GOVERNMENT OF INDIA
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G20
भारत 2023 INDIA

International study on

Financing Needs for New Age Critical Clean Energy Technologies: CO_2 Capture, Utilization, and Storage (CCUS)

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International study on financing needs for new age critical clean energy technologies: CO_2 Capture, Utilization, and Storage (CCUS)

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Foreword

The world is going through the after-effects of a disruptive once-in-a-century pandemic, conflicts, and considerable economic uncertainty. India's G20 presidency is therefore a time to provide hope and stability to the world. It is a matter of great pride for every Indian as we have taken over the G20 presidency at the start of the 'Amrit Kal' of our independence (75th year of independence). We aspire to strengthen the G20's status as the premier global forum for cooperation on global economic and financial issues with compassion and care for the world as one family.

The G20 countries represent 85 per cent of the global GDP, 75 per cent of trade, and two-third of population. The G20 was born at the height of the 2008 financial meltdown, which compelled the world to set up a new representative multilateral group comprising of developed and emerging economies. In this context, PM Modi has highlighted that the world is looking at the "G20 with hope." India's G20 presidency is embodied in the theme of "One Earth, One Family, One Future" and is crystallized in the ancient Sanskrit ethos as "Vasudahaiva Kutumbakam." Its G20 logo comprising a blooming lotus which represents hope in these times and its seven petals cradling the globe affirms the value of all life – human, animal, plant, and microorganisms – and their interconnectedness on the planet Earth and in the wider universe. Shared knowledge that helps us overcome our circumstances, and shared prosperity that reaches the last person at the last mile. India will harness its G20 presidency for reviving global growth, stronger climate action, accelerating Sustainable Development Goals, and adopting to sustainable lifestyle through Lifestyle for Environment (LiFE) as other major priorities.

Creating sustainable energy ecosystems constitute an important dimension of global energy transitions. CO_2 Capture Utilization and Storage (CCUS) is expected to be a key part of the future clean energy investments globally in scenarios where end-of-century temperature rise is limited to 1.5°C. The capacity building, technical assistance, and demonstration of different CCUS technologies are indispensable. Grant-based financing through a specialized fund by pooling public funds from OECD countries and other donors must be created to scale up the deployment of CCUS projects. Multilateral Development Banks can also provide guarantees to deal with technology risks associated with CCUS demonstration projects. Also, equity and debt investments in CCU demonstration projects can be fully or partially guaranteed in emerging markets and developing countries so that project developers can assess the viability of large-scale commercial deployment and test the technical suitability per the country's domestic conditions.

I hope that this international study report provides useful insights and decision points in G20 deliberations and would generate interest in global policy makers and businesses.

January, 2023

Alok Kumar

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Acknowledgements

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Preface

Energy systems mitigation with CO_2 capture, utilization, and storage (CCUS) will be increasingly important over the next three decades. As unabated fossil fuel use would look incompatible with 1.5°C/2°C targets, median levels of coal and gas with CCUS are anticipated to increase to a median of 10 EJ and 20 EJ, respectively. CO_2 capture and utilization (CCU) could be an important form of greenhouse gas mitigation opportunity and could lead to 50-70% reduction in GHG emissions of key industrial products (e.g., cement, methanol), relative to current incumbents. Availability of CCUS likely reduces stranding of power plants and fossil reserves by more than 50% across integrated assessment modelling results. The global benefit through availability of CCUS in this case would be of the order of $1-2 trillion globally.

CCUS is expected to be a key part of the future clean energy investments globally in scenarios where the end-of-century temperature rise is limited to 1.5°C. These include investments in coal power plants ($1-16B annually in 2030), gas power plants ($7-22B annually in 2030) and biomass power plants ($1-46B annually in 2030). In scenarios involving large penetration of CO_2 capture and storage (CCS), investments in power plants are expected to be as high as 8-10% of global energy investments. In addition to these investments, $10-20B annually is also projected to be invested in 1.5°C scenarios where preferential investments are focused on CCS. The CCU market size may increase from a couple of in 2050.

This study suggests following recommendations which are encouraged for discussion and adaption by G20 countries to support CCUS projects.

- Grant-based financing through a specialized fund by pooling public funds from OECD countries and other donors must be created to scale up the deployment of CCUS projects. The scope of the Asian Development Bank CCS fund is very limited. Grants-based funding for capacity building and technical assistance will immensely benefit emerging markets and developing countries (EMDCs) in assessing the technical feasibility of CCUS technologies. Therefore, the creation of specialized funds should be done under the aegis of a global Multilateral Development Bank (MDB) such as the World Bank Group. Global Environment Facility, Climate Investment Funds, Green Climate Fund, and other funds can direct grants through this specialized fund, so that recipient countries do not have to apply to each fund separately, thereby reducing transaction costs and documentation requirements.
- MDBs can also provide guarantees to deal with technology risks associated with CCUS demonstration projects, especially CCU projects. Equity and debt investments in CCU demonstration projects can be fully or partially guaranteed in EMDCs so that project developers can assess the viability of large-scale commercial deployment and test the technical suitability per the country's domestic conditions.
- Research efforts into CCU must be diversified given its prospects and large public acceptability. This includes better inclusion of the chemicals and materials sector into modelling frameworks, developing better catalysts and reagents for facilitating individual CO_2 utilization pathways and improved global market assessment for such products.
- Existing and planned financing mechanisms should incorporate CCU, where relevant. Accounting for the net GHG benefits in such projects must be subject to rigorous inventory practices.

