, depends on the pathway and the nature of the CO2 derived product. The timeframes of CO2 removal permanence can vary greatly ranging from days to millennia (2).

3.1 CO2 Utilization Pathways Classification

The utilization pathways can be classified as [2]:

a) Cycling
b) Closed
c) Open

Cyclic utilization pathway: In this pathway, carbon moves through industrial systems over varying timescales (days, weeks or months) and recycled back to atmosphere. For example, CO2-based fuels and chemicals. Such pathways can help reduce the CO2 emissions by displacing fossil feedstock. However, most of these pathways do not provide net CO2 removal from the atmosphere. This pathway is shown as A-L-G (red) in Fig 3

Closed pathways: The closed pathway utilizes the CO2 and effectively locks it up forever. For example, CO2 utilization for EOR or mineralization. This is depicted as D (blue) in Fig 3

Open pathways: These pathways involve biological systems in which CO2 is naturally absorbed by plants or algae and turned into biomass. The CO2 may get released back into atmosphere after the use of such biomass for fuel or consumable products as shown in Fig 3 (green pathway)

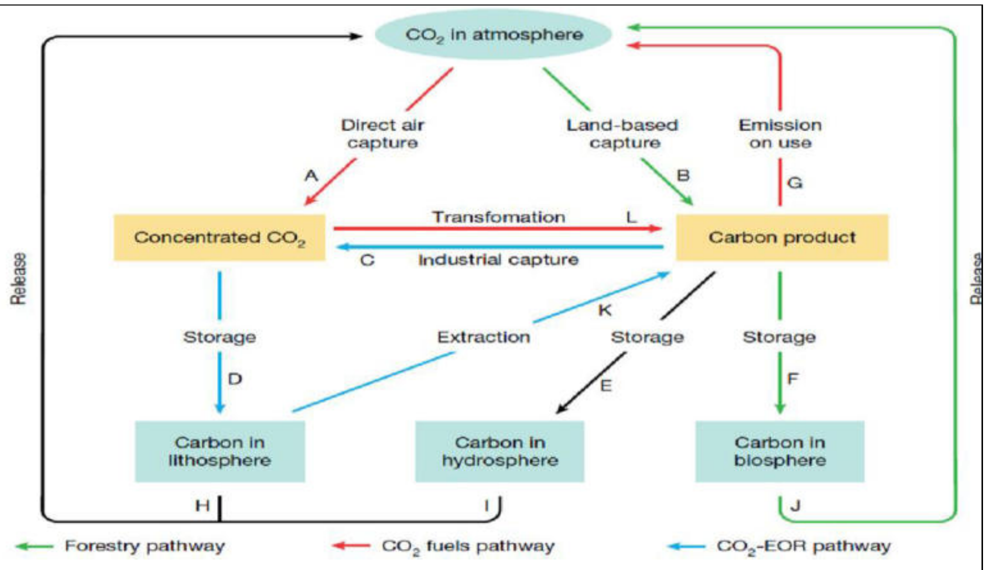


Fig 3: CO2 utilization and removal cycle (Source: Nature 2019)

From long term perspective, the CO2 loop will need to be closed in order to achieve net zero emissions.

CCU techniques are generally classified into two categories:

- Direct use of CO2 as in Beverages, refrigeration, EOR/EGR/ECBM, horticulture, agriculture (cultivation in greenhouses)
- Conversion of CO2: This refers to transformation through biological, chemical and physical processes into different forms that contain the carbon from CO2.

The main CO2 conversion routes are commonly classified into following groups:

- Biological conversion (Fermentation, Photosynthesis): Bio-ethanol, Bio-methanol, Drop-in fuel oil, syngas, methane (to chemicals), algae for Algae for liquid fuel, algae for bio-products. aquafeed
- Electrochemical conversion: Solar energy + CO2 → Fuel and Chemicals
- Catalytic / Thermal conversion: Plastics, chemicals, carbonates, Urea
- Mineralization: Soda ash, cementitious products, sequestration in Basalt rock

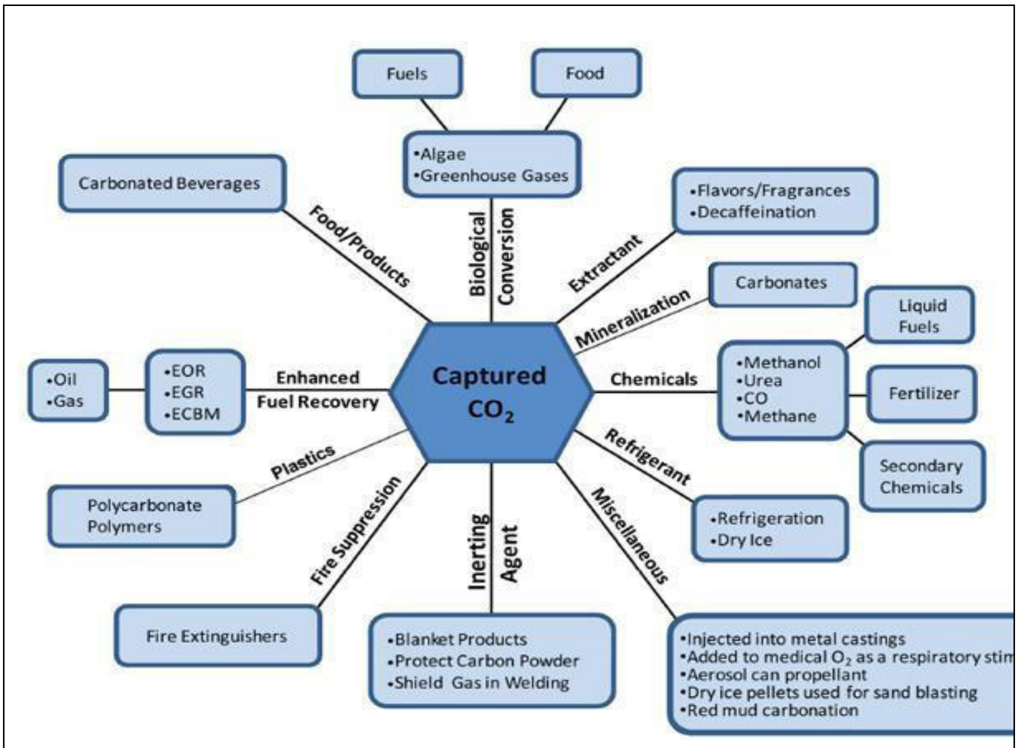


Fig 4: CO2 Utilization pathways (Source: NETL, 2019)

CO2 is a very inert molecule and has low energy level. CO2 conversion to useful product is therefore very energy-intensive process. Minerals are one of the few materials that have a lower energy level than CO2.

In view of very large number of emerging technologies being developed and claims by various developers and research institutions, first screening of the technological options is done using the following criteria:

- CO_2 utilization potential. This depends on the carbon content of the CO2-derived products.
- Market potential of CO2-derived products
- CO2 utilization technology maturity defined as Technology readiness level (TRL)

3.2 CO2 Utilization Potential

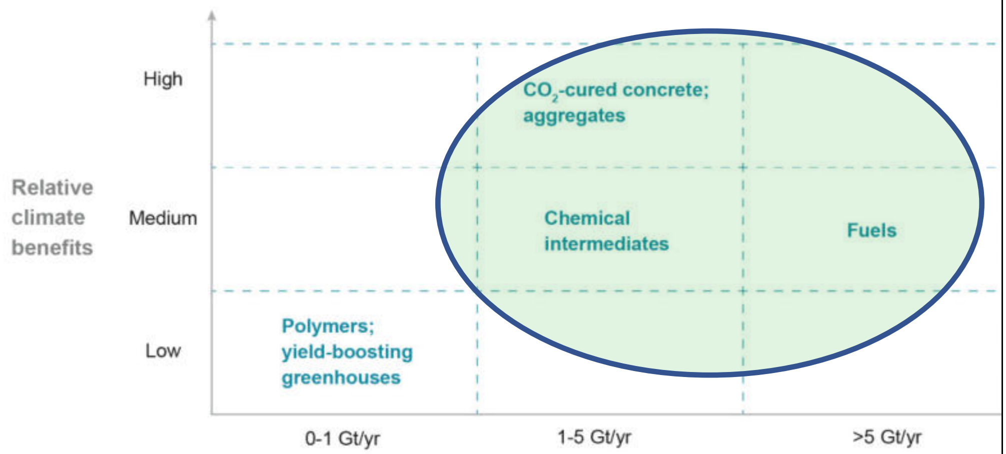


Fig 5: Theoretical potential and climate benefits of CO2-derived products and services (Source: IEA 2019)

As shown in Fig 5, the theoretical potential for CO_2 use and the likely climate benefits show fuels to have the largest potential due to their vast market size. The building materials show the greatest climate change mitigation potential mainly because of the low energy requirements and the permanent retention of carbon in the product (6). It should be noted that the pathways that involve chemicals, fuels have limited potential for *CO2 removal*, whereas pathways that involve construction materials can both utilize and remove CO2.

3.3 Market Potential of CO2-Derived Products

Theoretical potential as depicted in Fig 5 is the maximum limit possible and as it would be appreciated it gives the upper limit for the utilization potential. Following table provides the market potential with potential for CO2 utilization (42, 43).

#	CO_2 Derived Product	Conventional Approach	CO_2 Utilization Mn TPA	Market Size
1	Soda Ash/Baking Soda	Brine, Limestone, NH3	0.4 t/t	63 Mn TPA (2020 Global) CAGR 2 %
2	Cementitious material	Portland cement	Large	~ 1% of replacement of Cement/concr
3	Methanol	**NG** Via Syngas (CO/H2)	62	100 Mn TPA/90 plants. 34 Mn TPA fo chemicals
4	Methane	**Natural Gas**	1920	2560 Mn TPA. NG 2nd largest fossil (
5	Liquid Fuel	Fossil Crude	756	900 Mn TPA
6	Polycarbonate *	Multi-step synthesis	1.6	11 Mn TPA
7	Urea *	CO_2, NH_3	71	150 Mn TPA

Table 1: Market potential of CO2-derived products (Sources: Kohler et al. 2011, Otto et al. 2015

3.4 Business Potential of CO2 Utilization

As regards the business potential in terms of monetary values, CCUS industry is expected to be multi trillion dollar in the coming years, as stated earlier. There has been tremendous investment support from strategic investors for research and development of early-stage technologies. The investment in CCU is said to be in Triple Helix Scenario, meaning good investment opportunity (44). Following table provides one such perspective on the size of the CO2 utilization business potential:

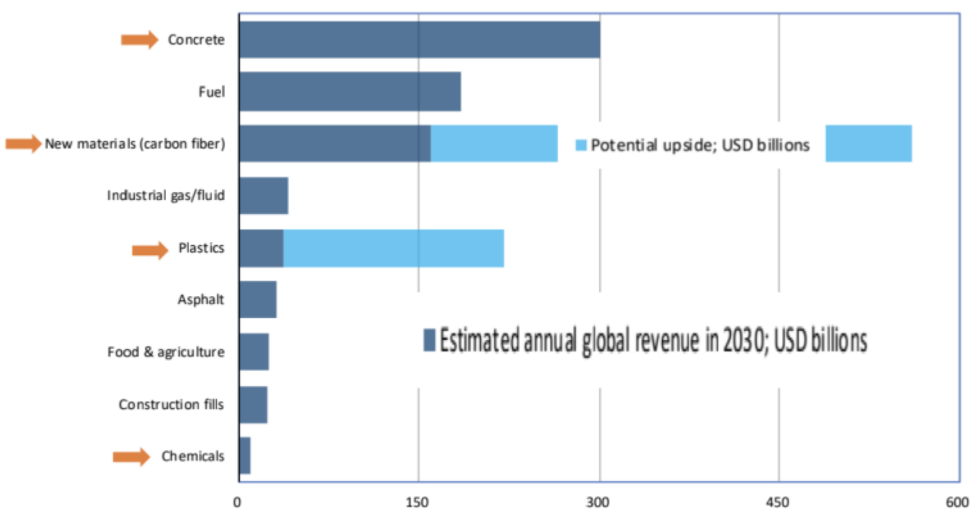


Table 2: CO2 utilization business potential for select pathways (Source: The Global CO2 initiative 2017, Issam Dairaneigh 2020

3.5 Technology Readiness Level

The TRL is one the most critical elements in commercialization of the technology. It indicates the stage in the journey of technology development from concept (TRL 1) to commercialization (TRL 9) of emerging technology (44). The level of maturity can be categorized into three main stages, i.e., the state of Research and Development (TRL 1–3), the Pilot Scale (TRL 4–6), and the Semicommercial/Demonstration Scale (TRL 7–9).

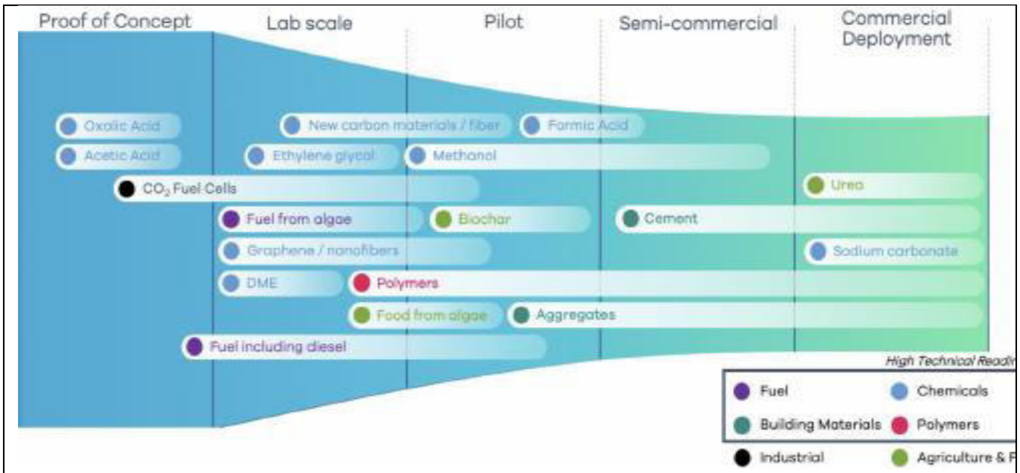


Table 3: Technology Readiness Level (Source: Dairanieh ADB webinar 2020)

It would be noticed from the above table that TRL is presented in the form of a bar of varying length (and rightly so) and not as single TRL point. The main reason being that there can be different pathways to produce the same CO2-derived product and these pathways can be at significantly different levels. It also must be understood that assigning the TRL to particular pathway or product is largely subjective and depends on the knowledge base and understanding of the person or group of persons assigning TRL. To that extent, TRL should be viewed and used judiciously in decision making.

3.6 Overview of Potential CO2 Utilization Pathways

The utilization of CO2 in the form that is available on "As Is" basis without extensive purification and/or conversion is one of the most economical approaches. CO2 capture and its purification to the extent as required for its usage or conversion would be the next best economical approach. Final selection of course will depend on the multiple factors – technoeconomic, environmental as well as societal – as applicable to the given scenario.

The literature is rife with information on various CO2 utilization pathways. There are already many publications available in public domain, covering the overview of various CO2 utilization technologies. In this section, we have covered the review of promising technologies with potential for implementing them in the industrial setup at large enough scale within the reasonable timeframe. We have included the technologies based on the assessment of various peer-reviewed literature on such implementable pathways and personal interaction wherever possible, with the technology developers. A balanced perspective is provided here towards the selection of the technologies for near term implementation and for devising the future strategic planning.

Horticulture:

Direct use of CO_2 for growing vegetables and plants in greenhouses has been practiced effectively at many locations world over. The glaring example of such use of CO_2 for horticulture is in the Netherlands, where Shell oil refinery supplies over 400,000 tpa of CO_2 to over 580 greenhouses (Shell). CO_2 helps enhance plant growth and yields. Another example is supply of CO_2, directly captured from air by Climeworks in their DAC plant near Zurich Switzerland to a nearby greenhouse, which boosted the growth of the plants inside it (45). *These select examples demonstrate that the scope exists for this form of CO2 utilization in an industrial region with greenhouse agriculture in close proximity*.

Water remineralization:

Desalination of sea water or brackish water is widely used to generate potable and water for use in industry and agriculture. Worldwide, there are some 12,000 large water desalination plants. With increasing paucity of potable water, market for desalination plants is likely to go up. The desalinated water needs to be remineralized using complex acidification process. The use of CO_2 for acidification is regarded as more natural and environment-friendly method. Water from low-lime regions or dams also frequently needs the addition of CO_2 (46). This is one of the *relatively new pathways of direct utilization of CO2,* besides already practiced use for beverages, refrigeration, EOR/EGR/ECBM.

EOR:

The direct use of CO_2 for EOR is established and practiced for many years. Conventionally, the intention of EOR is to maximize the amount of oil recovered from the oil reservoir using *minimum amount of CO2* by recovering the injected CO_2 to the maximum extent. In principle, CO_2-EOR can be operated such that, on a life-cycle basis, more CO_2 is injected than is produced upon consumption of the final oil product [2]. If EOR is deployed to maximize CO_2 storage, rather than oil output, then EOR can significantly contribute to net zero scenario.

Biochar

It is estimated that biochar technology has a great potential to sequester the carbon over 100 years (14). It is considered as a ‘close pathway’ on the use of a sustainable and renewable raw material. Biochar can be produced from biomass, agricultural residues, food waste etc., employing thermochemical processes such as hydrothermal carbonization, pyrolysis. The use of biochar as part of soil management, enhances economically valuable agricultural yield. The increased yield also reduces the land requirements, contributing to additional cumulative net emission benefit from those increased yields [2]. Biochar application for soil management is currently at a low TRL and is expected to be commercialized by 2030.

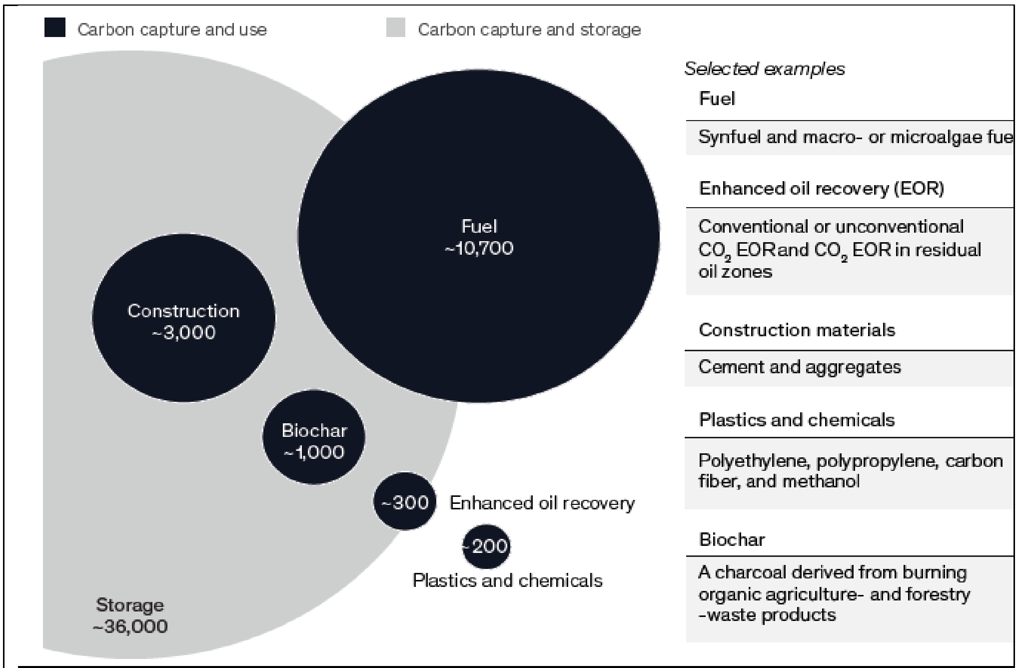


Fig 6: Technical potential of CCUS in 2030, mega tons/year of CO2 (Source: McKinsey)

Microalgae

Algal cells convert sunlight, water and CO2 into the energy-rich biomass through photosynthesis. Algae grow much faster than the rooted plants. Algal production can thrive even with non-potable water, nonarable land and as such seems to be the perfect and longer-term sustainable solution to the problems of climate change, energy security and food security. Algae, can be the source of fuel, food and animal feed given their cure-all characteristics.

For algae cultivation. CO2 with wide range of purity is acceptable. Technically, flue gas with minor pre-treatment and without intense purification can be used for algae cultivation. The need to purify the flue gas or process gas with CO2 essentially arises from reducing the transportation and distribution cost of CO2 to the site of algae cultivation (47, 48).

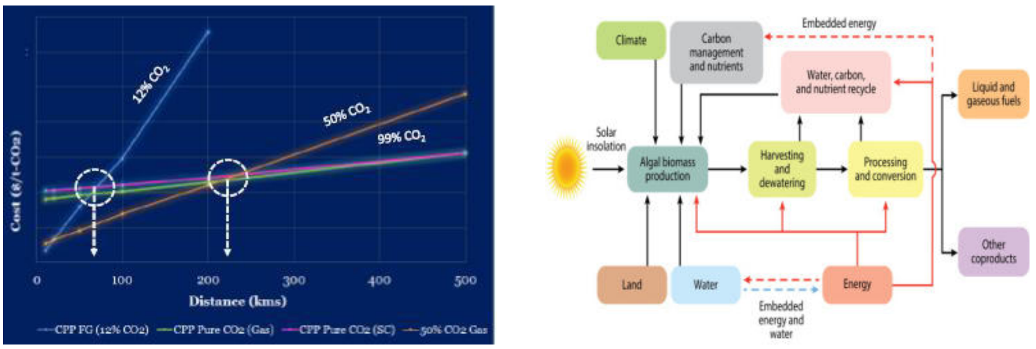


Fig 7: CO2 utilization for algal oil and algal bio-products (Source: Bhujade R, et al. 2017, 2019)

Algal biomass cultivation can be categorized as Bioenergy with carbon capture and storage (BECCS). BECCS provides two distinct services: bioenergy, and atmospheric CO2 removal. Some of the carbon in the biomass is converted to biochar which can then be stored by land application as stated earlier, enabling CO2 removal and making BECCS a negative emissions technology.

In the near term, relying only on oil production from algal biomass is not commercially feasible, if it is having to complete with fossil fuel in economic terms, unless the environmental benefits are factored in. Algae biomass is very good source of high-value products and coproducts. Combining the use of algal biomass for oil, biochar and high-value products will help algal pathway sustainable in the long-term scenario.

- <u>Methane through bioconversion of CO2</u>:

Biocatalytic system operates at moderate operating conditions and can utilize pure CO2 as well gas raw biogas (mix of CO2 + CH4) with 98% carbon conversion to methane (49). Electrochea is one of the technology developers in this domain, having 1 MW plant in operation producing 50 Nm3 of methane per hour. Electrochaea's two-step biomethanation process uses renewable hydrogen to combine with carbon dioxide in the reactor which houses the biocatalyst – a methanogenic archaea. The product that leaves the reactor is renewable methane. Through this process, 500,000 tpa of CO2 can produce 250 million NM3 of methane.

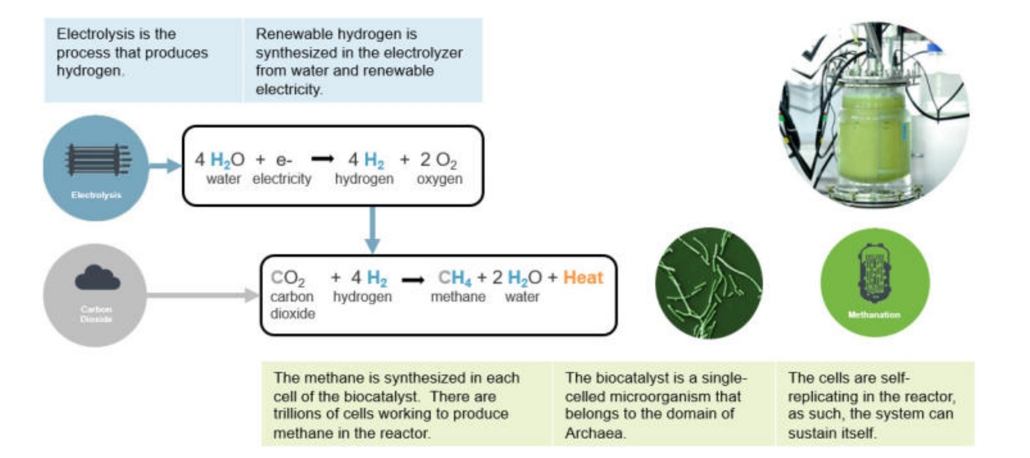


Fig 8: Methane through bioconversion of CO2 Source: Electrochea

- Electrochemical conversion of CO2 to chemicals

The electrochemical conversion of CO2 to fuels and chemicals building blocks (CO, C2, MEG, Ethanol) is a promising technology. Renewable energy is a key in this regard. Some of the leading research start-ups (for example Twelve Carbon Transformation, earlier opus 12) claim that there is no need to have pure CO2. Selectivity of CO2 to CO is reported to be 99%, which is significant.

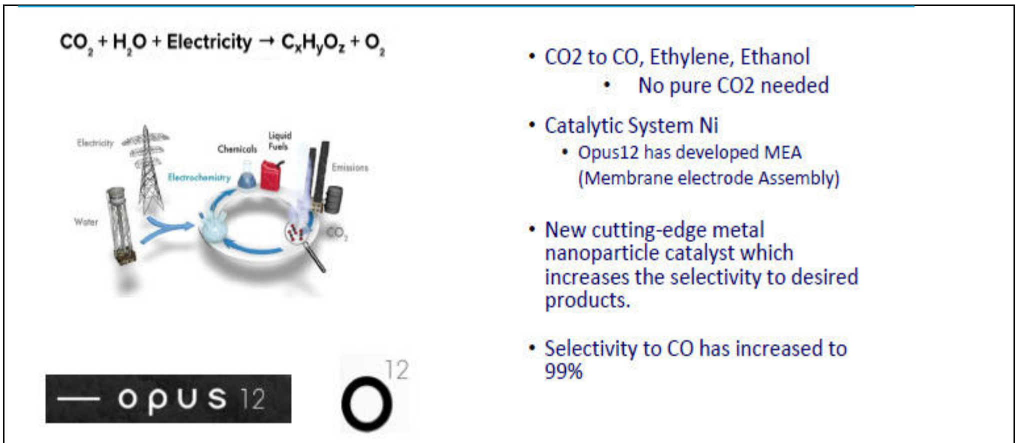


Fig 9: Electrochemical conversion of CO2 to chemicals. Adopted from Opus 12 technology (Source: Twelve (earlier Opus 12), https://www.twelve.co/)

- <u>CO2 to chemicals through SOEC</u>:

The SOEC works at higher temperature (> 700 deg C) which makes it more efficient than conventional electrolysers (17). SOECs can be used for direct electrochemical conversion of steam/water (H2O), CO2, or both into hydrogen (H2), carbon monoxide (CO), or syngas (H2+CO), respectively (17). SOECs can be thermally integrated with proven processes of chemical syntheses to produce synthetic natural gas or gasoline, methanol, or ammonia.

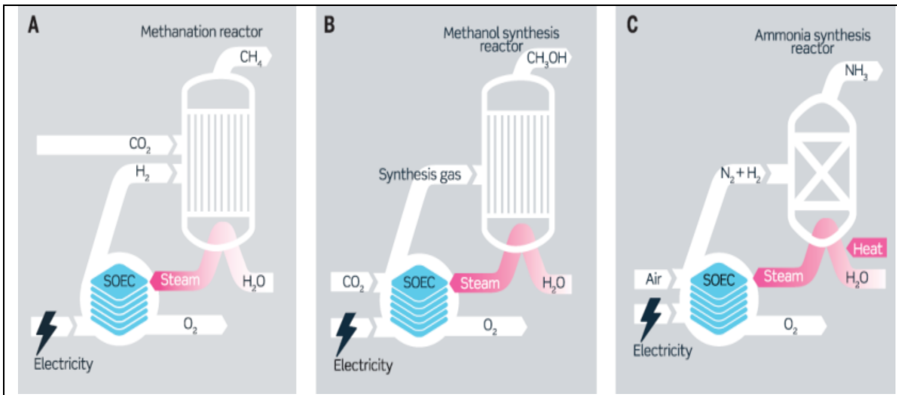


Fig 10: CO2 to chemicals through SOEC Source: Hauch Et al. 2020

SOEC basically consists of three parts: an anode, a cathode and an electrolyte. At the cathode, water molecules are split by a reduction reaction into hydrogen and oxide ions, the oxide ions are transported through the electrolyte to anode where they are oxidised into oxygen (50).

- <u>CO2 to liquid fuel through Solar-thermochemical synthesis</u>

In this approach, concentrated solar energy is used to synthesize liquid hydrocarbon fuels from H2O and CO2 (Sun-to-liquid). A high-temperature thermochemical cycle based on metal oxide redox reactions converts H2O and CO2 into syngas. Sun-to-Liquid company claims that cerium oxide (ceria) has emerged as an attractive redox active material because of its high oxygen ion conductivity and cyclability, while maintaining its fluorite-type structure and phase.

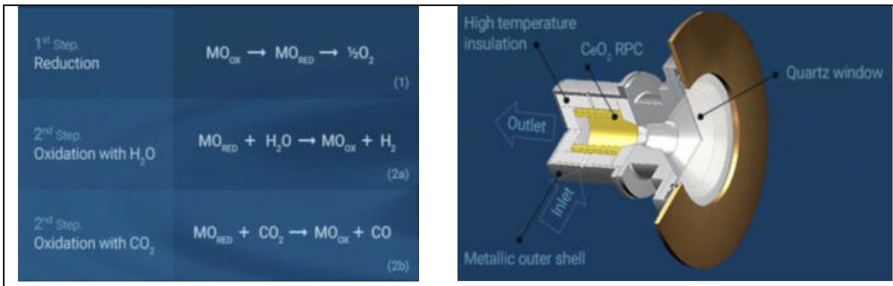


Fig 11: CO2 to liquid fuel through Solar-thermochemical synthesis_Source: SUN to LIQUID

Liquid fuel is best energy career for long haul and aviation fuel. Existing infra structure and engines are usable.

- <u>CO2 to Methanol</u>

Methanol is a platform chemical used in thousands of everyday products, including plastics, paints, cosmetics and fuels.

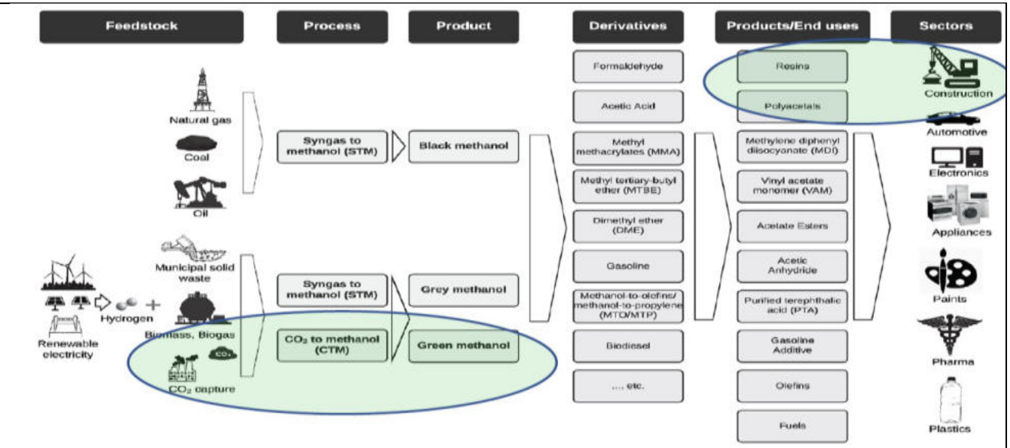


Fig 12: The methanol value chain (Source: Samuel Simon Araya et. al, 2020)

Methanol can be processed to make di-methyl ether (DME), a liquid fuel that closely resembles diesel — existing diesel engines need to be modified only slightly (adjusting compression ratios) to use DME instead of diesel (52).

Worldwide annual production of methanol nearly doubled over the past decade to reach about 98 Mt in 2019. Methanol demand is expected to continue increasing to reach more than 500 Mt by 2050 (IRENA). Currently, most of the global methanol production comes from natural gas and coal.

There are several pathways to produce green methanol – electro-fuel pathway (using H2 from electrolysis of water using renewable energy and combining with CO2), biomass pathway (syngas to methanol) and hybrid of these two pathways (biogenic syngas combined with H2 from electrolysis). Green methanol is considered as one of the two low carbon fuel options for decarbonizing shipping sector, other option being green ammonia.

In India, methanol economy has been given an impetus by the government over past few years. Recently, NTPC, the Government of India undertaking in power generation, has floated the tender in Jan 2020 to set up CO2 Capture, H2 Generation & Conversion to Methanol (composite facility) in aggregator mode at various NTPC power plants in India (the submission date for the proposal was March 30, 2021).

Methanol from CO2 is already demonstrated technically (TRL 7+) at sufficiently large scale. Carbon Recycling International (CRI), the winner of Best CO2 Utilization 2021 award (presented at 9th Conference on CO2 based Fuels and Chemicals held in March 2021), has been developing CO2 to Methanol technology since 2006. CRI's first industrial demo scale plant of 4000 tpa of methanol was commissioned in 2012. The commercial scale plant is planned in China based on CRI technology to produce 110,000 tpa of CO2 to methanol.

However, the challenge is economic feasibility of the process. To produce 1 t of methanol, 0.188 t of H2 and 1.373 t of CO2 are needed. Producing 1 t of hydrogen with a 100% theoretical efficiency requires 39.4 MWh of electricity. In practice, electricity consumption is closer to 50 MWh/t (21). The cost of hydrogen is thus closely linked to the cost of the electricity needed to produce it.

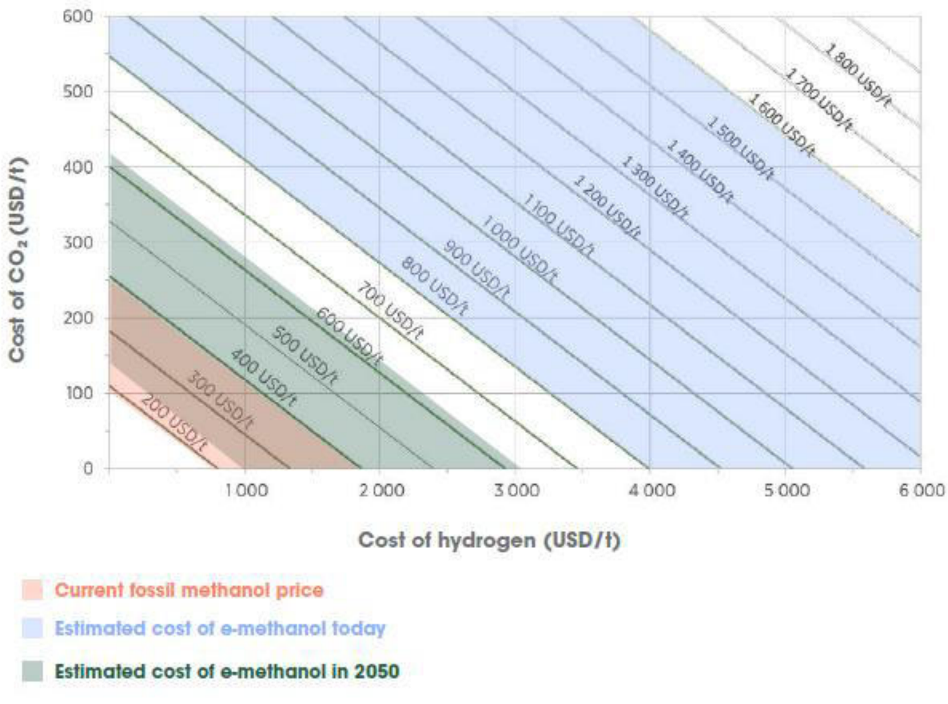


Fig 13: Cost of methanol as a function of hydrogen and CO2 cost (Source: Methanol Institute, Irena 2021)

The US Department of Energy's target for the cost of hydrogen production, $2 per kg of H2, would require carbon-free electricity to cost less than $0.03/kWh (Nature).

In the long term, e-methanol from CO2 and renewable hydrogen using solar/wind energy has a great potential to achieve negative carbon target.

<u>CO2 to other chemicals and intermediates</u>:

Some lab scale prototypes and pilot projects have been reported for the production of other chemicals of interest, such as formic acid, ethylene glycol, phosgene-free polycarbonate using ethylene oxide and CO2 [Asahi Kasei], CO2 conversion into formic acid [DNV], CO2 conversion to produce polyols [Bayer]. At the research level, various CO2-based compounds, such as carboxylic acids, (acetic acid), carbamates (linear and cyclic), formaldehyde, isocyanates etc., are under development.

<u>Mineralization</u>:

CO2 reacts with metal-oxide-bearing materials to produce carbonates. Minerals are one of the few materials that have a lower energy level than CO2. Mineralization stores CO2 and also can help substitute conventional products. The challenge, as in all potential technologies, is the high energy demand to overcome the slow reaction kinetics.

$$(Mg/Ca)_X O_Y Si_z + CO_2 \xrightarrow{\text{Heat}} \alpha\,(Mg/Ca)CO_3 + \beta\,SiO_2$$

Several reviews have been published on the CO2 mineralization processes, on both in-situ and ex-situ processes. In-situ processes are an attractive sequestration technology, injecting CO2 into geological formations, rich in silicates or alkaline aquifers. In India, CO2 sequestration in underground basalt rock using mineral carbonation has a great potential. CO2 storage capacity of deccan basalt rock (west-central India) can be up to 200 Gt.
Ex-situ mineral carbonation can also be an alternative to CO2 storage, where the carbonation process is carried out chemically.

There are some 12 technology companies – start-ups as well established – working on the use of CO2 for mineralization (52).

Fig 14: CO2 Mineralization technology providers Source: ADB CCUS webinar 2020

Very recently (April 2021) XPrize foundation announced the two winners - CarbonCure Technologies and CarbonBuilt - of $ 20 million NRG COSIA Carbon XPrize , with each creating valuable products out of CO2 emissions. Launched in 2015, the NRG COSIA Carbon XPRIZE was a five-year global competition developed to address rising CO2 emissions by challenging innovators around the world to develop breakthrough technologies that convert the most CO2 into products with the highest net value (53).

In CarbonCure technology, the CO2 is converted to a permanently embedded mineral with strength-enhancing properties which can then be incorporated into new concrete mixes. In

CarbonBuilt process, the CO2 is directly injected from flue gas streams into the concrete mixture where it is chemically transformed and permanently stored.

Carbon Upcycling-NLT produces nanoparticles with applications in various industries, particularly concrete, construction and plastics. Carbon Corp transforms CO2 into carbon nanotubes, with wide ranging applications such as lightweight, ultra-strong and cost-effective replacements for metals. Both these companies received "X-Factor" prizes in the XPRIZE competition.

The Calera Corporation has developed a process that directly mineralizes CO2 in flue gas to carbonates. The SkyMine® mineralization technology by the Skyonic Corporation transforms CO2 into solid carbonate and/or bicarbonate materials while also removing oxides and heavy metals from flue gas streams. In the Carbon8 process, CO2 gas is used to treat a wide range of thermal waste resulting in the formation of artificial limestone. Mineral Carbonation International (MCi) process combines CO2 with low grade minerals to make inert carbonates and silica.

Current data suggests that up to 1 Gt per year of the cement market could be substituted by mineralization products. Resulting reduction of the carbon footprint would range from 400 to 1500 Million tons CO2e per year.

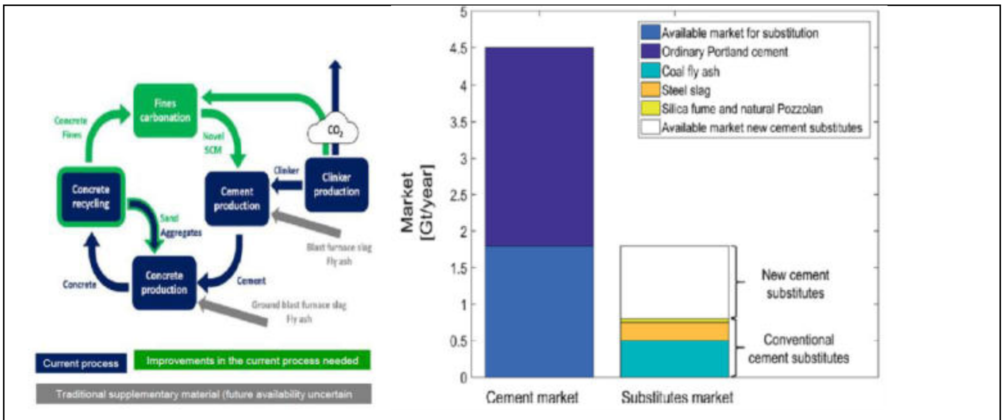


Fig 15: CO2 Mineralization potential Source: CO2 Value Europe Workshop Jan 2021, ADB CCUS Compendium webinar 2020

A highly prospective opportunity for early application of these technologies is the market for pre-cast concrete products and ready-mixed concrete. Existing regulations and product standards may stand in the way of early application in certain parts of the market. Updating existing product standards can take up to a decade; multi-year trials must demonstrate safe and environmentally friendly performance. In the interim, non-structural applications of concrete for which high mechanical strength is not required (for example construction of roads, floors and ditches) could be a target for early deployment of these new products.
As regards the near-term implementation of mineralization technology, the market is limited and there are also regulatory limitations. After discussion with DCBL, it emerged out that the technology will have application in India in the time span of mid-term say by 2030.

