Prefeasibility Study on Carbon Capture and Utilization in Cement Industry of India

Prepared by

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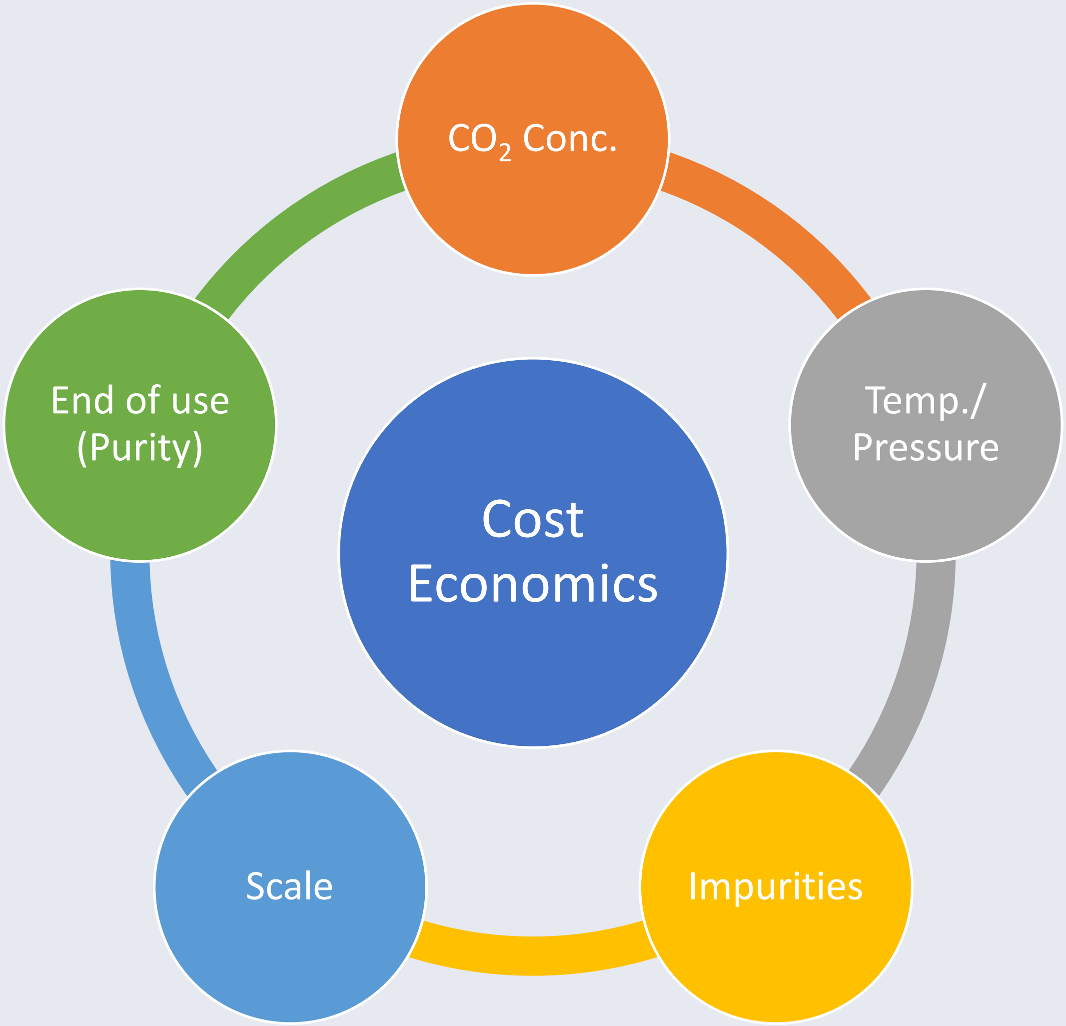
Part 1: Carbon capture

Devika Wattal

Key Findings

- Increased interest for CCS in the cement industry.
  - Process emissions (60%) & Combustion emissions (40%)
  - First of its kind study in India
    - CO_2 concentration in flue gas is low (not a typical case)
- Research landscape points towards active work in CCS in cement industry
  - Lowering emission from the cement plant
    - energy efficiency improvement
    - alternative fuel/raw material use
    - clinker substitution.
  - CO_2 capture technologies
    - *Post-combustion and oxyfuel combustion are most relevant for cement industry*.
- R&D activity in lab, pilot and demo scale:
  - Norcem CO_2 (absorption with amines, chemical adsorption, membranes)
  - CEMCAP (Calcium looping, membranes, Chilled ammonia process, oxyfuel)
  - Lafarge Holcim (CO2MENT, oxyfuel)
- Amine technology most mature among post-combustion processes
  - Tested and validated at commercial scale (TRL – 8)
  - Easily retrofittable

Cost Effective CO_2 Capture



Key Ingredients

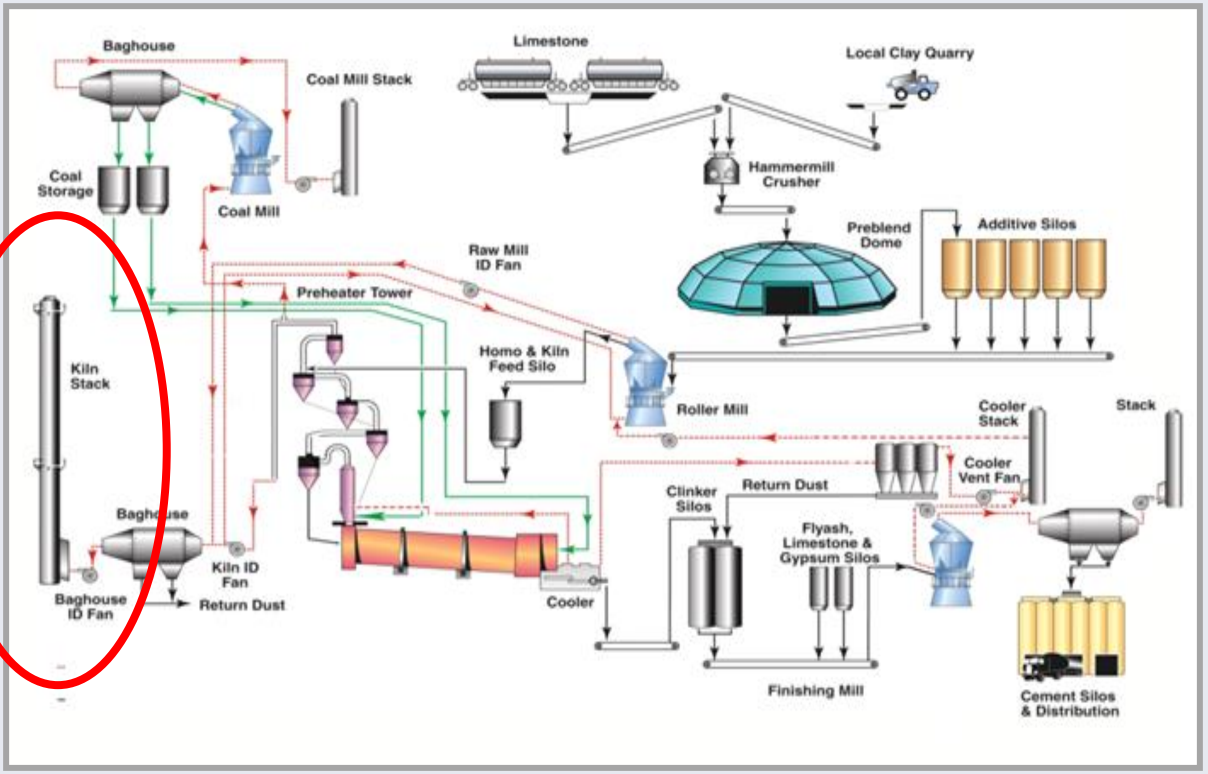
- Low CO_2 concentration
- High temperature
- High NO_x & SO_x emissions
- Scale
- CCUS route

Government, Industry and Finance community – Collaboration Critical

Recommendation to use an amine-based CO_2 capture plant for flue gases from the kiln stack

- *Most mature and well demonstrated (TRL -8)*
- *Capture at low partial pressure of CO_2*
- *High capture efficiency*
- *High selectivity at low partial pressure*
- *Easily retrofit*

Ariyalur Plant Emission



Parameters	Units	Direct (Raw mill stop condition)	Indirect (Both Raw mill & Kiln Running)
Oxygen (O_2)	%v/v	13.15	13.60
Carbon Dioxide (CO_2)	**%v/v**	**13.20**	**12.75**
Nitrogen (N_2)	%v/v	71.15	70.65
Carbon Monoxide (CO)	ppm	160.00	139.00
Sulphur Dioxide (SO_2)	ppm	8.00	3.00
Oxides of Nitrogen (NO_x)	ppm	170.00	161.00
Temperature	K	385	357
Pressure	mmHg	748	748
Moisture	%v/v	2.5	3
Flow rate	Nm^3/hr	635,292	685,119