- While financing mechanisms have been discussed for the next decade for initial projects, it is essential that CCUS is brought within the ambit of carbon markets in the medium-to-long term. The Doha summit of the UNFCCC has included CCUS within Clean Development Mechanism, though the actual deployment of projects remains limited. While the EU Emission Trading Scheme and some other markets include CCUS, it should be considered whether the geographical boundary of such projects may be outside such that carbon mitigation credits may be traded across G20 countries.
- Technical assistance should be provided to G20 countries where an effective assessment of sink potential is not present. The storage capacity in saline aquifers in developing countries may not have been assessed properly because such reservoirs have not been explored for any commercial reasons. On the other hand, stratigraphic data for depleted hydrocarbon reservoirs and coal seams may be available but it has not been fully utilized to estimate sink availability. It is recommended that requisite funds may be provided to explore this area such that future large point sources of CO2 are sited around sinks with high readiness.
- Finally, the motto of the 2023 G20 Presidency is One Earth, One Family, One Future. In this vein, it is recognized that many countries outside the G20 would also emerge as hubs of economic and industrial development over the next three decades. While their GHG emissions are currently low, it is imperative that that primary-level screening of CCUS opportunities is carried out here. G20 can facilitate these funds for G77 countries as part of developing CCUS knowledgebase and databases globally.

I complement my researcher team members at the Indian Institute of Management Ahmedabad for writing this international study report and Ministry experts namely NTPC, NETRA and PFC for commissioning and supervising this study. I hope that it will catalyze interesting and engaging interactions amongst G20 members, researchers, business community and financial institutions.

January, 2023

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Abbreviations and Acronyms

ADB	Asian Development Bank
AfDB	African Development Bank
AIIB	Asian Infrastructure Investment Bank
AR6	Sixth Assessment Report
BBL	Barrel (of oil)
BECCS	Bioenergy with Carbon Capture and Storage
CBD	Convention on Biological Diversity
CBI	Climate Bond Initiative
CCS	CO_2 Capture, Utilization and Storage
CCU	CO_2 Capture and Utilization
CCUS	CO_2 Capture, Utilization and Storage
CDM	Clean development Mechanism
CDR	Carbon Dioxide Removal
CDS	Credit Default Swaps
CI1	Climate Investor One
CIB	Commercial International Bank
CIF	Climate Investment Fund
CO_2	Carbon Dioxide
DAC	Direct Air Capture
DFI	Development Finance Institutions
EBRD	European Bank for Reconstruction and Development
ECBM	Enhanced Coalbed Methane Recovery
EIB	European Investment Bank
EMDCs	Emerging Markets and Developing Countries
EOR	Enhanced Oil Recovery
ESG	Environmental, Social, and Governance
EU	European Union
EV	Electric Vehicle
GCAM	Global Change Assessment Model
GCF	Green Climate Fund
GDP	Gross Domestic Product
GEF	Global Environment Facility
GFANZ	Glasgow Financial Alliance for Net Zero
GHG	Greenhouse Gas
Gt	Giga ton
GVA	Gross Value Addition

IAMs	Integrated Assessment Models
IDBG	Inter-American Development Bank Group
IFC	International Finance Corporation
IGCC	Integrated Gasification Combined Cycle
IO	Input-Output
IOCL	Indian Oil Corporation Limited
IPCC	Intergovernmental Panel on Climate Change
IsDB,	Islamic Development Bank
LDCs	Least Developed Countries
LDO	Light Diesel Oil
LEAP	Launching Entrepreneurs for Affordable Products
LTS	Long-Term Strategy
MDBs	Multilateral Development Banks
MESSAGE	Model of Energy Supply Systems And their General Environmental Impact
MRV	Monitoring, Reporting and Verification
Mt	Million ton
MWh	Mega Watt hour
NDC	Nationally Determined Contribution
NDF	Nordic Development Fund
NGCC	Natural Gas Combined Cycle
NGFS	Network for Greening the Financial System
O&M	Operating and Maintenance
OECD	Organisation for Economic Co-operation and Development
PC	Pulverized Coal
REDD	Reducing Emissions from Deforestation and Forest Degradation
REMIND	REgional Model of INvestments and Development
SIDS	Small Island Developing States
SLLs	Sustainability Linked Loans
SMR	Steam Methane Reforming
TCFD	Task Force on Climate-related Financial Disclosures
UAE	United Arab Emirates
UN	United Nations
UNCCD	United Nations Convention to Combat Desertification
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
WBG	World Bank Group

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Executive Summary

Energy systems mitigation with CO_2 capture, utilization and storage (CCUS) will be increasingly important over the next three decades as unabated fossil fuel use would look incompatible with global 1.5°C/2°C targets of the Paris accord. Most short-term mitigation opportunities with CCS exist in the industrial sector, where facilities with large process emissions may deliver low-cost CO_2 capture at \$0-20/t-CO_2. Particularly, the key opportunities exist in refining of biofuels and biogas, natural gas processing and ammonia/hydrogen production. CO_2 capture and utilization (CCU) could be an important greenhouse gas (GHG) mitigation opportunity here and could lead to 50-70% reduction in GHG emissions of key industrial products (e.g., cement, methanol), relative to current incumbents, if powered via renewable grids. Even as CCUS infrastructure and technological readiness initially get used for end-of-the pipe mitigation of fossil systems, it is necessary in scaling up long-term carbon dioxide removal (CDR) systems, where bioenergy may be combined with Bioenergy with Carbon Capture and Storage (BECCS).

The cost of GHG avoidance via CCS in the power sector is close to \$40-70/t-CO_2 and lower for industrial sectors where high-purity CO_2 streams are present. These costs are lower for higher-efficiency units involving supercritical and ultra-supercritical boilers in the coal sector. Integrated gasification combined cycle (IGCC) may deliver an even lower cost of GHG avoidance, however, the financial risks - and project contingencies – involved in such plants are higher based on past evidence (such as Plant Ratcliffe in Kemper County, USA). The costs for GHG avoidance via CCU have a higher variability than CCS (-\$100-1500/t-CO_2). However, CCU is associated with lesser risk due to no storage liability, an available market for the products and higher public support. The current costs for CCU may be high, but they are anticipated to decrease significantly as the scale increases. A higher scale of deployment would entail greater technological learning, which would result in reduced costs within the next decade or two. The CCU market size may increase from a couple of hundred thousand dollars in 2030 to almost \$4500 billion dollars in 2050.