UREA:

Currently, the production of urea worldwide is the largest consumer of CO2. However, it must be noted that the CO2 used for urea synthesis is the by-product of ammonia process, which is part of the integrated urea plant based on fossil feedstock (natural gas or coal). Almost all the urea plants in the world are integrated urea plants with fossil feed (natural gas or coal) as a main raw material. In the integrated urea plant, fossil feed is first transformed to produce ammonia. During the manufacturing process of ammonia, CO2 is produced as a by-product.

Reaction 1: $CH_4 + H_2O \rightarrow CO + 3 H_2$
Reaction 2: $CO + H_2O \rightarrow$ **CO2** $+ H_2$
Reaction 3: $3 H_2 + N_2 \rightarrow$ **$2 NH_3$**

In the urea section of the integrated urea plant, CO2 and ammonia react to produce urea.

Reaction 1: **$CO_2 + 2 NH_3$** $\rightarrow NH_2COONH_4$ (Fast, Exothermic)
Reaction 2: $NH_2COONH_4 \rightarrow$ **NH_2CONH_2** $+ H_2O$ (Slow, Endothermic)

When the amount of ammonia produced in the integrated plant is more than that can be consumed by using by-product CO2 and if the economics permits, then additional CO2 is captured from the flue gases to utilize ammonia fully. Thus, the capture of CO2 and its use for urea is well established process in the integrated urea plant. There is a trend to install the mega size plants to take advantage of a scale.

There are some 32 integrated urea plants currently operational in India. Most of these plants use natural gas as a feedstock. The total production in 2019-20 was around 25 million tpa of urea. To meet the large domestic demand, India imported 11 million tons of urea in 2019-20, which amounts to over 30% of the total requirement. India remained one of the biggest importers of urea in the world over many years.

To reduce the dependence on imported urea, currently five large capacity plants (each having 3850 tpd of urea capacity) are at different stages of implementation in India. The urea market is likely to continue growing and as such, urea production would remain high potential option for large scale CO2 utilization.

For production of urea using CO_2 produced in cement industry (or any such source of CO2), the basic raw material will be ammonia or green ammonia produced from the process which does not generate CO2 as a by-product.

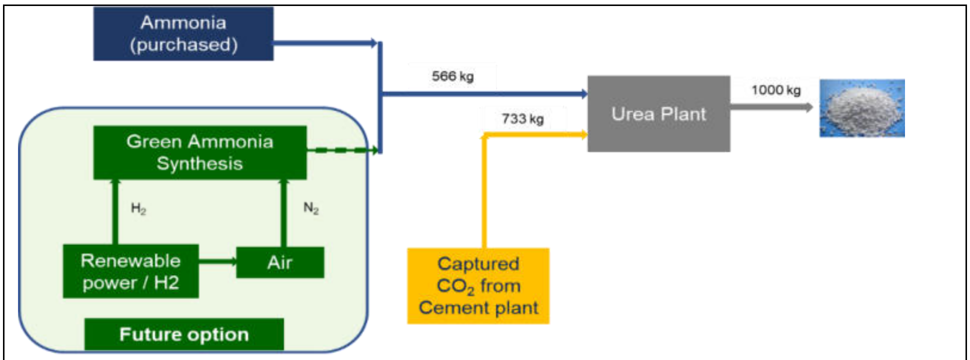


Fig 16: Urea production using CO2 from cement industry

India is one of the largest importers of ammonia and imported ammonia is mostly used for production of diammonium phosphate (DAP) fertilizer.

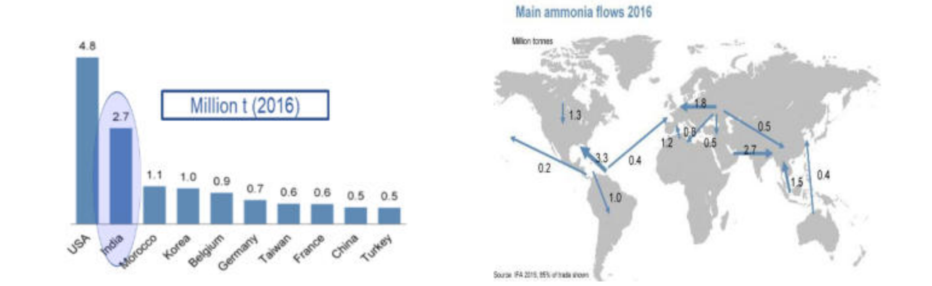


Fig 17: Ammonia imports data Source: Yara

The feedstock cost is the single large determinant of ammonia. For example, with a gas price of $ 6-8 per mm btu, about 90% of ammonia cash production costs is on account of natural gas. For an efficient plant using natural gas, it takes approximately 33 MMBtu of natural gas to produce one tonne of ammonia (19). The pricing of ammonia (and also of urea) is cyclic in nature in the world market. Natural gas price sets the price of ammonia and ammonia price sets a floor for the urea price.

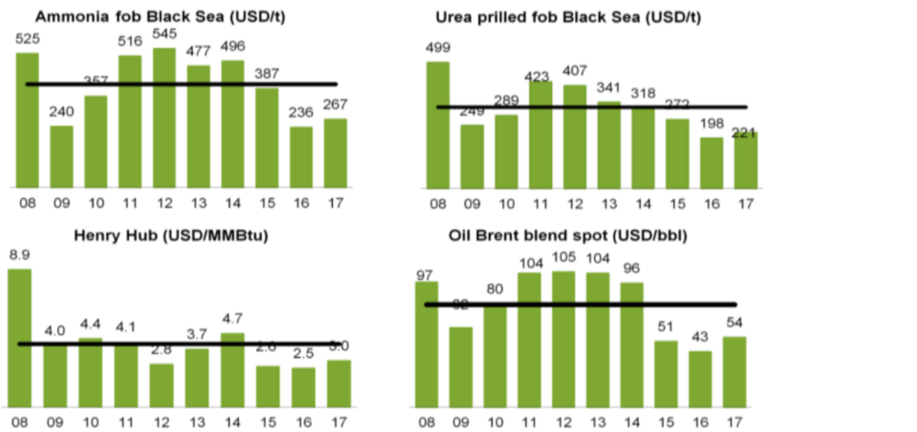


Fig 18: Price dynamics of crude, NG, ammonia and urea (Source: Yara)

In India, the price of urea to farmers is regulated by the Government of India, under the urea policy. To make sure adequate control over its quality, price and distribution, the industry is highly regulated under the Essential Commodity Act and Fertilizer Control Order, 1985. There is a pricing mechanism set by the government for urea producers as per the said policy. It is essential that the policy update must be checked at the time of investment decision process (Source: https://fert.nic.in/ureapolicypricing and administration).

The conventional process of urea production using fossil feed, results in significant net CO2 emissions, despite utilizing the CO2 produced during the ammonia synthesis step, decades of process optimization, matured technology and economy of scale. Decoupling the urea production from fossil feed can play very important role in reducing the CO2 emission. In this context, coupling utilization of CO2 with use of green ammonia allows the production of *blue* urea that can reduce carbon emission significantly (15).

<u>Soda ash:</u>

The CO2 utilization for production of soda ash is practised at a few locations and the technology has high level of maturity (TRL 9).

Soda ash is chemically the Sodium Carbonate (Na_2CO_3). Historically, the name "soda ash" seems to have derived from its method of production: it was extracted from the ashes of certain plants by using water. It is widely used in glass, soap & detergent, chemicals, water treatment, pulp / paper industry.

Initially, way back in 1791, the French chemist Nicolas Leblanc patented a process for producing sodium carbonate from salt, sulfuric acid, limestone, and coal. The process remained the major production method for sodium carbonate until the late 1880s. In 1861, the Belgian industrial chemist Ernest Solvay developed a method to convert sodium chloride to sodium carbonate using ammonia. In 19303, the Chinese chemist Hou Debang developed the process wherein CO2 is pumped through a saturated solution of sodium chloride and ammonia to produce sodium bicarbonate. Downstream process remains same as in Solvay process.

Currently, soda ash is produced mainly using the following technologies.

- Solvay process (mostly used in Coastal areas)
- Dual/Hou process (preferred for Inland installation)

The reactions occurring during the process are:

$$NaCl + NH_3 + CO_2 + H_2O \longrightarrow NaHCO_3 + NH_4Cl$$

$$2\ NaHCO_3 \longrightarrow Na_2CO_3 + H_2O + CO_2$$

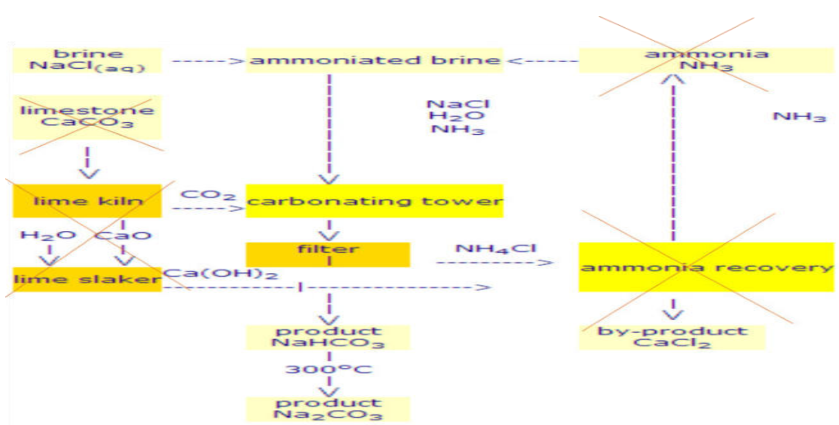


Fig 19: Process flow scheme for soda ash production

There are a few examples of installing plants for using CO2 captured from flue gases to produce soda ash. One such most prominent example is CO2 capture and utilization plant at Tuticorin Alkali Chemicals and Fertilizers Limited (TFL), in India, built in technical partnership with technology provider Carbon Clean, in 2016. The plant is regarded as the world's first low-cost, industrial-scale carbon capture and utilisation plant.

Tata Chemicals Europe has been also in the process of building CO2 utilization plant to produce soda ash. It is regarded as the first large-scale CCU project of its kind in the UK, capable of capturing and utilizing up to 40,000 tonnes per year of CO2. The plant is scheduled to commence operations in 2021.

In 2016, a plant in Texas is reported to chemically capture 75 to 83 ktCO2/yr from a cement plant and transform it into sodium bicarbonate, bleach and hydrochloric acid. The project is operated by Skyonic Corporation (IEA 2020).

DBCL is also reported to have planned to put up the large-scale demonstration plant for production of soda ash using CO2 (6).

Country	Project	Operation date	Capacity ktCO2/yr	CO2 Source
USA	Searles Valley Minerals (Trona soda ash plant)	1976	270	Coal fired power plant
USA	Carbon Free Chemicals and Capitol Aggregates' Skymine® plant	2016	83	Cement production facility
India	**Tuticorin** Alkali Chemicals & Fertilizers and **Carbon Clean Solutions** plant	2016	60	10 MW coal power plant
India	**Dalmia Cement** and **Carbon Clean Solutions**	Planned	500	Cement production facility

Table 4: CO2 Utilization projects for Soda ash in Cement Industry (Source IEA 2019)

In India, soda ash plants have cumulative installed capacity of 1.2 million tpa. The capacity utilization is less than 80% over the years. To meet the domestic demand, 0.9 million tons of soda was imported in 2019-20. The global production of soda ash is 58 million tpa (2019).

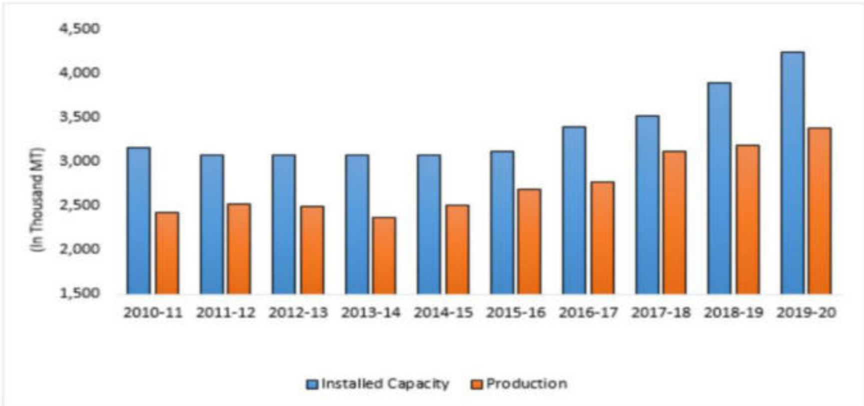


Fig 20: Production capacities of soda ash in India (Source: AMA-India 2020)

Though the annual requirement of around 6% is estimated, the potential for CO2 utilization to produce soda ash seems limited.

4. Selection of CO2 Utilization Pathway and Product

The multistep method has been used to evaluate promising pathways before arriving at the final product of choice.

Initial assessment of the technologies is done to reduce the number of CO2 conversion options for further consideration. The broad criteria used for initial screening study are: TRL, current and future market size, and business potential.

Based on these parameters, ADB consultants short listed the following options for considerations of DCBL:

- Short term: Soda ash (DCBL is reported to be considering this option as reported in various publications)
- Medium term: Mineralization
- Long term: Methane, Methanol, Algae

4.1 MULTI-CRITERIA ANALYSIS

DCBL agreed broadly to the above recommendations. As a short-term option, DCBL advised to include urea besides soda ash, as one of the products for further evaluation. DCBL provided the matrix of eight parameters and weightage for the MCA analysis.

#	Parameter	Weightage	Description
1	TRL (7 and above)	40	*TRL 6-7, Demonstration | TRL 8: First-of-a-kind commercial demo | TRL 9: Actual system proven in an operational and competitive environment* (description added by RB/ADB)
2	Capex	10	*Utilization tech* capital cost INR/ton of CO2 utilized
3	Opex	10	*Utilization operational cost* (including operational cost of capture) expressed in INR/ton of CO2 utilized
4	ROI/Payback time	10	Approximate Return on investment (payback time)
5	Market Demand	13	Broad Market demand (domestic + international) of the product to match project scale
6	Electrical	8	Total Energy demand of process electricity (kWh/ton of CO2 utilized) **Capture + use**
7	Steam	4	Total Energy demand of process steam (GJ/ton of CO2 utilized) **Capture + use**
8	Avoidance of CC	5	Complete avoidance of Capture Technology in utilization
	Total Score	100	

Table 5: MCA Parameters and Weightage

It is worth noting here that the weightage given to TRL is highest (40%) followed by economic parameters (30 %), totalling 70% weightage towards the overall score.

- TRL is defined on the scale of TRL 1 (Proof of concept) to TRL 9 (Commercial deployment). The time frame required to deploy the technology at commercial scale depends on the TRL. The time frame can be as high as 10 to 20 for TRL 1 to 3 (R&D stage projects) and 7 to 10 years for TRL 4-6 (Development stage projects). Typical time frames for various technologies is provided below:

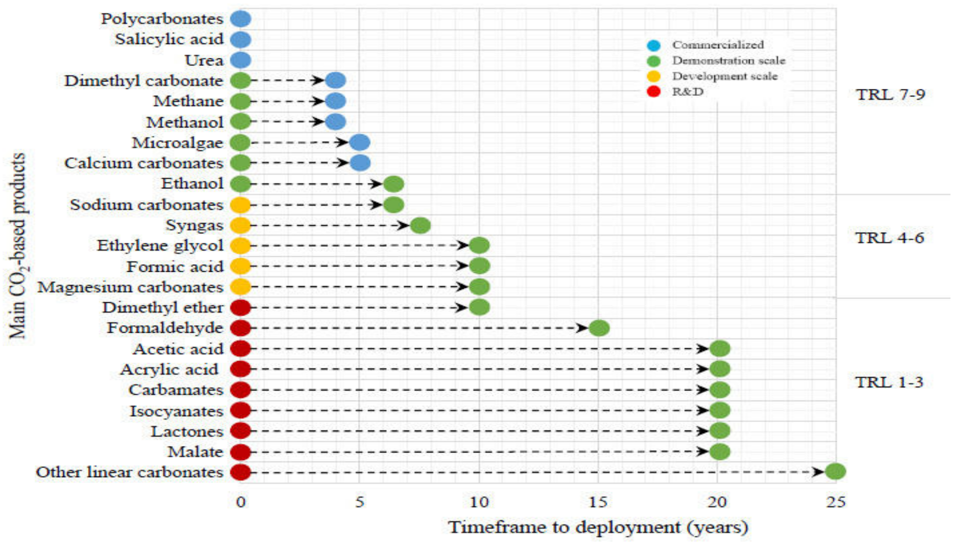


Fig 21: Timeframe for commercial deployment

- DCBL indicated the requirement of TRL of 7+ for the technology evaluation. That means the technologies which are ready to deploy within 5 years.
- The weightage of over 70% for TRL and economic parameters and minimum requirement of TRL 7 is in line with the intent of implementing the project in near term. It should be also noted that the technologies which are in development stage with relatively low TRL will get lower ranking in the score with the above criteria, even if such technologies may be promising in the medium and long term.

#	Description	Urea	Soda Ash	Mineralization	Methanol	Algae feed	Algal Biocrude
	Process	Generic	Modified Salvay	Carbonation	Hydrogenation	Photosynthesis	HTL
	Tech Status	Commercial	Commercial	Commercial/Demo	Pilot plant	Pilot plant	Pilot plant
1	TRL	9	9	8 to 9	7 to 9	5 to 8	5 to 8
2	CO2 purity	High purity	High purity	10-100%	High purity	10-100%	10-100%
3	Major feedstocks	NH3	Brine, NH3	Mineral/residues	H2	Nutrients	Catalyst
5	Market Demand	++	+ Large	Very large +++	+++	++	+++
6	Electrical Demand	Yes	Yes	Yes	Yes	Yes	yes
7	Steam Demand	Yes	Yes	Not essential	Yes	Not essential	Not essential
8	Avoidance of CC	No	No	Possible	No	Possible	Possible
9	**Unique features**	Govt. subsidies on product pricing. Low GHG reduction potential	Low GHG reduction potential	***High GHG reduction potential*** *Double benefits: Product replacement and CO2 permanent removal*	**Low C carrier** of H2 **in liquid form.** Wide applications as fuel/ feedstock. **"Renewable power, the Key"**	Effluent/non-potable water (Large water handling) Large land area (non-agri)	Wet/dry Biomass, **No drying of Feed** *(even 80% water in feed acceptable)* MSW/ETP waste, Distillery/Paper mill waste, plastic waste can be processed.

Table 6: Technical features of short-listed CO2 utilization options

Taking into account the parameters as proposed by DCBL, ADB consultants developed the detailed methodology for assessing the technologies. The detailed MCA includes the economic value of the final products, the energy requirement and carbon capture avoidance potential besides the parameters used for initial screening. Cost effectiveness is an important factor that determines the deployment of emerging technologies. The CCU involves two interconnected processes - carbon capture and its conversion. As such, the costs of CO2 capture need to be considered. Only a few pathways are currently economically viable.

4.2 RANKING OF CO2 UTILIZATION TECHNOLOGIES

The ranking of the results depends on the distribution of the weighting factors amongst the criteria and indicators. A sensitivity analysis is therefore carried out to identify how a change in the indicator weight affects an alternative ranking.

The individual score for each of the options have been found. The detailed score is included in Annexure A1. The summary of the score is provided in the following table:

#	Parameter	Weightage	Urea	Soda Ash	Mineralization	Methanol	Algae feed	Algal Biocrude
1	TRL	40	40	40	38	36	32	32
2	Capex ($/t CO2)	10	10	7	7	10	5	4
3	Opex ($ /t CO2	10	9	10	9	1	3	3
4	Payback period	10	10	7	9	4	9	9
5	Market Demand	13	7.8	5.2	9.1	13	7.8	13
6	Electrical Demand	8	6.4	5.6	5.6	8	4	4
7	Steam Demand	4	3.6	2	4	4	4	4
8	Avoidance of CC	5	2.5	2.5	5	2.5	5	5
	Overall Score	100	89.3	79.3	86.7	78.5	69.8	74
	Technology aspects w.r.t. India	water, land availability, any advantage or barrier technology	Sea water, NH3	Sea water, NH3	In sync with Dalmia business	Country-wide market, Big policy support from GoI	Technology availability in in India with cost benefits	Technology in advanced stage available. Other waste can be co-processed

Table 7: MCA – Individual Score for CO2 Utilization projects

4.3 DISCUSSION AND FINALIZATION OF CO2 UTILIZATION PATHWAY AND PRODUCT

The framework for the above analysis includes technical, economic aspects and environmental aspects. Nevertheless, some limits of the analysis must be appreciated. It is to be noted that the scores are decided using the scoring guidelines as discussed and agreed upon, during the joint discussion amongst ADB and DCBL teams. The limit also comes from the choices of the weightage factors that may be subjective to certain extent, as they strongly depend on the personal understanding of the evaluating team members. To address this issue and reduce the subjectivity, the sensitivity analysis is performed to determine the impacts of the weightage on the results. The scores are based on the information as available at the time evaluation. The results may need to be revisited after lapse of longer time to take into account the advances in the technology developments.

The above analysis provides directional guidance towards shortlisting the product for prefeasibility study. There are, however other project implementation related factors (besides those considered for MCA) which need to be taken into consideration while deciding the final CO2 derived product.

In view of the above, the findings of the screening study were shared with the top management of DCBL. There was a general concurrence on the findings of study carried out by the ADB consultant team and much appreciation for coming out with the pragmatic solutions to the complex issue of shortlisting the product.

DCBL management suggested ADB team to provide more information on the fate of the carbon for the options evaluated to enable them decide the final product. This aspect was addressed appropriately by ADB consultant team and presented the details to DCBL.

As revealed in the MCA study, urea and mineralization are the top-ranking options as per the criteria considered for the evaluation. Though the mineralization is recognised as one of the most promising CO2 utilization options in developed countries, it emerged out during the discussions that deploying the option of mineralization in India may take longer time in order to complete the necessary testing and procedural requirements for regulatory compliance.

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- Soda ash and methanol emerged out as the next best options. ADB consultant team expressed the view that the soda ash has limited market.
- Methanol has a great potential for CO2 utilization as a long-term solution, particularly in view of the c33ontinual fall in the cost of renewable electricity and traction that is getting from the government and research institutes for the hydrogen economy.

During the discussion, DCBL expressed the view that two options – Urea and Soda ash be considered for the prefeasibility study. **After taking into account all the possible factors and organizational priorities, it has been decided to go for the prefeasibility study of Urea production**.

5. Prefeasibility of Urea Plant for CO2 Utilization

5.1 Background:

The proposed plant will utilize CO2 generated at Ariyalur Cement plant of Dalmia Cement (Bharat) Limited (DCBL). Ariyalur Cement Plant of DCBL was commissioned during the Year 2009-10, with an installed capacity of 2.0 million tpa clinker and 3.0 million tpa cement. The plant produces approximately 1.41 million tpa of CO_2 and 60% of this amount is process centric emission due to calcination of limestone. Besides Ariyalur cement plant, DCBL has other 12 cement plants at various locations in India. In year 2019-20, the total cement production from DCBL is reported to be 26.5 million tons. By year 2022, the cement production from all the cement units of DCBL is expected to reach 37.3 million tpa.

As part of the sustainability initiative, DCBL proposes to set up the carbon capture and utilization (CCU) facility of 500,000 tpa capacity of CO2 (100% purity basis) at Ariyalur Tamil Nadu, India. ADB consultant team reviewed various CO2 utilizations options and based on the Multi-criteria Analysis presented to DCBL, the ranking of short-listed projects, with implementation potential in near term for using CO2 from Ariyalur cement facility (details are given in previous sections). Of the six products evaluated (Urea, Soda ash, Methanol, Mineralization, Algae to feed and Algae to oil) and ranked, it was decided to carry out the *prefeasibility* study for Urea plant.

Urea, also known as Carbamide (NH_2CONH_2) is the main nitrogen fertilizer product. It has 46% nitrogen, the highest available in any solid fertilizer. Nitrogen is the nutrient with highest consumption, with a projected annual global growth rate of 1.1% (19). Urea is easily transportable without explosive hazard. Apart from its use as fertilizer, it has other industrial uses.

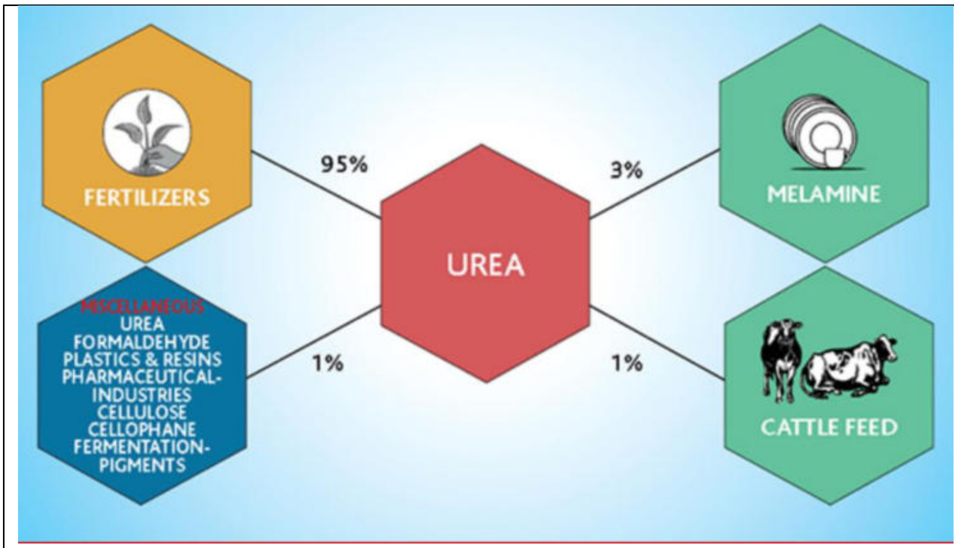

Fig 22: Urea usage

At present, there are 32 large size urea plants in the country manufacturing urea. The estimated production of Urea during 2019-20 is 25.0 million tons. India's dependency on import at present is to the extent of 25% of total requirement of Urea.

5.2 Design basis/Assumptions:

a. The pre-feasibility study referred to in this document has been undertaken to assess the CO2 utilization pathway for production of urea.
b. Plant location: The urea plant is assumed to be located near existing cement plant at Ariyalur, in the state of Tamil Nadu, India.

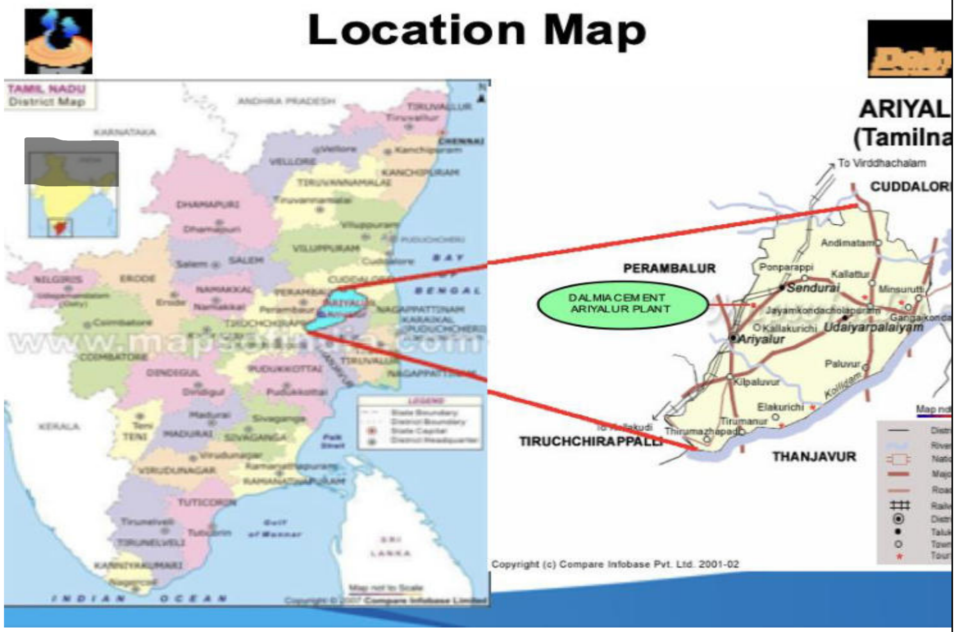

Fig 23: Proposed plant location

c. Plant capacity: At the start of the study, DCBL had indicated that they would like to have the CO2 utilization plant for consuming 500,000 tpa of CO_2 (100% purity basis). This capacity is in line with the concept of commercial demonstration plant size plant for new technologies. The commercial scale plants are those with *at least* 500,000 tpa of CO2 capture and utilization (14, 29). This capacity was proposed by DCBL before the exercise of selection of product was completed by ADB.
The urea production from 500,000 tpa of CO_2 will be around 0.682 million tpa. With annual operating hours of 8000, the plant capacity works out to be 2050 tpd of urea. Urea process has been optimised over the decades and now it's a matured technology. The trend is to install mega scale plants to take advantage of scale and reduce the cost of urea production. There are plants operating with a capacity of over 4000 tpd and plants as large as 6000 tpd are at design stage (Stamicarbon). In view of this, the urea plant capacity to consume 1.0 million tpa of CO2 (4100 tpd of urea production) was considered during the screening study.
For the prefeasibility study, two cases have been considered:
   - **Base case**: 0.5 million tpa of CO2 utilization (urea capacity of 2,050 tpd)
   - **Advanced case**: 1.0 million tpa of CO2 utilization (urea capacity of 4,100 tpd)

d. Product specifications:

Parameters	Units	Specs by technology providers	Indian producers

Nitrogen	% w/w min	46.6	46
Biuret	% w/w max	0.8 to 0.85	1.5
Neem oil	% w/w max		0.035
Particle size	mm	variable	90% material on 1 mm and 2.8 mm IS sieve

Table 8: Urea specification (Typical)

e. Raw material specifications:
For urea production, CO2 and ammonia are the main raw material. For the proposed urea plant for the utilization of CO2 produced at DCBL, purchased ammonia has been considered as an input.

Component	Composition
Ammonia	99.5% w/w min
Moisture	0.5 % w/w max
Oil	5 ppm w/w max

Table 9: Ammonia specifications for urea production

The CO_2 will be supplied from the proposed CO2 capture plant at Ariyalur Cement plant.

Component	Composition
CO_2	99% v/v min
Moisture	1500 ppm max
Impurities (SOx, NOx)	Traces

Table 10: CO_2 specifications for urea production

f. Battery limit conditions for feed, products, utilities etc.

Inputs	Temp	Pressure	Flow	
			Base Case	Advanced Case
CO2	Ambient	1.5 bar a	1500	3000
Ammonia		TBD during engg.	1160	2320
Electricity			10.5 MW	21 MW
Steam	300 Deg. C	22 bar a	53 TPH	106 TPH
CW	Delta T 10 Deg C	TBD during engg.	7250 TPH	14500 m3/h
Water	Ambient	5 bar a	2550 TPD	5100

Table 11: Battery Limit

5.3 Process Chemistry

The main reactions are as follows:

Reaction 1: $CO_2 + 2\ NH_3 \rightarrow NH_2COONH_4$ (Fast, Exothermic)
Reaction 2: $NH_2COONH_4 \rightarrow NH_2CONH_2 + H_2O$ (Slow, Endothermic)

Reaction 1 is fast and exothermic and essentially goes to completion under the reaction conditions used industrially. Reaction 2 is slower and endothermic and does not go to completion. The conversion (on a CO2 basis) is usually in the order of 50-80%. The conversion increases with increasing temperature and NH3/CO2 ratio and decreases with increasing H2O/CO2 ratio.

There is also a side reaction of biuret formation

$2NH2CONH2 \rightarrow NH2CONHCONH2$ (biuret) + NH3

This reaction is undesirable, not only because it lowers the yield of urea, but also because biuret burns the leaves of plants. There is an upper limit of biuret content in the urea product, as indicated in the product specifications.

The design of commercial processes has evolved around the process of separating the urea from other constituents and recycling back to reactor for maximum yield of urea. Attention was also devoted to developing materials to withstand the corrosive carbamate solution and to optimise the heat and energy balances.

During the initial process development stage, the simplest way was to decompose the carbamate to CO2 and NH3 by depressurising and heating. The earliest urea plants operated on a “Once Through” principle where the off-gases were used as feedstocks for other products.

Subsequently “Partial Recycle” techniques were developed to recover and recycle some of the NH3 and CO2 to the process. It was essential to recover all of the gases for recycle to the synthesis to optimise raw material utilisation. To optimise recompression cost, an alternative method was developed. This involved cooling the gases and re-combining them to form carbamate liquor which was pumped back to the synthesis. A series of loops involving carbamate decomposers at progressively lower pressures and carbamate condensers were used. This was known as the “Total Recycle Process”. A basic consequence of recycling the gases was that the NH_3/CO_2 molar ratio in the reactor increased thereby increasing the urea yield.

Urea plant capacity has continually increased since the establishment of industrial production processes in the late 1940s. In 1969, Toyo Engineering Corporation (TEC) scaled up its urea process and successfully commissioned 1,800 MT/D urea plant, which was the largest single train plant in those days. And until 1990s, 1,700 – 2,200 MT/D grass roots urea plants were the largest in single train. Nowadays most of grass roots fertilizer projects are aiming at larger urea capacities of 5000 to 6000 tpd.

5.4 Process Technology providers:

The current global leading licensors of urea technology are as follows:

- Stamicarbon, Netherlands
- Saipem, Italy
- Toyo Engineering Corporation (TEC), Japan

These companies contribute more than 90 per cent of the total urea technology market. There is not much variation in the overall cost of production or energy consumption levels and the selection of a particular technology will depend on the competitiveness for the given project.

In India, all the three technology providers have reference installations. For the pre-feasibility study, process based on ammonia stripping (Saipem) has been considered. The final selection of a particular technology will be mainly based on its techno-economic competitiveness, as applicable for the project at the time of project implementation.

The Urea plant will be laid out in single stream having prilled urea plant with stripping process technology.

5.5 Process Description:

The urea production process consists of five process steps:

A. Synthesis - Ammonia and CO_2 are synthesised to form ammonium carbamate, which in turn is partly dehydrated to urea.
B. Decomposition - The unconverted ammonium carbamate is decomposed back to ammonia and CO_2.
C. Recovery - ammonia and CO_2 gases released from the decomposition step are scrubbed out with water, cooled and recycled to the synthesis section.
D. Concentration – The excess water is removed to produce molten urea. Usually, evaporation is used to produce fertilizer grade urea, whereas crystallization is used to produce technical grade urea.
E. Finishing – The highly concentrated urea solution from the concentrators is processed either through a prilling tower or urea granulator to produce urea

Depending on the licensor, the urea synthesis reactor is typically operated at around 190 deg C and 150 to 160 Bar (g)

5.6 Process block Diagram

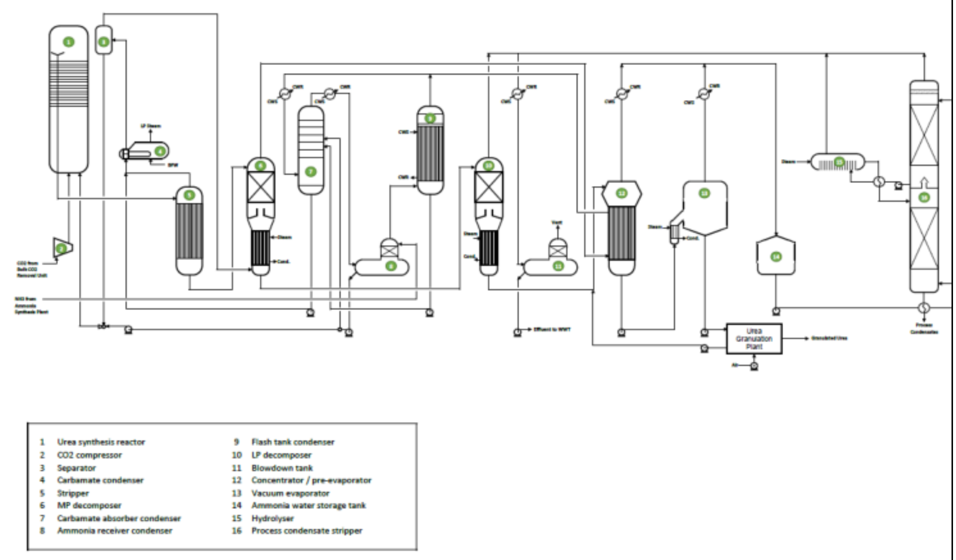

Fig 24: Urea process block diagram. Source: IEA 2016

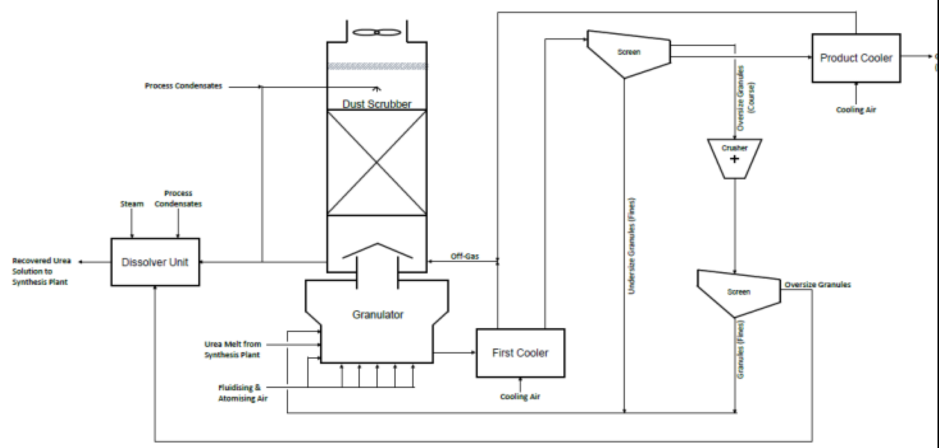

Fig 25: Prilling section of urea manufacturing process. Source IEA 2016

5.7 Overall Material and Energy requirement (Design case)

Particulars	Units	Unit consumption	Base case Quantity per	Advanced Quantity per
CO2 Consumption	t	0.733	**500000**	**1000000**
Ammonia	t	0.566	386085	772169
Electricty	kWh	120	81855389	163710778
Steam (300 deg C/ 22 bar)	t	0.62	422920	845839
Cooling water circulation	m3	85	57980900	115961801
Water reqt	m3	1.25	850446	1700891
Urea production/Sale	t	1	682128	1364256
Opearting hours	Hrs		8000	8000
CO2	TPD		1500	3000
Ammonia	TPD		1158	2317
Urea	**TPD**		**2046**	**4093**
Electricity	kW		10232	20464
Steam	TPH		53	106
CW	M3/h		7248	14495
Water	M3/d		2551	5103

Table 12: Material and energy requirement

Off-site and Utilities:

Ammonia Storage

The provision for 7 days of storage is proposed. Accordingly, for base case the capacity of storage tank be one tank (1x 10000) tons of double wall design. For advanced case, two tanks of 1000 tons or one tank of 20000 tons should serve the purpose.

Urea Storage, Handling and Bagging

The urea silo capacities of 30000 tons capacities for base case and 60000 tons for advanced case have been envisaged keeping product inventory of about 15 days.

Cooling Water System

The cooling water system provides cooling water to all users and controls the chemical composition of circulating cooling water to prevent corrosion, biological growth and
solids deposits in piping etc. Cooling water return from various units is to be routed to the cooling tower.

Steam System

Steam is envisaged to be available at battery limit of the urea plant. Steam is required for the following purpose:

- Process use (Chemical reaction, Stripping steam etc.
- Steam drives for some of the rotating equipment (during detailed engg, configuration of motor driven/steam driven should be studies to optimise the cost.
- As heating medium for steam heated exchangers
- Steam tracing of lines

Power System

Total power requirement is expected to be available from state electricity board.

Instrument air:

Instrument air is very vital for process control instruments, (1+1) Centrifugal Air Compressors along with air dryer and receiver units will be required for the Project.