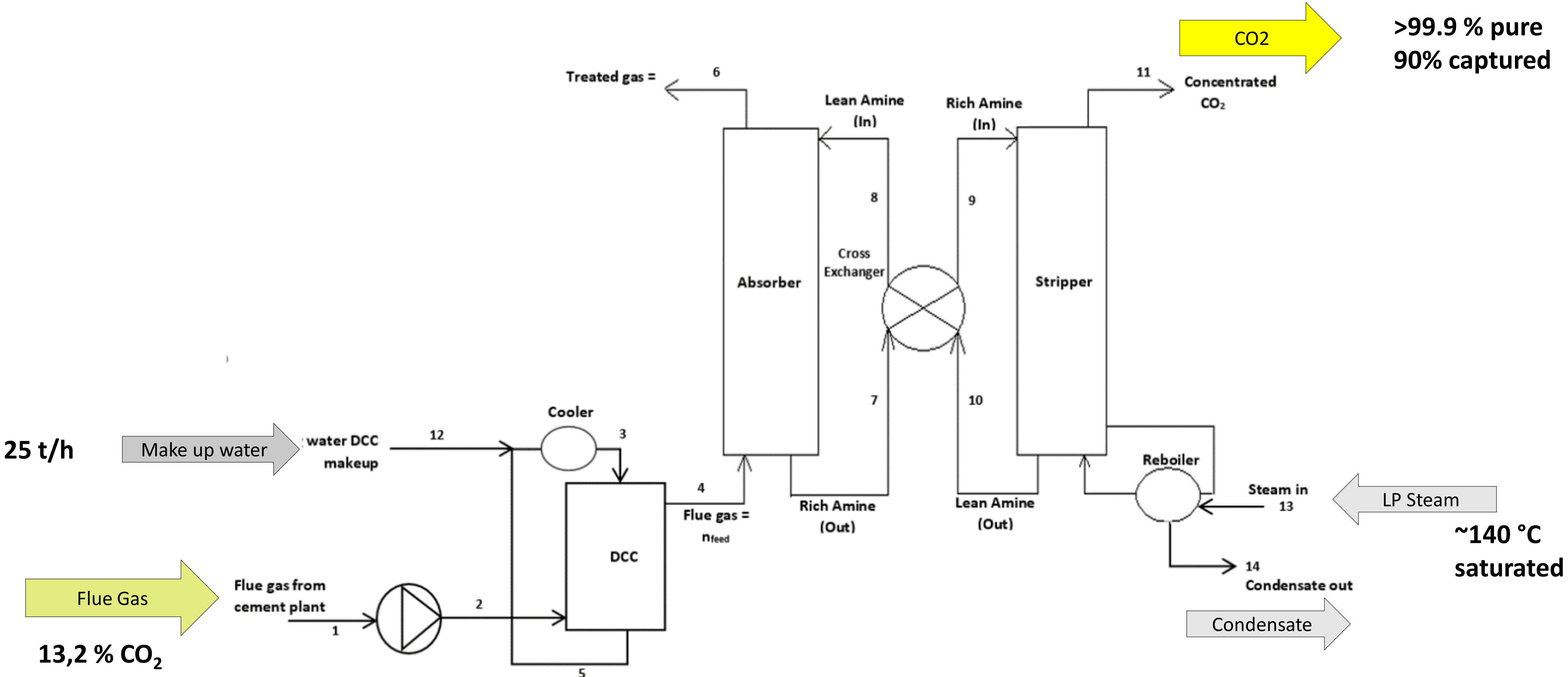
Space availability for CO_2 capture and Utilization, **100 x 100 m²** plot, located on the west side of the Cement Mill MCC room (site layout)*

Total Direct CO_2 Emissions (all fossil CO_2 sources)	[t CO_2/yr]	1,536,293	1,552,242

-> CO_2 capture plant designed for 0.5Mtpa

* Details provided in the civil section of the report.

CO_2 Capture Conceptual Design - PFD



[Chemical absorption with amine-based solvents]

Process Parameters

Design parameters	value	unit
Flue gas flow	290000	Nm3/h
CO_2 concentration in flue gas	13,2	% vol
Capture rate	90	%
CO_2 capture capacity	68	t/h
Plant availability	85	%
Yearly captured amount	~500.000	t/y
CO_2 purity	>99.9	%wt
Process requirements		
Heat input (coal 11 t/h)	66	MWth
Power input	12,5	Mwel
Make up water	25	t/h
Solvent use (MEA-30%)	756	t/y

Cost Estimations

- Conservative estimates based on MEA technology – leading to high estimates, especially for OPEX
- CAPEX: 5.800 MINR (+/- 30% uncertainty)
- OPEX: 1.491 MINR/y
  - Steam
  - Electricity (air cooling mainly)
  - Water
  - Solvent
- Cost reduction opportunities:
  - Heat integration with hot flue gas
    - Reduce steam cost and make up water
  - Steam sourcing from captive plant
    - Reduce steam costs
  - Better solvent than MEA
    - Better performance (and may reduce solvent cost)
- Sensitivity to cost
  - CO_2 concentration (higher CO_2 concentration)
  - Production volume
  - Utility cost

From the financial model*:
Total cost of CO_2 Capture - $56/t$CO_2$

* Mr. Baliga to discuss the details of the financial model.

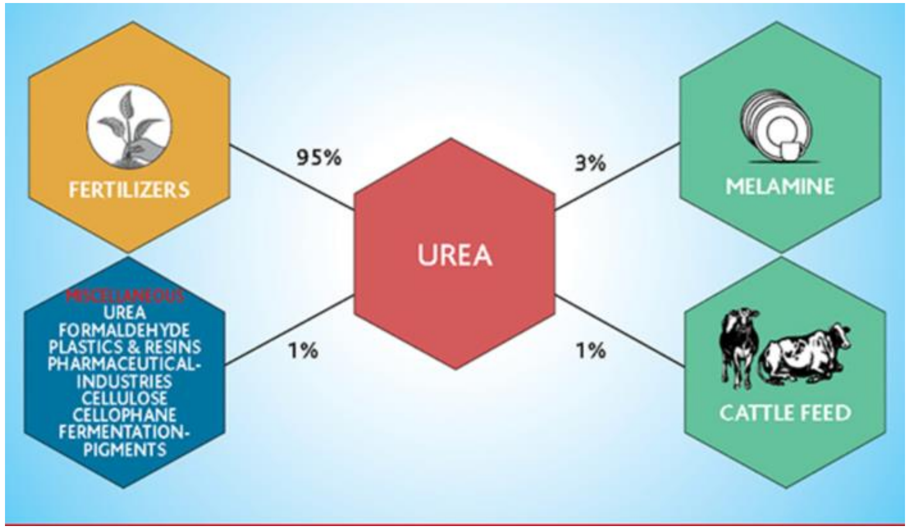
Part 2: CO_2 Utilization Project – Prefeasibility CO_2 to Urea

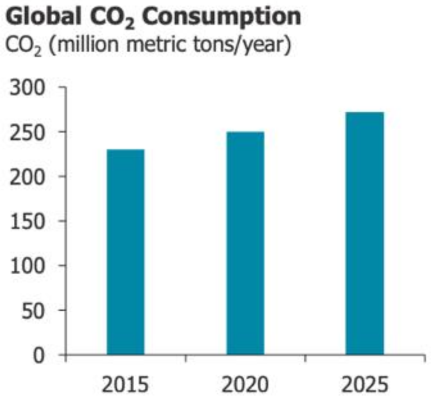
Ramesh Bhujade

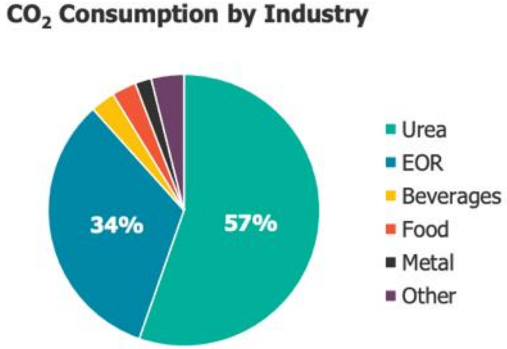
Presentation Outline

- Urea: Product and Technology Overview
- How is Urea selected as CO_2-derived product ?
    - Approach
    - Multi Criteria Analysis
    - Product Selection
- Urea Cost: Sensitivity analysis
- Summary

Urea and CO_2 Utilization







Source: IEA 2019

- Urea, also known as *Carbamide* (NH_2CONH_2)
- Fertilizer industry is the largest consumer
- Has *46% N_2, the highest* available in any *solid fertilizer*
- Easily transportable, *no explosive hazard*
- Leaves *no salt residue after use* on crops

- Use of Urea in construction industry has been examined to mitigate thermal and shrinkage cracking in concrete.

- Global CO_2 consumption is projected to grow to 272 million tons per year, driven by urea production & EOR application

Urea production using CO_2 is a proven technology. Implementable option without any technical risk

Urea chemistry

Integrated Urea Plant

Ammonia Production

Reaction 1:
$\mathbf{CH_4} + H_2O \rightarrow CO + 3\ H_2$

Reaction 2:
$CO + H_2O \rightarrow \mathbf{CO_2} + H_2$

Reaction 3:
$3\ H_2 + N_2 \rightarrow \mathbf{2\ NH_3}$

Urea Synthesis

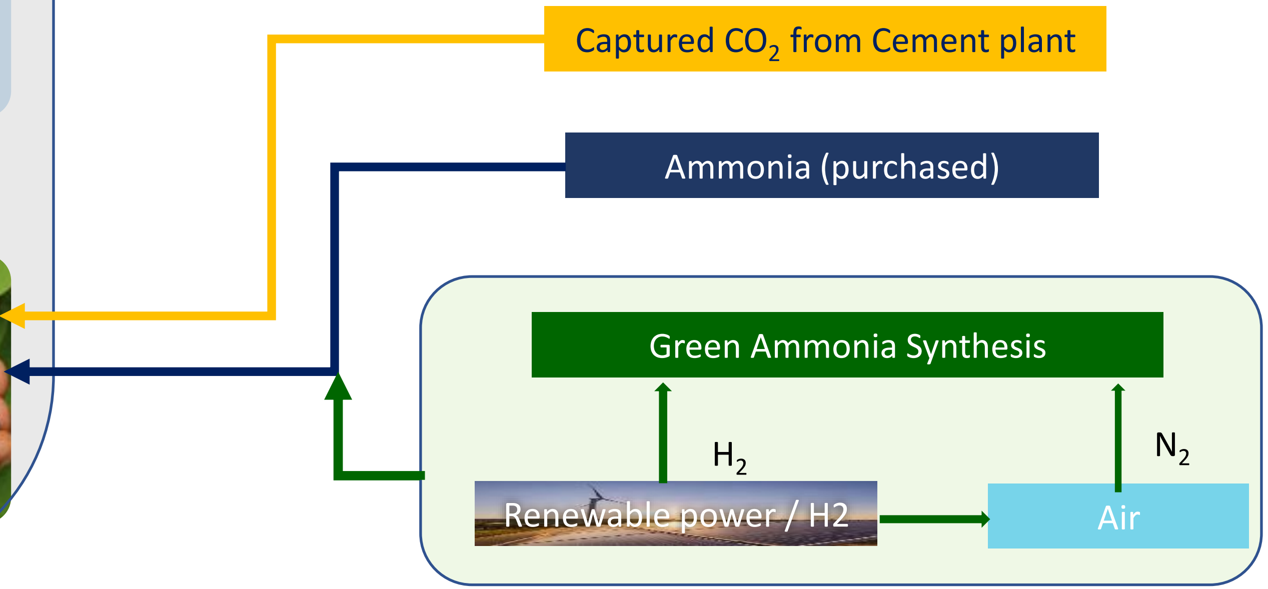
Reaction 4:
$\mathbf{CO_2} + \mathbf{2\ NH_3} \rightarrow NH_2COONH_4$