CCUS is expected to be a key part of the future clean energy investments globally in scenarios where end-of-century temperature rise is limited to 1.5°C. These include investments in coal power plants (\$1-16 billion annually in 2030), gas power plants (\$7-22 billion annually in 2030) and biomass power plants (\$1-46 billion annually in 2030). In scenarios involving large penetration of CCS, investments in these power plants are expected to be as high as 8-10% of global energy investments. In addition to investments for power plants, \$10-20 billion annually is also projected to be invested in 1.5°C scenarios where preferential investments are focused on CCS.

CCUS has the potential to reduce the magnitude of stranded assets in the fossil fuel supply chain. Availability of CCUS likely reduces stranding of power plants and fossil reserves by more than 50% across integrated assessment modelling results. The global benefit through availability of CCUS in this case would be of the order of \$1-2 trillion globally. Alongside this, CCUS availability would also aid in employment security in two ways. First, it would avert the job losses of close to 20 million individuals, who are engaged in the coal supply chain globally. Second, CCUS would create new jobs in the technological development for CO_2 capture technologies, and monitoring/storage of long-term CO_2 storage.

Revenue risks are currently crucial and inhibitory for power sector CCS projects. A business model in practice links CCS projects in the power sector to additional financial revenues via Enhanced oil recovery (EOR). This however could induce a high risk during times of low crude oil prices, e.g., the closure of the Petra Nova project, where the CCS operations were suspended due to low oil prices in the COVID shutdown period and are yet to resume. Due to the large and diversified nature of CCUS projects, cross-chain risks also exist because the profitability of each supply-chain component depends on feasibility of other components, which may not yet be market ready. Failure of any one component may lead to low load factor for the plant under GHG emission constraints. As all stages of CCUS are capital-intensive, risks in CCUS supply chain could therefore enhance considerably, disincentivizing investors. For instance, a coal-fired power plant might have to assume the availability of a post-combustion capture technology, CO_2 compression, transport infrastructure, and storage availability. Storage liability risks are also present in CCS projects particularly. Even as the risk of CO_2 leakage has been very low thus far, it is important to manage liability risks, failing which the storage operator may potentially be penalized for any long-term leakage. Reducing risk aversion to storage liability requires a clear standard for operators, which states the time duration until which they will be liable for leakages and leakage limits.

The products generated by CO_2 utilization would be financially viable only if a suitable market price exists. However, several products being thought of have price volatility associated with them, e.g., CO_2 methanation pathway. This risk is therefore bound to exist unless there is some pricing security for 'green products' synthesized using CCU, maybe supported by carbon markets. Current CCUS projects are largely based on one-to-one models, where one single large point source sends CO_2 to one sink. This adds to cross-sector risks. Abating this risk requires development of a hub-and-cluster model, where networks of sources and sinks are formed. In addition to introducing economies of scale, this de-risks investments in CCUS.

Given the current stage of CCUS, multilateral agencies and development financial institutions are more likely to be key sources of finance. As CCUS matures and the sector de-risks, commercial lenders may also become important financiers. An important component of low-cost finance for CCUS is in the form of outcome-based sustainability loans or sustainability linked loans (SLLs). Under these mechanisms, proceeds may be borrowed for any activity, but the lending interest rates are lower if certain Environmental, Social, and Governance (ESG) criteria are being met. More than three-quarters of SLLs have been issued in the United States or Europe. Green bonds could also be potentially an important source of financing for CCUS. These green bonds may be supported by financial corporates, governments, development banks (such as the World Bank or IFC). However, several such green bonds preclude key CCUS applications, such as retrofit of coal-fired power plants. Green bonds are currently over a trillion $ market, though their issuance has fallen in this year due to rising interest rates.

The capital-intensive nature of CCUS means that capital incentives would be an important part of policy interventions. For instance, to reduce revenue risks, it is important to have sequestration tax credits in addition to investment tax credits. The former could provide a higher incentive for CO_2 that is not stored/utilized due to absence of market. These credits must be indexed to inflation. Investment tax credits are being provided in some countries such as the United States, where \$180/t-CO_2 and \$85/t-CO_2 of effective incentive exists in direct air capture (DAC) and point source CO_2 capture respectively. That said, there are limitations to the sectors and capture thresholds of plants where these currently apply. The suitability of revenue treatments such as production tax credits, versus capital incentives would depend on the fuel type. For instance, CO_2 capture units in gas plants have a lower capital and therefore lower incentives – than coal plants because of lower size of such units. A healthy carbon price could also reduce CCUS revenue risks for all fuels and involved technologies.

Climate related financial disclosures are critical to driving investments in CCUS. The Task Force on Climate-related Financial Disclosures (TCFD) sets clear guidelines for such disclosures. For CCUS projects, a clear disclosure methodology should be developed that includes Scope 1, 2 and 3 emissions, how the project contributes to national greenhouse gas emission reductions, support of CCUS research and public engagement activities aimed at CCUS deployment.

The Doha Meeting of the UNFCCC included CCS within the ambit of the Clean Development Mechanism (CDM). That said, no projects have been funded under the CDM because this would require having CCS legislations and regulations in place. Financial support via the CDM alone will likely be inadequate and additional financing will still be required.

Non-market climate finance mechanisms such as the Global Environment Facility (GEF) and the Green Climate Fund (GCF) also have the potential to be important drivers of international support to CCUS. Particularly, the GEF scale funding is higher and can help in CCUS deployment via grants, equity investments and concessional loans. The GCF scale is lower and while it may not directly help fund CCUS infrastructure, it could provide cross-sectoral finance for development legal and regulatory standards in developing countries.

If private sector finance is itself inadequate to lower the price of electricity/commodities, governments and/or multinational development banks may subsidize CCUS products via viability gap funding. This could be particularly important in products that offer other societal benefits, such as urea. This may be beneficial to early movers to reduce 'wait and see' until the financial market provides a robust coverage of CCUS.