Waste Management & Disposal System

Urea plant will be provided with deep Urea Hydrolyser System, which will generate
condensate for re-utilization in the Plant itself.

Cooling tower blow down will be treated in effluent treatment plant and the treated effluent can be used for green belt development, to the maximum extent possible. The treated effluent from STP and ETP will be discharged after ensuring that the effluents local and national standards as applicable.

Urea dust and ammonia emissions are the expected emissions from prilling tower and they will meet the emission standards as applicable.

Dust Handling

To control the emissions in the bagging plant where urea is handled, the plant will be provided with de-dusting system. Dust from various points will be collected and sent to urea plant where it will be dissolved in urea solutions and reprocessed in urea plant

Flare and vent stacks of adequate height shall be provided in the Ammonia and Urea
Plants.

5.8 Assessment of operating human resources requirement.

It is envisaged that; operation will be on 24x7 basis in three shifts. During normal operation at full rated capacity, total strength is estimated to be around 100 as given in Table below:

	Description	Estimated requirement	Remarks
1	Plant Head	1	Daily position
2	Assistant Head	1	Daily position
3	Shift Superintendent	5	General shift + 4
4	Shift Supervisors	10	General shift + 8
5	Control room operator	10	General shift + 8
6	Field operators	10	General shift + 8
7	Electrical group	5	General shift + 4
8	Instrumentation group	5	General shift + 4
9	Mechanical group	10	General shift + 8
10	Laboratory	5	General shift + 4
11	Technical services	5	General shift
12	Material management	3	General shift
13	Safety and Fire fighting	2	General shift
14	Finance and account	4	General shift
15	HR and Admin	4	General shift
16	Marketing	2	General shift
17	Contract workers	18	As required
	Total	100	

Table 13: Human resource requirement

CAPEX

Case →		Base Case	Advanced Case
CO2 Consumption basis	TPA	500000	1000000
	Capex	$ Million	$ Million
Total Installed Cost of Equipment of Urea plant (ISBL)	A	137	205
Direct Cost (Site development, utilities interface	B	17	25
OSBL Civil Works and land grading	C	4	7
Total Direct Cost (TDC)	D= A+B+C	158	237
Indirect Cost (License fee, Engg, Field expenses, Start-ups etc.)	E	69	113
Total Capex	F	227	350

Table 15: Capex Estimate

OPEX:

- CO_2 is assumed to be available at Urea plant battery limit at 1.5 bar (a) and at ambient temperature.
- CO_2 will be compressed to desired pressure using the compressor located within the Urea complex. Cost of compression is included as part of Urea production cost
- Ammonia cost: Ammonia at purchase price of $ 300/t is assumed to be available at Urea plant battery limit.

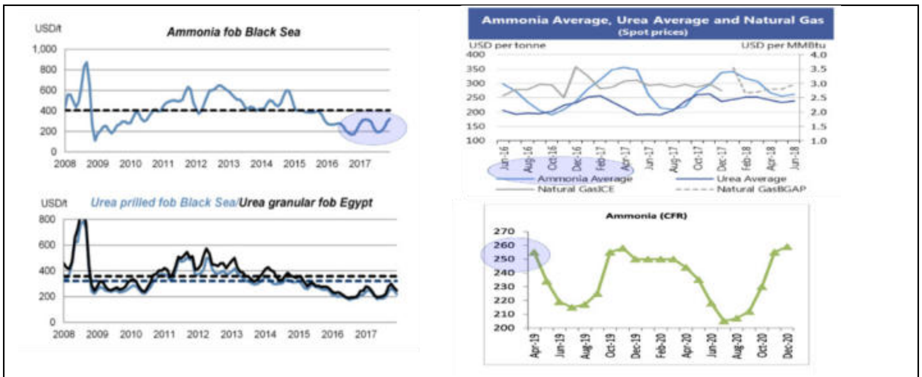

Fig 27: Ammonia price trend

- For calculating the steam cost, biomass fired boiler has been considered, after discussion with DCBL. There is no provision of natural gas at the DCBL site. Coal has not been considered as source of energy. ADB is unlikely to finance new coal-fired energy Projects (ADB 2021). The cost of steam at battery limit of urea plant is the delivered "over the fence" cost. The cost of steam for advanced case (1.0 million t of CO2 per annum) is slightly less as compared to steam cost for base case (500,000 tpa of CO2) since capex recovery cost for higher amount of steam will be less.
- The cost of electricity as assumed to be available from the Tamil Nadu Government electricity board through grid. The currently the prices:
    - Rs 6.35/kWh (variable)
    - Rs 350/KVA per month (Fixed demand charges)

  With the advent of renewable solar energy, cost of electricity is dropping continually. As a feedback from DCBL, the base case will assume the electricity cost at INR 4/kWh.
- Cooling water cost will be based on electricity cost.

- Urea sales realization:

  Fertilizer prices are cyclical like in the international market. In general, when demand is low, there tends to be a ”supply-driven” fertilizer market in which the established “price floor” indirectly determines fertilizer prices. This price floor is set by the producing region with the highest natural gas prices. When fertilizer demand is high, there is typically a ”demand-driven” market with fertilizer prices above floor prices for swing (highest cost) regions. The fertilizer market balance and capacity utilization are other key factors that impact prices for urea and other N-fertilizers.

  Urea is the “Controlled Fertilizer”, meaning the Government of India controls the MRP of Urea. The MRP of urea is statutorily fixed by the Government of India and the difference between the delivered cost of urea at farm gate and net market realization by the urea units is given as subsidy to the urea manufacturer/importer by the Government of India. There is the New Urea Policy-2015 (NUP-2015), notified by Department of Fertilizers on 25th May, 2015, which was initially made effective from 1st June, 2015 upto 31st March, 2019, with the objective of maximizing indigenous urea production, promoting energy efficiency in urea production and rationalizing subsidy burden on the government. Policy Update must be checked at the time of investment decision process

  As mentioned earlier, five urea plants of 3850 tpd capacity each are being executed by Public Sector Undertakings of the Government of India. For technical evaluation of the projects, realisation price of urea is considered as Rs 22043/t. (USD 310/t of Urea). India imported 11 Million tons of Urea in 2019-20. Avg. import price of urea was $ 295/ton.

  For the present prefeasibility study, urea realization price of $ 270/t has been assumed.

Sensitivity of steam cost on urea cost:

The main determinant towards urea cost is the ammonia price. In the overall opex, ammonia contributes almost 70% of the total cost. Energy cost (steam and electricity) constitute approximately 10 to 12 % towards the total urea cost.

The sensitivity of steam cost on the opex of urea shows that the increase in steam cost by 25% has less than 2% increase in urea cost.

Though energy cost is not that significant as compared to main raw material cost (ammonia and CO_2), every effort is made by the technology providers to optimize the energy consumption. In the typical design, steam and electricity systems are optimised in such a way that there is minimum venting or export of steam from the urea plant. One of the major consumers of energy is the CO_2 compressor. It can be run using steam turbine or electrical motor. If the urea plant is part of the larger integrated production facility at same location (for example, cement plant, CO_2 capture plant), steam and energy systems can be designed to optimise the overall cost.

Table 16 below shows the summary of urea plant opex for two cases: 1) Base case (500 ktpa CO_2 and Advanced Case (1000 ktpa CO_2 consumption. This standalone economics of the urea plant is done to visualise the impact of capacity, and sensitivity of input costs.

It may please be noted that the detailed economic evaluation of the integrated facility (CO_2 capture and CO_2 utilization plants) is presented in the Financial Assessment section of the report.

Description	Units	Base Case	Advanced Case	Steam cost impact	CO_2 cost impact
Captured CO_2 consumption	Mn t/year	A = 0.5	**2A** = 1.0	2 A	2 A
NH_3 required	Mn t/year	B = 0.386	2 B	2 B	2 B
Urea plant capacity	tpd	C = 2050	2 C = 4100	2 C	2 C
Steam Cost	$ / t	D	D	**1.25 D**	D
CO_2 cost	$/ t	E	E	E	**1.4 E**
Opex	$ /t of Urea	F	0.98 F	0.989 F	1.05 F
Capex	$ / tpa CO_2	G	1.54 G	1.54 G	1.54 G
Impact/Observations		2050 tpd Urea plant is sub - optimum capacity	Doubling the capacity increases capex by only 54%	25% higher steam cost increases opex by < 2 %	40% increase in CO_2 cost increases opex by < 5%

Table 16: Opex and preliminary payback period

CO_2 UTILIZATION:

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IV. Environment assessment

Prepared by Dr. M. Velan

Section Outline

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2. CO_2 Emission Control from Cement Industry
3. Baseline Environment quality
4 DCBL Cement Facility Emissions
5. Environmental Impact Assessment
6. Environment Management Plan
7. Regulatory and Licensing Requirements
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1. Introduction

Global emissions of CO_2 from human activity have increased from an insignificant level two centuries ago to nearly doubling of the concentration in the ambient air. The most notable human activity associated with the generation of CO_2 emissions is the combustion of carbon-based fuels (including oil, natural gas, and coal) in power generation and industries like Steel, Cement, Refineries etc. Many scientists, including the Intergovernmental Panel on Climate Change (IPCC), believe there is a danger from even a modest increase in the Earth's temperature (called "global warming") as it could alter the global climate and cause significant adverse consequences for human health and welfare (DOE, 2007a). Cement Industry is one of the major contributors of CO_2 emission ranking next to Power generation and also it is a growing Industry. With more than 4.0 billion tonnes of cement produced globally each year, the cement industry generates approximately 8% of all global CO_2 emissions. The CO2 emitted from Industries can be stored geologically or converted to useful products. the process of carbon capture and conversion into useful products enhances the financial viability of the project through the sale of the by-product. Dalmia Cement Bharat Ltd (DCBL) made a commitment during Global Climate Action Summit to emerge as a carbon negative cement group by 2040 with an impetus on carbon capture and utilization. With this background, Asian Development Bank (ADB) has provided funds to prepare Pre-feasibility report on CCU for DCB's Ariyalur Cement factory in Tamilnadu and the result is this report.

2. CO_2 Emission Control from Cement Industry

Cement production causes global CO_2 emissions of about 1.50 ± 0.12 Gt CO_2 in 2018 (Robbie M. Andrew, 2019). About 0.5 t CO_2 per ton of cement is emitted of which about one half is due to combustion of fossil fuels for heat supply and the other half as inherent co-product from calcination. In calcination, the raw material limestone consisting mainly of calcium carbonate ($CaCO_3$) is decomposed to CO_2 and calcium oxide (CaO) at about 950 ◦C and the CaO thus obtained is then converted to cement clinker in a kiln at about 1450 ◦C. To provide heat for both the calcination process and the kiln, combustion of coal is typically employed. Although using other fuels such as biomass has the potential to lower CO_2 emissions, capturing CO_2 from the cement plant flue gases (15-30 % CO_2 concentration, from combustion and calcination) has been identified as most effective measure for reducing absolute CO_2 emissions in cement plants (Rodr´ıguez et al., 2012).

2.1 CO_2 Capture Technologies

Carbon dioxide is naturally present in the atmosphere as part of the Earth's carbon cycle. However, recently it has been declared as the planet's public enemy number one and how to deal with it is a subject of great controversy. CO_2 capture means to separate CO_2 from other gases. For gas separation, four main unit operations are frequently used: membranes, cryogenic distillation, adsorption, and physical and chemical absorption. CO_2 concentration in cement kiln flue gases (approximately 15 to 30 mol%) is higher than the power generation industry, which provides advantages for capturing CO_2 in cement production. Except for a few, limited cases where pure CO_2 is already available, provision of CO_2 by capture from diluted gas streams requires substantial amounts of energy. Supplying the energy for CO_2 capture by fossil fuels leads to additional CO_2 emissions and fossil fuel depletion. In addition to energy, capital goods for CO_2 capture cause further economic and environmental burdens. For most applications of direct CO_2 utilization, is released shortly after its use. Thus, a direct climate benefit cannot be expected. This study aims to analyse and compare the environmental impacts of cement production with or without the preferred carbon capture technology from the perspective of LCA and to provide a theoretical basis for the sustainable development of the cement industry.

2.2 CO_2 Utilization Technologies

Carbon Capture and Utilization (CCU) is an emerging technology field that can replace fossil carbon value chains with significant potential in emissions mitigation or even negative emissions. CCU includes a variety of technologies that separate the greenhouse gas CO_2 from point sources or ambient air and consume CO_2 to make products or services, aiming to provide economic, environmental, and social benefits. CCU products include concrete (e.g., Lafarge, Carboncure), carbonate aggregates (e.g., Carbon8, MCI), fuels (e.g., Sunfire, SkyNRG), polymers (e.g., Covestro, Novomer, Econic), methanol (e.g., CRI) or carbon monoxide (e.g., Opus12).

CO_2-based fuels and chemicals are interesting pathways; these could enable the substitution of petroleum-based products. But they provide short term CO_2 storage, and they emit CO_2 when they are used. The CO_2 avoided is limited. But even for CO_2-based fuels and chemicals, it is difficult for CCU technologies to compete with conventional oil technologies in view of high capture costs. The economic barrier is the main hurdle for the deployment of CCU technologies. The main objective is to identify the most promising CCU pathway. Three chemical processes were selected because they were promising: methanol, sodium carbonate and Urea. For CCU, it is necessary to calculate the CO_2 avoided rather than the CO_2 used in the process. A life cycle analysis could help to identify CO_2 technologies with environmental benefits. Life Cycle analysis (cradle to gate) carried for these products shows that the CO_2 avoided is of the order of 1.34, 1.38, 1.49 for Soda ash, Methanol and Urea (reference product).

Table 2.1 Environment performances of chemicals

	Soda Ash,	Methanol,	Urea
CO_2 mobilization period	**Decade**	**Week-Month**	**Week**
Carbon footprint of CO_2 process (t CO_2/T of product)	-0.28	-0.73	-0.35
Carbon footprint of conventional process (t CO_2/T of product)	+1.06	+0.65	1.14
CO_2Avoidance (t/T of product)	**1.34**	**1.38**	**1.49**

Source : (ADME 2014 , Bazzanella et al. 2017)

The CO_2 avoidance of Urea is high when compared to Soda ash and Methanol and hence it is selected as the product to be produced by utilizing the CO_2 from DCB's Cement plant at Ariyalur. Once Urea is applied to agricultural land reacts with water to release the CO_2 and ammonia. About 0.7 t of CO_2 per tonne of Urea returns to the atmosphere and the NH_3 decomposes further to supply nitrogen at a controlled and appropriate rate to crops which is a disadvantage. On the contrary, Urea assists the plants to grow at a faster rate and remove $CO_2$by biological fixation. India being a agrarian Society and there exists a demand supply gap for fertilizer, production of Urea as a product through CCUU route by DCBL can contribute to the growth of agriculture sector as well as contribute to climate change control process.

A longer-term option is the direct photo-conversion of CO_2 from ambient air via 'artificial photosynthesis'. This would be a major technological breakthrough leading to new CO_2 conversion technologies using only air and sunlight to produce chemicals and fuels. In conclusion, CCU will allow us to create value and decrease CO_2 emissions by focusing on CO_2 applications with environmental benefits (using less fossil energy, emitting less CO_2…)

3. Baseline Environment Quality

Project Details

The proposed CCU Project requires the construction of CO_2 capture Unit consisting of Direct Contact Cooler, Absorber (incl. water washers), Desorber, Pumps, fan, HEXs, Electrical and instrumentation and BOP. The Utilization Unit requires construction of ammonia plant, Urea Synthesising Unit and a prilling tower connected with Cooling tower. A Captive power plant for supplying steam to the desorber and for utilization section and to additionally generate about 50 MW electric power to run the ammonia compressor, rotating equipment and pumps is also envisaged. The capture facility will be located in an area of 100 X 100 m^2 in the west of the existing main facility and the Urea manufacturing section and Captive power plant (CPP) will be located adjacent to it in an area of about 11.0 hectares. A pressurized pipeline shall carry CO_2 gas to the Urea plant. One electrical substation with linked electrical power line is also planned. The raw CO_2 supply is from the DCB cement production plant and its infrastructure facilities like water supply and sewage disposal will be utilized. However, a separate effluent treatment facility will be provided to treat the process and cooling tower effluents from the CCU plant. The proposed Utilization project would consume about 1.02 million tons of CO_2 per year and produce about 1.4 million tons of Urea.

The project is expected to be built and commissioned within a period of 3 years from the date of issue of LOI for plant and machinery.

3.1 Monitoring, Verification, and Accounting of CO_2 consumed

On-line monitoring instrumentation facility would be provided to monitor the mass flow and pressure of the CO_2 supply to the Urea plant and it would enable costing of the product as well as the quantity of CO_2 that is used for Urea manufacture.

3.2 Operations and Maintenance

The capture and Utilization unit will operate 330 days in a year with 35 days for planned shutdown and anticipated operation issues. While selecting the equipment utmost care will be given to select highly reliable components. The plant will be operated with trained manpower.

3.3 Environment Setting

Project Location

The prosed project is to be implemented at DCB ‘s cement facility at Ariyalur in the State of Tamilnadu. DCBL Ariyalur Cement Plant is located in Govindapuram village in Ariyalur district of Tamilnadu between 11^o 10’21”-11^o 11’17” N Latitude & 79^o 05’45”-79^o 06’42” E Longitude (Survey of India Topo Sheet No. 58 M/4).2). The proposed CCUS project is to be sited within Cement Plant, on the West side of existing Cement Mill MCC Room. The coordinate of North-East corner of the proposed site will be latitude 11°11'3"N and longitude 79° 6'1"E. Plant North is oriented about 6^o anticlockwise with respect to true North. The topographical map and satellite image of DCB’s Ariyalur facility is given in fig 3.1 & 3.2.

Fig 3.1 Location map of DCB's Ariyalur facility

Fig 3.2 Satellite Image of the Project Site

There is no environmental issues about the site. There is no National Park, Wildlife Sanctuary, Biosphere Reserve, Hot Spot, Historical Monument within 15 km radius area. Kallankurichi Kaliyuga Varadharaja Perumal Temple is at 3.4 km in SE direction from the Plant. There are 6

Reserved Forests (RFs) from 9.0-15 km distance from the Plant. They are : Vannankurichi RF - 9.0 km in E, Manageri RF - 12.2 km in E, Kunnam RF- 12.0 km in NW, Vilangudi RF - 13.0 km in SE, Sedalavadi RF - 13.3 km in NE, Chittali RF - 14.4 km in NW

Drainage

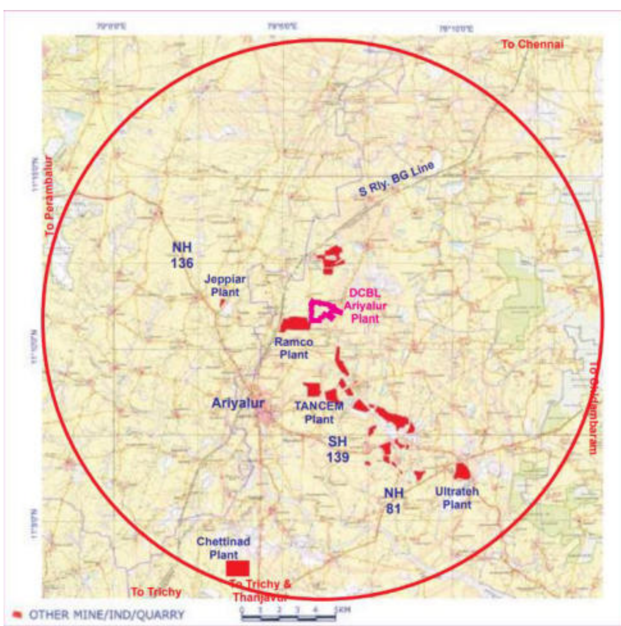
A seasonal nallah Kallar River originates near the Plant area at 1.0 km distance in the east. Seasonal Marudaiyar River drains the Region which flows at 7.4 km distance from the Plant in the south. However, there will not be any impact on the Plant due to the nallahs.

Road / rail / Port links

The State Highway (SH) 139 Ariyalur-Sendurai-Jayamkondam Road runs adjacent to the Plant Area. Ariyalur Bypass (3.2 km in SW), NH-136 Ariyalur-Perambalur Section (4.3 km in SW), NH-81 (Trichy Chidambaram Section (9.7 km in SE) and SH-143 (4.2 km in W) are the major roads in the Plant Area. Southern Railway BG Line connecting Chennai-Ariyalur-Trichy-Madurai-Kanyakumari runs at 1.4 km in the west and Ariyalur Station is at 3.7 km in SW direction **(Figure 3.3).**

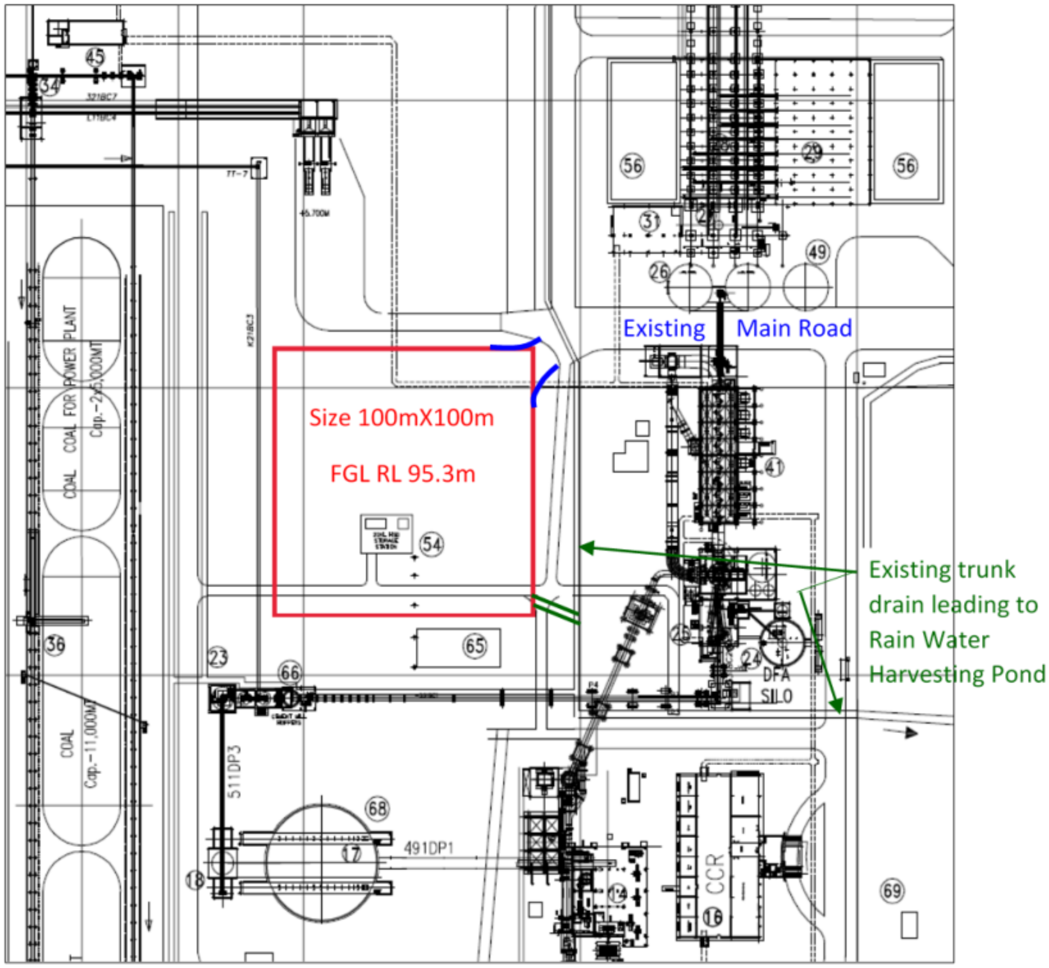
Trichy Airport is at 60 km in SW and Chennai Airport is at 230 km in NE. Karaikkal Port (88 km in SE), Cuddalore Port (94 km in NE) and Chennai Port (247 km in NE), Tuticorin Port (362 km SE) are the nearby Ports. Taluk & District Head Quarter Ariyalur is at 3.7 km southwest from the Plant. Nallambathai hamlet of Govindapuram village is located at a distance of 0.3 km in north and Govindapuram is at 1.6 km in west.

Fig 3.3 Topo map – 15 km surrounding the plant



The project site would be on the North east side of the existing cement facility. (Figure 3.4).The infrastructure requirement of the project would be linked to the main project. The land requirement is about 11.0 hectares. The proposed site plan is shown in fig. 3.4

Fig. 3.4 Site Plan



Climatic Data

Sub-tropical climate prevails over the study area. The nearest IMD station is Trichy Airport and the climatic data for the past one decade is as follows:

The temperature is maximum during March to May and it drops from June onwards. The maximum temperature ranges from 40 °C to 44 °C and minimum temperature from 18 °C to 27 °C. The salient features of climatic data are:

Annual average temperature: 29.4 °C

Annual average maximum temperature: 36.0 °C

Annual average minimum temperature: 24.4 °C

Annual average humidity: 62.9 % Annual average

visibility: 5.5 km , Annual average wind speed: 13.4 kmph

No. of rainy days: 79 ;Total days with thunderstorm: 36 ; No. of days with fog : 5

Rainfall

Trichy District receives rainfall both in Southwest and Northeast Monsoons with rainfall ranging from 730 mm to 900 mm. The nearest rain gauge station is located at Ariyalur. The 70 years normal annual rainfall in the area is around 1096 mm. The North East Monsoon contributes major amount of rainfall, which is about 50 % of the rainfall, and the remaining rainfall occurs during Southwest and Transitional period. The season wise and monthly normal rainfall for the Ariyalur station is furnished below :

Table 3.1 Season wise and monthly rainfall for the Ariyalur station

Rain gauge station	Jan – May (Transitional Period)	June – Sep (South West Monsoon)	Oct – Dec (North East Monsoon)	Annual Normal (mm)
Ariyalur	199	379	518	1096

Wind Data

Winds are generally of low to moderate speed during most of the months except during northeast monsoon, which creates cyclonic weather and brings rainfall aided with strong winds. The predominant wind direction is from W/NE/NNW directions. The average wind speed is 6.7 km per hour. During the months of May-June the maximum temperature reaches up to 44° C. and during the December-January the lowest temperature reaches up to 20 ° C. The mean relative humidity measured is 61.2%. The sky is generally clear or occasionally partly clouded except the NE Monsoon Periods.

Water requirement

Existing water demand of the DCBL complex is is 1,600 cu.m/day and it is met by 1,400 cu.m/day from permitted borewells within the Plant premises and 200 cu.m/day treated effluent,. The 1,400 cu.m/day ground water is met out of the permitted quantity of 1,620 cu.m/day from Govt of Tamilnadu.

The make-up water requirement of the proposed CCUS Unit is estimated to be about 1525 m^3 /h (Urea 1500 + CC plant 24.5 m3/hr) and it can be met by drilling additional boreholes for which prior permission to be obtained from State/ Central Ground Water Control authority.

Land Requirement

The Plant Area is predominantly dry, barren flat terrain and covered with red soil. About 112.06 Ha (276.91 Acres) is utilized for the Cement & Captive Power Plants out of the total extent of 204.78 Ha. The proposed CCUs Unit may require about 11 Hectares which can be met from the above land. The site falls in Seismic Zone III.

Background Environment Quality (2019-20)

The Environment quality monitored during 2019-20 as monitored by DCB is given below.

Table 3.2 Baseline Environment Quality

Envl. Component Main -Parameter		Maximum	Minimum	Mean	Desirable Norms
Ambient Air Quality (24-hly), ug/m	PM_{10}	78.0	51.6	55.5-70.0	100
	$PM_{2.5}$	33.9	20.0	23.7-30.5	60
	SO_2	31,3	19.3	22.1-26.7	80
	NO_X	33.8	20.8	24.9-30.0	80
Ambient Noise, dB(A)		52.8	41.2	46.93	45-55
Ground water TDS mg/l		1876	389	721	500 -2000

Source : (DCB,2020)

The monitored ambient air quality in the study area was found to follow the National Ambient Air Quality (NAAQ) 24-hourly Norms for Industrial, Residential, Rural and other areas. Ambient Noise Levels (Leq) monitored during day and night times were found to be well within the Ministry of Environment and Forests & Climate Change (MoEF&CC) norms. The ground water quality was found to be in compliance with BIS:10500-2012

Biological Environment

There is no cutting of trees or clearing of bushes, etc. as the site is within the DCB boundary. There is no eco sensitive area exists in the study area and only domesticated animals exist. There is no habitat fragmentation or blocking of migratory corridors due to Project activities and there is no wild life movement or migratory birds movement in the study area.

4. DCBL Cement Facility Emissions

The DCB cement industry manufactures different grades of cement. It has many stationary sources of air emissions. Significant sources of emissions include preheater, Kiln furnace and captive power plant. As part of the permit requirements, the facility must comply with emission standards for cement industry and captive power plant standards. Table 4.1 lists stack emission data. CO_2 emissions are not reported by the facility as it is not required to be reported as per the latest emission standards for cement industry by CPCB. But DCB is monitoring CO_2 emission as part of voluntary Carbon disclosure.

Table 4.1: Stack Emissions from operating DCB cement Complex

Raw mill/Kiln Main Stack				
No	**Parameters**	**Units**	**Direct (Raw mill stop condition)**	**Indirect (Both Rawmill & Kiln Running)**
1	**Oxygen (O2)**	%v/v	13.15	13.60
2	**Carbon Di Oxide (CO2)**	%v/v	13.20	12.75
3	**Nitrogen (N2)**	%v/v	78.00	78.00
4	**Carbon Monoxide (CO)**	ppm	160.00	139.00
5	**Sulphur Di Oxide (SO2)**	ppm	8.00	3.00
6	**Oxides of Nitrogen (NOx)**	ppm	170.00	161.00
7	**Temperature**	°K	385	357
8	**Pressure**	mmHg	748	748
9	**Moisture**	%v/v	2.5	3
10	**Flow rate**	Nm3/hr	635292	685119

Note: At Ariyalur plant, due to 12% moisture in the Limestone, Hot gas from Cooler output (85000 Nm3/hr), having around 21% O2 is used for drying Limestone moisture in Raw mill continuously.

Table 4.2: Stack Emissions from operating DCBL Captive Power Plant

Captive Power Plant			
S.No	**Parameters**	**Units**	**CPP Boiler**
1	Oxygen (O2)	%v/v	10.86
2	Carbon Di Oxide (CO2)	%v/v	7.11
3	Nitrogen (N2)	%v/v	78.00
4	Carbon Monoxide (CO)	ppm	36.00
5	Sulphur Di Oxide (SO2)	mg/Nm3	404.00
6	Oxides of Nitrogen (NOx)	mg/Nm3	216.00
7	Temperature	°K	378
8	Pressure	mmHg	752
9	Moisture	%v/v	1.96
10	Flow rate	Nm3/hr	341509

Source: (DCBL, 2020).

4.1 CO_2 Accounting & Reporting

GHG inventory report has been prepared by DCBL in line with the ISO 14064-1:2006 and WBCSD Cement Sustainability Initiative Cement CO_2 and Energy Protocol Version 3.1, Emissions and Energy Inventory standard. The ISO 14064-1:2006 requires that: "The organization should prepare a GHG report to facilitate GHG inventory verification, participation in a GHG programme, or to inform external or internal users." Accordingly, this report has been prepared by DCBL periodically to facilitate GHG verification of the emission inventory and to enhance transparency of stakeholder communication and is given as an Excel sheet.

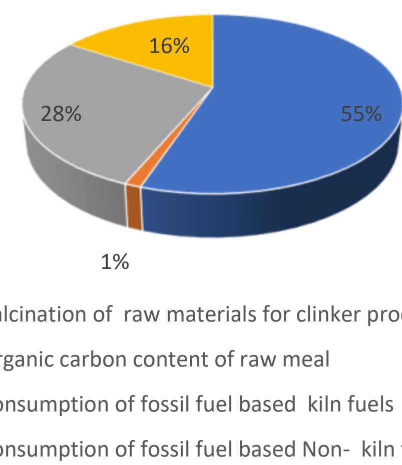
The table below presents the emission inventory for the year 2018-2019, 2019-2020:

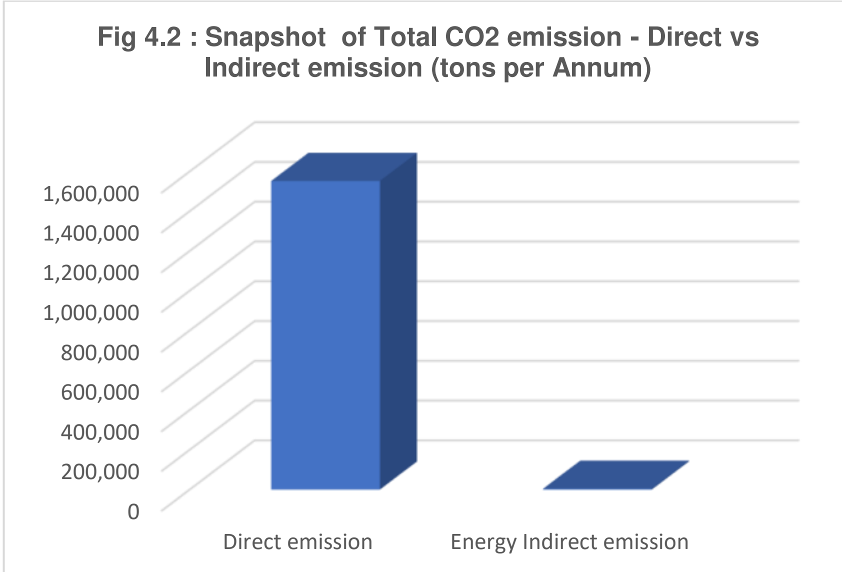
Table 4.3: Absolute GHG emissions in t CO_2 / yr

CO_2 Direct Emissions (Scope 1)	**2018-19**	**2019-20**
Calcination of Raw Materials for clinker production	8,21,178	8,55,747
Organic carbon content of the fuel	17,766	17,766
Fossil based kiln fuels	4,11,179	4,32,390

Non kiln fossil fuels	2,86,170	2,45,591
Total	15,36,293	15,52,242
CO_2 Direct Emissions (Scope 2)		
CO_2 from external power generation	3,325	3749
CO_2 from net inbound (+) / outbound (-) clinker	--37,312	0
Total indirect CO_2 (main sources)	-33,987	3749
Grand **Total (Scope1+ Scope 2)**	15,02,306	15,55,991

Fig 4.1 : Contribution of Direct Emission sources





4.2 DCBL Carbon negative by 2040

Ariyalur cement plant has gross CO_2 emission of 15,55,991 tonnes per annum (max.value assumed).DCBL plan to become 100% renewable energy company by 2030 and hence CO_2 emission of 3749 due to electricity consumption in the plant to that extent will be reduced. After accounting replacement of conventional electricity by renewables, about 13,31,738 tonnes of CO2 per annum has to be captured by installing capture plant to become Carbon negative. Initially DCBL, Ariyalur is proposed to become carbon negative by installing a Capture plant of 3000 TPD of CO_2 and production of 2270 TPD Ammonia and 3738 TPD Urea .On successful commissioning of the project, it can be extended to other Units of DCB for the company to become carbon negative. For the Ariyalur Unit, the capture unit of 1000,000 tonnes per annum CO_2 capture Unit capacity can be expanded to 1,33,2000 to become carbon negative. And the space requirement for future expansion is available in the existing plant premises.

On the basis of the present CO_2 emission level of 0.519 tonnes per tonne of cement from Ariyalur plant, it has to target capture capacity of about 19,19,0556 tonnes of CO_2(say 20.0 million tonnes) for an installed cement capacity of 37 MTPA in 2040 for the whole company DCB to become carbon negative. With 100% renewable energy which is the perspective plan of DCBL, the CO_2 emission will be reduced to 1,75,58,856 tonnes instead of 1,91,90,556 tonnes as well reducing pollution and conservation of fossil fuel.

Table 4.4 : DCBL CO_2 emission 2020 / 2040

Ariyalur Unit, 2020	**Dalmia Cement (Bharat) - Total CO_2 emission per tonnes per annum 2020 and 2040**			
Total CO_2 emission in 2020 for 3 MTPA	Year - 2020 Installed capacity – 28.0 MTPA	Year- 2040 Installed Capacity - 37 MTPA	Year 2040 *Gross CO_2 avoidance due to 100% renewable energy use	Gross CO_2 reduction required for DCB Ltd become CO2 negative)
15,55,991	**1,45,22,583**	**1,91,90,556.**	**16,31,700**	**1,75,58,856**

(* replacement of 62 Units conventional electricity consumption per tonne of cement by setting target figure of 60 units of renewable energy by increasing energy efficiency)

4.3 Greenhouse Gas Emissions from the proposed CCU plant

Direct and Indirect CO_2 Emissions. Carbon emissions of 1.0 MTPA from the DCB Ariyalur Plant would be captured and used to produce Urea. It is anticipated that approximately 1.0 million tons of CO_2 would be sequestered every year during its life time of about 30-35 years. However, the overall amount of CO_2 generated would increase due to the burning of natural gas as fuel for ammonia manufacture, process steam and electricity from Captive Power Plant (75-100 megawatt (MW)), and worker commutes. The net CO_2 emissions for the project were estimated (Table .4.5). A net decrease of approximately 0.95 million tonnes of CO_2 emission would be realized over the life of the project. These 0.93 million tons of CO_2 are currently vented to the atmosphere and would not be if the proposed project were implemented. This is about 0.06% of the global CO_2 emissions from cement production. If fossil fuel is considered for power production, avoided CO2 will be drastically reduced. Hence, DCBL must undertake 100 % renewables for cement production.

Table 4.5 Net CO_2 Emission reduction by DCBL due to Proposed CCU Project

Activity/Source	**Emissions (Short Tons)**
Electricity Usage (100% renewables)	67,320
Worker Commutes	1000
Sequestration	**(-1,000,000)**
Total Emissions Reduction	**(-9,31,680)**

Estimation of Carbon Footprint for different Project Options:

In order to assess the carbon footprint with and without CCU, five different Scenarios varying the CO_2 capture rate as 0.5 mpta , 100% CO_2 sequestration, source of ammonia, and biomass to arrive at the optimum process is detailed below:

Table 4.6 – Carbon Foot print analysis

	Item	Baseline 1 (no CCU)	Project scenario 1 (ammonia from fossil fuel)	Project scenario 2 (green ammonia)	Project scenario3 (biomass boiler)	Project scenario3 (biomass and green ammonia)	Project scenario 5 (100% CO2 utilization with biomass and green ammonia)
		tonne per annum	tonne per annum	tonne per annum	tonne per annum		tonne per annum
Cement plant	Process emissions	1,306,651	751,095	751,095	751,095	751,095	0.00
Capture plant emissions (Capturing 0.5 mtpa)							
	electricity	0	99,990	99,990	0	0	0
	coal	0	261,954	261,954	0	0	0
	process emissions	0	55,556	55,556	55,556	55,556	130,665
Ammonia unit	Natural gas	664,669	664,669	0	664669	0	0
	electricity	12,989	12,989	0	0	0	0
Urea unit (0.5 mpt CO_2 utilization)	electricity	83,992	83,992	83,992	0	0	0
	gas	110,603	110,603	110,603	0	0	0
Net emissions		2,178,903	2,040,847	1,363,189	1,471,320	806,651	130,665
Combined emissions reductions(vs Baseline), tpa		N/A	138,056	815,714	707,583	1,372,252	2,048,238

Scenarios:

- Baseline with cement and urea business as usual case;
- Scenario 1. Fossil Based ammonia
- Scenario 2 Green Ammonia
- Scenario 3 Biomass boiler
- Scenario 4: Green ammonia and biomass
- Scenario 5 : 100% CO_2 sequestration with green ammonia and biomass boiler

5. Environment Impact Assessment

The environmental Analysis Approach

This chapter describes potential impacts of this DCB's Proposed CCU project on the Environment parameters such as air quality, water quality, soil quality etc.

5.1 Approach to the Analysis

An EIA is intended to be a clear, focused analysis of impacts. Accordingly, systematic approach is used to identify, and then answer the relevant impact questions. The initial step was to develop a detailed description of the project activities and the potential effects on environmental resources. This served as the framework of the analysis of impacts and further evaluate whether these effects would in fact occur, and if so, how extensive, how severe, and how long-lasting they would be.

5.2 Analysis of Significance

In the impact analysis, systematic review process is adopted to evaluate the importance, or **significance, of the predicted impacts.** These significance criteria were based on legal and regulatory constraints and **on our professional technical judgment**. The impacts (both beneficial & adverse) during the construction and operation of the project has been studied and is detailed below:

5.2.1 Construction Phase

During the construction period minor impacts on air quality and noise due to vehicle movement and construction activity is anticipated. By proper maintenance of field equipment, the impact can be reduced. Impact on water and land will be minimal. Solid waste generated during construction will be disposed as per the guidelines provided by the Statutory Authorities.