Reaction 5:
$NH_2COONH_4 \rightarrow \mathbf{NH_2CONH_2} + H_2O$

NG / Coal

$2\ NH_3 + CO_2$

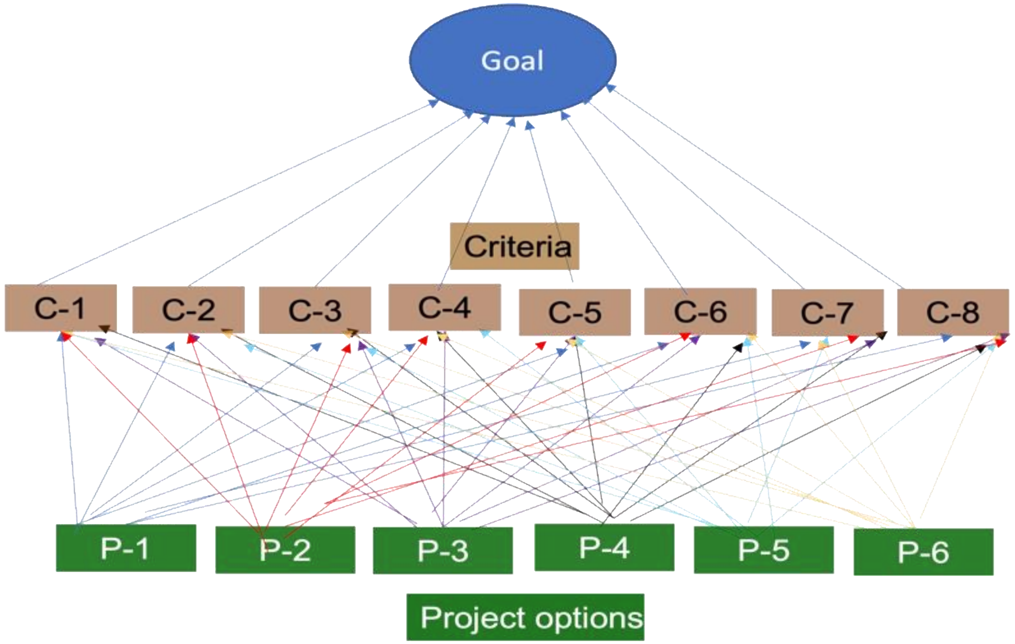
- Conventionally, Urea plants are integrated plants: Ammonia is produced at the same site as CO_2, with NG or Coal as a feedstock
- Stand-alone CO_2 utilization plant will need ammonia as a feed

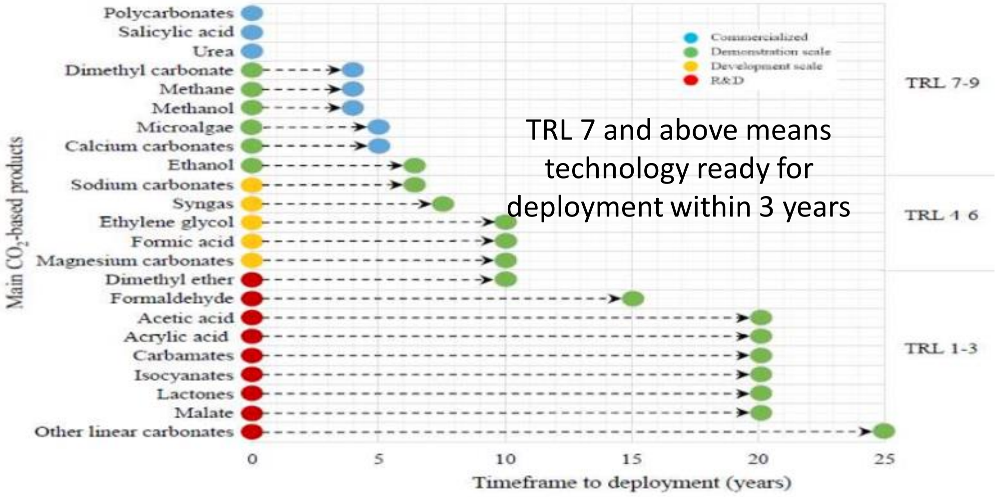


Large scale plants are operational, with technology optimized over the decades for resource optimization and process safety

How Is Urea selected ? Multi Criteria Analysis (MCA)

#	Parameter	Weightage
1	**TRL (7 and above)**	**40**
2	**Capex, INR/t CO_2**	10
3	**Opex, INR/t CO_2**	10
4	**ROI/Payback time**	10
5	**Market Demand**	13
6	Electrical, kWh/t CO_2	8
7	Steam, GJ/t CO_2	4
8	Avoidance of CC	5
	Total Score	100





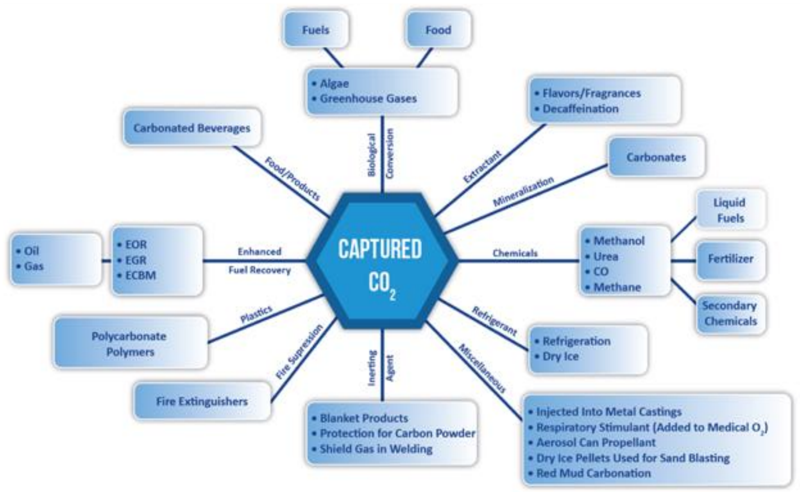
TRL 7 and above means technology ready for deployment within 3 years

Source: Remi Chauvy et. Al. 2019

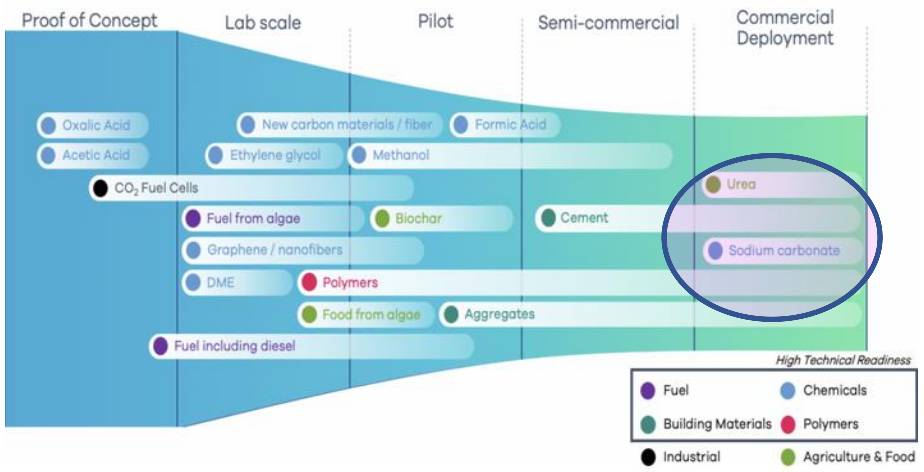
Economic parameters and TRL contribute over 70 % of the total weightage

CO_2 Utilization Selection Approach

Multiple pathways and products

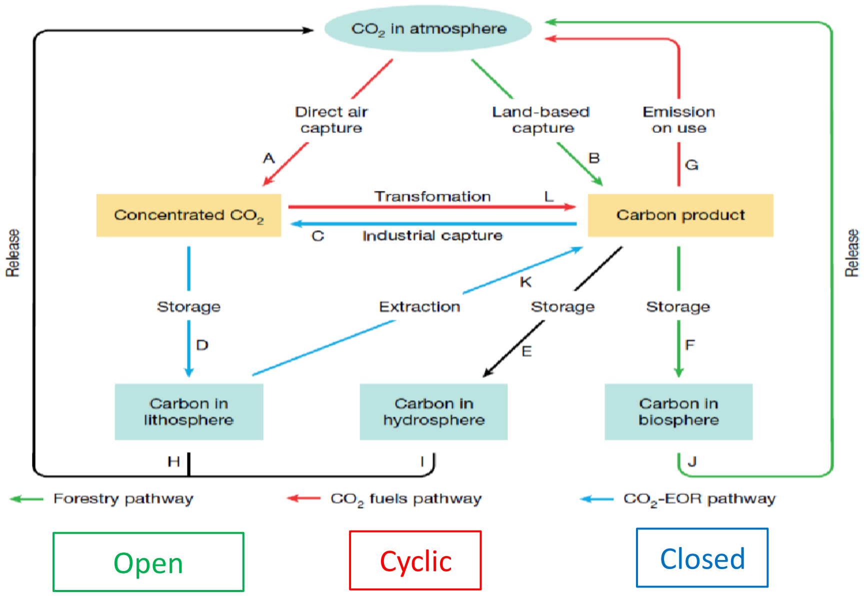


Technology Readiness Level

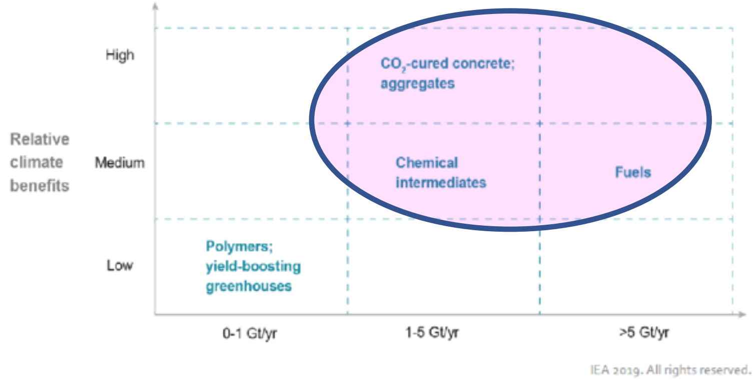


- Technology overview
  - Use w/o conversion or with Conversion
- Implementation
  - Within short term
  - TRL 7+
- Fate of C
  - Carbon neutral/ -ve
- CU Potential
  - Significant/Impactful
- Economics
  - Sustainable