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Chapter 1

CCUS – Future Outlook

1.1 Mitigating GHG emissions

The writing on the wall is clear – short-term and long-term energy and infrastructural systems need widespread change in order to meet the 1.5°C target set forth by the Paris Agreement. Following Paris, the vast majority of G20 countries have announced targets to reach net-zero greenhouse gas (GHG) emissions between 2050 and 2070 (Nascimento et al., 2022; Van Soest et al., 2021). These targets are ambitious and required concerted strategy because the G20 accounts for 84% of the world's economic output and 80% of its primary energy use and GHG emissions. A commonly used mathematical formulation to decompose GHG emissions into its drivers is the Kaya identity (or the ImPACT identity) (Kaya & Yokobori, 1997):

$$GHG\ emissions(I) = Population\ (P) \times \frac{GDP}{Population}(A) \times \frac{Energy\ use}{GDP}(C) \times \frac{Emission}{Energy}(T)$$

In its differential form, this transforms into (Waggoner & Ausubel, 2002):

$$i = p + a + c + t$$

Historic global trends in these values are shown in Figure 1.1. If we focus on individual terms here, it is clear that the last two terms may be used to control GHG emissions. The first term (population) has continued to increase slowly. Even as the population of some G20 member countries ages, it is anticipated to increase from 4.6 billion currently to 5 billion in 2050 based on median UN projections (UNDESA, 2020). This represents an annual growth of about 1.3% over the next three decades. GDP growth rates are more speculative, but some estimates based on the International Monetary Fund data indicate it may increase to 1.1-6.2% in G20 member states (Dadush & Stancil, 2009). Thus, the *p* and *a* term in the differentiated Kaya identity are positive. The third term emphasizes efficiency. Indeed, a $221 billion market exists in the energy efficiency sector though 70% of the investments have been in the United States, European Union, and China (UNEPFI, 2017). Historically, the *c* term has corresponded to -0.4% between 1990 and 2018. Considering this context, the *t* value, i.e., the carbon intensity of various end uses would need to decline by 5-10% in various sectors of the economy annually.

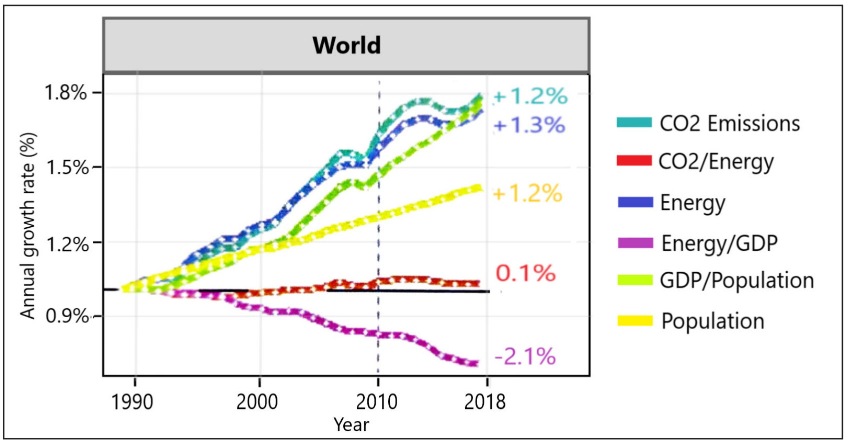

Figure 1. Incremental Kaya identity terms for the energy systems sector globally between 1990 and 2018. Figure reproduced under the Creative Commons Attribution 4.0 license.

Source: (Lamb et al., 2021). The numbers at the end of each line indicate the compounded annual growth rate of individual Kaya terms between 1990 and 2018.

The Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report (AR6) makes it clear that there is no "silver bullet" for this large annual reduction in the *t* term, and a variety of technologies would be required in this effort (Clarke et al., 2022). This includes fuel switching, energy efficiency, renewables, novel energy carriers, electrification, and carbon management. Carbon management may be divided into three key components, which are not always separate from each other: CCS, CCU and CDR (Figure 1.2).

What is CCUS (differentiating CCS, CCU and CDR)?

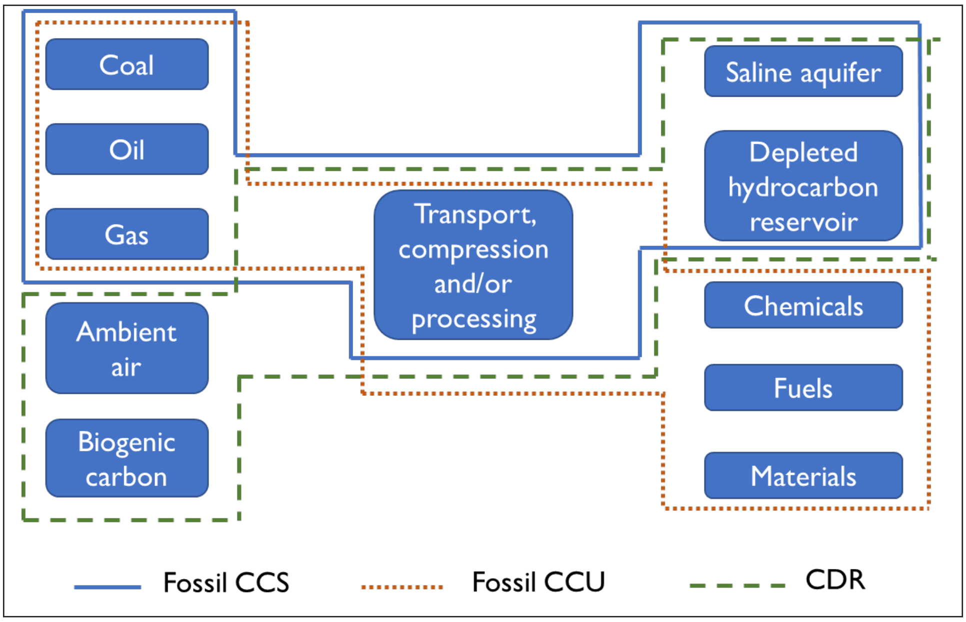

Figure 2. Generic schematic of fossil CCS, fossil CCU and CDR. Figure designed by authors.