5.2.2 Operation Phase

The proposed project when implemented can impact the Environment Parameters Air, water and soil. A preliminary survey of Environmental impact from the proposed project is given in Table-5.1

Table 5.1 : Project Environment impact matrix

Resource	DCB's Proposed CCU Project
Air Quality	During the construction period, short-term, minor impacts would be limited to emissions due to vehicular movement and construction activity. However limited air emissions from the CCU project is anticipated during its operation. The project would not produce emissions that would impede the area's conformity with the National AAQ standards. In fact it is anticipated that , there would be some beneficial impacts due to the reduction of green house gas emissions. The ammonia leakage and emission from Urea plant will be addressed by designing suitable flare and suitable detection system. The urea dust emission will be less than 30 mg/Nm^3 by installing suitable dust extraction system in the prilling tower. Air quality standards for amine degradation products are not available at present. Nitrous oxide emission from Ammonia plant also will be designed with emission less

	than 400 mg/Nm^3.
Geology and Soils	As the proposed project does not produce any solid / liquid waste that would cause soil pollution, there is no adverse impact on soil quality.
Water Resources	The proposed project may cause some modest increase in water usage due to the to the Urea Production process; due to continuous drawl of large quantity of ground water to meet process requirements, there is going to be lowering of ground water table. Check Dams with ground water recharging of rain water is proposed to augment ground water resources. Before commencing the project, approval of State Ground Water Board or Central Ground water Authority permission shall be obtained for extraction of about 1600 m^3 per hr of ground water. A comprehensive waste water management system is proposed in the Fertilizer Complex to treat the liquid effluent and the treated water will be utilized within the plant itself. Domestic liquid waste generated during construction phase/ operational phase will be connected to a seperate sewage treatment plant. Zero discharge concept is proposed for the project and hence there is no likely adverse impact on water resources.
Terrestrial Vegetation	As the project land is within the main plant area, there is no clearance of vegetation and hence there is no impact .There is no R&R issues.
Wildlife	There is no endangered species in and around 10km of the project site
Land Use	Any change in land use would be limited to a small area and would not noticeably alter any particular land use site or in adjacent areas.
Population	The effect on the local population, if any, would be minimal.
Employment and Income	The effect on the employment and income of local community, would be primarily beneficial and of longer duration.
Noise	There may be temporary minor noise impacts during construction and operational. however, noise levels in the project area are not expected to exceed ambient noise level standards by proper design of Equipments and providing a green belt around the plant. .
Cultural Resources	The project area is industrialized already and no impacts are expected.
Waste Management	The Hazardous waste generated in the project will be disposed as per Hazardous waste Handling and disposal rules. Other solid waste will be disposed as per the latest Waste Management rules'2016 and would not

	cause air, water, or soil to be contaminated with hazardous material that poses a threat to human or ecological health and safety.
Threatened or Endangered Species	There is no threatened or Endangered species within 10 km of the project site.
Infrastructure	There would be marginal improvement in the infrastructure of the area in and around the project site and change to the existing traffic patterns is expected to small extent.
Human Health and Safety	The project, with current and planned mitigation measures, would pose no more than a minimal risk to the health and safety of on-site workers and the local population.

6. Environment Management Plan

The Environment management plan covers Pollution prevention and control requirements for various types of pollution (air, water and Solid waste) anticipated during construction and operation of CCU plant. This plan aims at Environment Protection and meeting Statutory requirements.

6.1 Air pollution Management system

Emission of pollutants such as particulate matter (urea), oxides of nitrogen, ammonia vapour and carbon dioxide are anticipated in the Urea plant .Emission of SO_2,NO_x , SPM and mercury arises due to Construction and operation of the Captive power plant (CPP). Capture plant emission consists of Carbon di oxide, water vapour and ammonia. Air pollution Control measures have been envisaged in Environment management Plan (EMP) for the project to protect the air Environment. The proposed EMP for construction and operation of the project is discussed below:

Site preparation, construction

Construction emissions would primarily be due to the use of diesel generators and motors, heavy construction equipment, deliveries to the site, the application of architectural coatings, and fugitive dust. There will be emission of carbon monoxide, Sulphur dioxide, oxides of nitrogen and particulate matter due to the use of heavy equipment machinery and transport vehicles. However, it is for a short duration and hence the increase in the concentration of the above construction activities is assumed to be negligible. Construction equipment mufflers would be provided and proper maintenance of the equipment in good working order, air and noise pollution level can be controlled to comply with emission norms.

Operation and maintenance

The operational emissions would primarily be due to the proposed Carbon Capture Unit, Urea Plant and captive power plant.

Regarding pollution in the Carbon Capture Unit, the pre-scrubber and absorber remove pollutants such as SO_2 and oxides of nitrogen generated in the process and hence the cleaned flue gas doesn't need further cleaning and can be released as it is However, in the treated flue gas of Capture section, there might be emission of ammonia created by the degradation of the solvent and to quantify the ammonia emission is difficult at this stage as it again depends on the type of solvent used. Even if small quantity of ammonia is released, it will be diluted in the atmosphere by dispersion through stack of sufficient height to meet the AAQ standard for ammonia prescribed by Central pollution Control Board. Emission Standards for ammonia release and degradation products of solvent is at present not available in the Indian.

In the urea plant, the atmospheric discharges will originate from the following sources:

- cooling tower (water vapour and traces of chlorine and a biocide dispersant);
- ammonia reformer stack (nitrogen, oxygen, water vapour, carbon dioxide,
- argon and traces of sulphur dioxide and oxides of nitrogen);
- ammonia process vents (carbon dioxide, water vapour and hydrogen);
- urea vents and tank (air, water vapour and ammonia);
- granulation scrubber vent and tank (air, water vapour and traces of ammonia
- and urea dust);
- ammonia flare (nitrogen and water vapour).

As per Hazardous Waste Management rules-2016, Amine solvent is classified as hazardous substance. Spent amine solvent generated from the process need to be reported as Waste Category No.20.Spent catalyst (category no.18.1), Carbon residue (categoryno.18.2),Sludge or residue containing arsenic (category no.18.3),Spent ion exchange resin containing toxic metals (category no.35.3), Chemical sludge from waste water treatment (category no.35.2) are categorized as hazardous substances and Authorization from State Pollution Control Board (SPCB) has to be obtained to handle these wastes during operation.

During plant start-up and shutdown of the urea plant, which involve purging of the process equipment with nitrogen, waste gases will be generated. Those produced in the ammonia section will be burnt in the flare and released to the atmosphere in the form of water, carbon dioxide and nitrogen. Waste gases from the Urea section, consisting of carbon dioxide, nitrogen, oxygen and hydrogen, will be scrubbed and discharged directly into the atmosphere. Most of the gaseous emissions from the plant will be normal atmospheric components - nitrogen, oxygen, carbon dioxide, water vapour and inert gases -and these have no direct impact on the environment. The anticipated concentrations of oxides of nitrogen, oxides of sulphur have been compared with guidelines for such emissions published by the CPCB and hence it is concluded that there will be no adverse impacts arising from these sources. The trace emissions of ammonia and urea dust are also considered unlikely to cause any adverse environmental impacts. Of the gases released to the atmosphere, only ammonia has the potential to produce detectable odours. It has been calculated that normal concentrations of ammonia will be well below odour detection levels at residential areas.

Urea dust and Ammonia contained in the exhaust air from the Prilling Tower can be a source of air pollution in Urea plant. The Fig 6.1 explains the inbuilt emission control system in the Urea plant to ensure 100% recycling of raw materials/products that would have ended up as emission. A Wet type dust extraction system (Fig 6.2) to reduce the Urea dust and Ammonia content in the exhaust to less than 50 mg/Nm3- shall be provided in the Urea conveying and Bagging System with cyclone separator & wet scrubber with DM water. The dust from product flowing on conveyor belts and chutes is sucked with the help of fans and dissolved in water. The lean urea solution is re-prilled in Urea Plant. Twin objectives of dust free working environment and better quality product has been achieved after commissioning of this system.

Figure 6.1. The inbuilt emission control system in the Urea plant

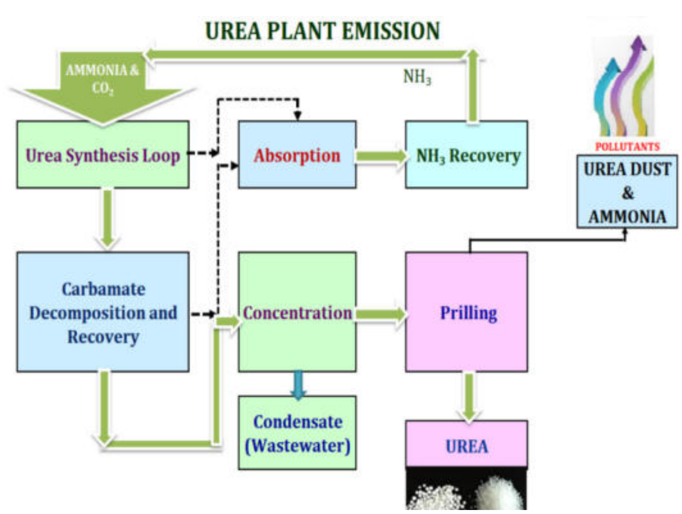
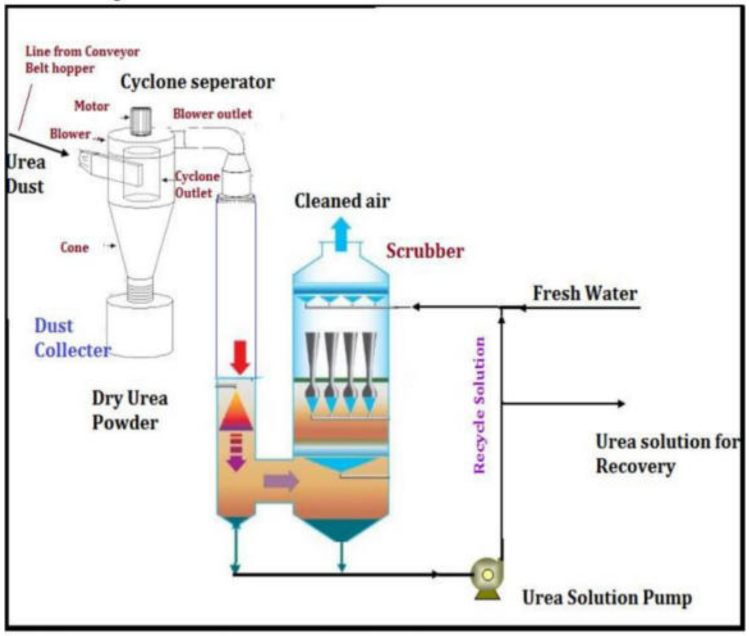


Fig 6.2 Wet dust extraction system in Urea conveying and Bagging System



6.1.1 Fugitive emissions

The fugitive emissions are leaks from flange, pump, sealed or tightened equipment. A significant proportion of fugitive emissions are losses from unsealed sources, including storage tanks, open-ended (not blanketed) lines, pressure-relief valves, vents, flares, blow-down systems and spills. In other cases, these losses may be caused by leaks in the sealing elements of particular items of equipment, such as:

· Pipes / flanges;

· Valves and fitting;

· Compressors,

· Pumps;

· Sampling connection;

· Incorrect process conditions.

The emissions from the pipes derive essentially from flanges and connections, such as sampling points. The general approach for minimizing fugitive emissions, is thus to minimize the length of pipe runs and to minimize the number of connections. The valves are generally considered the main sources of fugitive emissions in the process industries. Fugitive emissions from the compressors arise generally from seal on compressed gas line and oil seal. Fugitive emissions from a pump arise from seal on liquid line and oil seal. The good approach to minimize fugitive emissions from valves, compressors and pump is the implementation of the preventive maintenance and the leak detection program. Fugitive emissions from sampling connections can be controlled by returning the purged materials to the process, or by sending it to a control device.

Table 6.1: The sources and the types of fugitive emissions from the proposed plants

Source	Type of release
Ammonia Plant	
Valves, flanges, seals, sample points	NH_3, CO_2, H_2, Natural gas
Urea Plant	
Valves, flanges, seals, sample points	NH_3, CO_2, H_2,Naturalgas, Dust (from loading system)

6.1.2 Odour Control

As a part of gaseous emissions control, proper odour control is also required. The odour from the ammonia plant may originates due to fugitive emissions or leakages of ammonia. Therefore, in the design preventive measures will be provided to control fugitive emissions at the source.

6.2 Liquid Effluents and Water Pollution Management System

A comprehensive waste water management system shall be provided in the CCUS plant to treat the liquid effluent to meet the Environment Clearance / State Pollution Control Board Statutory requirements. The sources of effluent generated in the CCU plant and its usage are as follows:

i. Capture Plant Effluent

The flue gas entering the Direct Contact Cooler (DCC, scrubber) is so hot and dry that there will not be any water condensation, but water will evaporate instead. So there is no water effluent. Since water is lost (evaporated), the DCC needs in total about 18 m3/hr of fresh water. This is a very large amount, so measures have to be taken in the detailed design to reduce this water requirement, for instance by heat recovery from the flue gas. The water requirement of 18 m3/hr will be met from the existing plant facility. The sewage generated in CCUS facility will be treated in a separate facility.
As per the latest CPCB standard, the plant will be designed for Zero Liquid discharge. The quantum of waste water generated in the Capture process is negligible and hence it would be integrated in the wastewater treatment facilities of the Urea plant.

ii. Urea Plant Effluent

Liquid wastes are generated from the boiler blow downs, air compressor intercoolers, turbine condensates, steam condensates, process condensate, and oily effluent from the various processing units. In the design itself necessary systems shall be provided to have negligible impact on environment. An effluent treatment Plant has been designed to cater the treatment needs of effluent generated from various sections of the Unit. In addition, adequate provisions have been made in each Plant to ensure maximum recycle of process condensate with minimum generation of effluent. A separate effluent monitoring cell shall be set up to keep round the clock vigilance on effluent quality to ensure that the discharges are much lower than that specified by State Pollution Control Board. A description regarding the treatment approach of various effluent streams of the Urea plant is given below:

iii. **Urea & Bagging Plants**

Provision of separate high pressure Urea Hydrolyser section for treatment of about 80 M^3/hr. process water generated during Urea production process. Finally treated water is of such a good quality that it is used as boiler feed water. The main source of process water is the urea synthesis reaction:

$$2 NH3 + CO2 \rightarrow CO (NH2)2 + H2O$$

Where 300 kg of water are formed per ton of urea. A urea plant of 4000 TPD generates theoretically about 1200 m3 water/day (~50 m3 /hr). This water contains 6% NH_3, 4% CO_2 and 1% urea (by weight)

A. Boiler Blow Down

Boiler blow down will be routed to the cooling tower basin as make-up.

B. Condensate from Air Compressor Intercoolers

Condensate from Air Compressor Intercoolers will be routed to the cooling tower basin as Make-up.

C. Turbine Condensate

Turbine condensate will be sent to the polishing unit and shall be reused as BFW (boiler feed water) after polishing. In case the turbine condensate is off spec, it will be transferred to the Common effluent treatment section.

C. Steam Condensate

Steam condensate will be sent to the polishing unit and reused as BFW after polishing. In case the steam condensate is off-spec, the same shall be transferred to the Common effluent treatment section.

F. Process Condensates

Process condensate generated in Ammonia Plant is treated in dedicated stripper and the treated condensate is sent to the polishing unit and reused as BFW after polishing. In case the process condensate is off-spec, the same shall be stored in a tank in Ammonia plant and gradually treated in the medium pressure process condensate stripper. Provision is also provided for diversion to Common effluent treatment section.

Process condensate generated in Urea Plant is treated in dedicated hydrolyser and stripper and the treated condensate is sent to the polishing unit and reused as BFW after polishing. In case the process condensate is off-spec, the same shall be stored in a tank in Urea plant and gradually treated in the hydrolyser and stripper. Provision is also provided for diversion to Common effluent treatment section.

G. Oily Wastewater

Oil contaminated Water is collected in a spill wall or into an oil trap of a pit for each potential source of oily water. Oil will be removed in oily water separator such as CPI separator prior to discharging to the Common treated effluent pit.

6.2.1 Condensate Polishing System

A New Condensate Polishing System will mainly treat process condensates from Ammonia & Urea Plants & Steam Turbine condensates. Condensates are first passed through Cartridge Filters. After microfiltration, condensates are treated in the Mixed Bed Polishing System to be reused as demineralized water. To regenerate cation & anions resins, sulphuric acid and caustic soda are used respectively.

6.2.2 Common Effluent Treatment Plant

An Common Effluent Treatment Plant (ETP) shall be installed to treat the Effluents and meet the treated Effluent Quality as prescribed by MoEF&CC / CPCB. The streams routed to ETP can be broadly classified as: Process Effluents and other Miscellaneous Effluents, Cooling Tower / Boiler Blow Downs, Sanitary Waste, Contaminated Rainwater. The Process Effluents from the Ammonia and

Urea units shall be collected in an effluent receiving sump & routed to the pre-treatment section of the Effluent Treatment Plant. The Cooling tower blow down effluent from Ammonia and Urea Cooling towers are separately routed to the ETP.

The pretreatment Unit of the ETP shall consist of a Gravity and Coalescing media type oily water separator unit to remove Oil and Suspended Solids from the Effluent. The effluent from the Pretreatment unit shall be mixed with the Cooling Tower Blowdowns and shall be equalized. The equalized effluent shall be further treated in a biological treatment unit with aeration for removal of BOD and COD. The Treated Effluent from the biological treatment unit shall be further passed through a Filtration Step and then finally Dis-infected. The treated Effluent shall be stored in a Holding Pond of adequate size for stabilization and the Treated Effluent from the holding pond shall be utilized for process use such as service water, fire water and for green belt Development around the Complex. The effluent from the Canteen is routed to a sanitary effluent treatment package unit having a design flow capacity of 10 m3 /hr. The treated sanitary effluent along with treated ETP Effluent shall be used for horticulture purpose.

The Effluents from the fertilizer complex shall be analyzed and the report shall be submitted to SPCB at regular intervals. This constant monitoring will ensure that there is no impact on water environment.

The floor washing water from urea synthesis section is collected in dedicated pits inside urea plant and treated in hydrolyser and stripper. The treated stream is routed to treated effluent pit.

The re-generation effluent generated during regeneration of polisher resin is collected in dedicated neutralization pit having neutralization facility and after pH correction, transferred to Common treated effluent pit. The treated effluent pit have neutralization facility for pH correction The air sparer are also provided to improve the water quality by increasing dissolved oxygen concentration. The treated effluent from treated effluent pit is routed to equalization pond by means of closed pipe line. The control valve installed at up-stream of discharge pump controlled by DCS and operating logic is configured with pH of discharged treated effluent. If the pH of treated effluent goes beyond 8.0 or less than 6.5, then the control valve automatically closed and stop the transfer to equalization pond. In such cases the pump discharge recycled back to treated effluent pit by recycle line. The diagram showing the common effluent treatment and re-use facility is illustrated below:

6.2.3 Final treated effluent

Final treated effluent in Common effluent treatment facility, is directed to the holding ponds having storage capacity of 35,000 M3 (one week storage) . The various effluents generated in various sections is is shown in fig. 6.3 and in Table 6.2

Table 6.2 Waste water Generation in the Fertilizer Complex

Type of Effluent	Source	Quantity M^3/Hr
Process Effluent	Ammonia Unit	12
Process Effluent	Fertilizer Unit	10
CPP / Ammonia Boiler blow down	Offsites	5
Ammonia Cooling Tower Blowdown	Offsites	110
Urea Cooling Tower Blowdown	Offsites	85
Washing / Flare Seal Effluent	Offsites	15
Miscellaneous Effluent (bagging plant etc.)	Offsites	10
DM plant regeneration waste	Offsites	15
Condensate polishing unit (CPU) waste	Offsites	10
Total effluent generation m^3/ hr		**272**
Design Capacity of ETP with 10% design margin		**300**

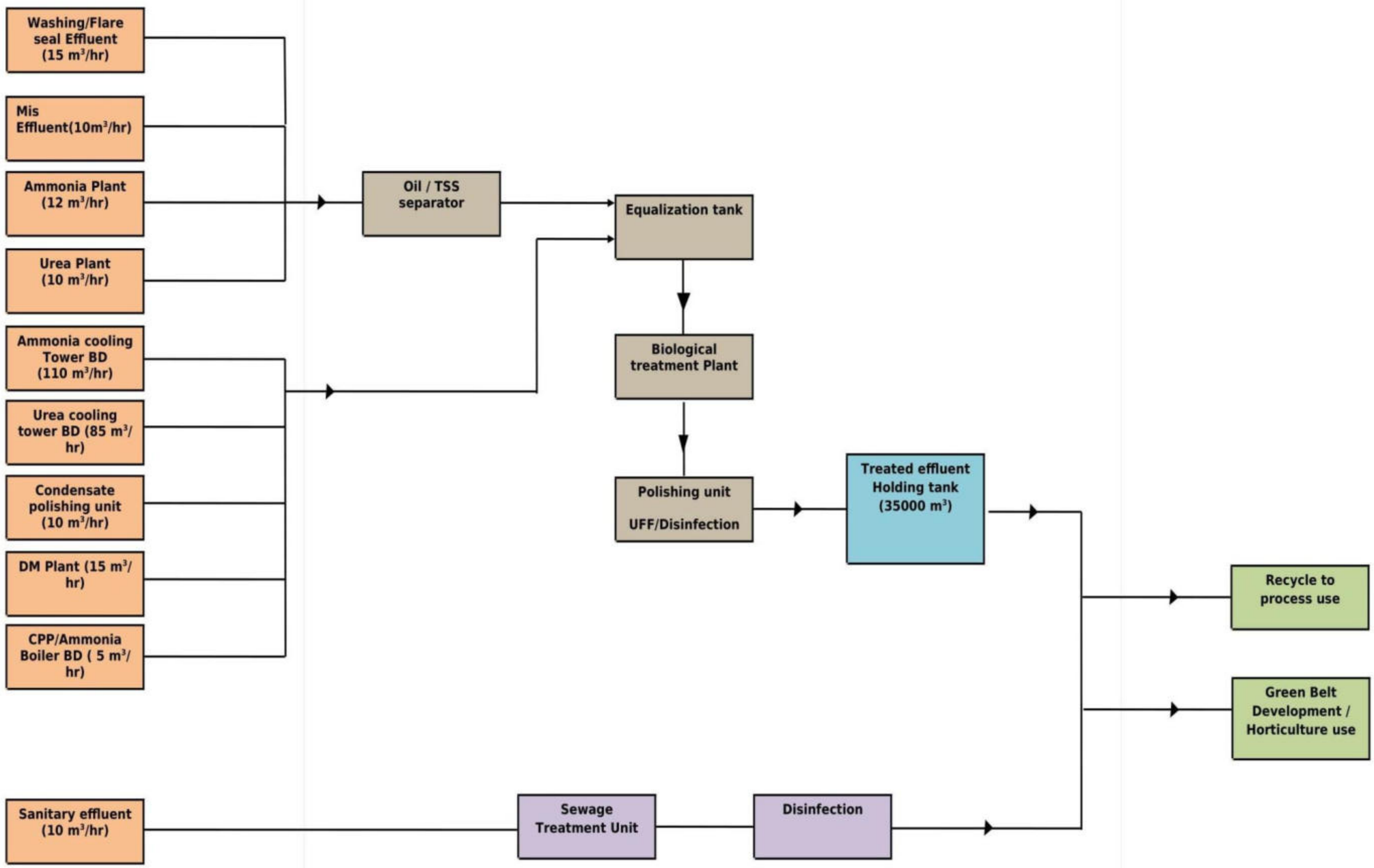


Figure 6.3: Flow diagram of Common Effluent Treatment Facility

6.2.4 Design of ETP

The Common Effluent treatment Plant will be designed as the design parameters given below to meet the Statutory norms.

Table 6.3 ETP Design Treated Effluent Quality

Parameter	Concentration (mg/l)
pH	6.5-8.5
Ammonical Nitrogen	10
Total Kjedahl Nitrogen	75
Free Ammonical Nitrogen	2
Nitrate Nitrogen	10
Cyanide as CN	0.1
Vanadium as V	0.2
Arsenic as As	0.2
Suspended Solids	100
Oil & Grease	10

6.2.4.1 Solid Waste Management

During construction, operation and maintenance of the proposed project different types of wastes would be generated which is given below:

- Used lube oil,
- Used metal parts,
- Used gaskets,
- Oily rags,
- Filters,
- Containers,
- Contaminated soils from spills and leaks,and
- Domestic solid wastes
- the slurry removed every 2-3 months from the solvent reclaimer.

The exact disposal protocol would follow that established by DCB to dispose of their other wastes. Used oil, oil contaminated waste slurry from solvent reclaimer facility are considered as hazardous in nature and they will be used in the cement kiln facility as fuel. Based on the anticipated volumes of domestic wastes to be generated, it will be disposed in the kiln. The following strategies are recommended for solid waste management: The ETP Sludge shall be used as manure. The provisions of Hazardous Waste (Management & Handling) Rules, 2008 will be complied with for spent catalysts. The Waste Oil generated shall be sold to authorized agencies. The solvent amine used in Capture Unit is Toxic for groundwater and aquatic environment. Any spillage from tank will be collected and reused.

These hazardous materials will be handled as per SOP (Standard operating procedures) under proper supervision and the guidance as per MSDS (Material safety data sheet). Besides that, the proper labelling of containers, display of MSDS and availability of secondary containment, spill control equipment will be ensured. The different type of solid wastes generated in the CCU and disposal practice is given below:

Table 6.4 :Types, Sources and Disposal of Solid Wastes

Type of Waste	Sources	Disposal
Used oil/waste oil (Category 5.1 – 5.2)	Compressors, pumps, DG sets, captive power plant	Storage and sold to recyclers
Spent catalyst from Ammonia & urea plant (category 18.1)	From different section of Ammonia Plant	sold to recyclers
Spent Carbon (category 18.2)	Demineralization plant	Sold to recyclers or incinerated in kiln
Sulphur cake (category17.1)	From filter	Can be burnt in cement kiln.
Discarded containers (category 33.3)	Chemical handling, raw material	Sold to authorized vendors

Beside these initiatives, still there are grey areas need to be addressed. Few of them are:

- Cleaning/de silting of all the storm water drains inside the premises for free flow of storm water during rainy season.
- Hazardous waste storage area to be maintained as per CPCB guidelines.
- The exact amount of hazardous wastes generated, stored and recycled needs to be mentioned on the Board outside the units as per Supreme Court Order.
- Stack emission and AAQ monitored data to be displayed on line at Entrance of factory

Regarding the slurry that is generated in the capture Unit, it can be incinerated in the cement kiln itself as Dalmia has got the permission from State pollution Control Board to incinerate industrial wastes including waste water treatment sludges.(similar product)

6.3 Noise Pollution Control

Short-term and long-term minor adverse effects to the noise environment would be expected with the implementation of the proposed project. The effects would be primarily due to heavy equipment noise during construction . During operation, major noise-producing equipment would be compressors, blowers, pumps etc. The CCU facility is in the preliminary design stages. Therefore, a complete equipment list and associated manufacturers specifications is not yet finalized. While finalizing the equipment, the design noise level of equipment will be kept below 75 dB to keep the noise level below 85dB for equipment to meet the AAQ noise level prescribed by CPCB. By proper design and operation of the plant, DCB's Proposed Project would introduce relatively small long-term incremental increases in the noise environment and no noncompliance of relevant standards is anticipated. Silencers shall provided at vents to reduce noise level in the surrounding areas. Thick Plantation has been carried out around the boundary wall to reduce the sound level. The noise level at different places inside as well as outside the factory premises shall be monitored to keep the noise level well within the limits.

6.4 Rainwater harvesting

Rainwater harvesting is normally practiced for recharging ground water levels and provide water for human consumption. Rainwater harvesting measures at plant site shall be subjected to harvest rainwater from the roof tops and storm water drains to recharge the ground water and also to use for the various activities at the project site to minimize fresh water consumption and reduce the water requirement from other sources. A suitable rainwater harvesting schemes will be worked out during the execution of the project.

6.5 Tree Plantation and Green Belt Development

It is statutory to develop green belt in and around the plant at 33% of the plant area to improve the ecological balance as per the Statutory requirements. DCBL will initiate a program for extensive tree plantation in and around the CCCU Unit. CPCB has issued a list of tree species for green belt development.

The guidance of local Forest officer can be availed in firming up the green belt development program. The treated effluent water from ETP shall be used by laying pipeline for green belt development. During species selection, focus shall be given to identify native trees for planting.

7. Regulatory and Licensing Requirements

Environmental Approval Process

As per the Ministry of Environment, Forests& Climate Change (MoEF&CC), New Delhi, any new project or modernization or expansion project need to have an Environmental Clearance from MoEF. In accordance with this, the Project Proponent has to conduct Environmental Impact Assessment (EIA) study. Form-I & Prefeasibility Report (PFR) has to be submitted to MoEF&CC for approval of Terms of Reference (TOR). The Expert Appraisal Committee (Industry) of MoEF&CC shall issue TOR for the project. Based on this the PP has to conduct the EIA/EMP study. Public hearing has to be conducted and a report on the same has to be included in the EIA report. and submit the same to MoEF for Environment Clearance. Only on getting the Environment clearance, construction activity of the Project should commence. This process takes at least a year.

7.1 Legal Framework

The following are the existing Environmental regulations with amendments upto date are relevant to this Project during construction and operation :

- The Environment (Protection) Act, 1986
- The Environment (Protection) Rules, 1986
- The Public Liability Insurance Act, 1991
- The Public Liability Insurance Rules, 1991
- The Water (Prevention and Control of Pollution) Act, 1974
- The Water (Prevention and Control of Pollution) Rules, 1975
- The Air (Prevention and Control of Pollution) Act 1981.
- The Air (Prevention and Control of Pollution) (Union Territories) Rules, 1983
- Hazardous Wastes (Management and Handling) Rules, 2016.
- Manufacture, Storage and Import of Hazardous Chemical Rules, 2016
- Noise Pollution (Regulation and Control) Rules, 2000
- E Waste (Management and Handling) Rules, 2016
- The Batteries (Management and Handling) Rules, 2001
- Wild Life and Forest conservation Act,1972
- Forest Conservation Act, 1980
- Plastic waste Management rules - 2016

Proposed project shall be designed taking into account the above-referred legislations/rules and as per the directives of Environmental Clearance documents. Besides this the proposed effluent and emission standards will also be compiled for this Project

7.2 Environment Standards

The following Standards shall apply to the construction and operational phases of the FerProject:

7.2.1 Emission Standards

MOEF&CC has prescribed the following **emission standard for power plants**

Table 7.1. Proposed Captive Power Plant emissions limits.

Concentration Mg/Nm3	CO	NOx	SOx	PM	Mercury
Norms mg/Nm3		100	100	30	0.3

7.2.2 New emissions norms prescribed by MOEF&CC for Fertilizer factory is given below:

MINISTRY OF ENVIRONMENT, FOREST AND CLIMATE CHANGE
NOTIFICATION

New Delhi, the 29th December, 2017

G.S.R. 1607(E).—In exercise of the powers conferred by sections 6 and 25 of the Environment (Protection) Act, 1986 (29 of 1986), the Central Government hereby makes the following rules further to amend the Environment (Protection) Rules, 1986, namely:—

1. **Short title and commencement**.- (1) These rules may be called the Environment (Protection) Second Amendment Rules, 2017.

(2) They shall come into force on the date of their final publication in the Official Gazette.

2. (a) In the Environment (Protection) Rules, 1986, in Schedule I, for serial number 17 and entries relating thereto, the following serial number and entries shall be substituted, namely:—

Sl. No.	Industry	Parameter	Standards	
(1)	(2)	(3)	(4)	
"17.	Fertilizer Industry	**A.Effluent Standards**		
		(i) Straight Nitrogenous Fertilizer Plant/Ammonia (Urea Plant), Calcium Ammonium Nitrate and Ammonium Nitrate Fertilizers		
			Limiting concentration not to exceed in milligram/litre (mg/l), except for pH	
		pH	6.5 to 8.5	
		Suspended Solids	100	
		Oil and Grease	10	
		Ammonical Nitrogen as N	50	
		Total Kjeldhal Nitrogen (TKN) as N	75	
		Free Ammonical Nitrogen as N	2.0	
		CN concentration	0.1	
		Ammonical Nitrogen as N	Urea	10
			Other than urea plant	20
		B .- Emission Standards		
		(i) Straight Nitrogenous		

		(a) Ammonia Plant- Reformer		
		Oxides of Nitrogen (as NO_2)	400 mg/Nm^3	
		(b) Urea Plant – Prilling Tower		
			Pre 1982 units	150 mg/Nm3
			Post 1982 units	50 mg/Nm3 **
		*Values to be reported at 3% O2 ** Total emission of 0.5 kg/ tonne of product. Note: (i) Fluoride norms shall be applicable only for NPK plant. (ii) Plant commissioned on or after the date of notification, shall be treated as „New Plant". (iii) The height of the stack emitting Sulphur Dioxide, Oxides of Nitrogen or Oxides of Phosphorus or acid mist shall be a minimum of 30 metres or as per the formula H=14 (Q)0.3, whichever is more, where "H" is the height of stack in metres and "Q" is the maximum quantity of SO2 NOx or P2O5 equivalent expected to be emitted in kg/hr through the stack at 100 per cent rated capacity of the tail gas plant(s) and calculated as per the norms of gaseous emission. (iv) Tail Gas plants having more than one stream or unit of Sulphuric Acid, Nitric Acid or Phosphoric Acid at one location, the combined capacity of all the streams or units for a particular acid shall be taken into consideration for determining the stack height and applicability of emission standards individually. (iii) Tail gas plants having separate stack for gaseous emission for the scrubbing unit, the height of this stack shall be equal to main stack or 30 metres, whichever is higher.";		

Waste Water Generation Standards-

(1)	(2)	(3)	(4)
"11	Fertiliser Industry	Naphtha, Natural Gas & Mixed Feedstock (Naphtha + Natural Gas) Based (Straight Nitrogenous Fertiliser)	3.0 m^3/tonne of Urea or equivalent produced
		Straight Phosphatic Fertilizer (Single Super Phosphate (SSP) & Triple Super Phosphate (TSP) excluding manufacturing of any acid	0.4 m^3/tonne of SSP or TSP
		Complex Fertilizer	Standards of nitrogenous and Phosphatic fertiliser are applicable depending on the primary product.".

Table 7.2 : A comparison of Indian Standards with World Bank for fertilizer Industry

Emission Type	WB	India
Nitrogen oxides in Ammonia plant	300 mg/Nm3	400mg/Nm3
Ammonia in Urea Prilling tower	50mg/Nm3	Not available
Urea dust in prilling Tower	50mg/Nm3	50mg/Nm3

Table 7.3.Noise level standards for Fertilizer factory

Ambient Standard for Noise, specified by CPCB is given below:

Noise (Ambient Standards)

S. No.	Area Code	Category of Area	Limit in dB (a) Leg	
			Day Time	Night Time
1.0	A	Industrial area	75	70
2.0	B	Commercial area	65	55
3.0	C	Residential area	55	45
4.0	D	Silence zone	50	40

Notes:
(1) Daytime is reckoned in between 6 a.m and 9 p.m.
(2) Nighttime is reckoned in between 9 p.m and 6 a.m.
(3) Silence zone is defined as areas up to 100 meters around such premises as hospitals, educational institutions and courts. The silence zones are to be declared by the competent authority.
(4) Mixed categories of areas should be as "one of the four above mentioned categories" by the competent authority and the corresponding standard shall apply.

8. Life Cycle Assessment

A life cycle assessment (LCA) is crucial to count for each CCU plant capability to prevent CO_2 emissions The main advantage of a capture of CO_2 is is reduction of the original feedstock consumption (usually a fossil fuel) and the prevention of emissions associated to them, when compared to well-known and conventional pathway(s) to synthesize a specific product. This will possibly offer financial incentives for the deployment of CO_2 capture. There are many C-rich chemical products that could be synthesized via

CCU route, e.g. synthetic fuels, both liquid (such as methanol) and gaseous, typically Synthetic Natural Gas (SNG), urea (via reaction with ammonia, which is in turn made using H_2), or higher molecular weight organic compounds. Most of these products are obtained from fossil fuels which can be replaced using CO_2 as renewable feedstock.

Already the use of CO_2 as a renewable resource has been demonstrated in the manufacture of polymers with a reduced CO_2 footprint. In the cement sector, innovative processes and products using CO_2 enable the production of a new type of concrete or Urea or methanol etc. with a reduced CO_2 footprint. For CCU to be environment friendly, it is necessary to calculate the CO_2 avoided rather than the CO_2 used in the process.

Another factor to be considered in the LCA process is the period to which CO_2 molecule will remain bound to the product. CCU technologies bind the CO_2 molecule in a multitude of different products for different periods of time. The lifetime in which CO_2 is removed from the carbon cycle varies for e.g: uses such as the use of CO_2 as a fuel precursor are very short term (days to months); whilst others, such as its use as a precursor for plastics, have a longer term. In fact, the use of CO_2 as a precursor for some plastics may result in the CO_2 being fixed away from the atmosphere for decades and can, therefore, be considered a form of storage. In Urea product, CO_2 has a lifetime of one week to six months. The average lifetime estimated for some products using CCU process is given below:

Table 8.1. Average lifetime of CCU products

Product	Lifetime
Urea	6 months
Methanol and	6 months
Inorganic carbonates	Decades to centuries
Organic carbonates	Decades to centuries
Poly(urethane)s	Decades to centuries

Information on the environmental performance of CCU technologies is currently limited and scattered. Emission factors provide a useful shortcut for use in LCA, avoiding the need for detailed calculations of emissions. An emission factor is a typical quantity of Green House Gas (GHGs) released to the atmosphere per unit of activity, in this case, per unit weight of Urea produced (i.e. about 700 – 2000 g CO_2-e / kg fertiliser). Since fertiliser emission factor vary widely depending on production technology, it is preferable to use customized emission factors relevant to the particular plant from which the fertilizer is produced. Table 8.2. Summary GHG emissions (cradle-to gate) for Urea produced through conventional route in different parts of globe is given below:

Table 8.2. GHG emission for Urea (conventional route)

Country	GHG (kg CO_2-e/kg)
China	2.3
New Zeland	0.936
Europe	0.90
India	0.70
Africa	0.96
US	1.0
Russia	1.2
Average	1.14

Indian urea manufacturers are on a par with the best of the world in terms of low energy consumption and greenhouse gas (GHG) emissions, according to a study conducted by the Centre for Science and Environment, a New Delhi-based non-profit, under its Green Rating Project (GRP). Urea contributes to climate change with the release of nitrous oxide that has a GHG potential 300 times that of carbon dioxide (CO_2). However, the need is to address the gap between the best (Yara, Babrala 0.43 MT CO_2/MT urea) and worst (SFC, Kota 1.35 MT CO2/MT urea) among the Indian plants.

Moreover, the use of urea in the fields also gives rise to emissions of the potent greenhouse gases Carbon di oxide and nitrous oxide (N_2O). Considering that India produced 24.2 million MT of urea in 2017-18, the total CO_2 emissions from urea production in India would amount to 16.94 million MT in the same year. The GHG emissions from cradle to grave will be higher because besides Urea production, other related activities like transportation in its use add GHG emission. The life time GHG emission of Urea product is estimated (cradle to grave) is as follows. :

Table 8.3 : Lifetime GHG emission for Urea.

Source	**GHG_e emission g/Kg of product**
Cradle to plant gate	1.14
Urea hydrolysis	0.73
Direct N_2O from use	2.37
Indirect N_2O via NH_3	0.28
Indirect via NO_3	0.48
Total g CO_2 -eq/kg product	5.0

Source :(Fertilizer Europe.2011.)

Though the carbon footprint is only 1.14 kg/ at the plant gate, life cycle Carbon foot print is fivefold.

But the advantage is, when urea is applied on the field, plants absorb the released CO_2 by photosynthesis and reduce the atmospheric CO_2 concentration.

Another analysis is useful during the Life cycle analysis is, the Avoided CO_2 due to replacement of fossil based CO_2 with CO_2 captured from process for producing urea or any product. Also use of renewable energy for hydrogen production will drastically increases the avoided CO_2. In this regard, A.M.Bazzanella (2017) had made a detailed Life cycle analysis of Low carbon energy and feedstock technology suitable for the European chemical industries and the data applicable to production of Ammonia, Urea and Methanol is detailed below:

In a natural gas based ammonia synthesis, GHG emission are estimated at 1.83 tCO_2/tNH_3, of which 1.33 tons are feedstock related CO_2 emissions, the rest is accounted for by the process related fuel (55.9 $kgCO_2eq/GJ$ NG) and electricity consumption. If the same ammonia is produced through renewable CO_2 from process industry and hydrogen through electrolysis by renewable energy route, carbon foot print is at 0.12 tCO_2eq/tNH_3, (0.1 tCO_2eq/tNH_3 accounting for electrolysis and the remaining emissions for additional steam generation). As a result, replacing a ton of ammonia from natural gas as feedstock with renewable route , 1.71 t / t of Ammonia CO_2 can be avoided .