Fate of CO_2 captured and Utilized



Potential to make Climate Impact



Graphic Sources: pl refer to detailed report

Technology Review, Screening & Criteria-based Quantitative Selection. Multiple pathways make product selection more challenging

Projects under evaluation – Tech features

#	Description	Urea	Soda Ash	Mineralization	Methanol	Algae feed	Algal Biocrude
	Process	Generic	Modified Salvay	Carbonation	Hydrogenation	Photosynthesis	PS+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	CO_2 purity	High purity	High purity	10-100%	High purity	10-100%	10-100%
3	Major feedstocks	NH_3	Brine, NH_3	Mineral/residues	H_2	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 regulatory reqts. Double benefits: Product replacement and CO_2 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)	Additional flexibility with HTL. No drying of feed. Co-processing of different wastes possible

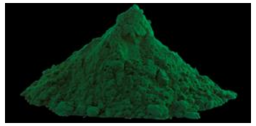
Products shortlisted for Multi-Criteria Analysis (MCA), after preliminary screening

MCA – *Individual* Score for CO_2 Utilization projects

#	Parameter	Weightage	Urea	Soda Ash	Mineralization	Methanol	Algae feed	Algal Biocrude
1	TRL	40	40	40	38	36	32	32
2	Capex (\$/t CO_2)	10	10	7	7	10	4	5
3	Opex (\$/t CO_2)	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	68.8	75
	Technology aspects w.r.t. India	Water, land availability, any advantage or barrier technology	NH_3	Sea water, NH_3	In sync with Dalmia business Regulatory requirement	Country-wide market, Big policy support from GoI	Technology availability in India with cost benefits	Technology in advanced stage available. Other waste can be co-processed








Urea and Mineralization are top-ranking options for short term implementation

CO_2 to Urea: Cost Sensitivity Analysis

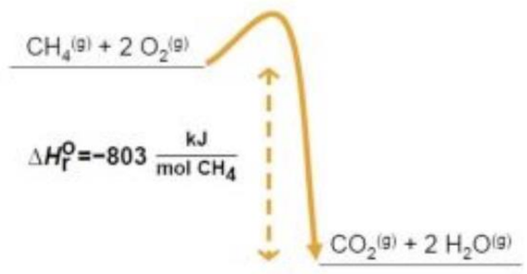
Description	Units	Base Case	Advanced Case	Steam cost impact	CO_2 cost impact
Captured CO_2 consumption	Mn t/year	A = 0.5	**2A** = 1.0	2 A	2 A
NH_3 required	Mn t/year	B = 0.386	2 B	2 B	2 B
Urea plant capacity	tpd	C = 2050	2 C = 4100	2 C	2 C
Steam Cost	$ / t	D	D	**1.25 D**	D
CO_2 cost	$/ t	E	E	E	**1.4 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%

- Ammonia is the main cost determinant. Contributes about 70% towards opex of Urea. Steam/electricity combination can be optimized to suit the site conditions
- Detailed financial assessment covered separately by the Finance Specialist
- LCA has been covered in the detailed report by the Environment Specialist

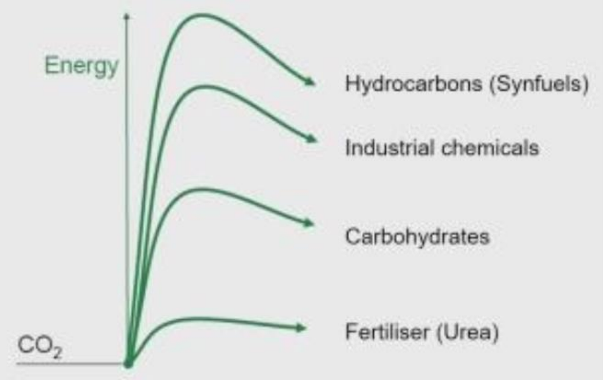
Advisable to opt for large scale plant for speedy and economical implementation

Summary

Thermodynamics of CO_2
CO_2, the stable compound



CO_2, Conversion is energy intensive process



Source: Chris Venter 2021 et. al, Brudermüller, 2019

Multiple CO_2 Utilization pathways at various TRL:

- CO_2 utilization w/o conversion, Bioconversion, Electrochemical conversion, Chemical/Catalytic conversion, Mineralization

- Hundreds of publications with varying benefits as claimed by technology developers, makes CO_2-derived product selection challenging
- Multi-Criteria analysis (MCA) helped decide most suitable CO_2 utilization strategy.
- Major criteria, as set for pre-feasibility: TRL (7 plus), Economic viability, Market potential and GHG reduction potential
- Technology pathways & products short listed:
  - Soda ash, Urea, Mineralization, Methane, Methanol, Algae,
- Products ranking through MCA and client-specific requirements
  - **Short term**: Urea, Soda ash
  - Medium term: Mineralization, Methanol
  - Long term: Algae to fuel and feed

MCA model developed by ADB consultant team can be used as a tool for screening of CO_2 utilization technologies

ADB

Part 3: Financial assessment

B. C. S. Baliga

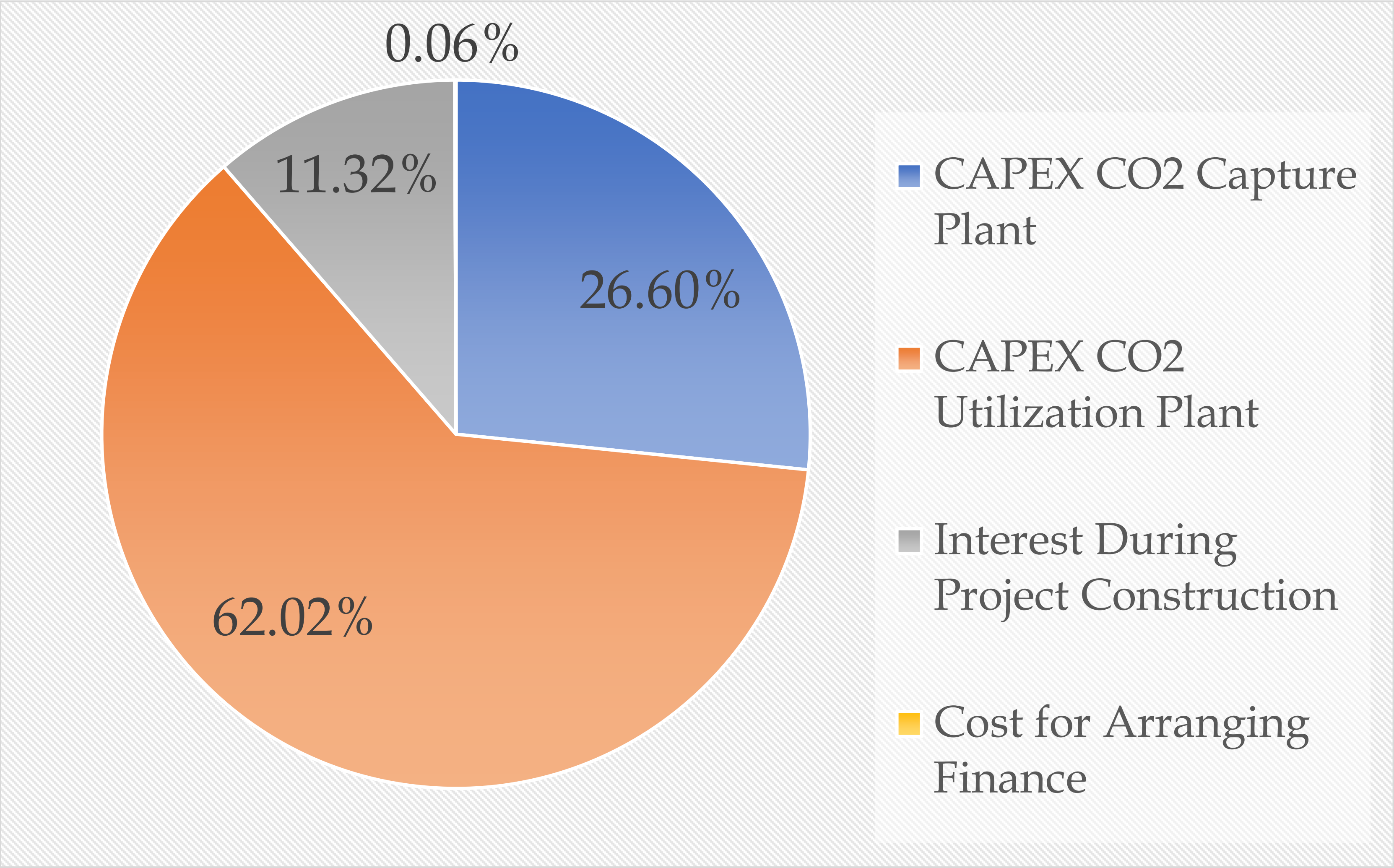
Values of Variables in Base Case

	Variable	Value
1	Capacity of the Project	Conversion of 0.5 MTPA CO_2 to urea
2	CAPEX & OPEX	As furnished by the concerned specialists of the Team
3	Construction period	3 years
4	Inflation rate	4% per annum
5	Expected rate of return on equity (Equity IRR)	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	Price of Electricity	As per the latest tariff published by the Tamil Nadu Generation & Distribution Corporation Limited, *i. e.* demand charge of $4.84 per KVA per month and usage charge of $0.09 per unit
11	Sale Price of Urea	$270 per ton
12	Other Income	Nil