CCS came into discussion after the Kyoto protocol was signed, which emphasized percentage emission reductions for industrialized economies (McLaren & Markusson, 2020). As such, the idea associated with CCS is the capture of CO_2 from large point sources, its compression and subsequent injection into deep geologic formations. The depth of such formations would nominally be above 800m, and CO_2 would get converted into supercritical phase due to the pressure conditions. Under a well-regulated reservoir, it is anticipated that >99% of the CO_2 would remain in place over a millennium (Alcalde et al., 2018). While CCS has been deemed near-essential for energy transitions compatible with a 1.5°C, the associated costs of capturing and compressing the CO_2 are very high (Chapter 2). Some of these costs may be offset if the geologic sinks used for CO_2 storage are depleted oil and gas reservoirs, or unmineable coal seams. However, as Table 1.1 shows, these opportunities are limited and regionally specific. Moreover, CCS is associated with long-term monitoring requirements and the public may have some concerns associated with it (Arning et al., 2019).

Table 1. Geologic storage potential across underground formations globally in Gt-CO_2. These represent order-of-magnitude estimates

Reservoir type	Africa	Australia	Canada	China	CSA	EEU	FSU	India	MEA	Mexico	ODA	USA
Enhanced oil recovery	3	0	3	1	8	2	15	0	38	0	1	8
Depleted oil and gas fields	20	8	19	1	33	2	191	0	252	22	47	32
Enhanced coalbed methane recovery	8	30	16	16	0	2	26	8	0	0	24	90
Deep saline aquifers	1000	500	667	500	1000	250	1000	500	500	250	1015	1000

CSA: Central and South America, EEU: Eastern Europe, FSU: Former Soviet Union, MEA: Middle East, ODA: Other Asia (except China and India), WEU: Western Europe.

***Source**: (Clarke et al., 2022). Data: (Selosse & Ricci, 2017). Adapted under the terms mentioned in the IPCC website https://www.ipcc.ch/copyright/.*

As an alternative to geologic sequestration, CO_2 capture and utilization (CCU) may be considered another viable option. Here, the captured CO_2 is transformed into value-added chemicals, fuels or materials. CCU is not associated with the traditional risks of geologic storage. It also generates long-term revenue options for businesses reliant on traditional fossil fuel supply chains. Consider the case of methanol, which has traditionally been created via reforming of virgin fossil fuels. Replacing this supply of fossil fuels with a circular flow of CO_2 captured from a point source such as a coal-fired power plant reduces the net emissions associated with the methanol supply chain by around 60% (von der Assen et al., 2013). Currently, methanol is used as a chemical with a global market size of $31 billion annually. Thus, the produced methanol from CCU could displace a substantial portion of it. However, many key stakeholders are visualizing the produced methanol to replace light diesel oil (LDO), which is a commonly used industrial fuel. The current price of LDO in the Indian market is around $1.1/L, thus implying suitable revenue opportunities. In the most optimistic case, a dedicated fleet of methanol-fueled vehicles could also be operated via this mechanism (Daggash et al., 2018).

The integrated assessment modeling consensus indicates that while CCS/CCU would be critical in abating fossil carbon emissions, a new strand of literature has emerged in the field of (CDR). Here, instead of the conventional fossil CCS chain, the source of carbon is replaced with a biogenic carbon source (i.e., biomass) or direct capture from the atmosphere in what is called as direct air capture (DAC). When this carbon is captured and sequestered underground, it yields so-called "negative emissions" as the carbon flux in such systems is from the atmosphere to the geosphere. Alternatively, if such carbon streams are utilized to produce fuels or chemicals, they may be compatible with net-zero emissions since the upstream carbon uptake neutralizes the carbon emitted during combustion or conversion.

1.2 Future casting of CCUS in different scenarios

The development of CCUS has evolved over the last five decades. In the early 1970s, the global prices of crude had increased exorbitantly. Global prices of oil nearly quadrupled from $2.90/bbl in 1970 to $11.60/bbl in 1974. This led to the search for solutions of higher extractability of existing crude oil reserves, particularly in the United States. While the use of other fluids was prevalent for flooding, supercritical CO_2 was injected into depleted oil reservoirs in the Permian Basin around this time. Most of the CO_2 being used for these injection wells was from natural CO_2 formations. While there were initial concerns about the long-term storage integrity of CO_2, field studies over the past five decades have shown very minimal leakage risk (Sminchak et al., 2020). Cumulatively, about 487 Mt-CO_2 have been stored via EOR across 26 projects. Out of these, twenty use captured CO_2 while six use CO_2 from natural reservoirs (Martin-Roberts et al., 2021). Deep saline aquifers have been used for storing about 73 Mt-CO_2, mostly in the Sleipner project in Norway.

Most of the successes in the CO_2 capture domain have largely been in sectors with existing high-purity process emissions. Only a few examples have been noted in the power sector. These are discussed in greater detail in Chapter 2. If all of these cases are added, they comprise nearly 35 facilities capturing 45 Mt-CO_2/year. It is notable that this is quite contrary to what was initially planned. Out of the 42 planned projects between 2009 and 2021, only 20 could reach a realistic level of CO_2 capture process development. These projects were anticipated to sequester almost 475 Mt-CO_2 (Martin-Roberts et al., 2021). The reasons for these included high initial investment and supply chain issues. Chapter 2 discusses some of these risks and Chapter 4 talks about mechanisms to alleviate some of these.