In the case of Urea, CO_2 footprint of fossil urea production is estimated at 1.14 tCO_2/t urea and through captured CO_2 and green hydrogen, carbon foot print is -0.35 tCO_2/t urea, so Avoided CO_2 compared to the fossil route would then correspond to 1.49 tCO_2/t urea. For CCU, it is necessary to calculate the CO_2 avoided rather than the CO_2 used in the process. Avoided CO_2 through captured CO_2 and natural gas based hydrogen is higher and hence climate point of view, thrust to be given to produce products through CCU route replacing fossil based carbon component and use of renewable energy for power requirements will go a long way to help sustainable development and protection of our mother earth.

9. Policy and Regulatory support for CCU

CO_2-based products produced with captured CO_2 are much more expensive than traditional chemical synthesis routes due to energy penalty in the capture process. Hence it is likely that CO_2 based products are difficult to compete with conventional oil technologies. CCU technologies need some sort of support through a regulatory framework and a long-term policy (>20 years). There is the emissions trading system (ETS) market in European Counties and 45Q tax benefit in USA, which encourages more no of CCU projects to be taken up in developed countries. but such system is not functioning in India. Commercial scale research projects to produce products through CCUS route is still in initial stage in India. So, it is necessary that Government should necessarily implement a mechanism for setting the price of CO_2 (carbon market, tax, etc.) . and the eligible CO_2 conversion technologies. In a simple way, the subsidies offered by western countries in the form of tax benefits, emission trade etc.can l be tried in India for further growth of the CCU. To conclude, If CCU is to be competitive it needs to provided with comparable subsidies.

10. Conclusion and Path forward

This Project on implementation can make DCBL, a carbon negative company and it will set momentum for CCUs Projects in India. India is a signatory to UN Climate protocol and the reduction of carbon footprint will contribute to Intended National Determined Contribution for India. EIA study made reveals that the Environmental effects of the proposed CCU project are additive to those of the existing projects, but the combined total effect on the environment parameters is still not expected to be substantial. However control measures based on BAT will be provided in the plant to keep the pollution under control. A detailed EMP is given in Chapter-5. Overall, the proposed project would not cause air, water, or soil to be contaminated with waste (assuming Best operation and maintenance practices) to a degree that would pose a threat to human or ecological health and safety. Also the supply demand gap for Urea can be reduced and DCB can contribute to welfare of farmers in India . It is an important climate change solution since such large scale CCU Project for production of Urea or Chemicals on large scale is not yet implemented worldwide. By implementing this project, about one million tonnes of CO_2 will be avoided in entering the atmosphere, thereby protecting the climate from further global warming. Also there will be conservation of fuel and reduction of CO_2 to that extent. A policy decision by Government to support such type of CCU project by providing tax concessions or emission trading can make the CCU route comparable with fossil fuel route which is the need of the hour. The EIA identifies no significant adverse environmental impacts for the proposed project. The proposed project could result in beneficial impacts to the nation's energy efficiency and agricultural economy, and could contribute to a reduction of greenhouse gases.

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V. Civil engineering design

Prepared by Subhamoy Kar

Section Outline

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1. Introduction

This chapter covers the Civil Engineering features of the proposed CCUS project for Ariyalur Cement Plant of Dalmia Cement (Bharat) Ltd.

2. Site General Information

a) Site Location

Ariyalur Cement Plant is located at Govindapuram village in Ariyalur district of Tamilnadu at latitude 11°10'58"N and longitude 79°6'4"E.

The proposed CCUS project is to be sited within Cement Plant, on the West side of existing Cement Mill MCC Room. The coordinate of North-East corner of the proposed site will be latitude 11°11'3"N and longitude 79° 6'1"E. Plant North is oriented about 6o anticlockwise with respect to true North. Land area required for this project is 100m X 100m.

Fig. 2.1: Satellite Image of the Site

There is an existing diesel storage facility within the proposed CCUS site, which is to be relocated elsewhere in the Cement Plant.

Aforesaid site will house the CO2 Capture Plant. For Utilization facility i.e., Urea Plant, the site will be identified at a later stage of the project when more precise information about land requirement and land availability are obtained.

b) Topography

The Cement Plant grade is terraced, with different finished grade level (FGL) for different facilities. Those terraced grade levels range from RL 94.5m to RL 99.3m above mean sea level.

In the proposed CCUS Project site, the natural ground level varies from RL 94.5m to 95.5m, as per the Contour Map. Considering the grade level of adjoining facilities, FGL of CCUS project site is proposed to be RL 95.3m.

c) Seismicity

The project site is located in Seismic Zone II as per IS:1893. Zone factor is 0.10.

d) Wind Speed

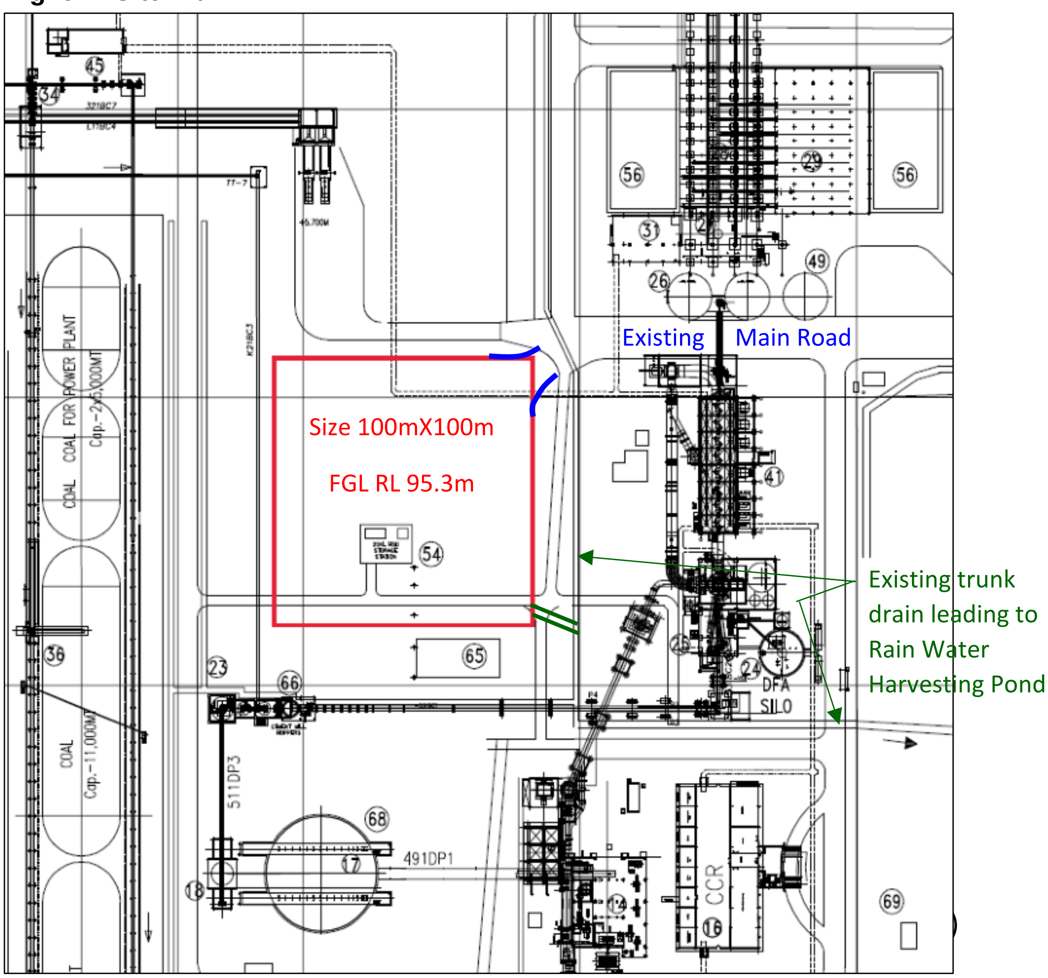
Basic Wind Speed (Vb) at the project site is 47 m/s as per IS:875.

3. Battery Limit and Tie-in Points

Battery limit of CCUS project is defined by the boundary shown in red color in Fig. 3.1.

Outside Battery Limit, the Tie-in points will be as follows:

Fig. 3.1: Site Plan



Road – At the edge of existing road pavement of main road on North-East corner of the CCUS site.

Drain – Near South-East corner of CCUS site, to the existing trunk drain leading to the Rain Water Harvesting Pond.

Piperack – At the CO_2 tie-in Point near Kiln stack. New rack structure will be constructed at about 3.0m away from existing flue gas duct support. Tie-in point near the Power Plant stack is not considered, as CO_2 is planned to be collected from Kiln only at this stage of project.

4. Codes and Standards

For all Civil and Structural work - Design, materials, methods or workmanship will follow Indian Standard (IS) Codes of practice, in general. Local regulations / acts will be complied to during design and execution.

For design of dynamic equipment foundation, relevant DIN and ISO standard may be followed.

Roads and culverts will be designed as per IRC (Indian Roads Congress) standard.

5. Site Preparation and Greenbelt Development

The natural ground profile of CCUS project site is sloping down towards South. Considering the grade levels of adjacent existing facilities, in view of drainage of storm water, the FGL of the CCUS site is proposed as RL 95.3m. The earthwork for site preparation is expected to involve maximum of about 800mm filling and 200mm cutting.

The finished grade surface could slightly be adjusted to suit specific site conditions and drainage patterns and it will be sloped away from the buildings to facilitate surface drainage. A network of storm water drains will be constructed in and around the plot and will be suitably connected to the overall drainage network of Cement Plant.

Greenbelt will be developed to cover 33 percent of Project area, as per stipulation of Ministry of Environment and Forest (MoEF). The greenbelt can be suitably located within the Cement Plant, outside CCUS area.

6. Geotechnical Considerations and Foundation System

As per Geotechnical Investigation Report of the existing Cement Plant, ten (10) boreholes were drilled. Synopsis the bore-logs is presented in Table 6.1 below, which shows the soil stratification of the project area.

Table 6.1: Soil Stratification

Layer Number	Soil strata	Soil classification	Thickness of layer (m)
1 (Top soil)	Brownish or blackish sandy silty clay or silty sand	CL/CI/SM	0.0 – 1.0 1.8 in BH-9 only
2	Stiff layer of brownish sandy silty clay or clayey silty sand, mixed with pebbles / conglomerates (This Layer is absent in some of the boreholes)	CI/GM	0.7 – 2.1
3	Dense mix of pebbles and boulders (This Layer is absent in some of the boreholes)	GM	1.2 – 3.7
4	Yellowish weathered rock	GM	0.3 – 2.0
5	Yellowish / whitish sandstone impregnated with lime nodules	----	3.0 – 5.0 (As drilled down to termination depth - 9.0m max)

Ground water table is encountered in only one (1) borehole (BH-9) at about 5.0 depth below ground, which is likely to be perched water from rainfall.

Based on the above, it is inferred that open foundation system is adequate for CCUS project and there is no need to adopt pile foundations. Layers 2 to 5 in the above table are capable of supporting the heavily loaded foundations for buildings and structures.

The Geotechnical Report has calculated minimum net bearing capacity at 1.0m depth from natural ground level as 25 ton/m2. Since, the most part of CCUS site will be in filling (800mm max.), average founding depth is envisaged as 2.0m below FGL, both from bearing capacity consideration and in order to leave space for underground utilities. Only for tall structures / equipment (e.g. CO2 Vent Stack, Absorber and other Process Columns), greater founding depth may be adopted if necessary, to prevent overturning.

Presence of corrosive chemicals, viz. chlorides and sulphates in soil and ground water are on the lower side, which are presented in the Table 6.2.

Table 6.2: Results of chemical analysis

Sample	pH	Max. Chloride (ppm)	Max. Sulphate (ppm)
Soil	7.5	201	336
Ground water	7.35	186	314

Sulphate concentration in soil and ground water corresponds to the Exposure Class 2 as per IS:456 with respect to sulphate attack on concrete. For such exposure, no special cement and no protective coating on underground concrete surface are mandated by the Code.

Chloride concentration is less than the maximum permissible limit (500 ppm) and the pH is higher than the minimum stipulated value (6.0) in IS:456. Therefore, no special steel or corrosion protection measure is necessary for reinforcement bars and embedded steel in underground construction.

7. Structural Design Criteria

a) All steel structures in the project are envisaged as stick-built. Those will be designed in Limit State Method in accordance with IS:800.
b) Concrete structures and foundations will be designed in Limit State Method as per IS:456
c) Liquid retaining concrete structures and process sumps (e.g. Amine Drain Drum Sump) will be designed for crack control in Limit State Method as per IS:3370 (relevant part)
d) Foundation design will follow IS:1904
e) Loading on buildings and structures will comply to IS:875 (relevant part)
f) Seismic design of buildings and structures will comply to IS:1893 (relevant part) and IS:13920

8. Materials of Construction

Structural steel: Material of Structural Steel will be as per IS:2062 (Grade E250 to E350). Steel of Quality A will be generally used. For steel subjected to impact and vibration, Quality BR/B0 will be used as applicable for the required service temperature.

Reinforcement steel: Thermo mechanically treated (TMT) steel bars of grade Fe 500 / Fe 500D conforming to IS: 1786 will be used as reinforcement to concrete. Welded wire mesh reinforcement will conform to IS: 1566.

Cement: Ordinary Portland Cement of grade 43/53, conforming to IS:8112 / IS:12269 will be used for production of concrete.

Concrete: Concrete work shall be carried out as per IS:456. Characteristic compressive strength after 28 days (i.e., Grade) of concrete for various applications will be as follows.

a) For Reinforced Cement Concrete (RCC) superstructure and foundation – M25
b) For dynamic equipment (e.g., Compressor) foundation – M30
c) For underground trench and pit – M25
d) For plain cement concrete / mud mat – M10
e) For plinth protection around building – M20
f) For slab on grade (RCC Paving and Ground floor slab) – M20

Masonry: local popular brick or concrete block.

9. Buildings

Major buildings and structures envisaged in the project are described below along with their types of construction.

a) Compressor Building

Compressor Building will be steel framed structure, comprising of rigid frames in transverse direction and braced longitudinally for stability and lateral load resistance.

Building wall will be acoustically insulated metal cladding above 1.2m (approx.) high masonry wall. The metal cladding system will have permanently color coated exterior metal wall panel with rock wool insulation and inner liner panel. The inner liner will be perforated for sound attenuation.

Building roof will have acoustically insulated metal roof panels, similar to wall panels, laid in 8o slope towards roof drainage system.

Ground floor will be 150mm thick reinforced concrete slab-on-grade over 250mm thick boulder soling and 75mm thick mud mat. Thickness of slab in laydown area will be designed as per imposed load specified in Design Criteria. The floor will have IPS floor finish with metallic hardener.

Steel columns of the building will rest on 300mm high pedestals aboveground supported on underground RCC footing, with mud mat underneath.

b) Warehouse

Warehouse is envisaged as steel framed structure, enclosed with brick / concrete block masonry, duly plastered and painted. The building will have concrete roof slab, with waterproofing treatment and sloped towards the rain water downcomers.

Ground floor of the building will be 150mm thick reinforced concrete slab-on-grade over 250mm thick boulder soling and 75mm thick mud mat. The floor will have IPS floor finish with metallic hardener.

Steel columns of the building will rest on 300mm high pedestals aboveground supported on underground RCC footing, with mud mat underneath.

10. Structures

a) Pipe and Cable Rack

From CO2 tie-in point in the existing Cement Plant, steel pipe rack will be constructed up to the CO2 capture equipment in CCUS area. Also, interconnecting cables from existing plant facility is envisaged to run on overhead rack. Wherever possible, cable and pipe routing will be clubbed and cable will normally be laid above the pipes.

Height of pipe / cable tray will not less than 3000mm above FGL. Where the rack crosses roads, clear headroom will be minimum 7000mm.

The racks will be designed as a rigid frame in the transverse direction and braced in the longitudinal direction. Expansion provision shall be provided wherever there is a change in direction or where length of the rack exceeds 100 metres. Access ladder and grating platform will be provided at suitable locations, as necessary for maintenance purpose. Pipe rack columns will be supported on concrete foundations with underside of base plates at about 300mm above FGL.

b) Technological Structures

Technological structures will be steel framed structures, stabilized by horizontal and vertical braces and considering functionality of the structure. These will be designed to support the equipment and piping placed on them. Framing and handling arrangement (e.g., monorail) will facilitate the erection and removal / lowering of equipment. Grating platform with handrail will be provided at suitable locations, as necessary for maintenance purpose. Steel stair will be provided to access the maintenance platforms. Structural columns will be supported on concrete foundations with underside of base plates at about 300mm above FGL.

Technological structures will be needed in both Capture facility and Utilization facility.

In this pre-feasibility study, cost of technological structures is accounted as part of equipment cost and therefore, the same is excluded in the Civil cost.

c) CO_2 Vent Stack support structure

A four-legged latticed steel structure is envisaged to support CO2 Vent Stack. The stack will be vertically supported near the bottom level and will have guide supports above, for transfer of lateral load to the structure. The structure is foreseen as a tall slender structure and will be designed to limit the wind induced oscillation, as stipulated in IS:875 (Part-3). Structural columns will be supported on concrete foundations with underside of base plates at about 300mm above FGL.

d) Compressor foundation

Compressor foundation will be a reinforced concrete table-top foundation designed as per IS:2974 and provisions of DIN 4024 will also be followed. The foundation will be suitably proportioned so that amplitude and frequency of the foundation are within permissible limits. Dynamic analysis will be carried out to calculate natural frequencies in all modes including coupled modes and to calculate vibration amplitudes. Frequency and amplitude criteria as laid down in the aforesaid standard or by the machine manufacturer will be complied. Other criteria, viz. limit of eccentricity and bearing pressure will also govern the design.

e) Other Civil Works:

i) Tank foundations -

Above ground flat bottom tanks will be supported on ring wall foundations. Tank with double containment wall will be supported on circular mat foundation.

ii) Equipment foundations –

Process Columns, viz. Absorber, Desorber, Urea Synthesis Tower, Distillation Tower etc. will have octagonal concrete foundations. Other ground supported equipment will be provided with isolated or combined foundations as per available space.

iii) Relocation of Diesel Storage facility –

All civil work of the existing Diesel Storage facility within CCUS area is to be demolished and will be reconstructed in a suitable location away from CCUS unit. Equipment, piping and steel construction (if any) will be shifted to the new location.

11. Underground Constructions

Since this is a brown-field project, it is envisaged that interconnecting pipes and cables will be laid overhead on rack, in order to minimize clashes with existing underground utilities. Cable trench may be constructed in limited stretch to facilitate entry or exit to the equipment / building.

Amine Drain Drum Sump is envisaged as a rectangular reinforced concrete underground pit, comprising of base slab and side walls. It will have grating cover on top, supported on a steel framing.

12. Roads and Pavements

New double lane approach road will be constructed from the existing main road near North-East corner of the proposed CCUS site and will be extended up to the laydown area. Roads will be made of bituminous flexible pavement. Double lane road will have 7.0m wide black topping with 1.5m wide shoulders on both sides of the road. Single lane roads will be provided to access the process areas, which will have 3.75m wide black topping with 1.0m wide shoulders on both sides.

Plant areas which are likely to receive chemical spillage, will be provided with concrete pavement with concrete curb / dike wall, in order to prevent ground contamination. Reinforced concrete slab-on-grade of 150mm thickness will be constructed over 75mm mud mat in such areas, taking care of suitable grade slopes to meet surface drainage requirements.

Open areas within the battery limit which are not covered by concrete pavement or road, will be provided with 150mm thick compacted gravel surfacing.

13. Storm Water Drainage

Storm water for the CCUS area will be collected through a network of surface drains and will be discharged into the existing trunk drain of Cement Plant near the South-East corner of CCUS site, at a suitable point with deeper invert level. The trunk drain finally leads the storm water to existing Rain Water Harvesting Pond. Surface drains will be concrete open drains of rectangular cross-section. Grating cover will be provided, as necessary for personnel safety. At road crossing, RCC pipe / Box Culvert will be provided.

14. Boundary wall / Fencing and Gates

Since the CCUS project is located within the area of Cement Plant, no separate boundary wall and gate house are needed for the project.

Galvanized chain link fencing supported by intermittent steel posts and with lockable chain link gate is envisaged around the outdoor transformers.

15. Painting and Fireproofing

Steel structures of Capture Plant will receive two coats of synthetic enamel paint over compatible primer. Steel structures of Urea Plant will be provided with suitable combination of epoxy and polyurethane coating. All gratings and anchor bolts will be galvanized.

Fireproofing of structures are not envisaged, as presence of hydrocarbon is limited or nil in CCUS area.

16. Conclusions

The project site identified in this Section is adequate for the Carbon Capture facility. Once the land requirement for the Utilization facility is ascertained, it can be sited on vacant land on the East side of existing Raw Mill Bag house (Plant Layout item #9) and Blending silo (Plant Layout item #10). However, confirmation from Dalmia Cement will be required that the vacant land will not be used for future unit of Cement Plant (as indicated in the Contour Map).

Regarding geotechnical aspect, the site is generally having good subsoil conditions, as necessary to support the loads of CCUS Plant by open foundations. So, there is no need of piling in the project. The soil and ground water conditions does not warrant any special cement, corrosion resistant steel or protective coating in underground construction.

Design, materials and other features of plant have been elaborated in the preceding sections of this chapter.

VI. Financial assessment

Prepared by B. C. S. Baliga (Role: Finance (National))

Section Outline

LIST OF TABLES

ABBREVIATIONS

ACT	ADB Consultants' Team
ADB	Asian Development Bank
CAPEX	Capital Expenditure
CCP	CO_2 Capture Plant
CCU	CO_2 Capture and Utilization
CO_2	Carbon Dioxide
CIF	Cost, Insurance and Freight
CUP	CO_2 Utilization Plant
DBL	Dalmia Bharat Limited
DCBL	Dalmia Cement (Bharat) Limited
FOB	Free on Board
FY	Financial Year
INDC	Intended Nationally Determined Contributions
IRR	Internal Rate of Return
MIRR	Modified Internal Rate of Return
MTPA	Million Tons Per Annum
NPV	Net Present Value
OPEX	Operational Expenditure
SPV	Special Purpose Vehicle
VGF	Viability Gap Funding
WACC	Weighted Average Cost of Capital
WDV	Written Down Value

NOTES

(i) The fiscal year (FY) of the Government and its agencies in India ends on March 31.

(ii) In this report, "$" refers to US dollars, "INR" refers to Indian Rupees and EUR refers to EURO, unless otherwise stated.

EXCHANGE RATES APPLIED

US$1 = INR72.2928

EUR1 = INR86.2169

Section Summary

This report assesses the financial feasibility of the CO_2 Capture and Utilization Project designed by the ADB Consultants' Team. The report provides the Net Present Value (NPV), Internal Rate of Return (IRR), and Modified Internal Rate of Return (MIRR) over the life of the project. The project provides for converting 0.5 million tons of CO_2 per annum into of 0.68 million tons of urea. In the base case scenario, the capital expenditure is $365.43 million (INR26,417.98 million) and operational expenditure is $167.35 million (INR12,098.23 million) per annum.

The net revenue is $183.60 million (INR13,272.96 million) at the base price of $270 (INR19,519.06) per ton of urea, NPV for the project is negative and equity IRR is 0.01%. The acceptable rate of return on equity for Dalmia Cement (Bharat) Limited (DCBL), the promoter of the project, is 20%. Thus, under the base case scenario, the project does not provide a rate of return acceptable to DCBL.

Sensitivity of NPV, IRR and MIRR to different variables has been tested. Under the base case scenario, cost of electricity has been determined at the electricity tariff charged by the Tamil Nadu Generation and Distribution Corporation Limited. However, DCBL states that it will procure electricity at a much lower rate of INR3 per unit. Further, open market urea sale price in India has increased steeply in the recent months and at present is higher than $330 per ton. It is seen that the project yields an equity IRR of more than 20% at the urea sale price of $330 per ton and electricity tariff of INR3 / unit. Viability Gap Funding (VGF) by way of capital subsidy will be required at lower sale prices of urea. The quantum of VGF required at different sale prices of urea has been calculated and presented.

Impact of sale of carbon credit at various rates has been studied. The project will provide an equity IRR of more than 20% if carbon credit will be sold at $50 per ton, electricity tariff will be INR3 / unit, rate of interest on debt will be 9% per annum and $4 million will be provided as VGF with values of other variables remaining the same as in the base case. Sensitivity to cost of other key inputs such as ammonia, electricity and steam has also been tested.

Government of India requires at least 75% of the urea produced by any urea manufacturer in India to be neem coated. The government determines the price to be received by the manufacturer for neem coated urea on cost plus basis so as to provide a reasonable rate of return to the manufacturer. Sale price of the neem coated urea to the farmer is fixed at $81.92 (Rs.5,922.22) per ton. The difference between the price determined by the government and the price to be paid by the farmer is paid by the government to the manufacturer by way of subsidy. Thus, the manufacturer of urea is assured of reasonable profit on the neem coated urea subject to the costs being justified.

1. Introduction

The Dalmia Cement (Bharat) Limited (DCBL) has announced its goal to become carbon negative by 2040 and has identified CO_2 Capture and Utilization(CCU) as a key to reach this goal. For this purpose, DCBL is considering setting up a large-scale demonstration plant in its cement factory at Ariyalur, Tamilnadu State, India. At present, DCBL proposes to capture 500,000 tons of CO2 per annum and convert it into a saleable product. The Asian Development Bank (ADB) has commissioned a study for a preliminary techno-economic evaluation of various CCU options available to DCBL and has constituted a ADB Consultants' Team (ACT) for preliminary techno-economic evaluation of various CCU technology options available to the Ariyalur Cement Plant.

There are several technology options available for CO2 capture. The CO_2 capture Specialists have surveyed the state-of-art CO2 capture technologies classified into three major categories: post-combustion, pre-combustion, and oxy-combustion. These CO_2 capture technologies have been analysed with reference to the capture approaches, critical challenges and developmental state of these technologies. Considering that the age of Ariyalur cement plant is about 30 – 50 years, CO_2 capture Specialists have concluded that the post-combustion CO2 capture technologies are the preferred option to retrofit in the existing facilities as CO2 can be captured from the exhaust gas of the cement plant without affecting the existing cement production. Further, among the available post-combustion technologies, chemical absorption with liquid solvents has been considered as the most mature technology till date and is recommended for adoption in the proposed CO_2 Capture Plant (CCP). The CO_2 captured by the process will be converted into urea using captured CO2 and ammonia as raw materials.

The objective of this analysis is to assess the financial feasibility of CCU Project based on the technology options selected by the CO_2 Capture Specialists and the CO_2 Utilization Expert. Based on the cost figures furnished by these experts, this analysis will project the annual income statements, balance sheets and annual cash flows over the life cycle of the plant of 25 years. Project IRR, Equity IRR and Project MIRR and Equity MIRR will be presented. Sensitivity of NPV, IRR and MIRR to various variables will be tested. Viability Gap Funding (VGF) required, if any, to make the project yield an acceptable level of return will be determined. This assessment could be a key information source for the investment decision and may help in appraising the project for financing by the financial institutions such as ADB and the commercial banks.

2. Approach and methodology

DCBL is a wholly owned subsidiary of Dalmia Bharat Limited (DBL). This assessment assumes that DBL will set up a Special Purpose Vehicle (SPV) for the CCU Project. Cost and revenue data for the assessment have been culled out from the reports of the CO_2 Capture Specialists and the CO_2 Utilization Specialist. The calculations presented in subsequent chapters are on the basis base cash with values of variables as tabulated in Table 2.1 here below:

Sl. No.	Table 2.1: Values of Variables in the Base Case Scenario	
	Variable	**Value**
1	Capacity of the Project	Conversion of 0.5 MTPA CO_2 to urea
2	Capital Expenditure and Operational Expenditure	As furnished by the concerned specialists
3	Construction period	3 years
4	Inflation rate	4% per annum
5	Expected rate of return on equity	20.00% per annum
6	Rate of interest on term loan	12% per annum
7	Debt / Equity ratio	70:30'
8	Customs Duty	29.8% including Goods & Services Tax
9	Depreciation	15% of Written Down Value
10	Electricity Tariff	As per the latest tariff published by the Tamil Nadu Generation and Distribution Corporation Limited, *i. e.* Energy Charges of Rs.6.35 per unit and Demand Charges of Rs.350/- per KVA per month.
11	Other Income	Nil

In Chapter 8, sensitivity of NPV, IRR and MIRR to changes in the values of the variables listed in Table 2.1 above will be tested.

3. Capital expenditure and operational expenditure

Capital Expenditure:

The project requires development of various facilities. The CAPEX includes the cost of equipment, the cost of transportation of equipment, insurance during the transportation of equipment, government duties, erection of equipment, civil works, pre-operative expenses, costs for arranging finance, interest during construction, *etc*. The main components of CAPEX for CCU Project are as follows:

(i) CO_2 Capture Plant (CCP)

(ii) CO_2 Utilization Plant (CUP)

(iii) Civil Works Required for Setting Up the Plants

(iv) Pre-Operative Expenses to be Incurred for Incorporation of the SPV

(v) Expenditure for Arranging Finance

(vi) Interest on Debt During Project Construction

(vii) Cost of land is not included as it is assumed that DCBL will make land available from the surplus land available with it

The CO_2 Capture Specialists have furnished capital equipment prices in EUR. These values are converted to $ and INR at the exchange rates published by the Reserve Bank of India. It is presumed that the prices indicated by the CO_2 Capture Specialists are Free on Board (FOB) prices at a European Port. 1% of the FOB Price of Capital Equipment has been assumed as the transportation cost of the equipment from the European Port to the project site. 1.5% of the FOB price of capital equipment has been provided for transit insurance. The rate of import duty applicable on such imports is worked out in Table 3.1. below:

Table 3.1: Determination of the Rate of Import Duty as Proportion of the Landed Cost of Imported Equipment

Sl. No.	Particulars	Notional Value	Reference
1	CIF Value	1,000.00	Assumed Value for Calculation Purposes
2	Landing Charge	10.00	1% of CIF Value
3	**Total Value Including Landing Charge**	**1,010.00**	
4	Basic Duty	**101.00**	Chapter 98 of the Manual of Customs Duty issued by the Central Board of Indirect Taxes and Customs. Tariff Code: 9801 00 11
5	**Total Including Basic Duty**	**1,111.00**	
6	Goods & Services Tax	199.98	HSN Code 9801 as per Goods and Services Tax Act
7	**Total including Goods & Services Tax**	**1,310.98**	
8	Total Customs Duty	300.98	
9	**Proportion of Customs Duty to Total Value Including Landing Charge**	**29.80%**	

The Civil Expert has furnished the cost of civil works for a 1 Million Tonnes per Annum (MTPA) CUP. Cost of civil works for 0.5 MTPA CUP has been considered as 50% of the cost of civil works for 1 MTPA CUP in consultation with the Civil Expert. Calculations of CAPEX of CCU Project are furnished in Table 3.2, Table 3.3 and Table 3.4 here below:

Table 3.2: Capital Expenditure for CO_2 Capture Plant

Sl. No.	Equipment	EUR Million	$ Million	INR Million
1	Direct Contact Cooler	3.000	3.58	258.65
2	Absorber (including water washers)	8.000	9.54	689.74
3	Desorber	9.600	11.45	827.68
4	Pumps & HEX	2.200	2.62	189.68
5	Steam Generator	5.000	5.96	431.08
6	CO2 Purification	1.400	1.67	120.70
7	Electrical and Instrumentation	0.900	1.07	77.60
8	Air Cooling	5.300	6.32	456.95
9	BOP	0.500	0.60	43.11
10	**Sub Total**	**35.900**	**42.81**	**3,095.19**
11	Transportation		0.43	30.95
12	Transit Insurance		0.64	46.43
13	**Total Cost Insurance and Freight Value**		**43.88**	**3,172.57**
14	Landing Charges		0.44	31.73
15	**Total Including CIF Value and Landing Cost**		**44.32**	**3,204.29**
16	Customs Duty Including GST		13.21	954.88
17	**Total Value of Equipment Including Customs Duty**		**57.53**	**4,159.17**
18	Utilities Integration	2.600	3.10	224.16
19	Flue Gas Integration	4.200	5.01	362.11
20	Civil works		9.14	660.80
21	**Sub Total**		**74.78**	**5,406.25**
22	Engineering		7.48	540.62
23	Installation & Commissioning		13.46	973.12
24	Project Management and Consultancy		1.50	108.12
25	**Total Capital Cost of CO_2 Capture Plant**		**97.22**	**7,028.12**

Table 3.3: Capital Expenditure for CO_2 Utilization Plant

Sl. No.	Details	$ Million	INR Million
1	Capital Cost of Equipment (All inclusive)	137.35	9,929.42
2	Site Development, Utilities Integration	16.48	1,191.53
3	OSBL Civil Works and Land Grading	3.59	259.60
4	**Total Capital Cost of CO_2 Utilization Plant**	**157.42**	**11,380.55**
5	License Fee, Engineering, Field Expenses. Start Up	69.22	5,004.43
6	**Total Capital Cost of CO_2 Utilization Plant**	**226.65**	**16,384.97**

Table 3.4: Total Capital Expenditure			
Sl. No.	**Particulars**	**$ Million**	**INR Million**
1	Total Cost of CO_2 Capture Plant	97.22	7,028.12
2	Total Cost of CO_2 Utilization Plant	226.65	16,384.97
3	**Sub Total**	**323.86**	**23,413.09**
4	Interest accrued during construction on the Term Loan availed for financing the capital works	41.35	2,989.03
5	Cost for arranging finance	0.22	15.86
6	**Total Capital Cost**	**365.43**	**26,417.98**
	Explanation	**$**	**INR**
7	Capital Cost per ton of CO_2 converted	730.86	52,835.96
8	Capital Cost per ton of urea produced	537.40	38,849.97

Interest accrued during the construction period on the Term Loan availed for financing the capital expenditure is calculated in Table 4.4 in the next chapter.

Pre-operative Expenses:

Pre-operative Expenses are expenses to be incurred for incorporation of the SPV and are assumed as 0.25% of the Capital Cost. This cost is amortized over 5-year period after the production commences as provided for in Section 35 (D) of the *Income Tax Act, 1961*.

Operational Expenditure(OPEX):

The operating costs are the process costs associated with the capture of CO_2 and its conversion to urea and includes cost of maintenance of the production facilities and will include the costs of *inter alia* the following:

- Ammonia
- Solvent used for capture of CO_2
- Fuel used for generating steam (Coal or the Natural Gas, as the case may be)
- Utilities (Water & Electricity)
- Labour
- Sales & Administration Cost
- Plant Maintenance
- Plant Insurance

The assumptions for arriving at the OPEX of the first year of operation are listed in Table 3.5 here below:

Table 3.5: Assumptions for Determining the Operating Cost		
Sl. No.	**Item**	**Assumption**
1	Cost of Plant Maintenance	1% of Cost of Capital equipment
2	Plant Insurance	1% of cost of capital equipment

Calculations of the OPEX of CCU project for the first year of operation are furnished in Table 3.6, Table 3.7 and Table 3.8 here below. The OPEX is increased by 4% for every subsequent year to provide for inflation.

Table 3.6: Direct Operating Cost for CO_2 Capture Plant					
Sl. No.	Particulars	Rate of Consumption	Total Annual Cost		Rate / Remarks
			$ Million	INR Million	
1	Steam	0	0.00	0.00	
2	Electricity	184.7 KWH / tCO_2	8.72	630.70	Fixed charge $4.84 per KVA per month and variable charge $0.09 per unit.
3	Water	0.36 m3/tCO_2	0.37	27.00	$2.07 / KL
4	Solvent	0.45 KG / tCO_2	0.44	31.50	$1,936.57 /ton
5	Fuel	0.16 t coal / tCO_2	5.53	400.00	$69.16 / ton of coal
6	Labour for CO_2 Capture Plant	20 Workers	0.10	7.20	$414.98 per Worker per Month
7	**Direct Cost for CO_2 Capture Plant**		**15.17**	**1,096.40**	

Table 3.7					
Table 3.7: Direct Operating Cost for CO_2 Utilization Plant					
Sl. No.	Particulars	Rate of Consumption	Total Annual Cost		Rate / Remarks
			$ Million	INR Million	
1	Ammonia	386,084.5 TPA	115.83	8,373.68	$300 per ton
2	Electricity	81,855,389 KWH per annum	7.73	559.03	Fixed charge $4.84 per KVA per month and variable charge $0.09 per unit.
3	Steam	422,919.5 TPA	9.94	718.59	$23.50 per ton
4	Cost of Circulating Cooling Water	57,980,900.50 TPA	1.16	83.86	$0.02 per ton
5	Water	850,445.50 M3 per Year	1.76	127.57	$2.07 / KL
6	Labour for CO_2 Utilization Plant	20 Workers	0.10	7.20	$414.98 per Worker per Month
7	**Direct Costs for CO_2 Utilization Plant**		**136.53**	**9,869.93**	

Table 3.8: Cost of Sales for First Year				
Sl. No.	Particulars	Total Annual Cost		Rate / Remarks
		$ Million	INR Million	
1	Direct Costs for Capture Plant	15.17	1,096.40	
2	Direct Costs for Utilization Plant	136.53	9,869.93	
3	**Total Direct Costs**	**151.69**	**10,966.33**	
4	Plant Maintenance	3.24	234.13	1% of Original CAPEX
5	Plant Insurance	3.24	234.13	1% of Original CAPEX
6	**Total Factory Overheads**	**6.48**	**468.26**	
7	**Total Manufacturing Cost**	**158.17**	**11,434.59**	
8	Selling & Administrative Costs	9.18	663.65	5% of sales
9	**Cost of Sales**	**167.35**	**12,098.23**	

Explanation		Amount	
		$	INR
10	Total Manufacturing Cost per Ton of CO_2 converted	316.34	22,869.17
11	Total Manufacturing Cost per Ton of urea produced	232.60	16,815.57
12	Total Cost of Sales per Ton of CO_2 converted	334.70	24,196.47
13	Total Cost of sales per Ton of urea produced	246.10	17,791.52

4. Project finance structure

source of funds, typical capital structure in the Indian cement industry, proposed financial structure and weighted average cost of capital

Source of Funds for CCU Projects:

At present, there are no dedicated funding sources providing concessional finance or soft loans for CCU projects in India. Raising funds through the issuance of Green Bonds (also referred to as Climate Bonds) could be an option. Though these bonds operate like the conventional bonds, these bonds have been quite popular with investors focused on sustainable and responsible investing. The green factor associated with these bonds brings with them the pricing advantage. They have high prospects to bring domestic and foreign capital on better financing terms including lower interest rates and longer repayment schedules. However, if dollar denominated bonds are issued, the cost of hedging against exchange rate fluctuations has to be factored in.

In the recent past, several organizations in India have raised funds through green bonds. These include IDBI Bank Limited, PNB Housing Finance Limited, Indian Renewable Energy Development Agency Limited, Rural Electrification Corporation Limited & State Bank of India in the public sector; Axis Bank Limited & Yes Bank Limited, private sector banks; and Tata Cleantech Capital Limited, Adani Green Energy Limited, CLP Wind Farms (India) Private Limited, Hero Future Energies, Greenko Energy Private Limited, ReNew Power Private Limited & Azure Power Global Limited in the private sector. All these bonds are mainly targeted to achieve the reduction of carbon emissions particularly by the adoption of renewable energy and increasing resource efficiency. None of these bonds are targeted towards CCU projects.

The following cases provide an indication of the interest rate at which funds can be raised through green bonds by a private sector company. The Adani Green Energy Limited raised $362.50 million through 20-year dollar denominated green bonds bearing interest at 4.625% per annum payable semi-annually in arrears. The bonds have been allotted on 15 October 2019 and the maturity date will be 15 October 2039. Azure Power Solar Energy Private Limited raised $350.10 million through dollar denominated green bonds bearing coupon rate of 5.65%. ReNew Power Limited raised $325 million through overseas green bonds at 5.375% per annum with a maturity period of three and a half years. Greenko Energy Private Limited raised $950 million through dollar denominated bonds at 5.1% per annum.

Green Bonds will enhance DCBL's reputation as it helps in showcasing DCBL's commitment towards sustainable development. It also provides issuers access to the specific set of global investors who invest only in green ventures. With an increasing focus of foreign investors towards green investments, it could also help in reducing the cost of capital for DCBL's proposed green venture. The green bonds to be issued may be secured with the assets of the proposed SPV and the corporate guarantee of DCBL.