Estimate of the Rate of Return Expected on Equity

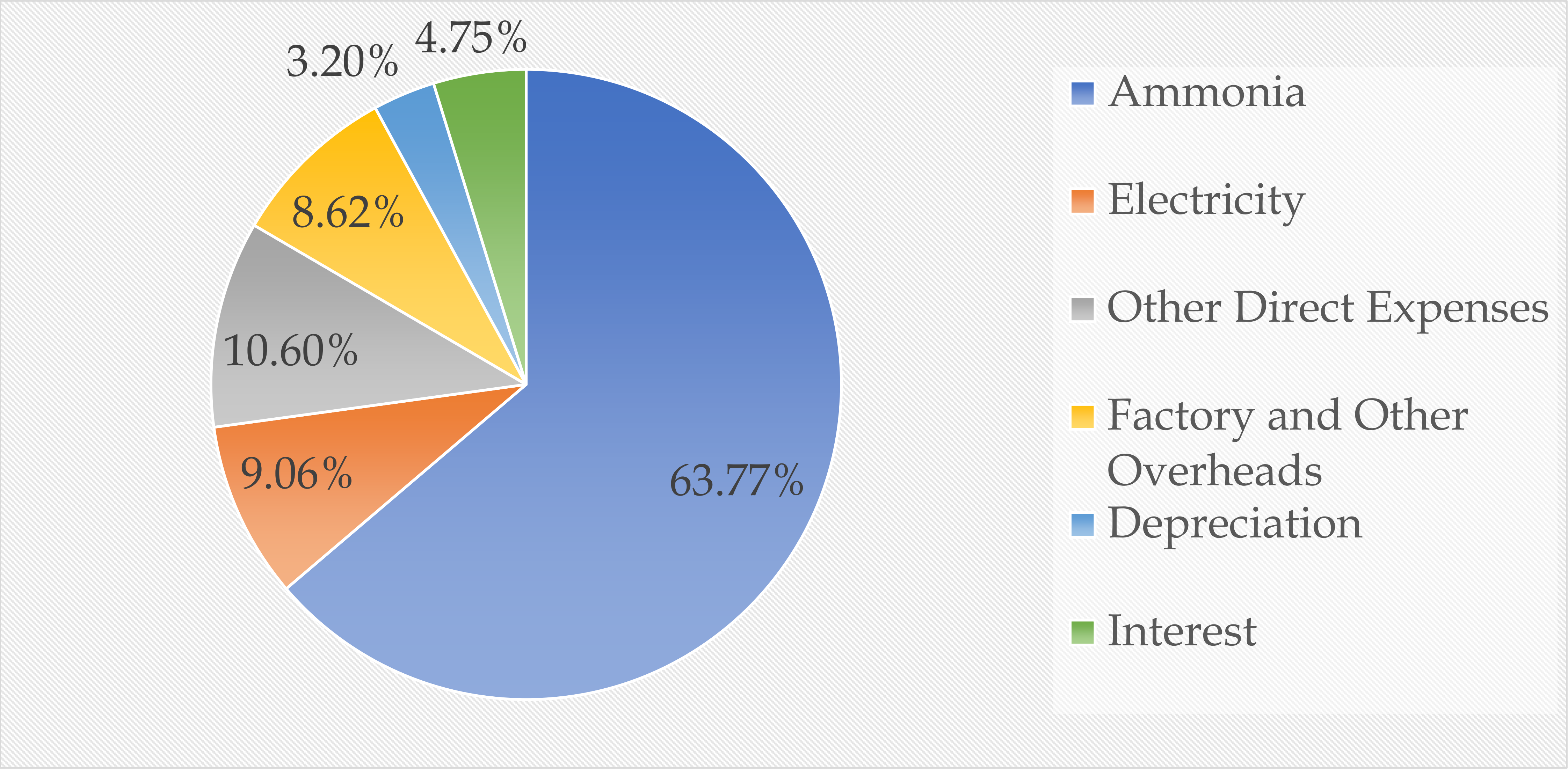
SL. NO.	EXPRESSION	EXPLANATION	VALUE	REMARKS
1	CAPM Formula		$R_E = R_{RF} + \beta * (R_M – R_{RF})$	
2	R_E	Expected Rate of Return on Equity	20.48% (Rounded off to 20%)	Calculated Using the CAPM Formula
3	R_{RF}	Risk Free Rate of Return	6.77%	Yield on 10-year Government of India Bonds
4	β	Measure of Volatility of the shares of Dalmia Bharat Limited vis-à-vis the market	1.57	Source: Economic Times
5	R_M	Market Expected Rate of Return	15.50%	

CAPEX Breakup

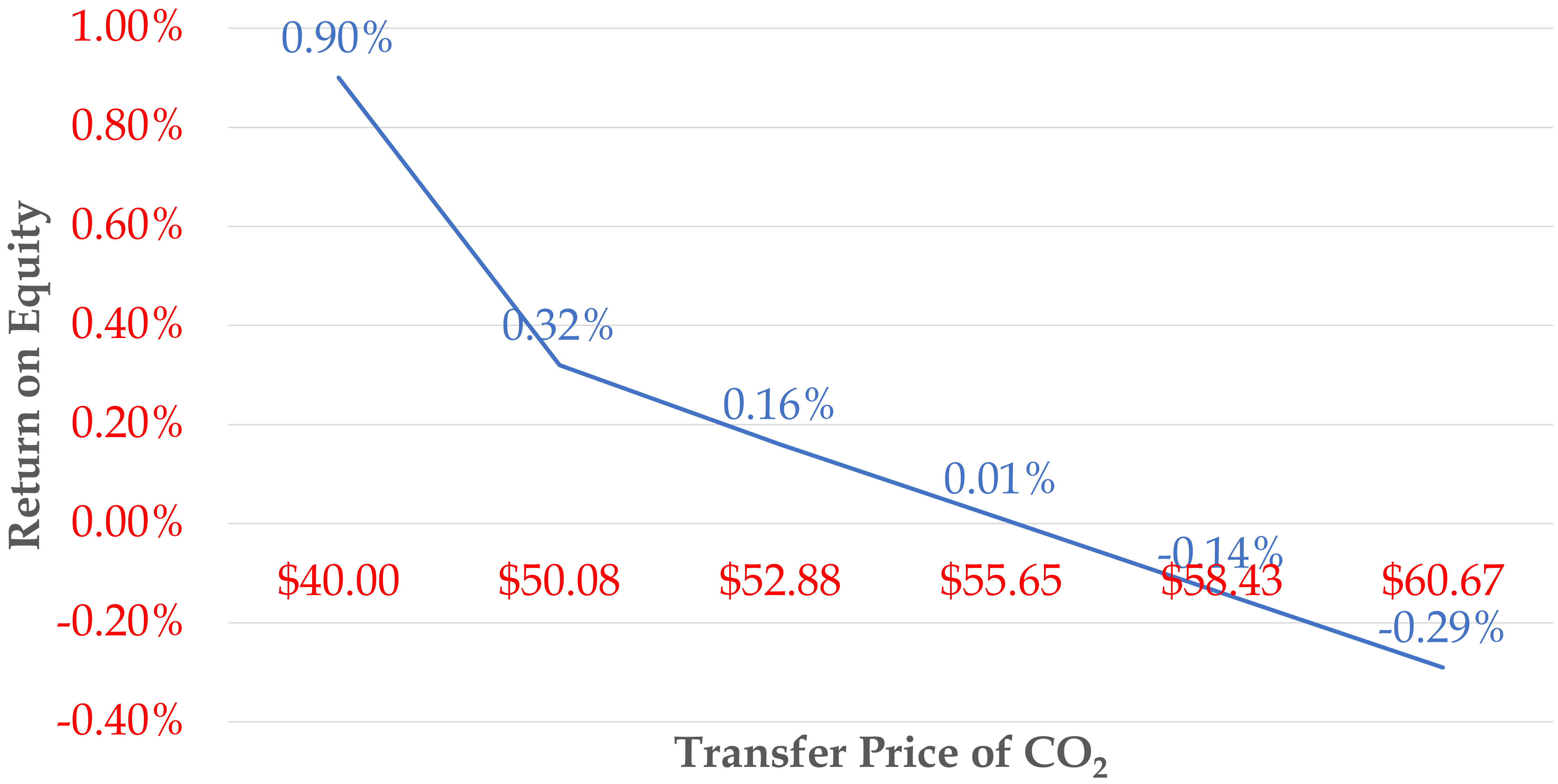


- CAPEX per ton of CO_2 converted: $730.86
- CAPEX per ton of urea produced: $537.40