CO_2 utilization has also emerged as an important market. Around 230 Mt-CO_2 is utilized every year, with the primary user being urea production. Beverages, food and fabricated metals also involve the capture of ~18 Mt-CO_2 annually (IEA, 2019). Given the high utilization potential already present in CCU (of around 248 Mt-CO_2 annually) and a high number of products that may further be synthesized, it has a higher potential than CCS. Moreover, it may be deployed across all countries since demand for these projects exist universally, whereas CCS may not be deployed in countries with low geologic sinks (Table 1). The only key limiting factor for large-scale CCU is availability of green hydrogen to transform CO_2 into methanol and other value-added chemicals via methanol.

To estimate the projections for required CCUS volumes, we use the database provided by the Network of Central Banks and Supervisors for Greening the Financial System (NGFS) and maintained by the International Institute for Applied Systems Analysis (NGFS, 2022). It should be noted that these estimates are being used here because the exercise was carried out in consultation with a number of important financial institutions, and its inputs have also informed the G20 Working Group on Sustainable Finance. It features inputs from important integrated assessment models (GCAM, REMIND, MESSAGE) and involves seven different scenarios. Out of these, we showcase results from three scenarios until 2030. These include (Battiston et al., 2022; ter Steege & Vogel, 2021):

- *Current Policies:* This scenario assumes that only existing climate policies continue into the future, and there is no strengthening of climate ambitions.
- *NDC:* This scenario assumes that the conditional and unconditional pledges announced by the UNFCCC parties are met. It also involves extension of such policy analogues beyond 2030.
- *Below 2°C:* This scenario assumes optimal carbon pricing such that the rise in global temperatures by the end-of-century remain below 2°C with a likelihood of 67%.
- *Net Zero 2050:* This scenario assumes that global CO_2 emissions (all GHGs for some economies) will reach net-zero by 2050, meaning emissions will be countered by an equal amount of CDR. The global temperatures do not exceed 1.5°C in this scenario, compared to the preindustrial levels.

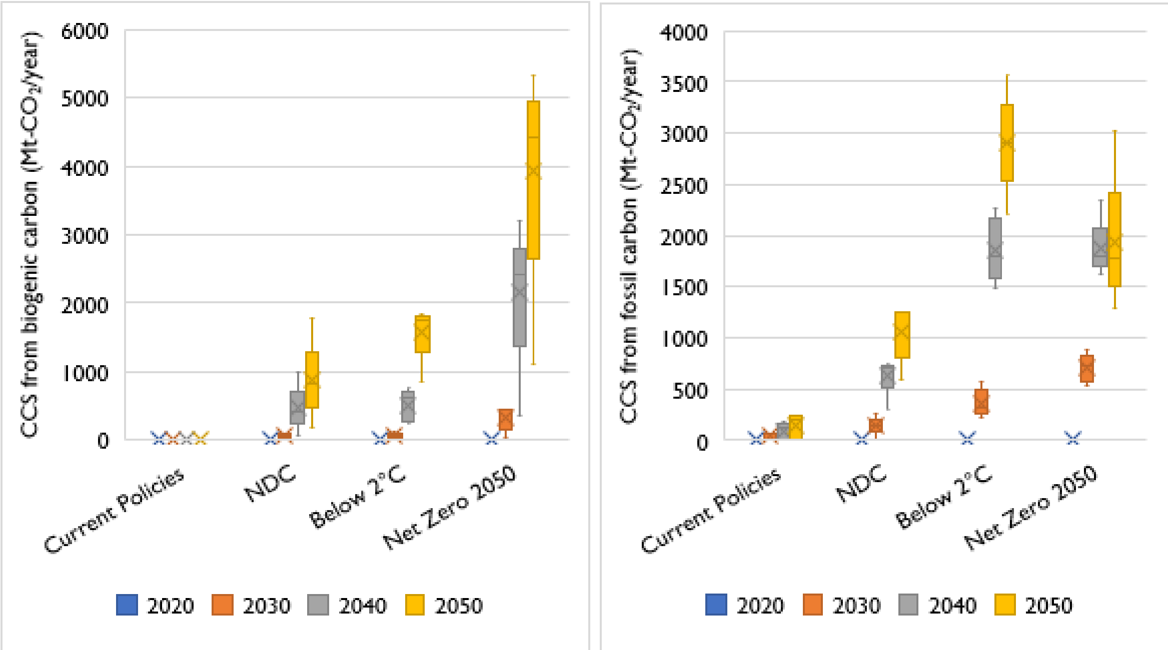

Figure 3. **Projected CCS volumes from biogenic carbon (left) and fossil carbon (right) sources during 2020-2050**

Source: *Authors made this figure from data in the IIASA's NGFS portal*

Figure 1.3 shows the projected volume of CCS in each of these scenarios. The key highlight of this figure is that adoption of fossil and biomass CCS is projected to increase across all the mitigation scenarios post-2020, and particularly after 2030. Moreover, higher stringency of the climate target results in higher adoption of biomass CCS, even more so than fossil CCS. These results are in line with the results in the IPCC AR6 (Clarke et al., 2022).

In the Current Policies scenario, there is no CDR via capture of biogenic carbon across any of the scenarios. This is because CDR does not play an important role in the stated policies by major economies. Some scenarios do show fossil CCS of about 200-250 Mt-CO_2/year, which is essentially an extension of the current trajectory of capture plants.

In the NDC scenario, the adoption of CCS is higher than the Current Policies scenarios. The minimum adoption of fossil CCS in this scenario is 590 Mt-CO_2/year in 2050, while the maximum is as high as 1250 Mt-CO_2/year. It is notable that the biggest jump in adoption is seen between 2030 and 2040. This is because several key commitments by major economies in this duration for decarbonizing the power sector. The NDC scenario also sees some adoption of bioenergy with CCS (BECCS), though that happens post-2040. Four out of five modeling runs project that BECCS will remain below 1000 Mt-CO_2/year in 2050.