The aggregate capital cost involved in the proposed CCU Project is $323.86 million (INR23,413.09 million) as can be seen from Table 6.4 in the previous chapter. No leasing deal of this size has been made in India, yet. Hence, the option of entering into a lease deed for the plant may not be available.

Typical Capital Structure in the Indian Cement Industry:

The Debt / Equity ratios of leading cement manufacturing companies of India at the end of each Financial Year (FY) over the 5-year period commencing from FY2015-16 till FY2019-20 are tabulated here below. As can be seen, major cement companies in India were largely equity financed during this period. Over this period, the Debt / Equity ratio of these companies has been in the range of zero to 1.67. As at the end of FY2019-20, the highest Debt / Equity ratio was 1.28. As a general trend, the Debt / Equity ratios of major cement companies of India have shown a declining trend.

Table 4.1: Debt / Equity Ratios of Leading Cement Companies								
Sl. No	Name of the Cement Company / Group	Net worth as on 31 March 2020		Debt / Equity Ratios over the years				
				Financial Years				
		$ Million	INR Million	2019-20	2018-19	2017-18	2016-17	2015-16
1	ACC Ltd.	1,593.70	1,15,212.80	0.00	0.00	0.01	0.01	0.00
2	Ambuja Cements Ltd.	3,071.56	2,22,051.80	0.00	0.00	0.00	0.00	0.00
3	Birla Corporation Limited	601.50	43,484.10	0.30	0.38	0.42	0.58	0.35
4	Dalmia Bharat Limited	1,057.09	76,420.00	0.00	0.00	0.00	0.03	
5	India Cements	749.02	54,149.10	0.59	0.66	0.70	0.63	0.65
6	JK Cement Limited	432.81	31,289.00	0.77	0.73	1.02	1.31	1.46
7	JK Lakshmi Cement Ltd.	237.74	17,186.80	0.69	0.87	1.25	1.42	1.27
8	Prism Johnson Ltd.	155.41	11,235.20	1.28	1.01	1.21	1.36	1.67
9	Ramco Cements Ltd.	680.37	49,185.60	0.54	0.32	0.25	0.30	0.57
10	Shree Cements Ltd.	1,789.45	1,29,364.20	0.18	0.29	0.38	0.17	0.11
11	Ultra Tech Cement Ltd.	5,297.39	3,82,963.20	0.47	0.59	0.64	0.22	0.23

(Source: Economic Times)

DCBL is a wholly owned subsidiary of DBL. It is seen from the latest financial statements of DBL that DBL is wholly equity financed and has no borrowings. The Tuticorin Alkali Chemicals and Fertilizers Limited, a SPV set up by the Southern Petrochemicals Industries Corporation Limited for CCU, is also wholly equity financed.

Capital Structure for the Proposed SPV:

For the purpose of this assessment, it is assumed that the long-term fund required by the proposed project will be financed through a bank term loan and the promoters' equity in the **70:30 ratio**. Assumptions made for determining the quantum of term loan to be availed are listed in Table 4.2 here below:

Table 4.2: Assumptions for Determining the Quantum of Term Loan	
Factor	**Assumption**
Composition of Long-Term Fund required	(a) Cost of capital equipment, (b) 25% of the initial working capital required, © Cost of arranging finance, (d) pre-operative expenses for setting up the SPV, and € Interest on loan during the construction period
Withdrawal of term loan	It is assumed that the capital expenditure will be incurred uniformly over the construction period and that the contribution to expenditure by loan and equity will be commensurate with progress of construction and will be in the 70:30 ratio
Debt / Equity Ratio	70:30'
Moratorium for Principal & Interest on the term loan	3 years
Repayment of Term Loan	10 equal annual instalments after the moratorium period
Rate of interest on term loan	12% per annum

Calculations for determining the term loan are furnished in Table 4.3 here below:

Table 4.3: Calculation of Quantum of Term Loan				
Sl. No	Particulars	$ Million	INR Million	Remarks

1	Total Cost of Capital Works	323.86	23,413.09	
2	25% of the Initial Working Capital Requirement	6.23	450.22	25% of Initial Working Capital
3	Pre-operative Expenses	0.81	58.53	0.25% of the total cost of Capital Works
4	Cost of Arranging Term Loan	0.22	15.86	
5	Interest on Term Loan During Construction	41.35	2,989.03	Calculations in Table 6.10
6	**Total Long Term Fund Required**	**372.47**	**26,926.73**	
7	Total Equity Contribution by DCBL	111.74	8,078.02	30% of Long-Term Fund
8	Term Loan including interest during Construction	260.73	18,848.71	70% of Long-Term Fund
9	Equity to be Contributed by DCBL at the Commencement of Production	1.87	135.07	
10	Amount Term Loan to be released at the time of commencement of production	4.36	315.15	
11	Amount Term Loan to be released during construction including interest during construction	256.37	18,533.56	
12	**Principal Amount of Term Loan**	**219.38**	**15,859.68**	

Interest during construction is calculated in Table 4.4, here below:

Table 4.4: Interest During Construction Capitalized								
Year of Construction	Term Loan Outstanding at the Beginning of Year		Loan Drawn During the Year		Interest Accrued During the Year		Term loan Outstanding at the End of the Year	
	$ Million	INR Million	$ Million	INR Million	$ Million	INR Million	$ Million	INR Million
Year 1	0.00	0.00	71.67	5,181.51	4.30	310.89	75.97	5,492.40
Year 2	75.97	5,492.40	71.67	5,181.51	13.42	969.98	161.07	11,643.89
Year 3	161.07	11,643.89	71.67	5,181.51	23.63	1,708.16	256.37	18,533.56
Totals			**215.02**	**15,544.53**	**41.35**	**2,989.03**		

Working Capital:

25% of the Initial working capital required will be financed through long-term funds and the balance 75% by way of a cash credit facility from a commercial bank. Subsequent increases in the working capital will be financed through internal accruals. The assumptions for calculating the working capital required during the first year of production are listed in Table 4.5 here below:

Table 4.5: Assumptions for Determining the Working Capital	
Factor	**Value Assumed**
Components of Current assets	Inventory of 30 days consumption of raw materials and other supplies at purchase cost

	30 days' inventory of finished goods at cost.	
	Receivables calculated as 45 days' sales at cost of sales.	
Components of current Liabilities	Payables calculated as 45 days purchase cost of raw materials and supplies	
	30 days' operating expenses	
Rate of Interest on Cash Credit facility	15% per annum	

Based on the above assumptions, the Working Capital required for the first year of operations is calculated in Table 4.6 here below:

Table 4.6: Working Capital Required During First Year of Production (YEAR 4)

Sl. No.	Particulars	$ million	INR Million
1	Annual Consumption of Raw Materials and Supplies	116.27	8,405.18
2	Annual Expenses on Labour, Utilities, Maintenance & Insurance	41.90	3,029.41
3	Annual Selling & Administrative Expenses	9.18	663.65
4	Inventory of 30 Days' Consumption of Raw Materials & Supplies	9.69	700.43
5	Inventory of 30 Days' Finished Goods	13.18	952.88
6	45 days' Receivables	20.63	1,491.56
7	**Total Current Assets**	**43.50**	**3,144.88**
8	45 days' Payables for Raw Materials & Supplies	14.33	1,036.25
9	One Month's Labour, Fuel, Factory Overheads, Selling & Administrative Costs	4.26	307.75
10	**Total Current Liabilities**	**18.59**	**1,344.01**
11	**Working Capital**	**24.91**	**1,800.87**
Note: Costs are increased by 4% every year for subsequent years to provide for inflation.			

Weighted Average Cost of Capital

The Capital Asset Pricing Model (CAPM) formula is used for determining the cost of equity in the proposed SPV. It is presumed that the proposed SPV will have the same risk profile as DBL and accordingly, β of DBL is applied in the calculations. The CAPM formula for determining the cost of equity is as follows:

Expected Rate of Return (R_E) = Risk Free Rate of Return (R_{RF}) + β * (Market Risk Premium (M_{RP})

Market Risk Premium (M_{RP}) = Expected Market Rate of Return (R_M) – Risk Free Rate of Return (R_{RF})

The current yield on 30-year Government of India Securities is 6.77% (14 April 2021), (https://in.investing.com/rates-bonds/india-30-year-bond-yield) which constitutes the Risk-Free Rate of Return (R_{RF}) as on 14 April 2021. Estimated Market Rate of Return is 15.5%. Therefore, Market Risk Premium as of date is 8.73%.[4] β of DBL is 1.57[5]. Based on the above data, Cost of Equity of the proposed SPV is calculated as follows:

$R_E = R_{RF} + \beta * (R_M – R_{RF})$
$R_E = 6.77\% + 1.57 * (15.5\% - 6.77\%)$
$= 6.77\% + 1.57 * 8.73\%$
$= 6.77 \% + 13.71\%$
$= 20.48\%$

For this assessment, the Expected Rate of Return is rounded to 20%.

[4] India Equity Risk Premium 2020 – Independent valuation services (incwert.com)
[5] https:// economictimes.indiatimes.com/dalmia-bharat-ltd/stocks/companyid-1846307.cms

Now, the Weighted Average Cost of Capital (WACC) of the proposed SPV is calculated using the following formula:

$WACC = R_E * (E/V) + R_D * (D/V) * (1 – T_R)$

Where,

WACC	= Weighted Average Cost of Capital of the proposed SPV
E	= Value of Equity
D	= Value of Debt
V	= E + D
R_E	= Cost of Equity
R_D	= Cost of Debt
T_R	= Corporate Tax Rate

Keeping in view the assumptions made, the values to be used in this calculation are:

R_E	= 20% (Calculated in para 7.13 above)
E	= 30% of (E + D)
D	= 70% of (E + D)
V	= 100% of (E + D)
R_D	= 12%
T_R	= 25%

Therefore,

WACC = 20 % * (30/100) + 12.00% * (70/100) * (1 – 0.25)
= 6.00 % + 6.30%
= 12.30%

WACC so calculated will be applied as the discounting rate for project NPV calculations.

5. Projected revenue by sale of CO_2 utilization products

ACT has surveyed various product and technology options available for converting the captured CO_2 into saleable products. Size of the domestic market for different product options has also been examined. The products and technology options have also been discussed with the top management team of DCBL over several meetings. After such due examination, the option of converting the captured CO_2 into urea has been selected for the purpose of this pre-feasibility study.

The process involves converting captured CO_2 and ammonia into urea. With the input of 0.5 MTPA CO_2, the annual estimated production is 0.68 million tons of urea. Current annual domestic demand for urea is estimated as 24.5 million ton. To meet this demand, 11 million tons of urea is being imported every year. Keeping this gap between the domestic demand and the domestic supply in view, it is presumed that the estimated annual production of 0.68-million-ton urea by the proposed project will be easily absorbed by the domestic market.

Further, the Government of India requires at least 75% of the urea produced by any urea manufacturer in India to be neem coated. The government determines the price to be received by the manufacturer for the neem coated urea on cost plus basis so as to provide a reasonable return to the manufacturer. All justifiable costs incurred for the manufacture of neem coated urea are allowed in the determination of the price to be received by the manufacturer. Price of sale of the neem coated urea to the farmer is fixed at $81.92 (Rs.5,922.22) per ton. The difference between the price determined by the government and the price to be paid by the farmer is paid by the government directly to the manufacturer by way of subsidy. Thus, the manufacturer of urea is assured of reasonable profit on the neem coated urea manufactured by him subject to the costs being justifiable.

However, for the purpose of this assessment, sale price of $270 per ton of urea has been assumed. Estimated production is 0.68 MTPA urea. Based on the base price $270 per ton of urea, the total sales revenue will be $183.60 million (INR13,272.96 million). 5% of the sales revenue is provided as the cost of sales and administration.

6. Other income

if any, by way of government CO_2 policy grants, incentives (including Indian government incentives on energy saving and CO_2 emission reduction), etc.

In the UN Framework Convention on Climate Change held in Paris in December 2015, India presented its Intended Nationally Determined Contributions (INDCs) wherein it promised to reduce the greenhouse gas emissions intensity of its gross domestic product by 30-35% by 2030 from 2005 levels with the help of transfer of technology and low-cost international finance, including from the Green Climate Fund. India also promised that by 2030, 40% of power generation capacity in India will be based on non-fossil fuel sources. For tackling climate change, India would better adapt to climate change by enhancing investments in development programs in sectors vulnerable to climate change. India would mobilize domestic and new and additional funds from developed countries to implement the proposed mitigation and adaptation action and work for quick diffusion of cutting-edge climate technology in the country. India has promised to continue with its ongoing interventions, enhance the existing policies and launch new initiatives.

The Government of India has taken several initiatives for combating climate change. The Ministry of Power of the government, through the Bureau of Energy Efficiency, has initiated energy efficiency initiatives in the areas of household lighting, commercial buildings, labelling of appliances, demand side management in agriculture / municipalities, capacity building *etc.* Memorandums of Understanding have been signed with financial institutions to work together for the development of energy efficiency market and for the identification of issues related to this market development. A Partial Risk Guarantee Fund for Energy Efficiency has been created as a risk sharing mechanism to provide commercial banks with a partial coverage of risk involved in extending loans for energy efficiency projects. A Venture Capital Fund for Energy Efficiency has been created to provide equity capital for energy efficiency projects.

The government has undertaken a two-pronged approach to cater to the energy demand while ensuring minimum growth in CO_2 emissions. On the one-hand, on the generation side, the government is promoting greater use of renewables in the energy mix through hydropower, solar, wind & nuclear power and at the same time shifting towards supercritical technologies for coal-based power plants. On the other hand, efforts are being made to efficiently use the energy in the demand side through various innovative policy measures. Encouragement by the government has also led to growing lender interest in India's renewable energy sector.

9.4. In India, at present, there are no government schemes of grants or incentives that are specifically targeted for supporting CCU projects. However, Section 32 of the Income Tax Act, 1961 allows 20% additional depreciation during the first year of operation if the capital equipment to be used in the project will be new. This depreciation will be in addition to the 15% per annum depreciation on Written Down Value(WDV) permitted for all continuous process plants. Section 35AD of the Income Tax Act, 1961 allows deduction of entire capital expenditure from the profit of the project from the very first year of operation for new units set up for manufacture of fertilizers. If the profit of the first year is not adequate to deduct the entire capital expenditure, the amount that could not be deducted is permitted to be carried forward for deduction from the profits of subsequent years until the entire capital investment is deducted from the profit. These tax exemptions will be useful only if there will be adequate profits during early years of production to permit these deductions.

9.5. Estimates by the Indian Oil Corporation Limited have indicated that the CCU projects may not be economically viable without grant money to subsidize the capital investment and to reduce the selling price of products to a more competitive level. Globally also, concerns have been expressed about the long-term sustainability, the feasibility of technical advances, and the economic viability of CCU technology by the public and private players. As a result, even though CCU technology is 40 years old, fewer than 100 projects have been developed worldwide, with a combined estimated capacity of around 32 million metric tons of CO_2—a small fraction of global emissions. The overall investment costs and the operational costs are a significant barrier to initiate even the first steps towards pilot and demonstration plants.

9.6. As international experience demonstrates that securing direct government support through grants, incentives and tax breaks are essential for CCU projects, as CCU projects are not likely to be viable without them, some governments have been providing tax incentives and policy initiatives to create a credible near-term investment opportunity in industries where the cost of CCU is relatively low. Substantial tax credits are available in the United States that incentivize new CCU projects. Norway and the UK have recently introduced government subsidies for specific CCU projects. Government of Norway would be providing 75% financial support for a carbon capture project that will enable capture of 400,000 tons of CO_2 per year being set up by HeidelbergCement Norcem plant in Brevik, Norway, making it the first industrial scale CCU project in a cement production plant in the world. The Peoples' Republic of China provides initial investment subsidy and electricity tariff subsidy and CO_2 utilization subsidy on CCU projects under high, medium, and low coal price levels, respectively.

9.7. As the biggest obstacles to CCU projects are the high investments and operational costs involved and keeping in view the incentives provided by other countries for CCU Projects, Government of India should be impressed upon to consider providing similar incentives. However, at present, no such incentives appear to be on the anvil.

7. Net income

year -wise over 25 years, net present value, internal rate of return and modified internal rate of return

The calculation of cost of sales for the first year has been furnished in Table 6.8 of Chapter 6. This cost is increased by 4% every year to account for inflation. Depreciation is calculated at the rate of 15% of the Written Down Value (WDV) per year as provided for in the Income Tax Act. Additional depreciation of 20% during the first year is permitted under the Income Tax Act, if the plant & machinery deployed are new. However, this assessment will not consider this additional depreciation as adequate profits are not available to take benefit of this provision. For the same reason, this assessment also does not consider the benefit available under Section 35AD of the Income Tax Act. Year-wise depreciation values over the life of the project at 15% of the WDV of the plant are furnished in Table 7.1 here below:

Table 7.1. Year-Wise Depreciation Values						
Construction Phase						
Year 1	Construction Phase					
Year 2						
Year 3						
Production Phase						
Year	**Total Capital Expenditure at the Beginning of the Year**		**Depreciation for the Year**		**Written Down Value at the End of the Year**	
	$ Million	**INR Million**	**$ Million**	**INR Million**	**$ Million**	**INR Million**
Year 4	365.43	26,417.98	54.81	3,962.70	310.62	22,455.28
Year 5	310.62	22,455.28	46.59	3,368.29	264.02	19,086.99
Year 6	264.02	19,086.99	39.60	2,863.05	224.42	16,223.94
Year 7	224.42	16,223.94	33.66	2,433.59	190.76	13,790.35
Year 8	190.76	13,790.35	28.61	2,068.55	162.14	11,721.80
Year 9	162.14	11,721.80	24.32	1,758.27	137.82	9,963.53
Year 10	137.82	9,963.53	20.67	1,494.53	117.15	8,469.00
Year 11	117.15	8,469.00	17.57	1,270.35	99.58	7,198.65
Year 12	99.58	7,198.65	14.94	1,079.80	84.64	6,118.85
Year 13	84.64	6,118.85	12.70	917.83	71.94	5,201.02
Year 14	71.94	5,201.02	10.79	780.15	61.15	4,420.87
Year 15	61.15	4,420.87	9.17	663.13	51.98	3,757.74
Year 16	51.98	3,757.74	7.80	563.66	44.18	3,194.08
Year 17	44.18	3,194.08	6.63	479.11	37.56	2,714.97
Year 18	37.56	2,714.97	5.63	407.25	31.92	2,307.72
Year 19	31.92	2,307.72	4.79	346.16	27.13	1,961.56
Year 20	27.13	1,961.56	4.07	294.23	23.06	1,667.33
Year 21	23.06	1,667.33	3.46	250.10	19.60	1,417.23
Year 22	19.60	1,417.23	2.94	212.58	16.66	1,204.65
Year 23	16.66	1,204.65	2.50	180.70	14.16	1,023.95
Year 24	14.16	1,023.95	2.12	153.59	12.04	870.36
Year 25	12.04	870.36	1.81	130.55	10.23	739.80
Year 26	10.23	739.80	1.54	110.97	8.70	628.83
Year 27	8.70	628.83	1.30	94.32	7.39	534.51
Year 28	7.39	534.51	1.11	80.18	6.28	454.33

Calculation of interest on the term loan availed for financing long-term fund required is furnished in table 7.2 below:

Table 7.2. Interest on term loan during production phase								
Construction Phase								
Year 1	Construction Phase							
Year 2								
Year 3								
Production Phase								
Year	**Term Loan Outstanding at the Beginning of the Year**		**Instalment Paid at the End of the Year**		**Term Loan Outstanding at the End of the Year**		**Interest Accrued During the Year**	
	$ Million	**INR Million**	**$ Million**	**INR Million**	**$ Million**	**INR Million**	**$ Million**	**INR Million**
Year 4	260.73	18,848.71	26.07	1,884.88	234.65	16,963.83	31.29	2,261.85
Year 5	234.65	16,963.83	26.07	1,884.87	208.58	15,078.96	28.16	2,035.66
Year 6	208.58	15,078.96	26.07	1,884.87	182.51	13,194.09	25.03	1,809.48
Year 7	182.51	13,194.09	26.07	1,884.87	156.44	11,309.22	21.90	1,583.29
Year 8	156.44	11,309.22	26.07	1,884.87	130.36	9,424.35	18.77	1,357.11
Year 9	130.36	9,424.35	26.07	1,884.87	104.29	7,539.48	15.64	1,130.92
Year 10	104.29	7,539.48	26.07	1,884.87	78.22	5,654.61	12.51	904.74
Year 11	78.22	5,654.61	26.07	1,884.87	52.15	3,769.74	9.39	678.55
Year 12	52.15	3,769.74	26.07	1,884.87	26.07	1,884.87	6.26	452.37
Year 13	26.07	1,884.87	26.07	1,884.87	0.00	0.00	3.13	226.18

Based on the above, the Income Statements, Balance Sheets and Cash Flow Statements for 25 years' life time of the project have been projected.

The ProjectNet Present Value (NPV) over its lifecycle is determined by applying the expected rate of return on the equity of the SPV, *i. e.* 20% as the discount rate and the Equity IRR is determined by applying the WACC of 12/3% per annum in the base case scenario. The Project NPV is negative at $185.33 million (INR – 13,398.16 million). The Project IRR over the lifecycle is 3.99% and Equity IRR is 0.01%. Thus, at the sale price of $270/- (INR19,519.06) and with the values of CAPEX and OPEX as furnished by the CO_2 Capture Specialists and the CO_2 Utilization Specialist, the project does not yield an acceptable rate of return.

Trends of Net Profit (Figure 7.1), Return on Equity (Figure 7.2), Net Worth (Figure 7.3), Debt / Equity Ratio (Figure 7.4), Net Cash Flow (Figure 7.5) and Debt Service Coverage Ratio (Figure 7.6) over life time of the project are presented in the following pages.

Figure 7.1. Trend in Net Profit

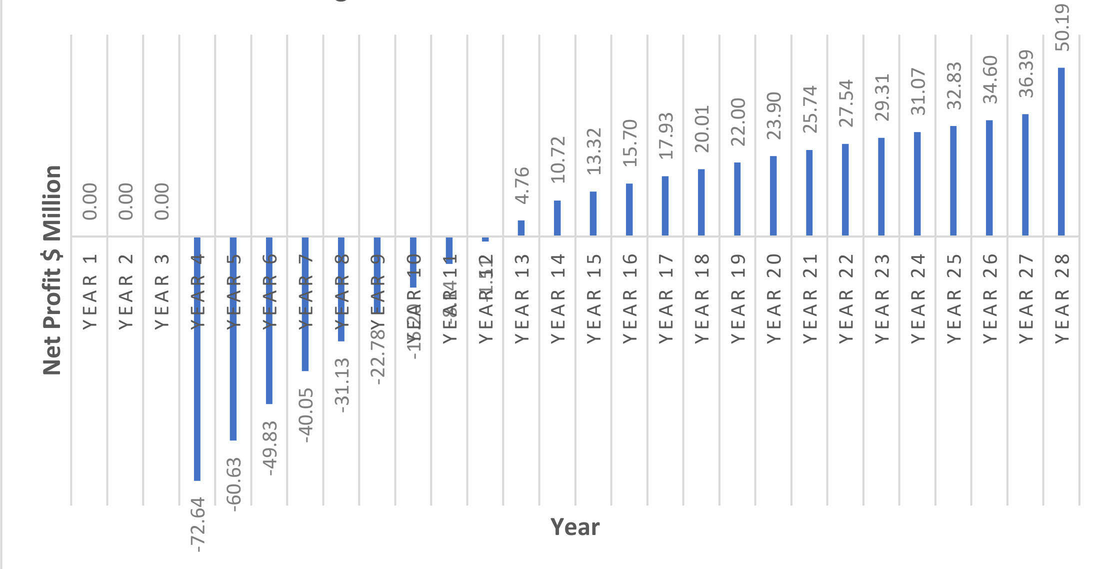
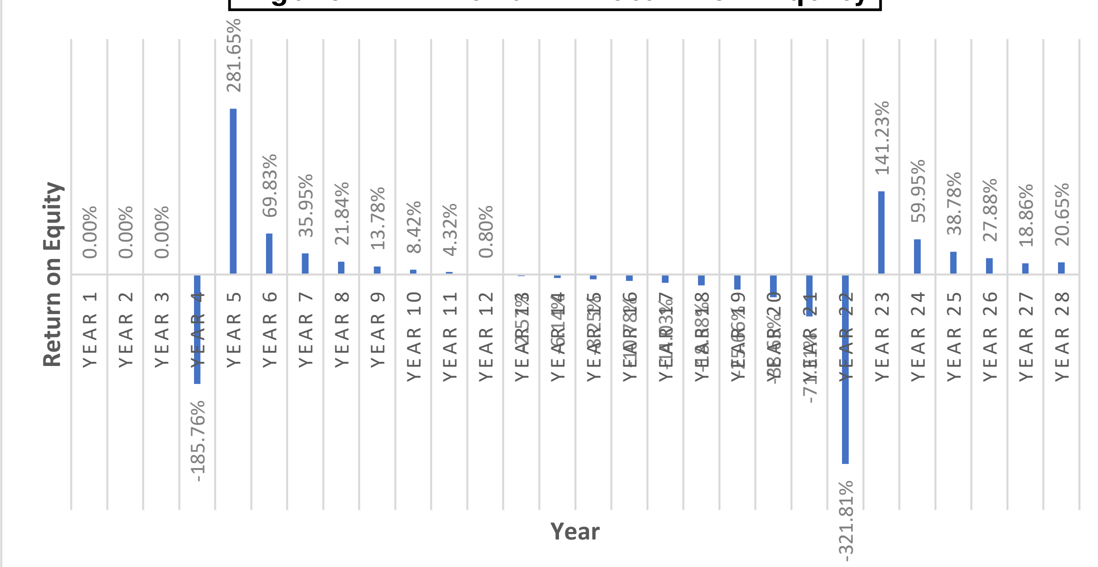


Figure 7.2: Trend in Return on Equity



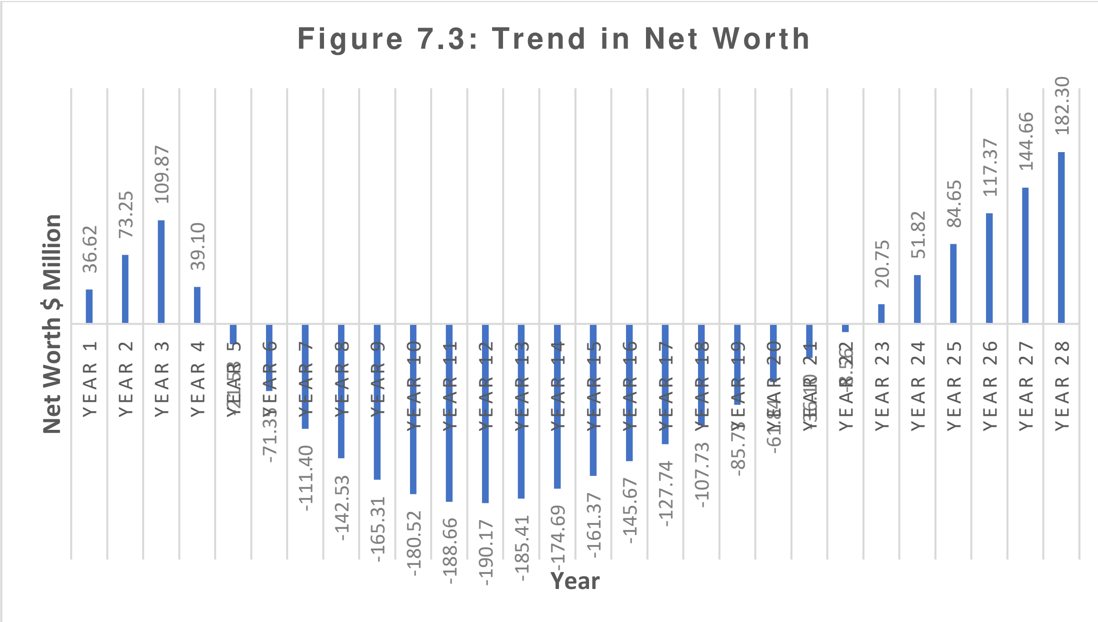


Figure 7.3: Trend in Net Worth
Net Worth $ Million
Year
36.62
73.25
109.87
39.10
-71.37
-111.40
-142.53
-165.31
-180.52
-188.66
-190.17
-185.41
-174.69
-161.37
-145.67
-127.74
-107.73
-85.73
20.75
51.82
84.65
117.37
144.66
182.30

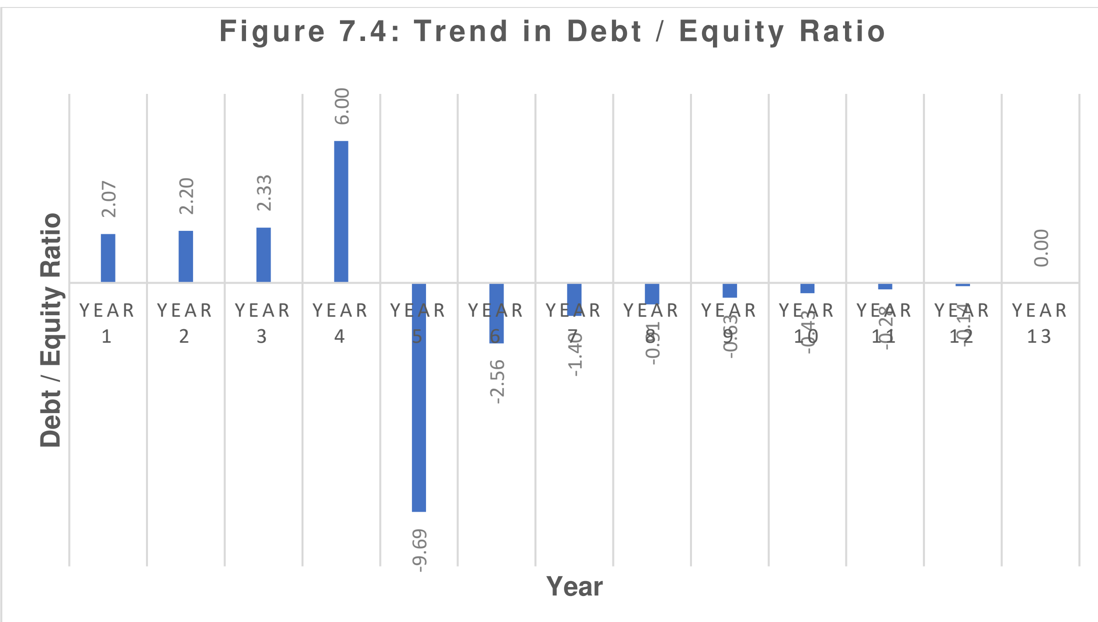


Figure 7.4: Trend in Debt / Equity Ratio
Debt / Equity Ratio
Year
2.07
2.20
2.33
6.00
-9.69
-2.56
-1.40
0.00

Figure 7.5: Trend in Net Cashflows

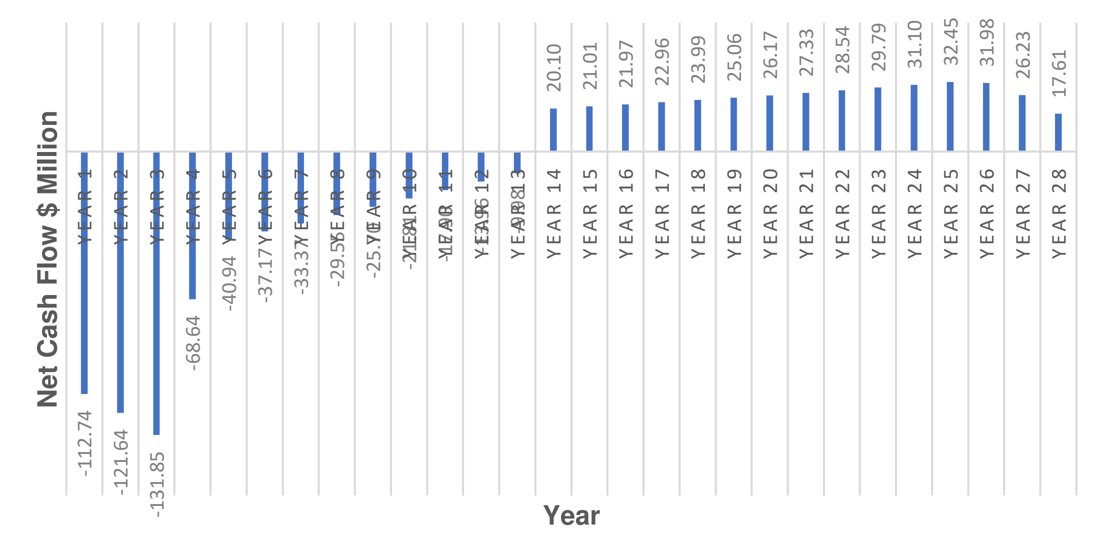
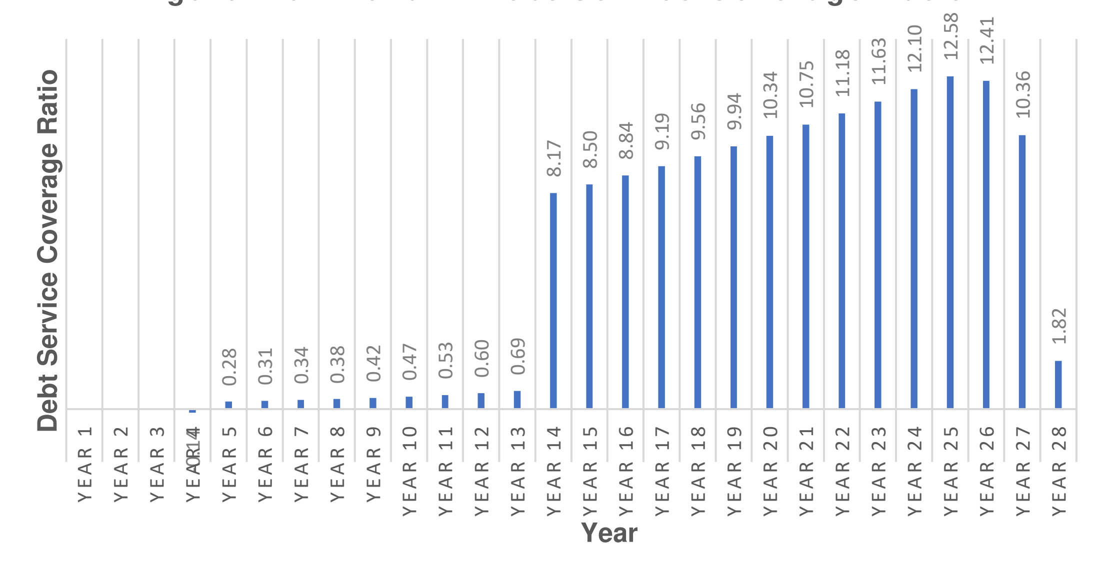


Figure 7.6: Trend in Debt Service Coverage Ratio



8. Financial model for sensitivity analysis

(a) weighted average cost of capital
(b) utilization product pricing, and
(c) co₂ pricing

The determination of NPV, IRR and MIRR in the previous chapters are based on the values of variables as listed in Table 2.1 of Chapter 2. The sensitivity of these parameters to changes in the values of variables listed in Table 2.1 of Chapter 2 has been tested. The results emerging therefrom are discussed in this chapter.

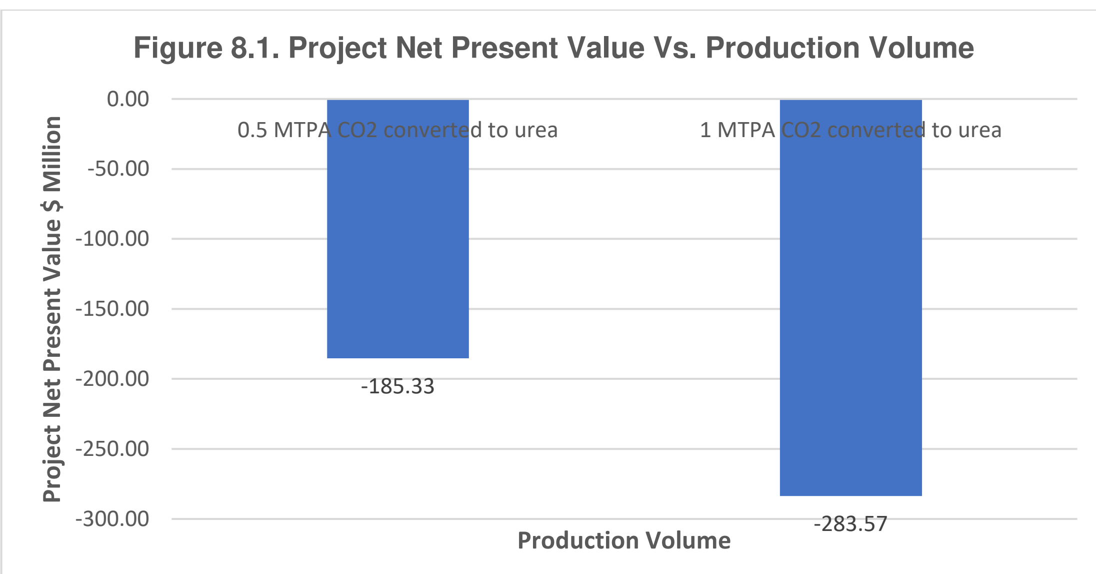
<u>Sensitivity to Changes in the Production Volume:</u>

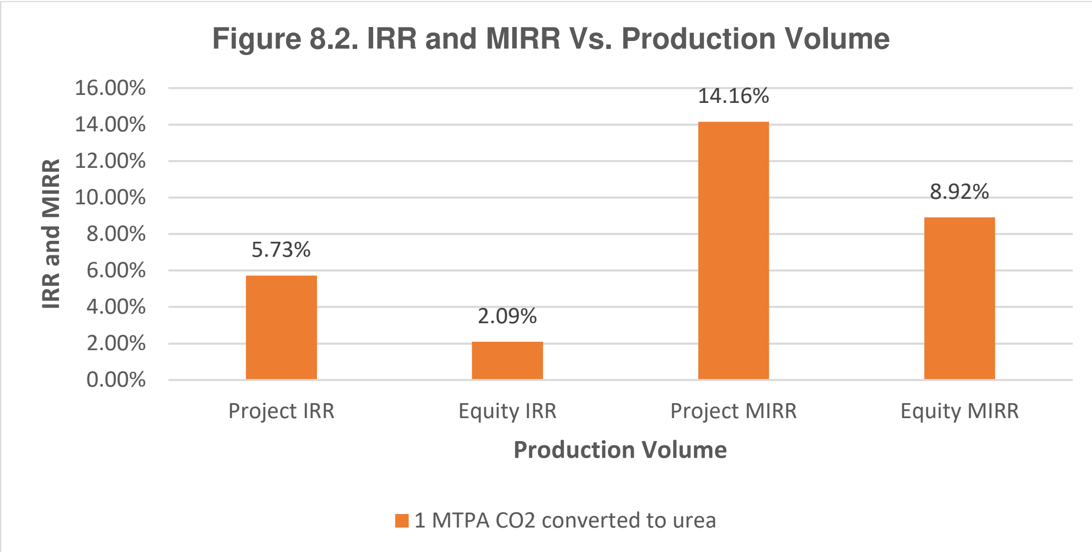
The impact of the increase in the conversion volume of CCU plant from 0.5 MTPA CO_2 to 1 MTPA CO_2 to urea on the NPV, IRR and MIRR can be seen from the resulting values listed in Table 8.1 below:

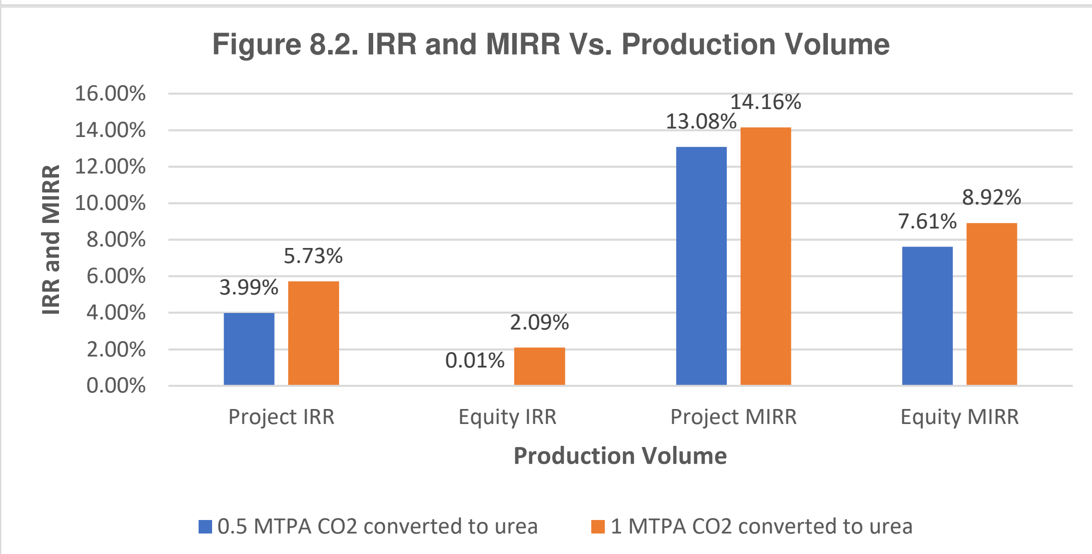
TABLE 8.1: Impact of Variation in Production Volume

Conversion Volume	Project NPV		IRR		MIRR	
	$ Million	INR Million	Project	Equity	Project	Equity
0.5 MTPA CO2 converted to urea (Base Case)	-185.33	-13,398.16	3.99%	0.01%	13.08%	7.61%
1 MTPA CO2 converted to urea	-283.57	-20,500.26	5.73%	2.09%	14.16%	8.92%

As can be seen, increase in production volume improves the returns. However, even at the conversion volume of 1 MTPA the project does not generatean acceptable rate of return. The results tabulated in Table 8.1 above are presented in graphical form in Figure 8.1 and Figure 8.2, here below.