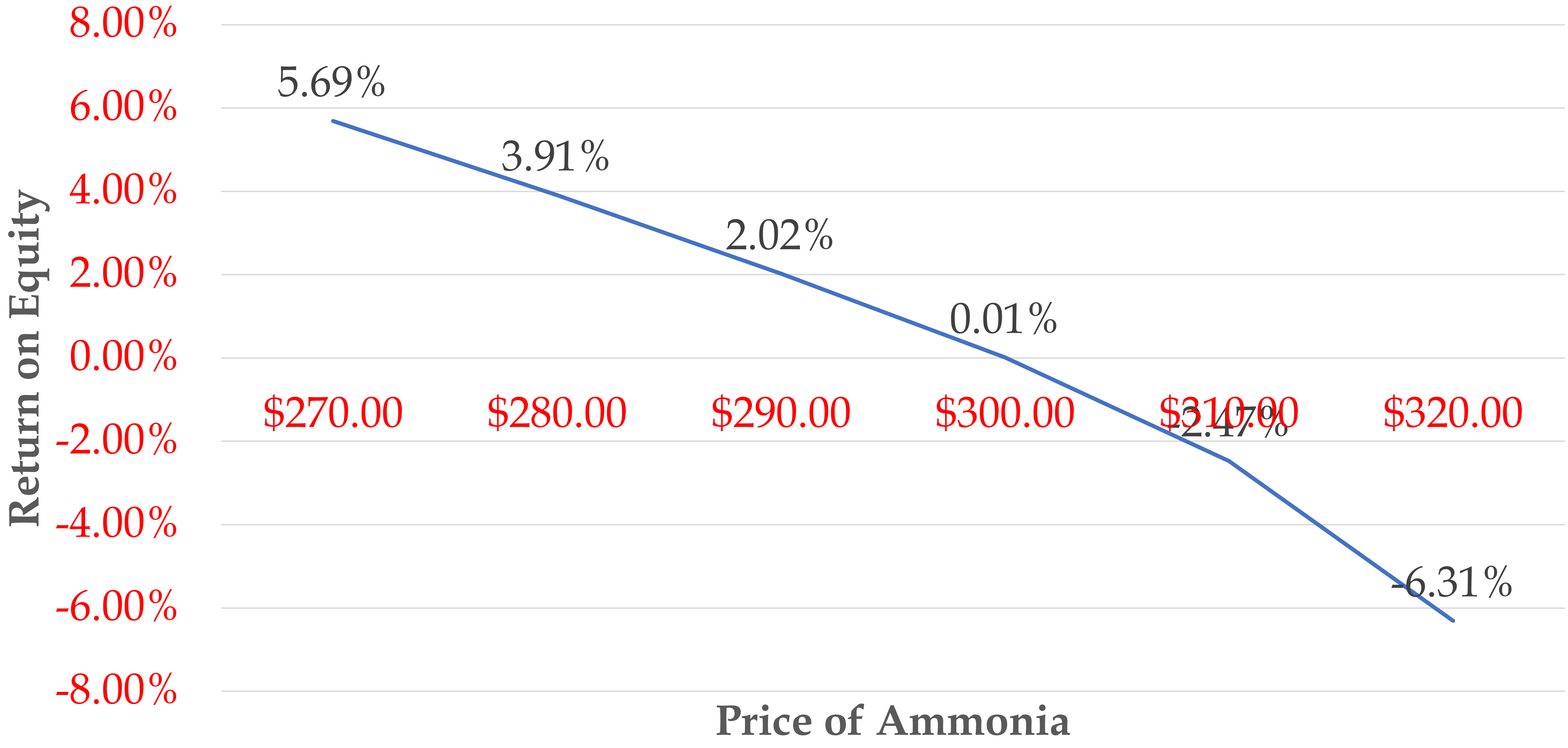
Breakup of Urea Production Cost over Project Period



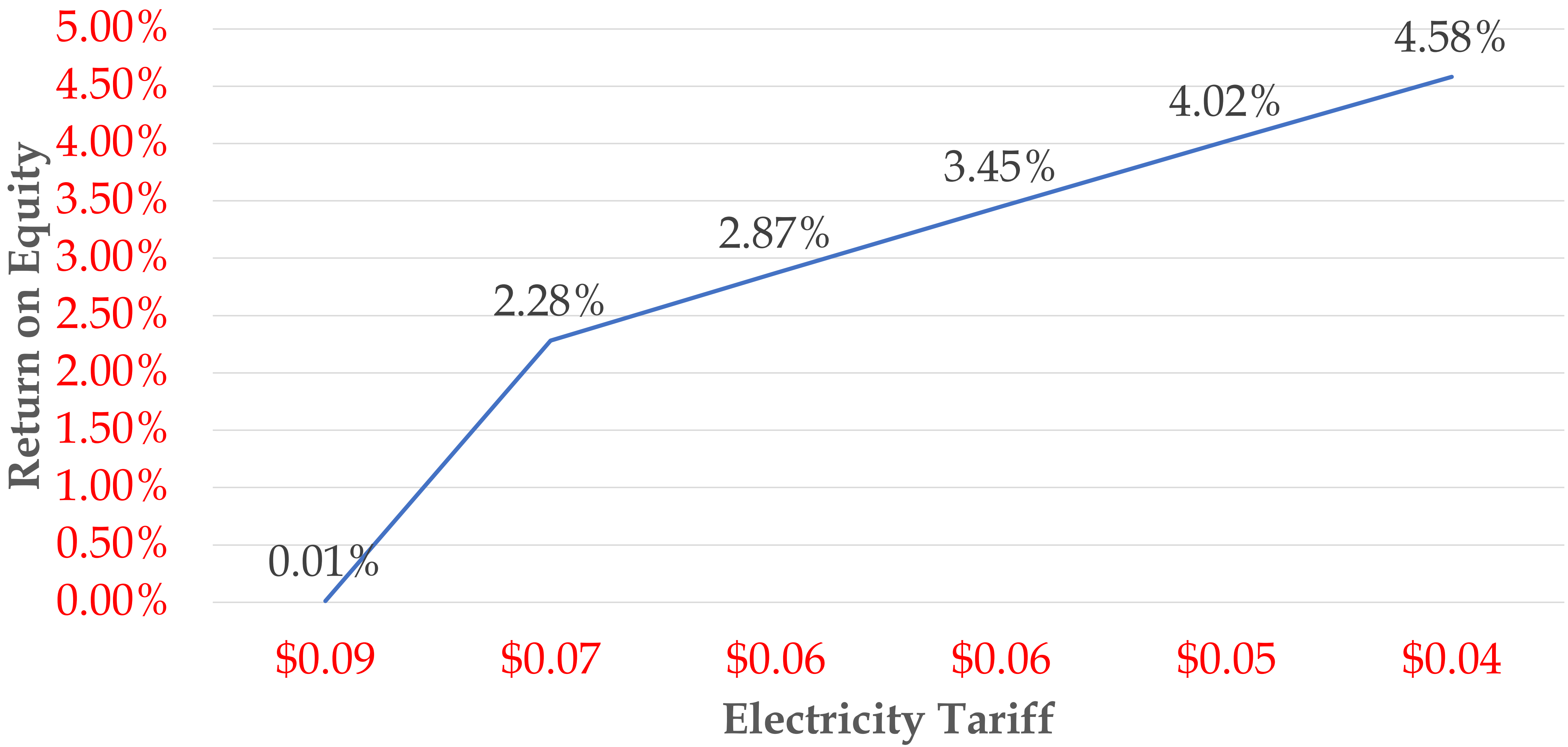
Sensitivity of ROE to Transfer Price of CO_2