The Below 2°C scenario projects higher adoption of fossil CCS, though the ranges become progressively narrow. For instance, the interquartile range for fossil CCS in 2040 is projected to be 1.6-2.0 Gt-CO_2/year, while that in 2050 is projected at 2.8-3.0 Gt-CO_2/year. This implies two features of the energy sector in the mid-century. First, it implies phasing down of all fossil fuels post-2040 in major economies. Moreover, it also implies that nearly all the fossil fuel use by 2050 will be mitigated via CCS. This scenario also sees substantial adoption of BECCS, with four out of the five modeling runs showing BECCS adoption of >1.7 Gt-CO_2/year in 2050.

The Net Zero 2050 scenarios show a little bit of reversal of the trend in fossil CCS adoption. In fact, most modeling runs show lower fossil CCS in 2050 than the Below 2°C scenario. This is because fossil fuels are phased down at a greater pace in this scenario. Moreover, as pointed out in the literature, aggressive 1.5°C scenarios often assume a rapid reduction in the technological costs of CO_2 capture. When this happens, the cost of CO_2 avoidance (Chapter 2) becomes lower for BECCS than for fossil CCS (Luderer et al., 2018). Thus, four of the five modeling runs indicate BECCS adoption of >4 Gt-CO_2/year in 2050, and all indicate at least 1 Gt-CO_2/year BECCS in 2050.

Scenarios for CO_2 utilization have also been developed by some researchers, though they have not been fully incorporated in IAMs. Particularly, Kätelhön et al. (2019) have developed two sets of scenarios for the EU context. The first scenario is the low-TRL scenario where CO_2 is directly converted to chemicals after reacting with other reagents such as hydrogen (which in turn is produced from electrolysis. The second scenario is the high-TRL scenario where CO_2 is initially transformed into methane or methanol, and subsequently converted into aromatics or olefins. These scenarios discuss the overall grid emission factor, at or below which it is feasible to synthesize these chemicals via CCU as opposed to incumbent products.

Table 2. Electricity carbon footprints (in gCO2e/kWh) for which the CCU-based production of chemicals becomes preferable to conventional production in terms of life-cycle GHG emissions

Chemical	High-TRL scenario	Low-TRL scenario
Benzene	100	213
Carbon monoxide		44
Ethylene from H_2		189
Ethylene from methanol	124	219
Methane	137	137
Methanol from H_2		215
Methanol from syngas	260	300
Mixed xylene	74	235
Para xylene	102	334
Propylene from H_2		213
Propylene from methanol	124	219
Styrene		317
Toluene	82	217

Source: (Kätelhön et al., 2019)

1.3 CCUS opportunities in various industrial sectors

CCUS may have wide-ranging applications in reduction of emissions from point sources to creation of value-added products. Here, we discuss some common avenues where mitigation opportunities may be present. Figure 1.4 shows the CO_2 emissions contributions from the five sectors, as categorized in the EDGAR database, with important linkages to CCUS discussed below.

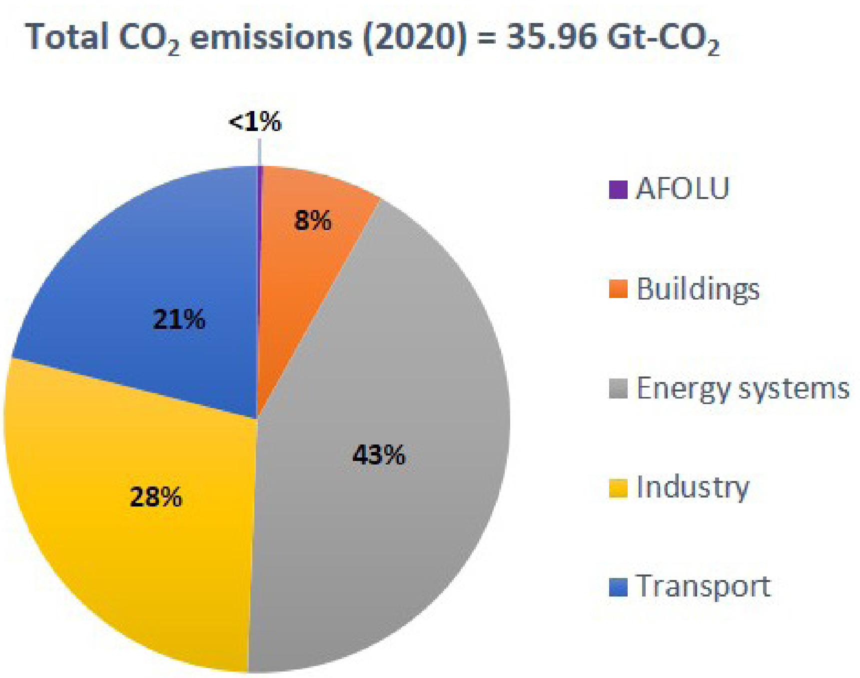

Figure 4. Sources of global CO_2 emissions in 2020 from the EDGAR database

Source: Authors' visualization based on data from (Minx et al., 2021)