<u>Sensitivity to Variations in the Weighted Average Cost of Capital:</u>

Sensitivity to changes in the Weighted Average Cost of Capital can be seen from the results tabulated in Table 8.2 below:

Table 11.2: Impact of Variation in Weighted Average Cost of Capital						
Expected Rate of Return on Equity	**Rate of Interest on Term Loan**	**Debt / Equity Ratio**	**WACC**	**Equity NPV ($ Million)**	**Equity IRR**	**Equity MIRR**
20%	9%	70:30'	10.73%	-149.77	0.78%	7.89%
20%	10%	70:30'	11.25%	-158.72	0.50%	7.78%
20%	11%	70:30'	11.78%	-167.10	0.24%	7.69%
20%	9%	60:40'	12.05%	-152.13	1.11%	7.97%
20% (Base Case)	12%	70:30'	12.30%	-174.97	-0.01%	7.59%
20%	10%	60:40'	12.50%	-159.22	0.87%	7.88%
20%	11%	60:40'	12.95%	-165.96	0.64%	7.79%
20%	9%	50:50'	13.38%	-155.07	1.42%	7.88%

20%	12%	60:40'	13.40%	-172.35	0.42%	7.70%
20%	10%	50:50'	13.75%	-161.18	1.22%	7.90%
20%	11%	50:50'	14.13%	-166.46	1.03%	7.82%
20%	12%	50:50'	14.50%	-171.54	0.84%	7.75%

Currently, interest rates in India have been moving downwards and debt can be procured at interest rate of 9% per annum. The project will yield an equity IRR of 1.42% if the debt / equity ratio will be 50:50 and rate of interest on debt will be 9% per annum. The above results are presented in graphical form in Figure 8.3 and, Figure 8.4 here below.

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Figure 8.3: Equity NPV Vs. WACC

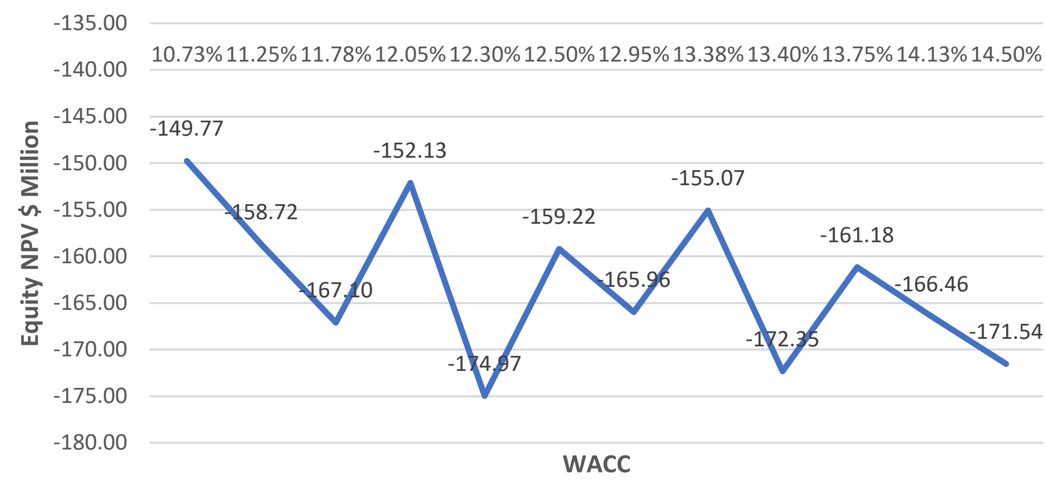
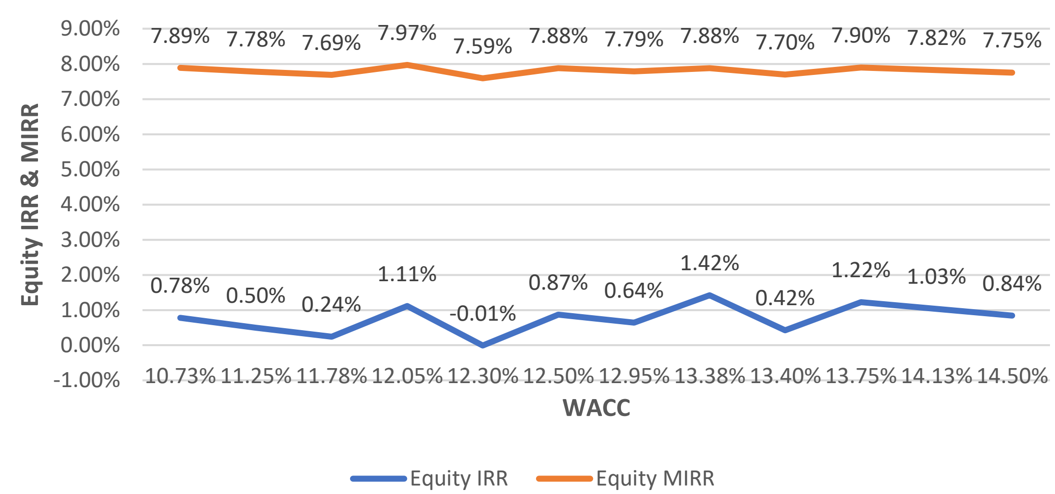


Figure 8.4: Equity IRR & MIRR Vs. WACC



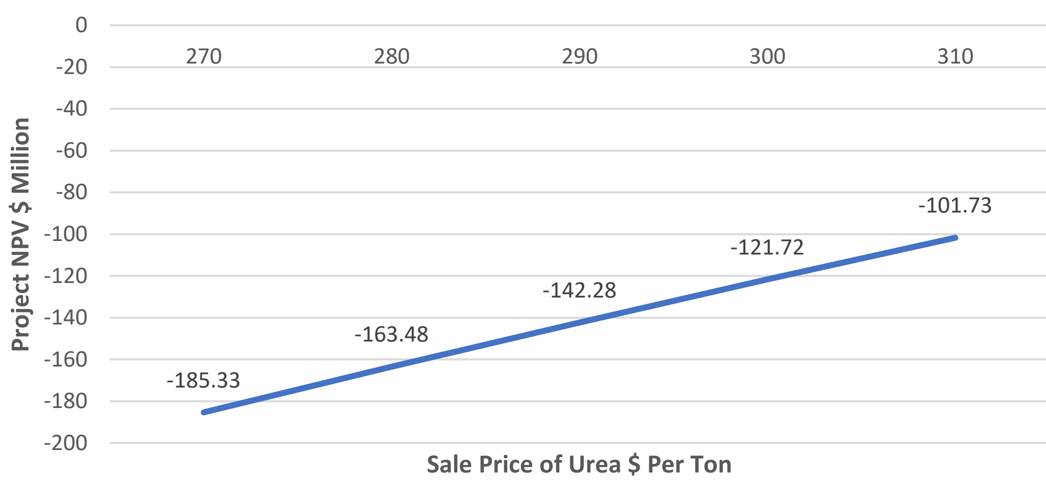
<u>Sensitivity to Variation in Sale Price of Urea:</u>

The impact of variation in the sale price of urea on the NPV, IRR and MIRR can be seen from the resulting values listed in Table 8.3 here below.As expected, increase in the selling price improves the returns.

Table 11.3: Impact of Variation in the Sale Price of Urea							
Sl. No.	Selling Price of Urea ($ per Ton)	NPV		IRR		MIRR	
		$ Million	INR Million	Project	Equity	Project	Equity
1	270 (Base Case)	-185.33	-13,398.16	3.99%	0.01%	13.08%	7.61%
2	280	-163.48	-11,818.72	6.50%	3.22%	14.56%	9.54%
3	290	-142.28	-10,285.60	8.65%	6.14%	15.73%	11.33%
4	300	-121.72	-8,799.29	10.56%	8.87%	16.65%	13.13%
5	310	-101.73	-7,354.01	12.29%	11.49%	17.40%	14.88%

The results tabulated in Table 8.3 above are presented in graphical form in Figure 8.5 and Figure 8.6 here below.

Figure 11.5. Project Net Present Value Vs. Sale Price of Urea



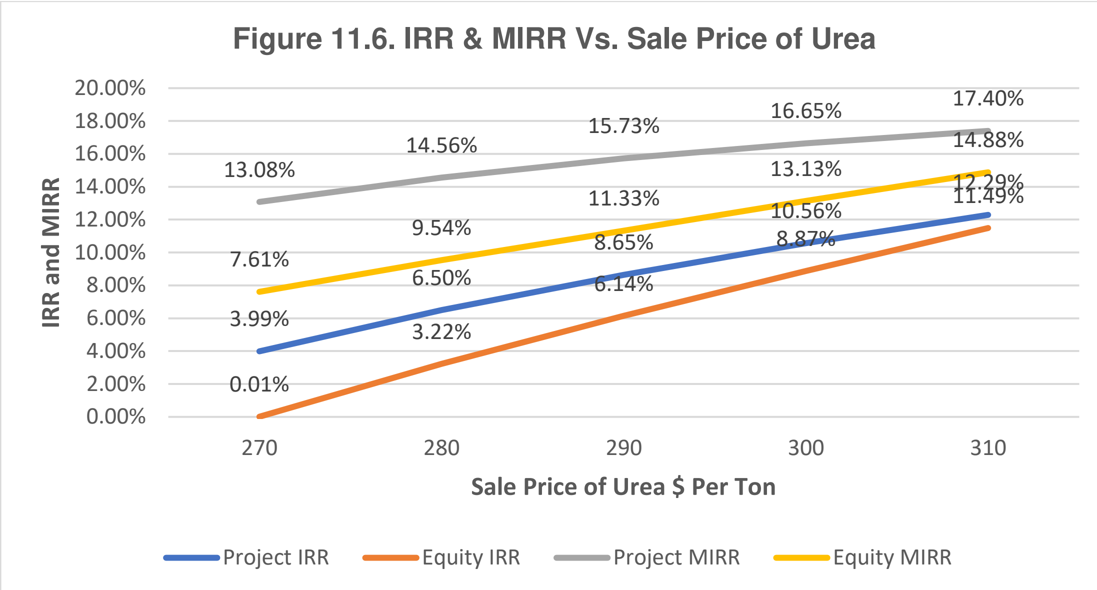


Figure 11.6. IRR & MIRR Vs. Sale Price of Urea

<u>Sensitivity to Variation Cost of CO_2:</u>

The impact of variation in the cost of CO_2 on the NPV, IRR and MIRR can be seen from the resulting values listed in Table 8.4 here below. It is seen that the IRR improves with the reduction in the cost of CO_2.

Table 8.4: Impact of Changes in the Cost of CO_2

Explanation		Total Capex	Cost of Capex per ton of CO_2 including Interest at WACC	OPEX per Ton of CO_2	Total Cost of Captured CO_2 Per Ton	Project NPV	IRR		MIRR	
		$ Million	$			$ Million	Project	Equity	Project	Equity
A	10% reduction in the cost of CO_2 as in **C** below	87.5	22.78	27.3	50.08	-177.84	4.26%	0.32%	13.26%	7.82%
B	5% reduction in the cost of CO2 as in **C** below	92.36	24.06	28.82	52.88	-181.59	4.12%	0.16%	13.17%	7.71%
C	Cost of CO2 based on the values furnished by CO2 Capture Specialists (Base Case)	97.22	25.32	30.33	55.65	-188.53	3.99%	0.01%	13.08%	7.61%
D	5% increase in values in the cost of CO2 as in **C** above	102.08	26.58	31.85	58.43	-189.07	3.86%	-0.14%	13.00%	7.50%

E	10% increase in values in the cost of CO2 as in <u>**C**</u> above	106.94	33.37	27.3	60.67	-192.83	3.73%	-0.29%	12.91%	7.40%

The results tabulated in Table 8.4 above are presented in graphical form in Figure 8.7 and Figure 8.8 here below.

Figure 8.7. Project Net Present Value Vs. Cost of Carbon Dioxide

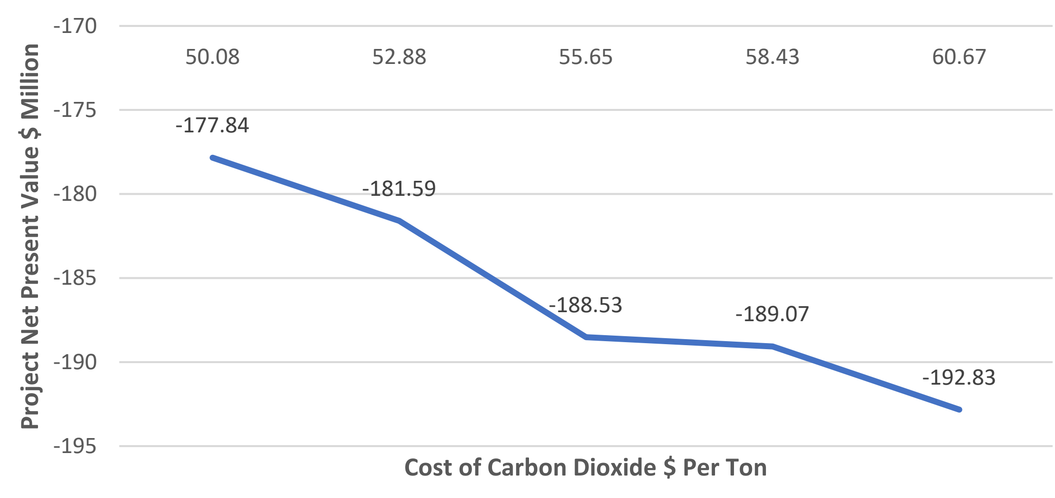
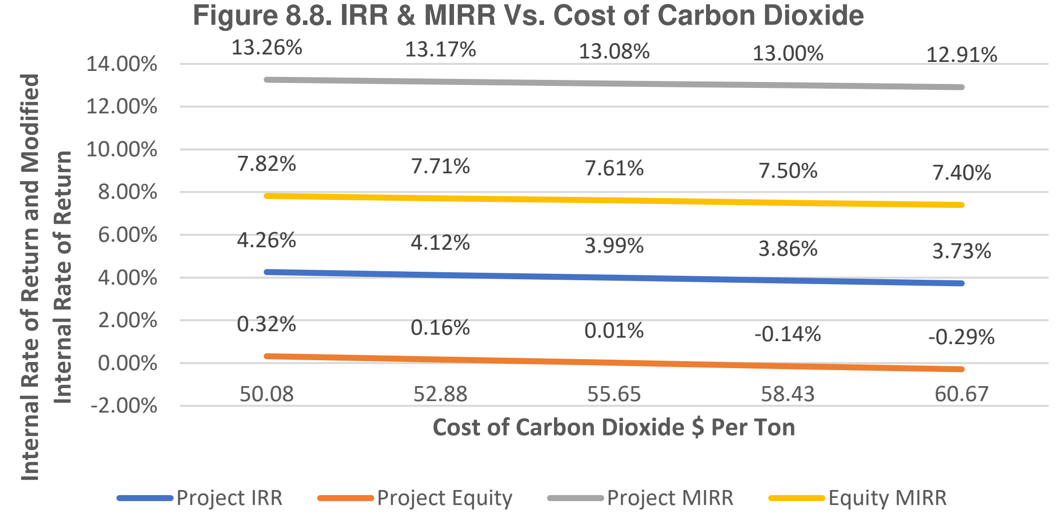


Figure 8.8. IRR & MIRR Vs. Cost of Carbon Dioxide



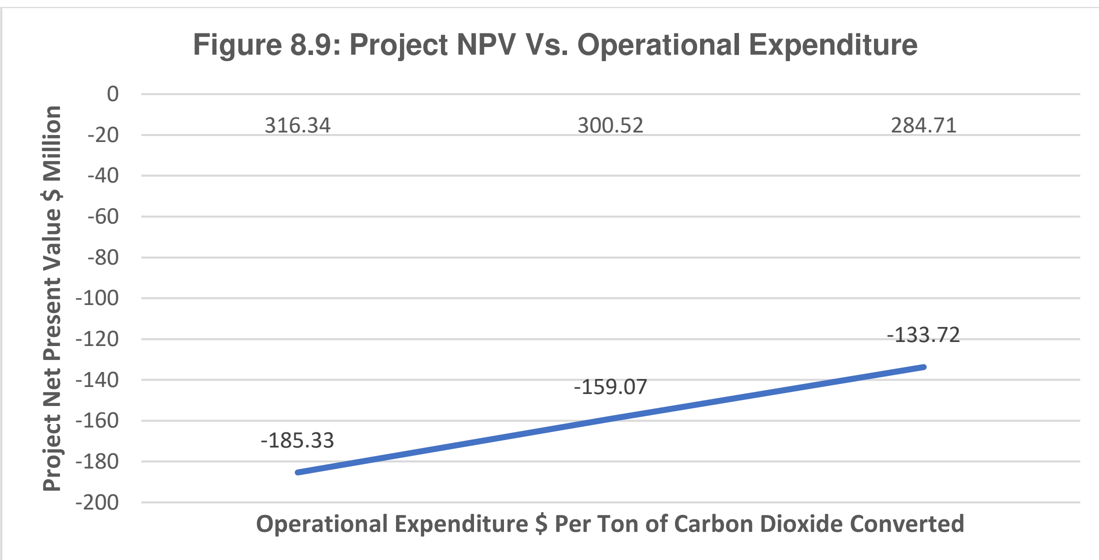
<u>Sensitivity to Reduction in Operational Cost:</u>

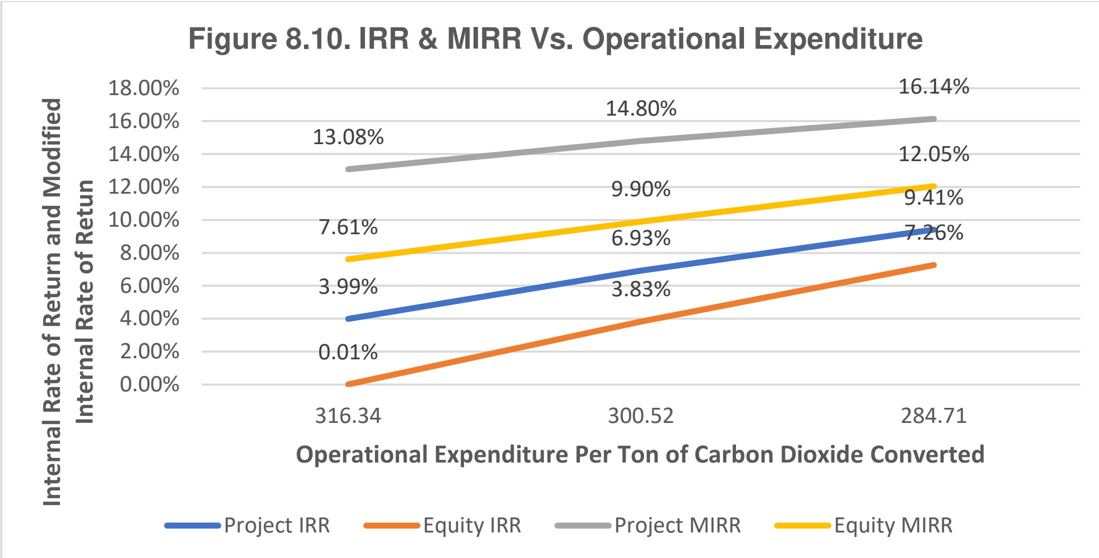
The sensitivity to reduction in the overall OPEX on the NPV, IRR and MIRR can be seen from the resulting values listed in Table 8.5 here below. As can be seen, reduction in OPEX significantly improves the returns.

Table 8.5: Impact of Reduction in Operational Expenditure			
Explanation	**Project NPV**	**IRR**	**MIRR**

		$ Million	INR Million	Project	Equity	Project	Equity
A	At Bae Values of Variables	-185.33	-13,398.16	3.99%	0.01%	13.08%	7.61%
B	As in **A** above but with 5% reduction in Operational Expenditure	-159.07	-11,499.65	6.93%	3.83%	14.80%	9.90%
C	As in **A** above but with 10% reduction in Operational Expenditure	-133.72	-9,666.90	9.41%	7.26%	16.14%	12.05%

The results tabulated in Table 8.5 above are presented in graphical form in Figure 8.9 and Figure 8.10 here below:





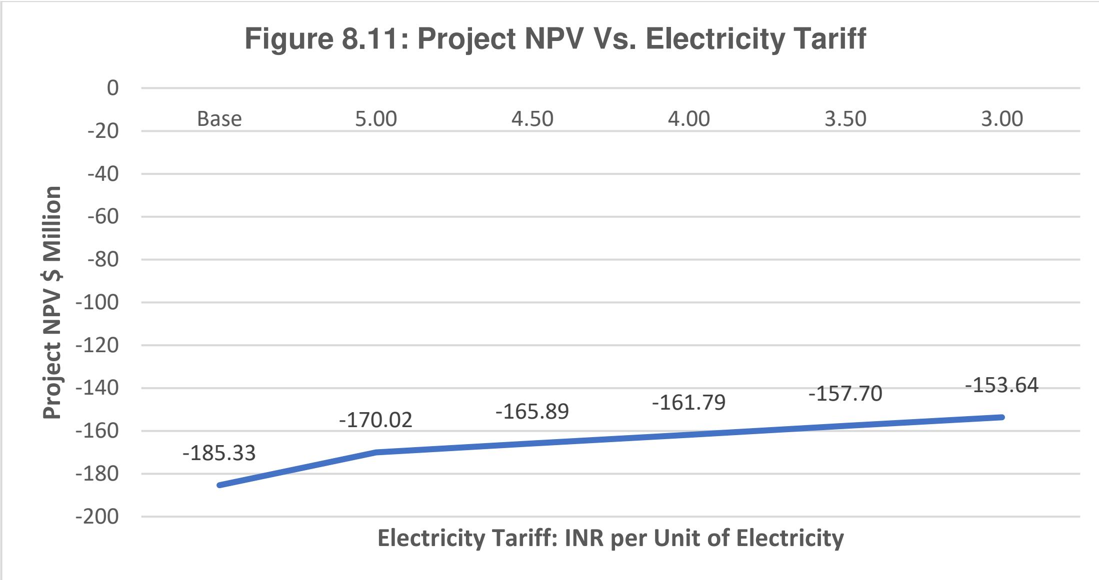
In the following paras. Sensitivity of NPV, IRR & MIRR to prices of different components of the operational cost is tested.

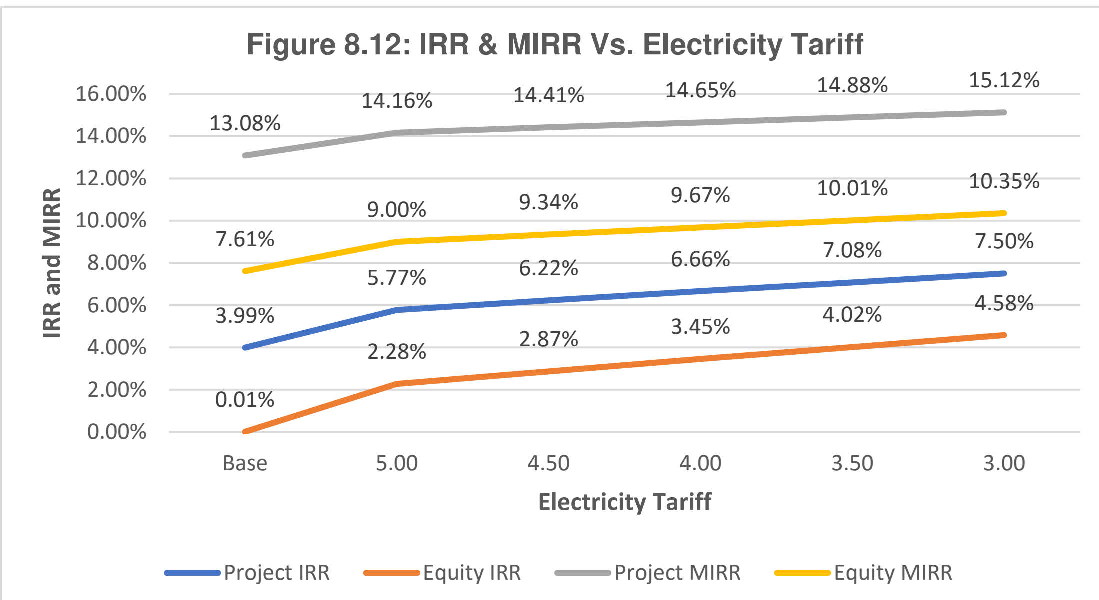
Sensitivity to Changes in the Tariff for Electricity:

Under the base case scenario, cost of electricity has been determined at the electricity tariff charged by the Tamil Nadu Generation and Distribution Corporation Limited. This comprises a fixed charge of INR350 per KVA per month plus variable charge of INR6.35 per unit of electricity consumed. However, DCBL states that it will procure electricity at a much lower rate of INR3 per unit. Therefore, sensitivity of IRR & MIRR to the electricity tariff has been assessed and the results are as tabulated in Table 11.6 here below. As can be seen, reduction in the electricity tariff significantly improves the returns.

TABLE 8.6: Impact of Variation in the Tariff for Electricity						
Assumption	**Project NPV**		**IRR**		**MIRR**	
Electricity Tariff INR / Unit	**$ Millions**	**INR Millions**	**Project**	**Equity**	**Project**	**Equity**
Base Case	-185.33	-13,398.16	3.99%	0.01%	13.08%	7.61%
5.00	-170.02	-12,291.48	5.77%	2.28%	14.16%	9.00%
4.50	-165.89	-11,992.81	6.22%	2.87%	14.41%	9.34%
4.00	-161.79	-11,695.99	6.66%	3.45%	14.65%	9.67%
3.50	-157.70	-11,400.82	7.08%	4.02%	14.88%	10.01%
3.00	-153.64	-11,107.03	7.50%	4.58%	15.12%	10.35%

The results tabulated in Table 8.6 above are presented in graphical form in Figure 8.11 and Figure 8.12 here below.





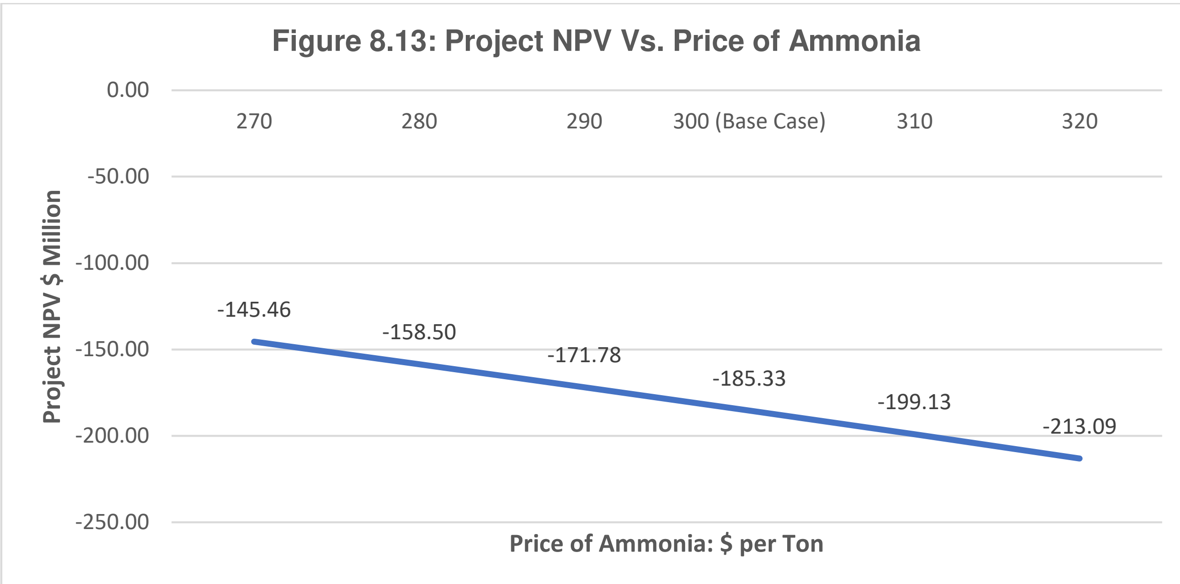
Sensitivity to changes in Ammonia Price:

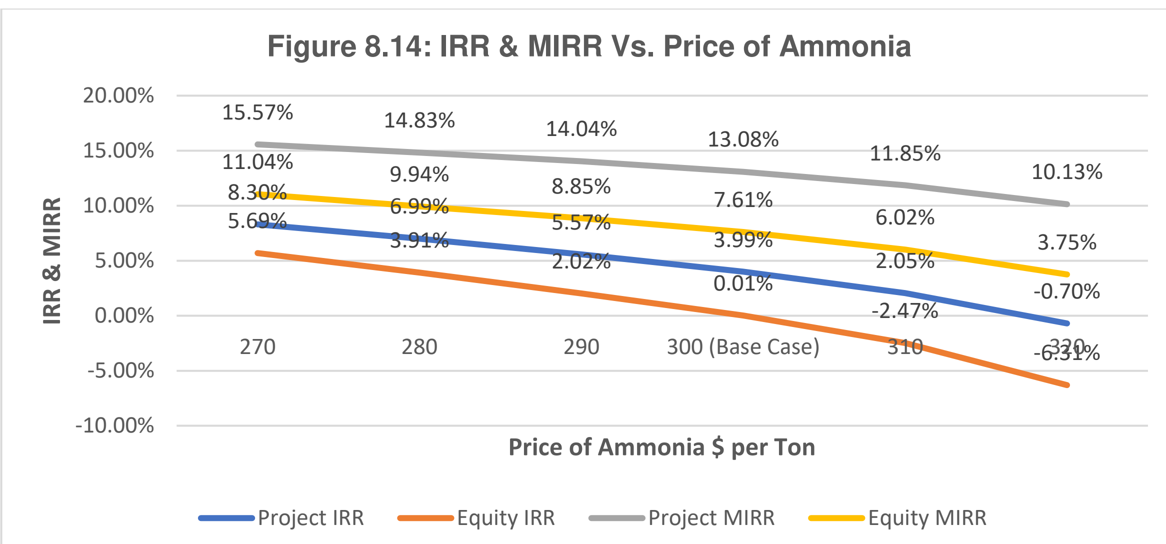
Ammonia is an important raw material for converting captured CO_2 to urea. The impact of changes in the price of ammonia on the NPV, IRR and MIRR can be seen from the resulting values listed in Table 8.7 here below. As can be seen, price of ammonia has significant impact on the return from the project.

TABLE 8.7: Impact of Variation in Price of Ammonia						
Assumption	Project NPV		IRR		MIRR	
Price of Ammonia $ per ton	$ Millions	INR Millions	Project	Equity	Project	Equity
270	-145.46	-10,515.39	8.30%	5.69%	15.57%	11.04%
280	-158.50	-11,458.18	6.99%	3.91%	14.83%	9.94%
290	-171.78	-12,418.44	5.57%	2.02%	14.04%	8.85%

300 (Base Case)	-185.33	-13,398.16	3.99%	0.01%	13.08%	7.61%
310	-199.13	-14,395.84	2.05%	-2.47%	11.85%	6.02%
320	-213.09	-15,405.00	-0.70%	-6.31%	10.13%	3.75%

The results tabulated in Table 8.7 above are presented in graphical form in Figure 8.13 and Figure 8.14 here below:





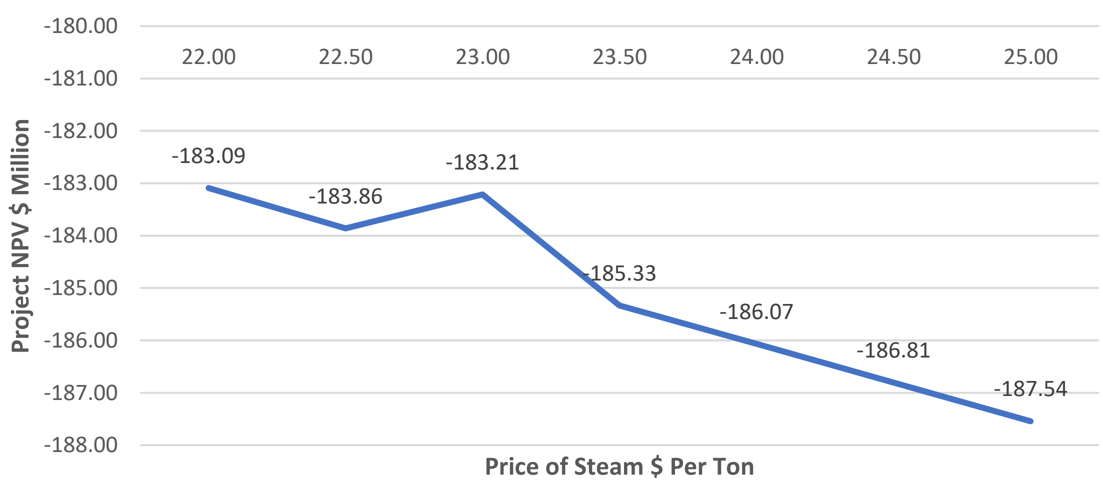
<u>Sensitivity to Changes in the Price of Steam:</u>

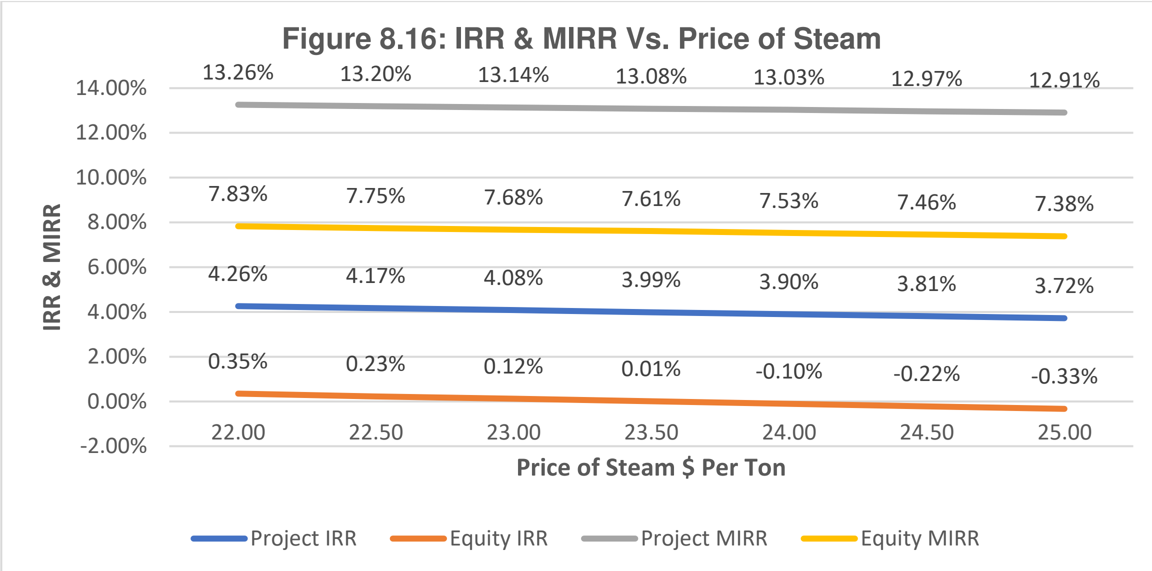
The CO_2 Utilization Expert has furnished details of steam consumption in CUP. The impact of changes in the price of steam utilized in CUP on the NPV, IRR and MIRR can be seen from the resulting values listed in Table 8.8 here below. As can be seen, reduction in the price improves the return from the project.

TABLE 8.8: Impact of Variation in Price of Steam						
Assumption	**Project NPV**		**IRR**		**MIRR**	
Price of Steam $ per ton	**$ Millions**	**INR Millions**	**Project**	**Equity**	**Project**	**Equity**
22.00	-183.09	-13,236.17	4.26%	0.35%	13.26%	7.83%
22.50	-183.86	-13,291.86	4.17%	0.23%	13.20%	7.75%
23.00	-183.21	-13,245.01	4.08%	0.12%	13.14%	7.68%
23.5 (Base Case)	-185.33	-13,398.16	3.99%	0.01%	13.08%	7.61%
24.00	-186.07	-13,451.32	3.90%	-0.10%	13.03%	7.53%
24.50	-186.81	-13,504.67	3.81%	-0.22%	12.97%	7.46%
25.00	-187.54	-13,558.03	3.72%	-0.33%	12.91%	7.38%

The results tabulated in Table 8.8 above are presented in graphical form in Figure 8.15 and Figure 8.16 here below:

Figure 8.15: Project NPV Vs. Price of Steam



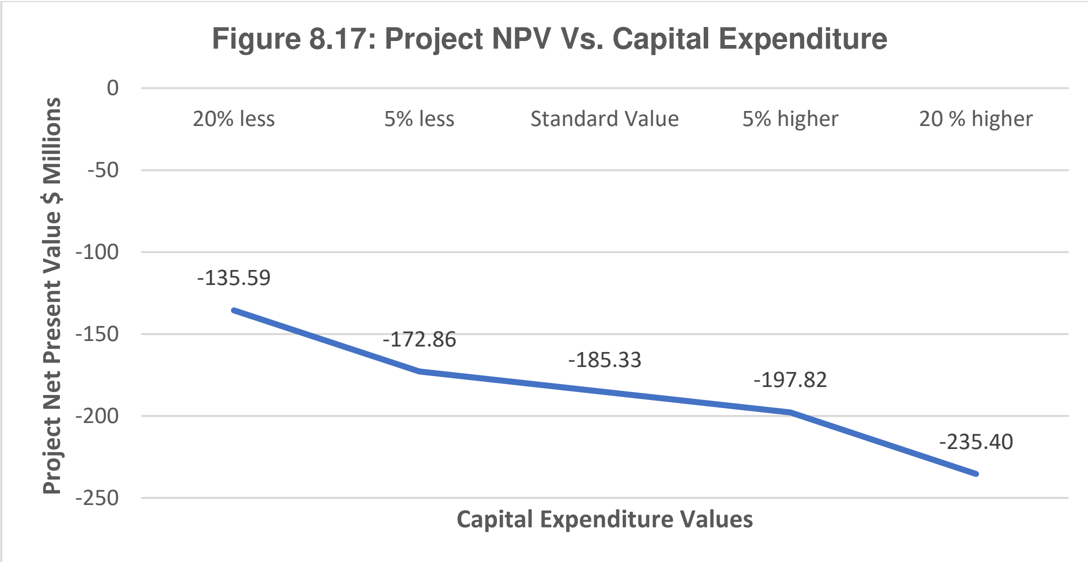


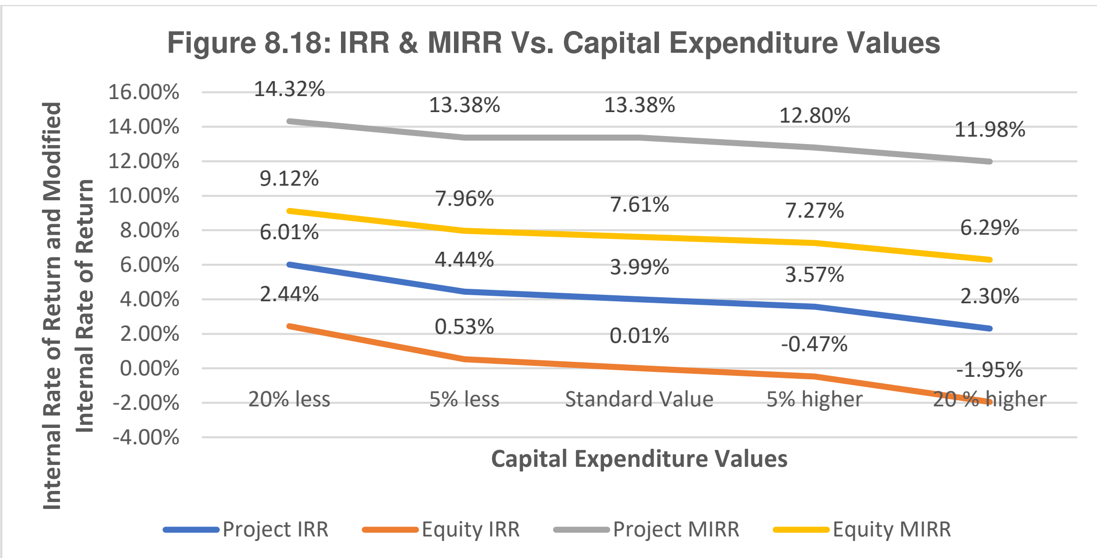
<u>Sensitivity to Changes in Capital Expenditure:</u>

The impact of changes in CAPEX on the NPV, IRR, and MIRR can be seen from the resulting values listed in Table 8.9 here below. As can be seen, reduction in CAPEX improves the return from the project.