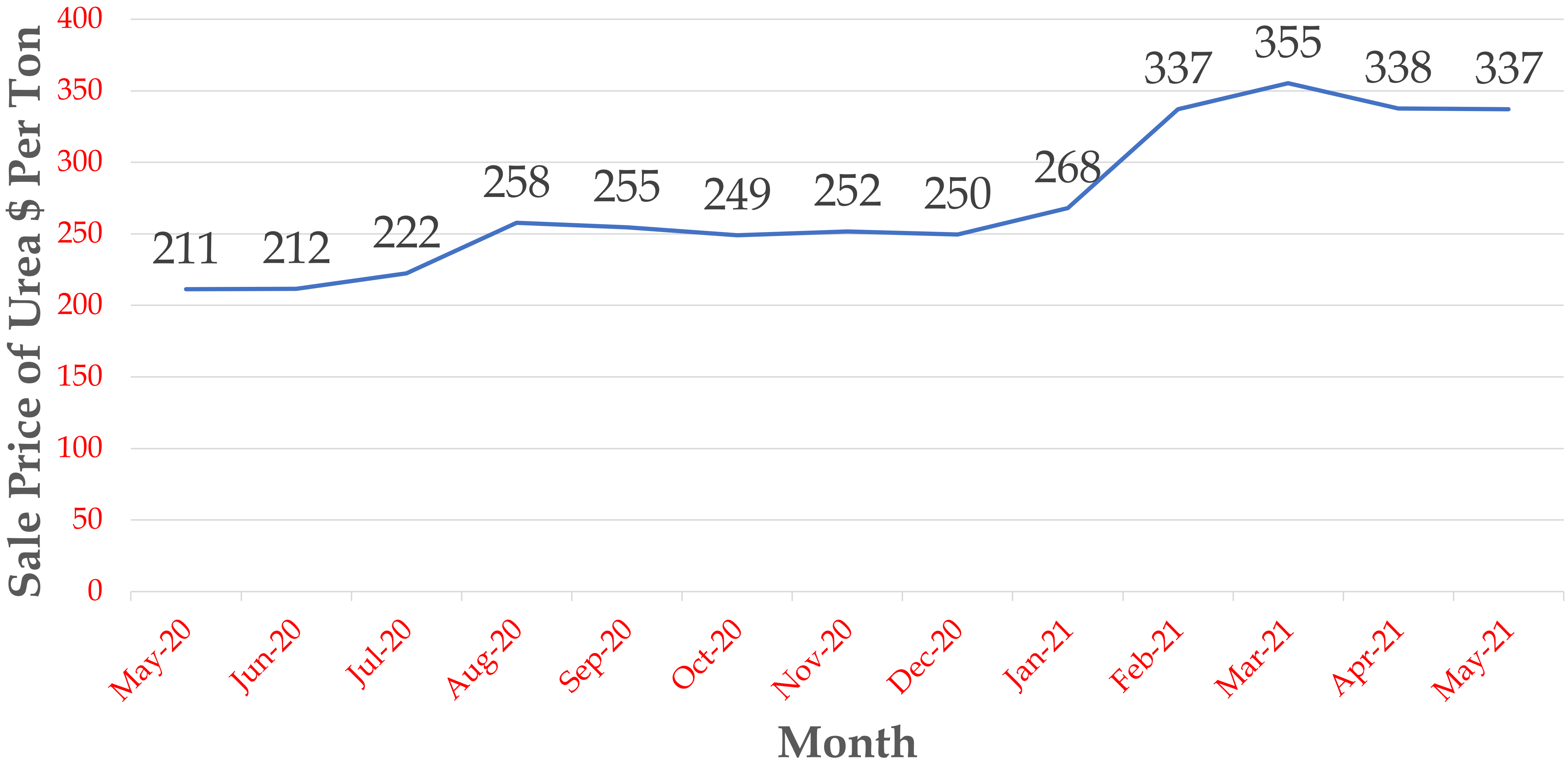
Sensitivity of ROE to Price of Ammonia



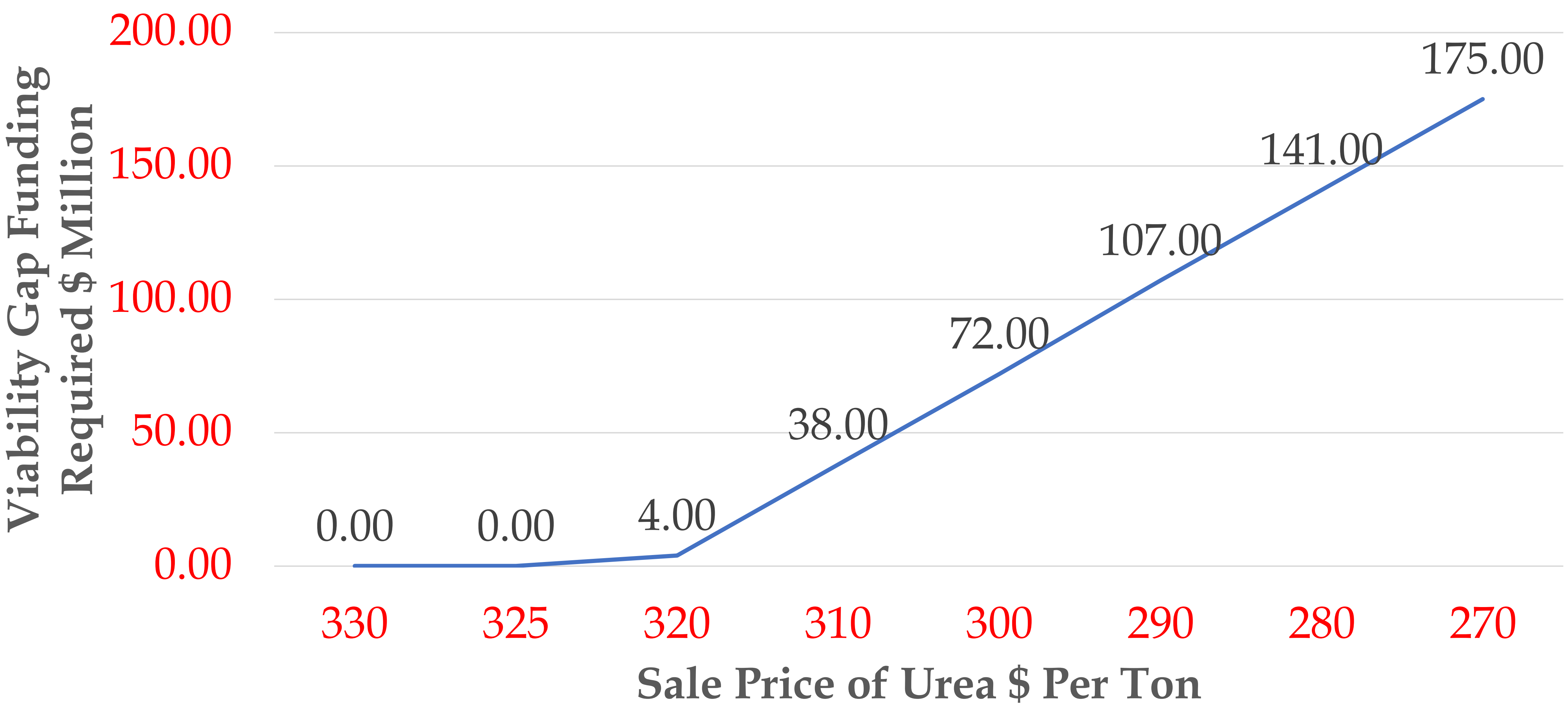
Sensitivity of ROE to Electricity Tariff



Movement of Urea Sale Price in India



Determination of Viability Gap Fund Required



Government Support for Urea Production

- GOI requires at least 75% of the urea produced by any urea manufacturer in India to be neem coated.
- GOI determines the price to be received by manufacturer for neem coated urea on cost plus basis to provide a reasonable return to manufacturer.
- All justifiable costs for manufacture are allowed in determination of price to be received by manufacturer.
- Price of sale to farmer is fixed at $81.92 (INR5,922.22) per ton. The difference between price determined by GOI and price paid by farmer is borne by GOI by way of subsidy to manufacturer.

Key Findings

- Demand for urea in India outstrips supply. Hence, there is ready market for urea
- With urea selling price of $330/ton and electricity tariff of $0.04 per unit, project yields ROE of 20%. At lower selling price of urea, viability gap funding will be required to achieve ROE of 20%.
- Ammonia accounts for 63.77% of the production cost of urea including depreciation and interest. Reduction in cost of ammonia significantly improves ROE. Reduction in other components of OPEX will also improve ROE.
- Impact of reduction in CAPEX on ROE is comparatively less.
- Rate of interest on debt does not have significant impact on ROE
- Reduction in electricity tariff can significantly improve ROE.
- GOI provides subsidy for neem coated urea for ensuring reasonable return to the urea manufacturers

Summary of findings

Summary

- **Capture**

Technologically feasible to build and operate a 0.5 million tonnes per year(tpa) CO_2 capture 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.

- **Utilization selection**

A quantitative Multi Criteria Analysis (MCA) methodology has been developed to assess various CO_2 utilization options.

- **Emissions reduction**

This study calculated CO_2 abatement(Scope 1&2) potential for several scenarios, based on a 0.5 million tpa carbon capture plant and corresponding urea plant. Different options can be used to reduce CO_2 emissions from the whole chain process.

Summary – base case

Item	Quantity
Debt/Equity Ratio	70:30
Weighted Average Cost of Capital (WACC)	12.30%
Electricity price, INR/kWh	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

Summary

Scenario	Total emissions, million tpa	Emissions reductions, million tpa (Scope 1 & 2)
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

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Thank You

Additional information

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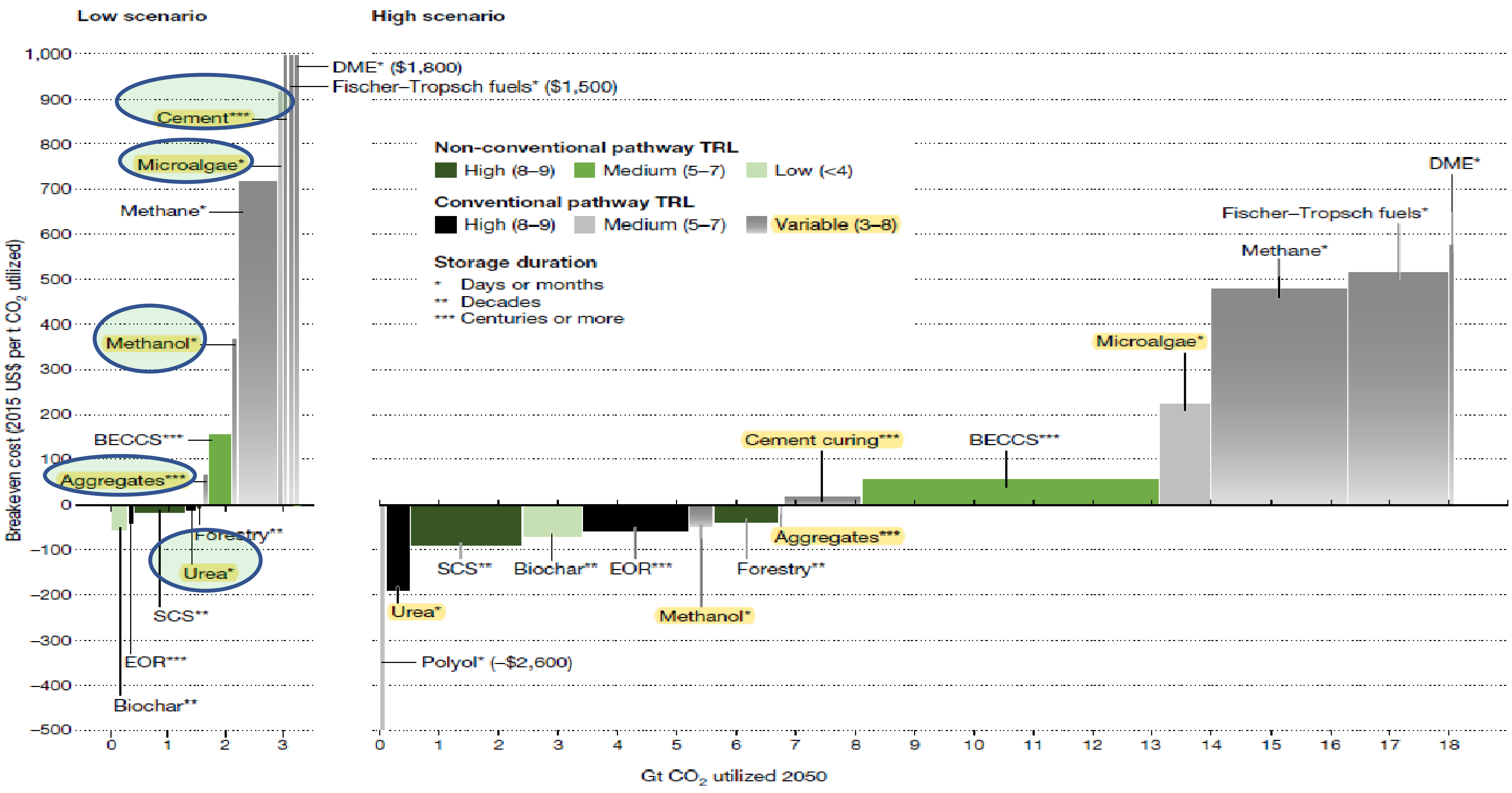
- For other references, please refer to detailed ADB publication Aug 2021. https://www.adb.org/sites/default/files/project-documents/52041/52041-003-tacr-en.pdf