Table 8.9: Impact of Changes in Capital Expenditure							
Explanation		Project NPV		IRR		MIRR	
		$ Million	INR Million	Project	Equity	Project	Equity
D	As in **A** but 20% reduction in capital expenditure	-135.59	-9,802.18	6.01%	2.44%	14.32%	9.12%
E	As in **A** but 5% reduction in capital expenditure	-172.86	-12,496.84	4.44%	0.53%	13.38%	7.96%
A	Base case	-185.33	-13,398.16	3.99%	0.01%	13.38%	7.61%
B	As in **A** above but with 5% capital cost overrun	-197.82	-14,300.61	3.57%	-0.47%	12.80%	7.27%
C	As in **A** above but with 20% capital cost overrun	-235.40	-17,018.03	2.30%	-1.95%	11.98%	6.29%

The results tabulated in Table 8.6 above are presented in graphical form in Figure 8.17 and Figure 8.18 here below:





<u>Sensitivity to Changes in the Rates of Inflation:</u>

The impact of changes in inflation rates on the NPV, IRR and MIRR can be seen from the resulting values listed in Table 8.10 here below. It is assumed that the rate of inflation on both the revenue items and expenditure items will be same. However, the inflation will not change the term loan instalments. Further, inflation will not have any impact on the interest payable on term loan as the term loan is assumed to be a fixed interest rate term loan. Resultantly, increase in the rate of inflation improves the return from the project as can be seen from the results tabulated in Table 8.10 here below:

Table 8.10: Impact of Changes in the Rate of Inflation						
Rate of Inflation	Project NPV		IRR		MIRR	
	$ Million	INR Million	Project	Equity	Project	Equity
2%	-191.02	-13,809.61	2.29%	-2.61%	12.54%	6.21%
3%	-186.68	-13,495.45	3.71%	-0.34%	12.96%	7.31%
4% (Base Case)	-185.33	-13,398.16	3.99%	0.01%	13.08%	7.61%
5%	-182.19	-13,170.79	4.77%	1.17%	13.36%	8.25%
6%	-178.79	-12,925.55	5.56%	2.35%	13.63%	8.88%

The results tabulated in Table 8.10 above are presented in graphical form in Figure8.19, and Figure 8.20 here below:

Figure 8.19: Project NPV Vs. Rates of Inflation

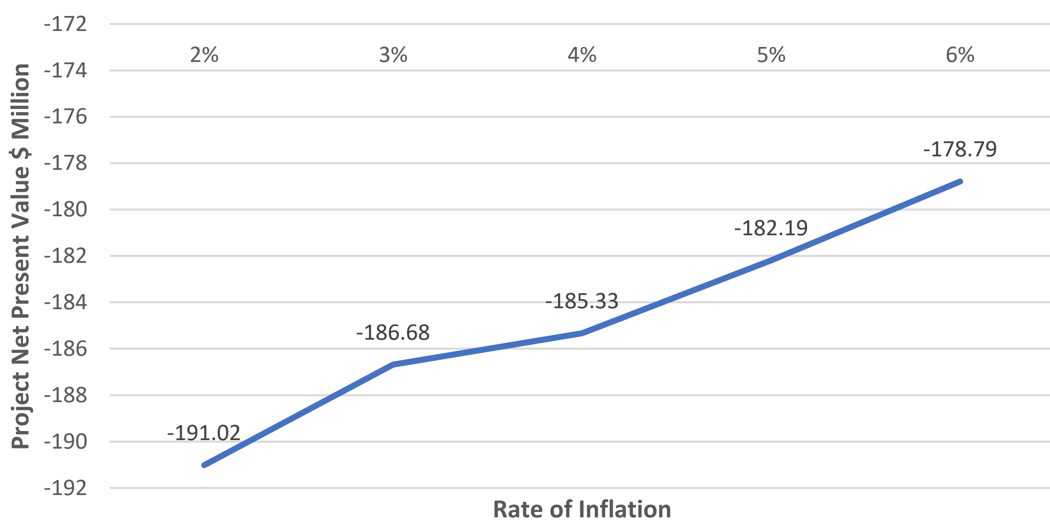
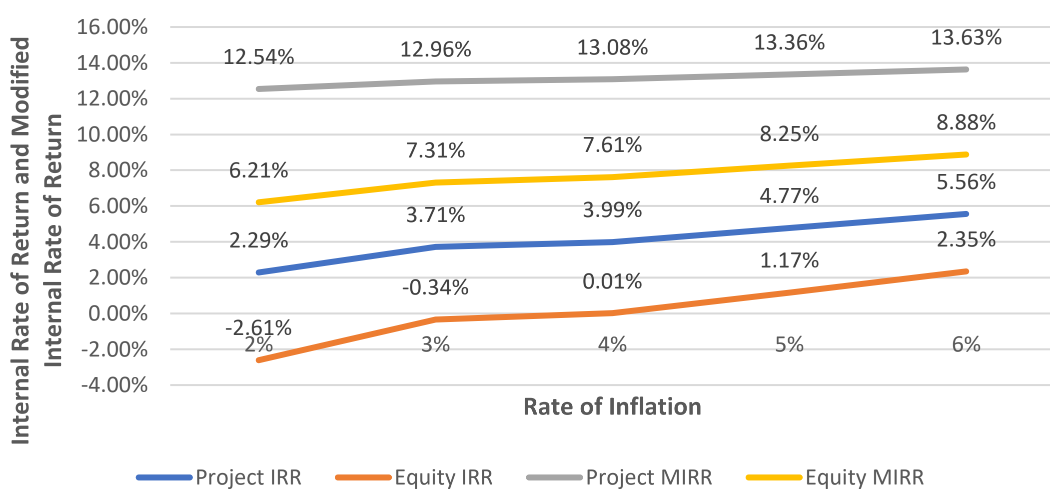


Figure 8.20: IRR and MIRR Vs. Rates of Inflation



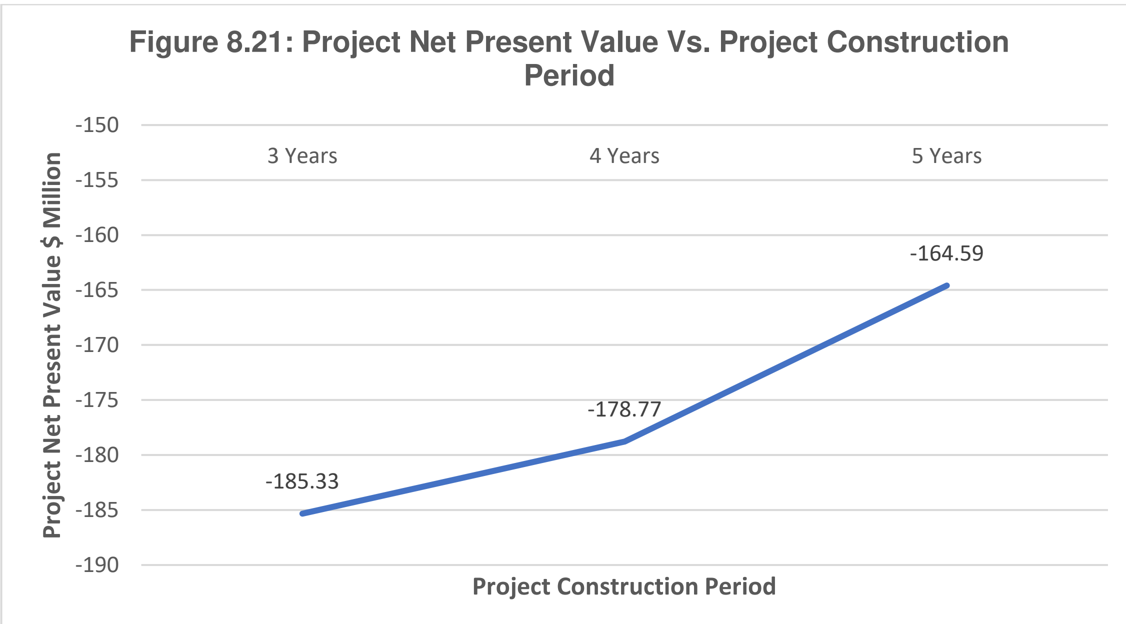
Sensitivity to Time Overrun:

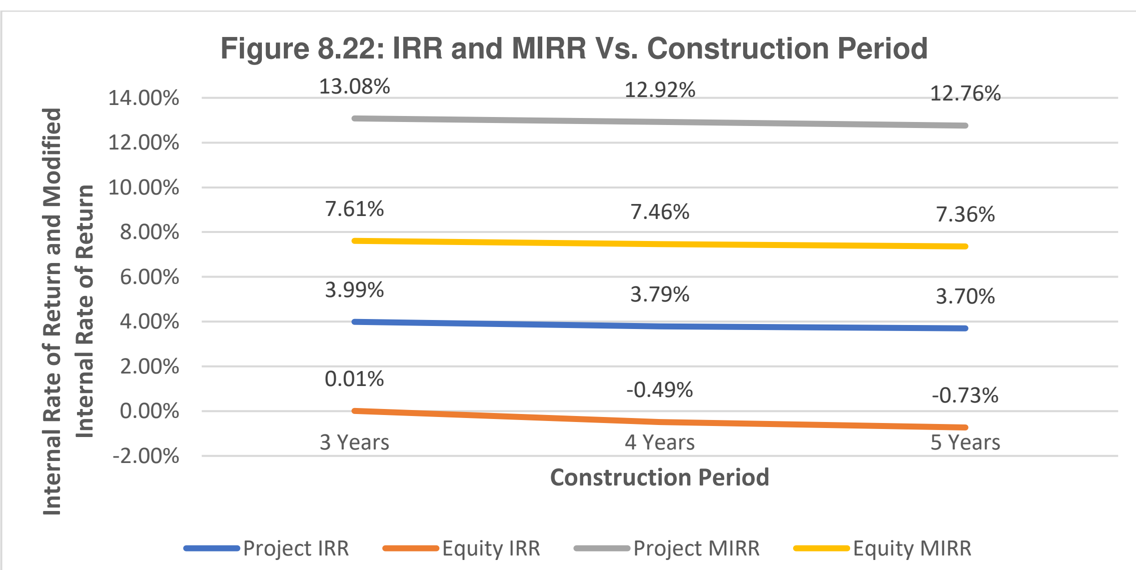
The impact of time overrun on the NPV, IRR and MIRR can be seen from the resulting values listed in Table 8.11 here below. As can be seen, impact of time overrun on the return from the project is not significant.

Table 8.11: Impact of Time Overrun

Construction Period	Project NPV		IRR		MIRR	
	$ Million	INR Million	Project IRR	Equity IRR	Project MIRR	Equity MIRR
3 Years (Base Case)	-185.33	-13,398.16	3.99%	0.01%	13.08%	7.61%
4 Years	-178.77	-12,924.11	3.79%	-0.49%	12.92%	7.46%
5 Years	-164.59	-11,898.33	3.70%	-0.73%	12.76%	7.36%

The results tabulated in Table 8.11 above are presented in graphical form in Figure 8.21, and Figure 8.22 here below:





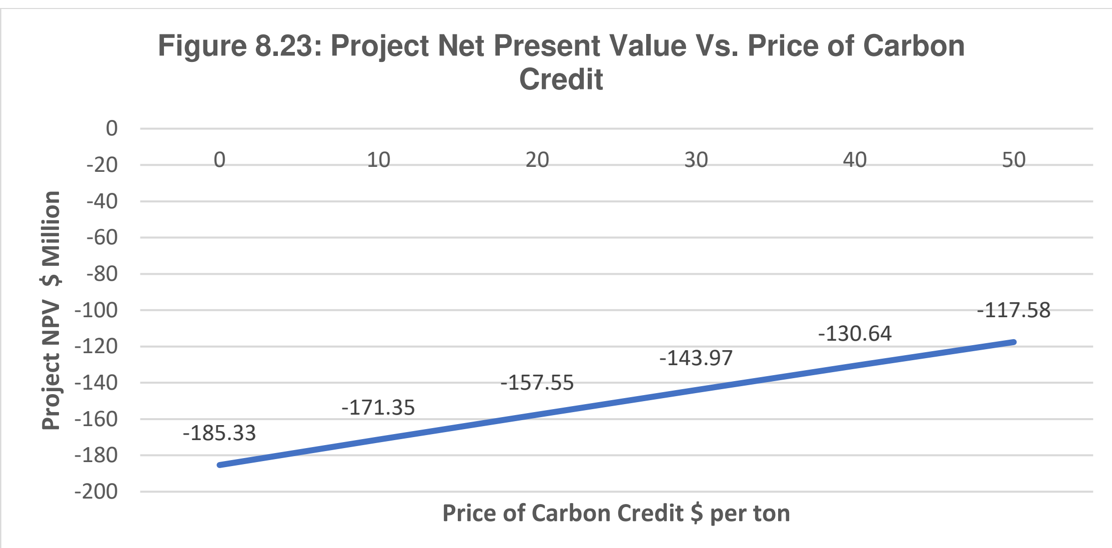
Impact of Sale of Carbon Credit:

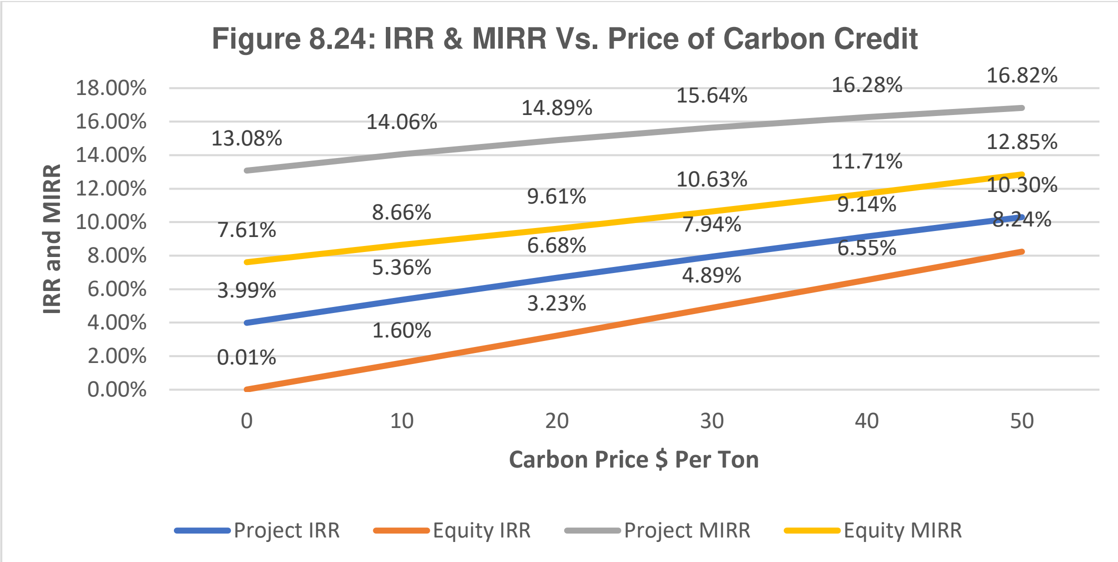
Assuming that the Carbon Credits to be earned by conversion of CO_2 to urea will be sold, the impact of sale of carbon credit on NPV, IRR & MIRR will be as tabulated in Table 8.12. Sale of carbon credit enhances the revenue and hence increase in the price of carbon credit improves the return from the project as can be seen from the results tabulated in Table 8.12 here below:

TABLE 8.12: Impact of Sale of Carbon Credit

Assumption	Project NPV		IRR		MIRR	
Price of Carbon Credit $ per ton	$ Millions	INR Millions	Project	Equity	Project	Equity
No Carbon Credit (Base Case)	-185.33	-13,398.16	3.99%	0.01%	13.08%	7.61%
10	-171.35	-12,387.32	5.36%	1.60%	14.06%	8.66%
20	-157.55	-11,389.65	6.68%	3.23%	14.89%	9.61%
30	-143.97	-10,408.18	7.94%	4.89%	15.64%	10.63%
40	-130.64	-9,444.31	9.14%	6.55%	16.28%	11.71%
50	-117.58	-8,499.86	10.30%	8.24%	16.82%	12.85%

The results tabulated in Table 8.12 above are presented in graphical form in Figure 8.23, and Figure 8.24 here below:





<u>Viability Gap Funding (VGF):</u>

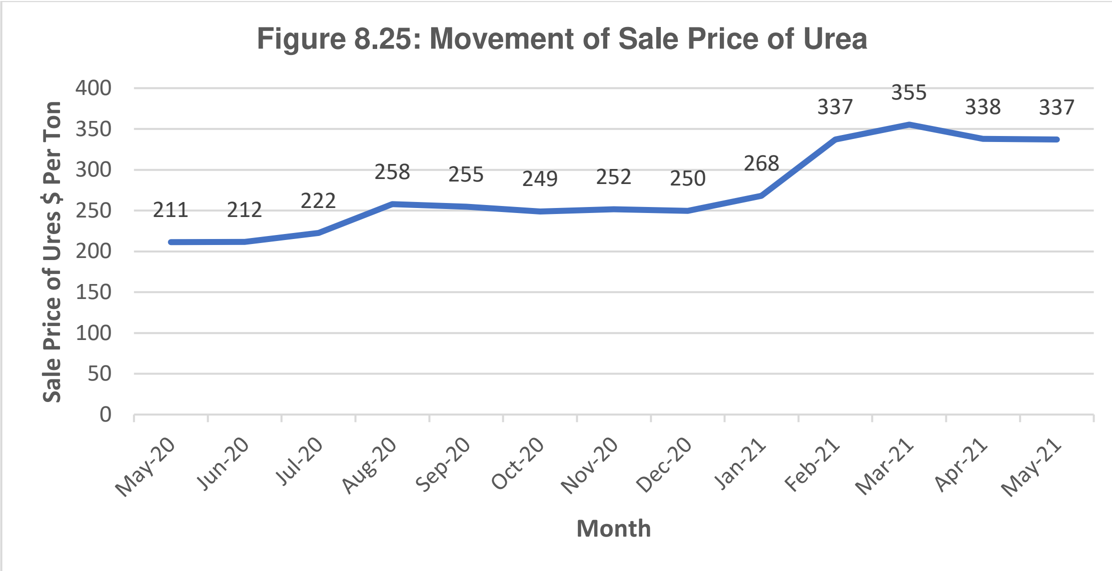
The base case calculations have been made assuming a urea sale price of $270 per ton. The equity IRR emerging from the base case scenario is 0.01% which is very low in relation to the expected rate of return of 20% as determined by the Capital Assets Pricing Model. During the recent meeting, DCBL has also confirmed that DCBL expects a return of 20% on its equity from the proposed project. It is, therefore, proposed to determine the nature and quantum of concessions that will make the proposed project viable.

Urea sale prices have seen a steep increase in the Indian Market during the recent months. Average urea sale prices in India of last thirteen months are tabulated in Table 8.13. here below.

Table 8.13: Urea Sale Prices in India

Month	Urea Sale Price in India per ton	
	INR	$
May-20	₹ 15,275.73	$211.30
Jun-20	₹ 15,293.15	$211.54
Jul-20	₹ 16,083.89	$222.48
Aug-20	₹ 18,630.64	$257.71
Sep-20	₹ 18,411.46	$254.68
Oct-20	₹ 18,001.40	$249.01
Nov-20	₹ 18,195.60	$251.69
Dec-20	₹ 18,046.17	$249.63
Jan-21	₹ 19,373.49	$267.99
Feb-21	₹ 24,376.50	$337.19
Mar-21	₹ 25,687.12	$355.32
Apr-21	₹ 24,416.70	$337.75
May-21	₹ 24,368.84	$337.09

The above-shown movement of urea sale price is demonstrated by the Figure 8.25 here below:

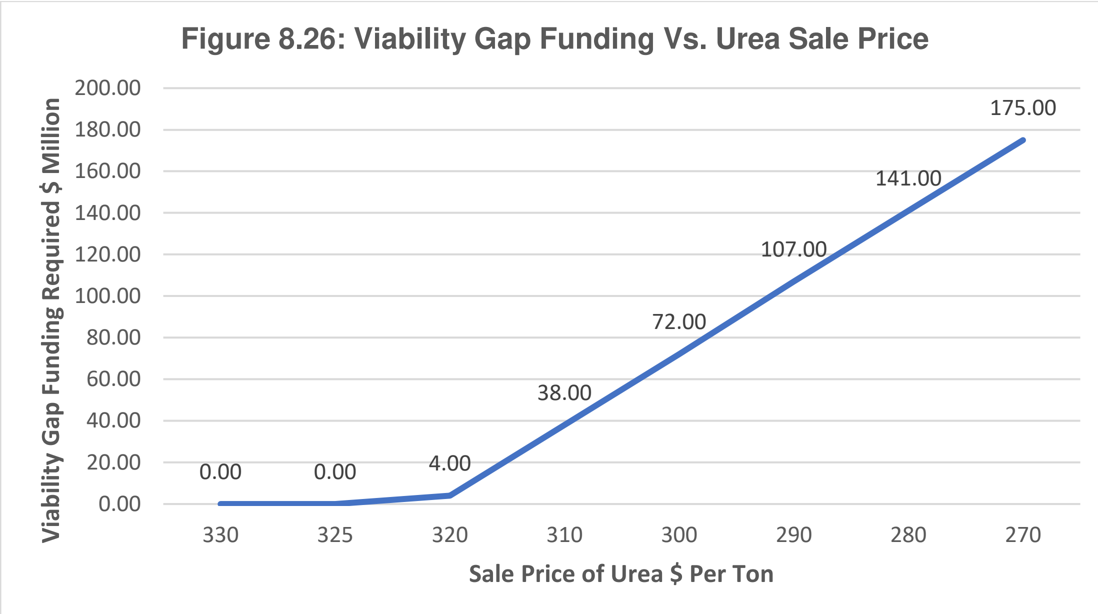


During a recent meeting, DCBL has informed that DCBL can procure electricity at a tariff of INR3 per unit. The project provides an Equity IRR of more than 20% for a urea sale price of $330 per ton at the electricity tariff of Rs.3 per unit and the rate of interest of 12% on debt without requirement of any VGF. As the interest rates have been falling in India, the project is tested for viability at the interest rate of 10% on debt. At this interest rate on debt, the project provides an Equity IRR of more than 20% for a urea sale price of $325/- per ton without any requirement for VGF. VGF will be required for urea sale prices of lower than $325/-. Quantum of VGF required at different levels of sale prices of urea are tabulated in Table 8.14 here below:

TABLE 8.14: Determination of the Quantum of Viability Gap Fund required

Assumption	Electricity Tariff	Interest Rate on Debt	Viability Gap Funding Required	Equity NPV	Equity IRR	Equity MIRR
Sale Price of Urea $ per Ton	INR / Unit		$ Million	$ Million		
330	3.00	12.00%	0.00	115.80	20.14%	19.74%
325	3.00	10.00%	0.00	112.32	20.33%	19.81%
320	3.00	9.00%	4.00	148.24	20.06%	19.70%
310	3.00	9.00%	38.00	132.48	20.05%	19.70%
300	3.00	9.00%	72.00	116.72	20.03%	19.69%
290	3.00	9.00%	107.00	101.76	20.12%	19.73%
280	3.00	9.00%	141.00	85.99	20.11%	19.72%
270	3.00	9.00%	175.00	70.23	20.09%	19.72%

The above results tabulated in Table 8.14 above are presented in graphical form in the Figure 8.26 here below:



<u>Substituting Biomass as Fuel for Boilers in the place of Coal / Natural Gas:</u>

The base case scenario assumes a coal fired boiler for CO_2 Capture Plant and a natural gas fired boiler for the CO_2 Utilization Plant. It is proposed to assess the impact on viability of the project if biomass will be used as the fuel in both the boilers. It is assumed that the cost of steam will increase by 10% in both boilers if biomass will be used as the fuel. Assuming electricity tariff of INR3 / unit and rate of interest of 9% on debt, the project will yield equity IRR of 4.55% with values of other variables remaining the same as in the base case scenario. A project for converting 1 million ton of CO_2 into urea will yield equity IRR of 8.05% under similar circumstances. Generating additional income through sale of carbon credit will improve the yields. The minimum sale prices required on the carbon credit for the project to reach the acceptable level of equity IRR of 20% for plants of two different capacities (0.5 MTPA & 1 MTPA) are tabulated in Table 8.15 here below:

TABLE 8.15: Impact of Using Biomass as Fuel in Both the Boilers							
Conversion Capacity	Cost of Biomass for CO2 Capture Plant	Cost of Steam for CO2 Utilization Plant	Electricity Tariff	Rate of Interest on Debt	Equity IRR without Sale of Carbon Credit	Revenue Required from Carbon Credit for reaching Equity IRR of 20%	Price of Carbon Credit Required for Reaching Equity IRR of 20%
Tons of CO2 Per Annum	INR Ton	$ per ton	INR / Unit			$ Million	$ per Ton of CO2
0.5 million	5,500.00	27.59	3.00	9.00%	4.55%	42.90	85.80
1 million	5,500.00	25.85	3.00	9.00%	8.05%	58.00	58.00

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9. Conclusions

In this assessment, the base case calculations have been made assuming a urea sale price of $270 per ton which was the average price prevailing in India during January 2021. Further, the base case scenario assumes purchase of electricity required by the project from the Tamil Nadu Generation and Distribution Corporation Limited whose tariff comprises fixed charge of INR350 / KVA / Month and consumption charge of INR6.35 per unit consumed. The equity IRR emerging from this base case scenario is 0.01% which is very low in relation to the rate of return of 20% expected by DCBL.

However, average urea sale prices have seen a steep increase in the Indian Market during recent months and the current sale price is higher than $330 per ton of urea. Further, DCBL has informed that DCBL will procure electricity at about INR3 / unit. The project yields an Equity IRR of more than 20% for a urea sale price of $330 per ton at the electricity tariff of INR3 per unit and the rate of interest of 12% on debt without requirement of any VGF. As the interest rates have been falling in India, the project is tested for viability at the interest rate of 10% on debt. At this interest rate on debt, the project yields an Equity IRR of more than 20% for a urea sale price of $325/- per ton without any requirement for VGF. VGF will be required for urea sale prices of lower than $325/- per ton. This assessment demonstrates that the main constraints for profitability are high CAPEX and OPEX of the project.

Government of India support is available for urea manufacturers. The government requires at least 75% of the urea produced by any urea manufacturer in India to be neem coated. The government determines the price to be received by the manufacturer for neem coated urea on cost plus basis so as to provide a reasonable return to the manufacturer. All justifiable costs incurred for manufacture of neem coated urea are allowed in determination of the price to be received by the manufacturer.

The project may therefore opt for production of 100% neem coated urea so as to have assurance of reasonable return on the investment. The project may also explore avenues for reduction in CAPEX and OPEX of the project. The government may also be approached for subsidizing CAPEX by way of VGF and for subsidizing OPEX by providing soft loans through financial institutions.

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VII. Emissions reduction by employing biomass and green ammonia

As aforementioned, substantial energy are required for the capture and utilization processes. The carbon capture process requires energy to regenerate the solvents, usually in the form of stream at elevated temperature and pressure and energy to operate rotary equipment (usually in the form of electricity). For urea synthesis process, high pressure and high temperature steam is required. If coal or gas are used to provide the energy needed for the CCU process, the overall carbon footprint will be reduced (as discussed in Section IV) but such reduction may be further enhanced by employing biomass, green ammonia and other abatement initiatives. This section will briefly discuss the potential applications of biomass and green ammonia into a CCU process.

Biomass-based boilers

Biomass is a renewable energy source, and it is widely considered as a carbon neutral energy carrier. Biomass is used in many parts of the world. In the U.S., biomass provides around 5% of total primary energy usage[6]. In India, biomass plays an even more important role and provides around 32% of India's total primary energy use, with a total of 10.17 GW biomass power and cogeneration installed across the country.[7] Biomass stores energy from the sun and such energy may be released by combustion, gasification, biological conversion (eg. anaerobic digestion) and other processes. Biomass may include agriculture waste, wood/wood wastes, metropolitan organic waste, animal waste, and others. The availability and the type of biomass vary significantly with locations. In India, bagasse from sugar mills is a major biomass used across the country to generate power and/or steam. It is worth noting that with more countries and corporations committed to net zero/carbon neutrality, biomass market is expected to grow rapidly for years to come which puts upward pressure on biomass price.

For the cement plant in study, biomass has already been used for its boilers. The plant management and operators have substantial experiences in procuring and using biomass for power/heat generation. Therefore from both operational perspective and emissions reduction perspective, biomass may be a good candidate to provide energy for the CCU plant. For the Advanced Case (capturing and utilizing 1 mpta CO_2), 523,908 tonne CO_2 per annum may be avoided by use of biomass boilers to generate steam. The corresponding urea plant may avoid 221,205 tpa (urea unit) CO_2 emissions, when biomass boilers are equipped to provide steam for the synthesis process.

The inclusion of biomass boilers for the CCU plant delivers substantial emissions reductions. It is noted that biomass-based boilers may have higher operational costs than conventional coal/gas boilers (in the financial assessment section, stream generated from biomass is assumed to be 10% more expensive than conventional coal/gas boilers). Due to its carbon neutrality, there may be financial incentives or carbon market instruments to support biomass energy project which may improve the financial viability of a future CCU project.

Green/blue ammonia

In this study, urea synthesis requires two feedstocks: CO_2 captured from cement plant emissions and ammonia. Conventionally, ammonia is produced with coal or gas as starting materials. Coal/gas is first converted to H_2 (gasification or steam reforming processes) and H_2 will then react with nitrogen (N_2) separated from air to produce ammonia (NH_3). The hydrogen production process from coal/gas also emits CO_2. Therefore, to improve the overall abatement, a low carbon process to produce ammonia should be investigated. In general, there are two types of low carbon ammonia:

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[6] US EIA 2021. Biomass explained. < https://www.eia.gov/energyexplained/biomass/>.

[7] Indian Ministry of New and Renewable Energy 2021. *Bio Energy*.< https://mnre.gov.in/bio-energy/current-status>

- Green ammonia
  For green ammonia production, H_2 is produced by an electrolysis process powered by renewable energy. Hydrogen then reacts (the Haber process) with nitrogen separated from air (an air separation unit (ASU) powered by renewable energy) to produce ammonia (process flow chart below). Ammonia produced this way is called green ammonia.

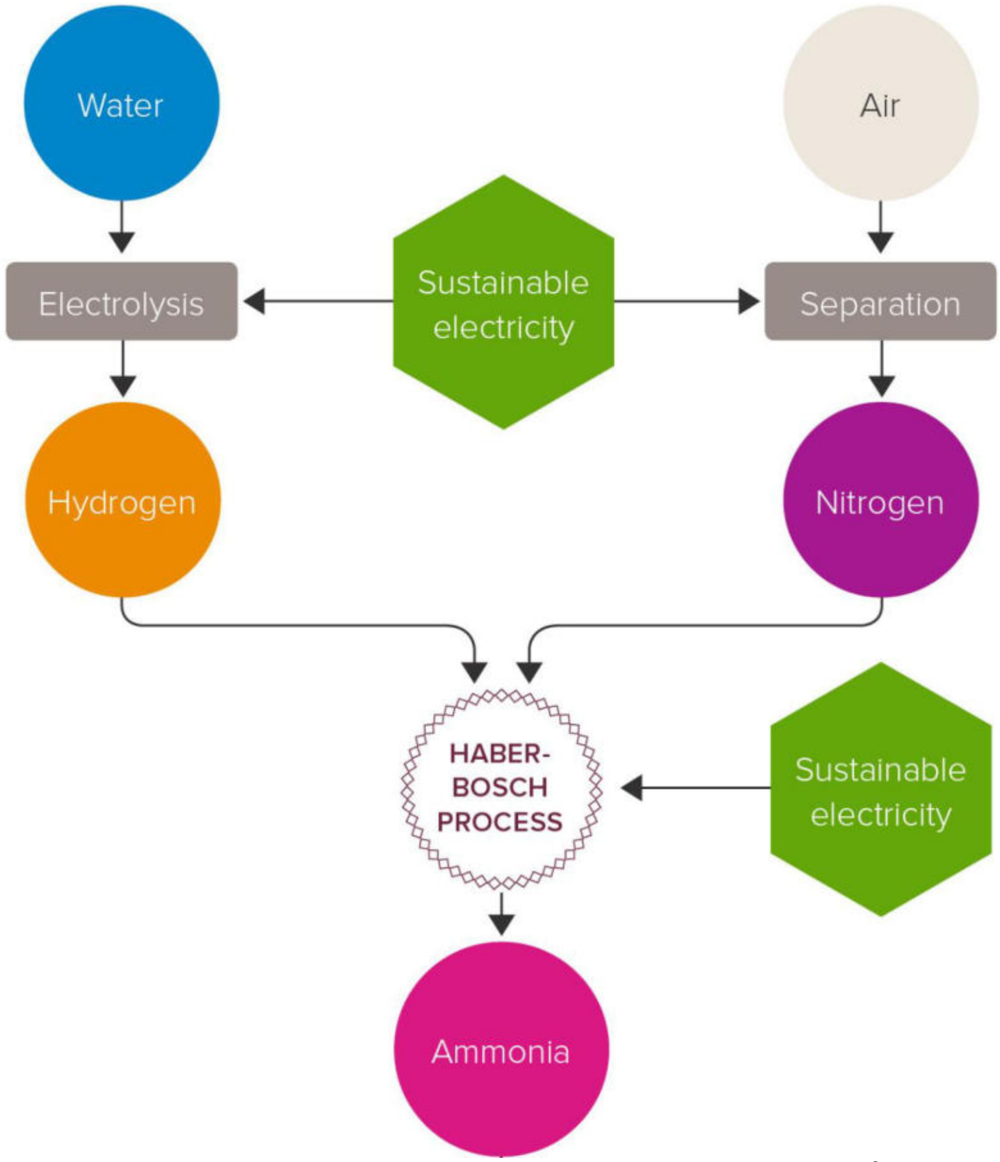

Figure VII-1 Green ammonia production process[8]

- Blue ammonia
  For blue ammonia production, H_2 is produced by converting fossil fuel (coal or gas) and CO_2 associated with the process is captured and stored underground. Hydrogen may then react with nitrogen to synthesize ammonia. Ammonia produced this way has very low carbon footprint and is called blue

[8] The Royal Society 2020. *Ammonia: zero-carbon fertiliser, fuel and energy store*.< https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/green-ammonia/>

ammonia. In 2020, the world's first blue ammonia was produced in Saudi Arabia and shipped to Japan for power generation (image below). [9]

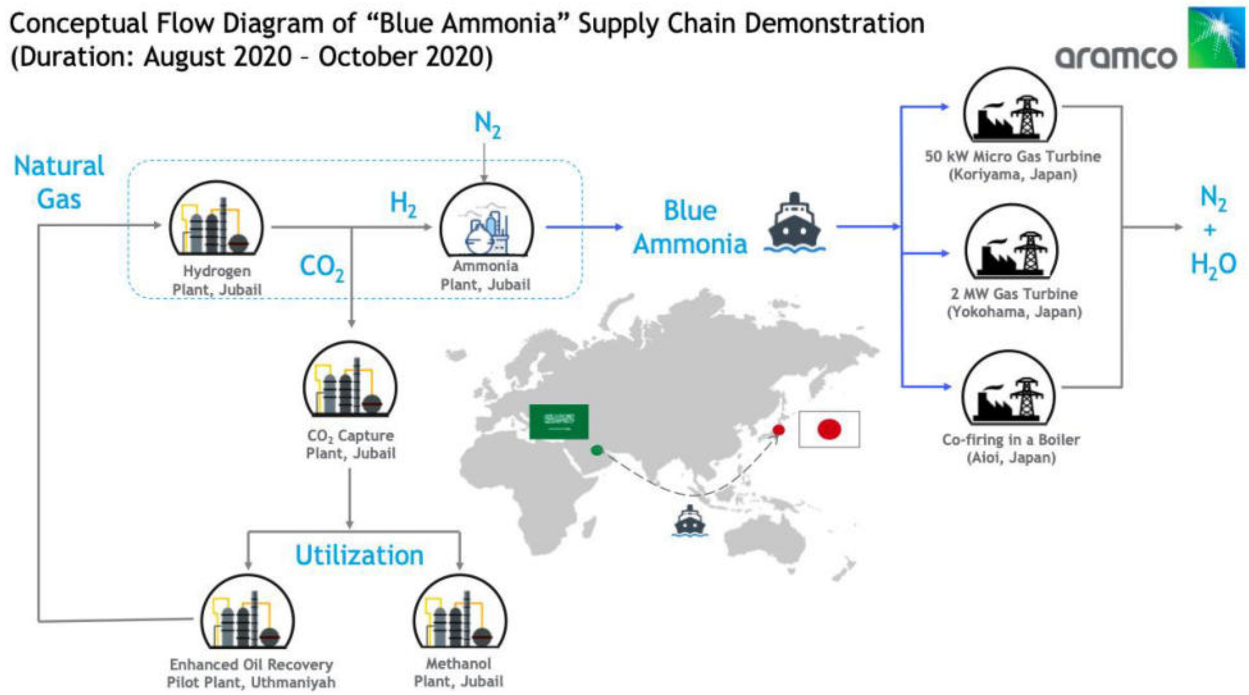

Figure VII-2 Flue Ammonia Supply Chain[10]

Ammonia production via fossil fuels is a mature technology, but green ammonia production is a relatively new production route at its very early development stage. Like any other technology at early development stages, the cost of green ammonia production is higher than conventional processes, with $650 per tonne reported[11]. For a 20,000-tonne green ammonia per annum plant, it was estimated that a CAPEX of AUD150-200 million (USD111-148million) is needed with an OPEX of AUD10-15 million (USD7.38-11.07 million, 1AUD=0.74USD) per annum. By a simple scale-up, more than USD2 billion CAPEX is needed to build a green ammonia plant sufficient for the conversion of 0.5 mpta CO_2. This would make the project infeasible. However, green ammonia production cost is expected to reduce substantially with technology process.

Summary

Detailed examination of those individual technologies are beyond the scope of this study. The project should look at the possibilities of including biomass, green ammonia, blue ammonia and other emissions reduction initiatives to achieve greater carbon abatement. The cement sector should explore long term strategy to research, develop and deploy those low emissions technologies.

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[9] Bloomberg 2020. Saudi Arabia Sends blue Ammonia to Japan in World-First Shipment.< https://www.bloomberg.com/news/articles/2020-09-27/saudi-arabia-sends-blue-ammonia-to-japan-in-world-first-shipment>.

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VIII. Conclusions and suggestions

Based on the preliminary technology and economic assessment, it is found that a large CCU project (0.5-1.0 mpta) can be implemented with commercially available technologies at an Indian cement plant.
However, there are a few challenges and opportunities to the commercial viability of such project. Urea price (greater than US$325 per tonne) and potential government support (cost recovery) are critical to the bankability of the project. Operational costs (electricity, steam, CO_2 capture etc) need to be reduced compared with the Base Case. Biomass-based boilers and renewable electricity can substantially increase carbon abatement. Furthermore, there are currently insufficient government policy support to incentivize corporations to invest in emissions reduction initiatives.
Therefore, the project team would make the following tentative suggestions:

- To achieve long term climate change targets, cement companies should invest in emissions reduction technologies to reduce costs for carbon capture technology and CO_2 utilization technology and build up expertise in CCUS.
- Cement sector should look at various pathways and carbon-neutral energy sources which align with the net zero trajectory.
- Cement sector should proactively hold discussions with governments for policy incentives to support their investment in emissions reductions.

Acknowledgement

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