CO_2 Utilization: Breakeven cost for various pathways



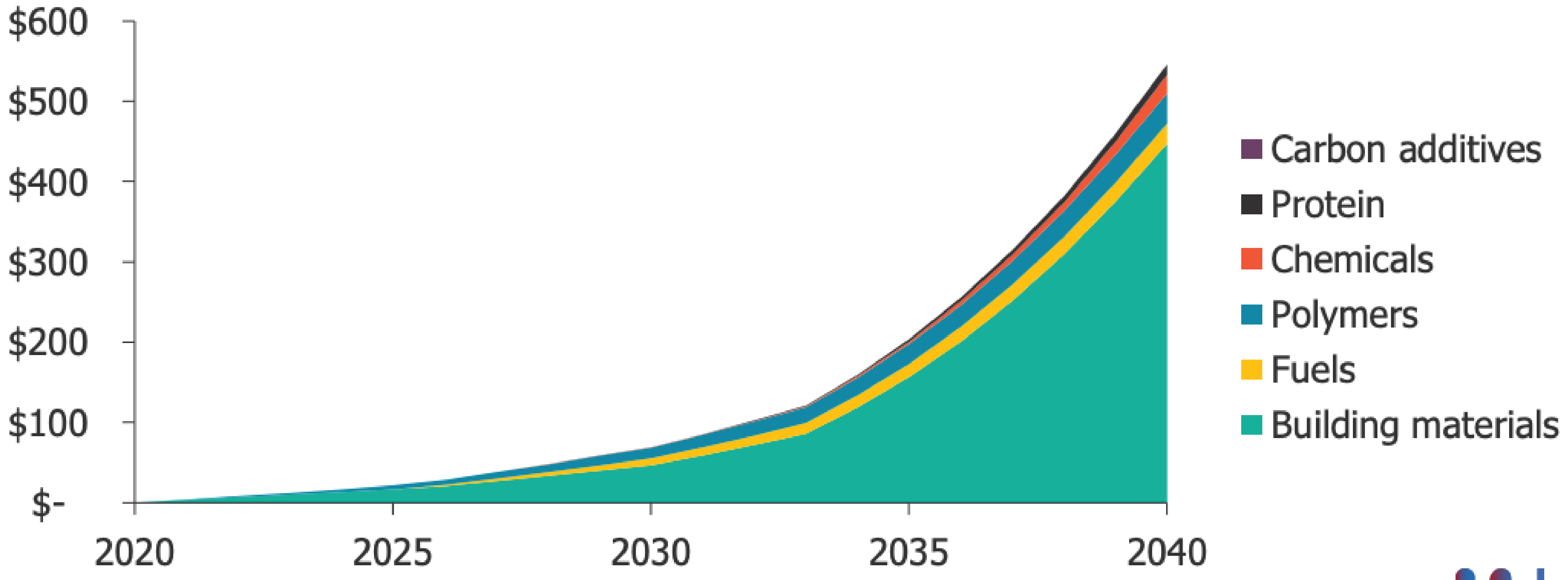
Source: Adopted from Cameron Hepburn et.al, The technological and economic prospects for CO2 utilization and removal, Nature | Vol 575 | 2019

Country specific factors play important role in economics

CO_2 utilization will be a $550 billion dollar market by 2040, driven by the building materials sector

GLOBAL CO_2 UTILIZATION MARKET

Market size (billion dollars, USD)



Carbon Prices in Different International Markets

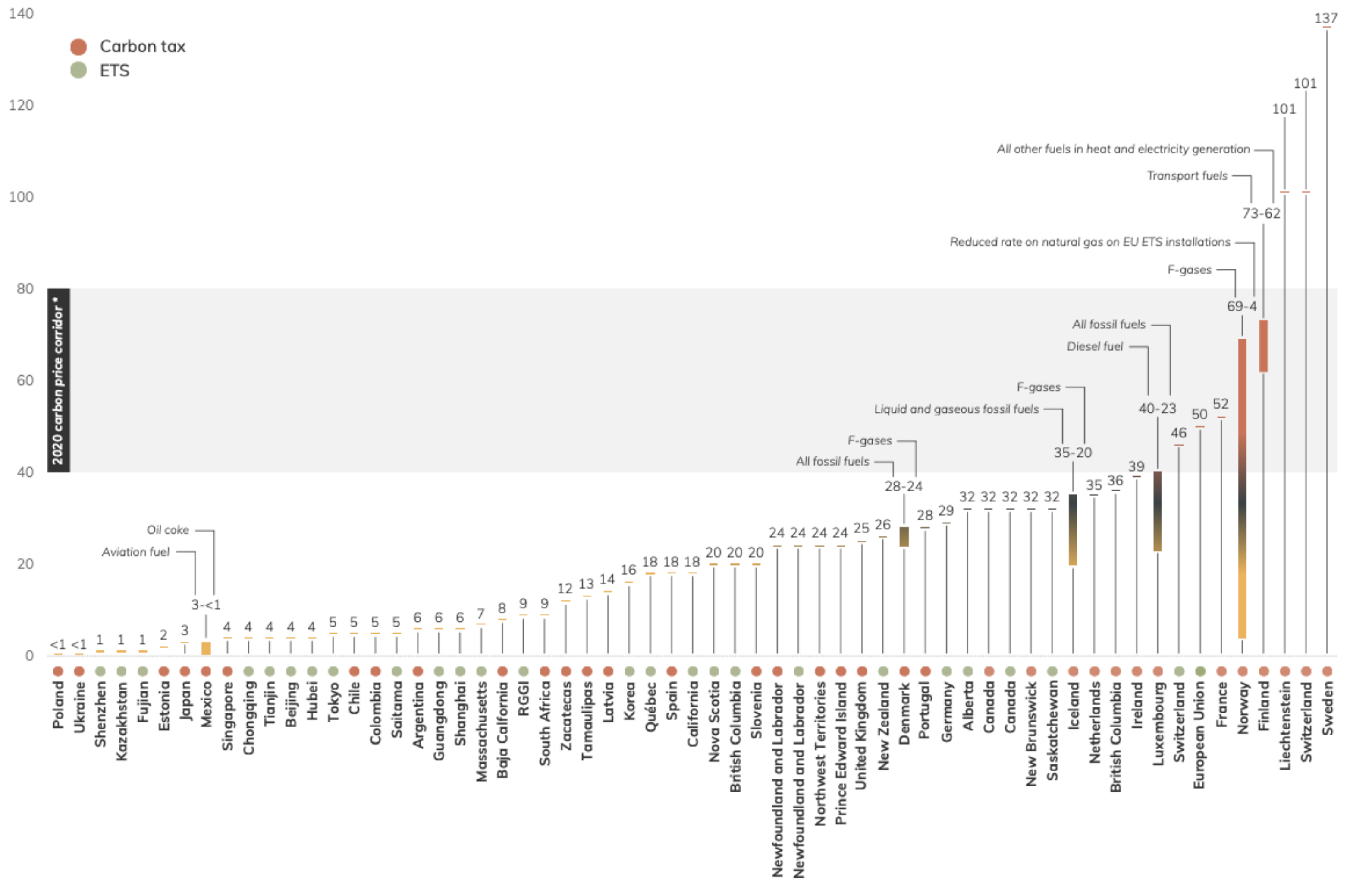
- Market Based Mechanisms and Carbon Taxes are used to indicate the price of CO_2 by governments

- Voluntary markets also provide signals on price

- Different prices help in determination of suitability of a mitigation action in that market

- Taking into account the revised RPO notification dated 14.06.2018, the three put together amount to a carbon tax of US$ 9.71

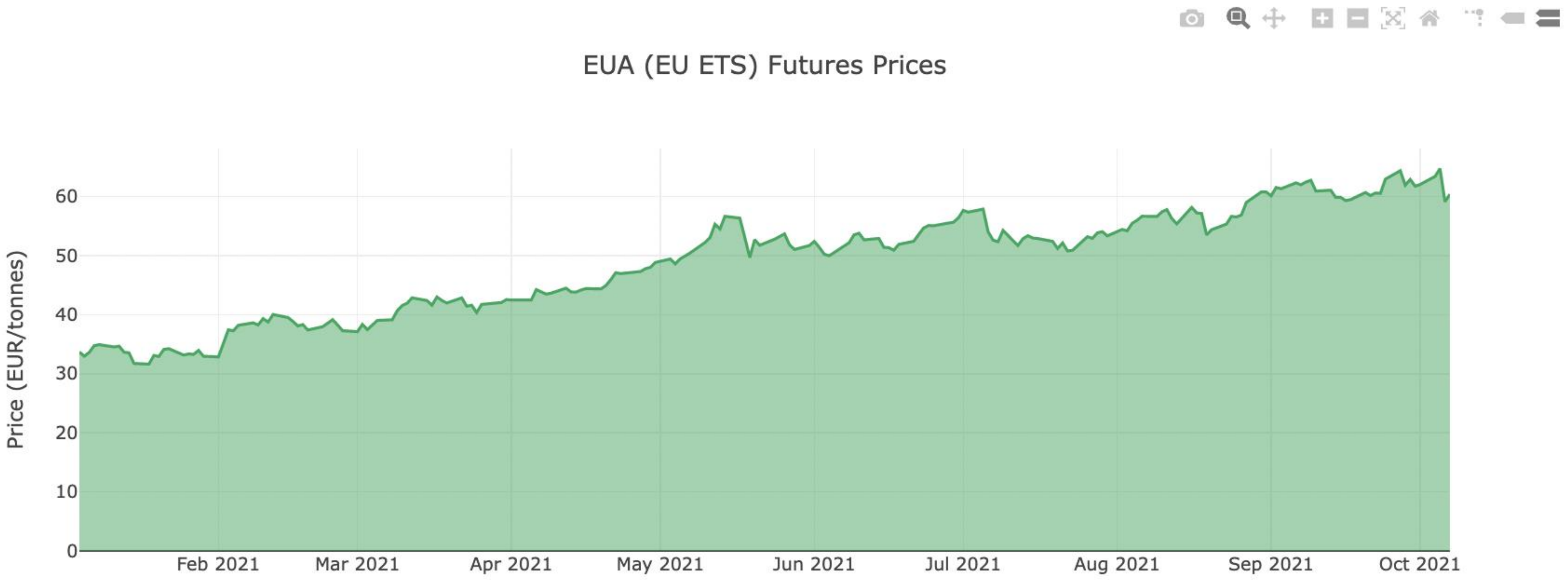
Carbon prices as of April 1, 2021



Nominal prices on April 1, 2021, shown for illustrative purpose only. China national ETS, Mexico pilot ETS and UK ETS are not shown in this graph as price information is not available for those initiatives. Prices are not necessarily comparable between carbon pricing initiatives because of differences in the sectors covered and allocation methods applied, specific exemptions, and different compensation methods.

*The 2020 carbon price corridor is the recommendation of the World Bank's 2017 High-Level Commission on Carbon Prices Report.

Price of Carbon Under EU-ETS



International Price of Urea