1.3.1. CO_2 capture

Power sector: Out of the ~36 Gt-CO_2 emitted in 2020 across sectors, 43% emissions occur in the energy systems sector. These emissions are mostly in the form of point sources. Notably, generation of electricity and heat results in 36% of global CO_2 emissions (13 Gt-CO_2). Petroleum refining is also an important contributor to CO_2 emissions in the energy sector, resulting in 1.6% of global CO_2 emissions. These emissions can be captured via CCUS approaches. Some fugitive CO_2 emissions also result from coal mines (due to spontaneous oxidation of the coal) and oil and gas processing (A. K. Singh et al., 2022). These have lower CO_2 concentration and therefore do not represent significant CCUS opportunities. As noted before, the power sector (particularly from coal combustion) is the biggest contributor to CO_2. A large part of the electricity generation fleet in these countries is old (U. Singh & Rao, 2016). Thus, there have been discussions surrounding retrofitting some of the existing plants with CO_2 capture units. The advantage in these cases is that the capital costs associated with the base plant are already amortized. Thus, the incremental cost of electricity is not that high. That said, older units may have subcritical units with boiler efficiencies below 80% and net plant efficiencies below 35%, which makes the cost of CO_2 capture expensive. This is because the emission factor of CO_2 emitted per unit of electricity generated is higher. The cost of CO_2 capture per MWh may be obtained by multiplying the cost of capture per tonne of CO_2 with the emission factor per MWh. Even as the first term is constant assuming state-of-the-art technology, a more inefficient unit will have higher emission factor, resulting in overall higher cost of capture per MWh. Thus, several supercritical and ultra-supercritical units with net plant efficiency of 38-45% could be considered for CCUS (Hu & Zhai, 2017). It is notable that some large point sources of CO_2 in India emit 25-30 Mt-CO_2. Translating this into a full-scale capture would entail mitigation of 1% of the country's total GHG emissions from just one power plant (Garg et al., 2017). Important opportunities for CCUS in natural gas combined cycle plants (NGCC) also exist, though the costs of capture in such units may be higher (Chapter 2). These opportunities are most notably present in the United States where the 45Q tax credits could incentivize capture of nearly 400 Mt-CO_2 annually (Psarras et al., 2020). IGCC plants may also be considered as good sources of CO_2 capture though such plants have not yet taken off at scale.

Industry sector: The industry sector is the next key contributor to CO_2 emissions with about 28% of global emissions. Again, most of these emissions may be categorized as point sources. Particularly, emissions in the metals sector (steel plants) comprise 8.2% of global emissions. Production of chemicals and cement adds an additional 4% and 6% of CO_2 emissions. Thus, close to 70% of global CO_2 emissions are currently occurring from point sources of CO_2. This places into context the role of CCUS in these sectors. The large point sources in the industry sector (most notably, steel, cement, fertilizers, and refineries) are also important candidates for CCUS. The fertilizer sector has already incorporated CO_2 capture in a number of important facilities across the world. The costs and other considerations associated with CCUS from industrial point sources is discussed in detail in Chapter 2. It is notable that the industry sector emissions consist of both process emissions and combustion emissions, as opposed to only latter in the power sector. The process emissions result from chemical decomposition/oxidation of a complex compound to form CO_2 and are generally higher in purity. For instance, 17% of the emissions from a refinery and 23% of emissions from a cement plant are process emissions and depict low-hanging fruits for CO_2 capture at low cost (Pilorgé et al., 2020).

1.3.2. CO_2 utilization for creating value-added products

CO_2 utilization to produce fuels, chemicals, and materials: We have already discussed the potential for creating methanol from captured CO_2 for use as a chemical or as an energy carrier. While we have discussed CCU in the next chapter as well, it is important to note that the time duration of CCU is different from CCS. While CCS ideally involves CO_2 storage over 1000 years with minimal leakage, the permanence of CO_2 storage in CCU depends on the end product. Some pathways involve CO_2 utilization to produce combustible liquid fuels, such as

algae biofuels, methanol (when used as an energy carrier) and Fischer-Tropsch Biofuels. These pathways are critical for transport subsectors such as aviation and shipping, where electrification is either cost-prohibitive or not yet possible. Since these pathways involve combustion of the fuel and emission of the CO_2, these are called as 'cycling' pathways (Hepburn et al., 2019). Other pathways, where CO_2 is permanently sequestered at comparable timescales to CCS, such as plastics, are called as 'closed' pathways. Some technological avenues like soil carbon sequestration, biochar and urea production involve interaction of the engineering carbon flow with the natural carbon cycle and are called as 'open' pathways (Hepburn et al., 2019).

While the literature characterizes partially circular pathways, we may also visualize a completely circular pathway in this report. Consider the case of CO_2 captured from a power plant or industrial source. If this CO_2 is reacted with green hydrogen (produced using renewable electricity), it can produce methanol. This methanol can be burned in multi-fuel boilers that are capable of using liquid fuels. It may also be used as a start-up fuel in coal-fired boilers. If the CO_2 stream from this boiler is again captured to produce methanol, it effectively creates a completely circular system which may produce energy at very close to net-zero emissions.

Enhanced oil recovery or enhanced coalbed methane recovery: The first example of deep injection of CO_2 in the world is from the Permian Basin in the United States from the early 1970s (Lake et al., 2019). Here, CO_2 was injected in depleted oil reservoirs not as a way of climate change mitigation but rather as an approach to accelerate oil recovery that had stagnated after primary and secondary recovery methods had been deployed. This is called as enhanced oil recovery (EOR) and has been quite successful in terms of long-term storage of CO_2 (Sminchak et al., 2020). Similarly, it has been posited that this approach could be utilized in the case of unmineable coal seams, to facilitate enhanced coalbed methane recovery (ECBM). While this approach is still at the demonstration stage (Pan et al., 2018), it has an advantage in terms of the permanence of CO_2 storage. Coal has a highly adsorptive porous structure, and it is anticipated that ECBM could deliver suitable sequestration at depths as low as 600m.

1.4 Macroeconomic impacts of CCUS

Macroeconomic impacts of CCUS refer to the impacts of CCS on the economy as a whole, instead of its impact at a facility level (which is discussed in Chapter 2). Given the large heterogeneity in CCUS potential and adoption globally, macroeconomic impacts are anticipated to vary substantially. We discuss three key macroeconomic impacts of CCUS: (1) impact on GDP, (2) impact on employment, and (3) reduction in stranded assets.

The impact CCUS will have on the GDP Is quite uncertain because different countries are anticipated to have different scales of CCUS adoption. CCS and CCU may affect the GDP differently.

For CCS, analysis for the United Arab Emirates showed that the impact remained limited currently, as the increment in hydrocarbon recovery was 0.1%. As such, it is difficult to notice any observable differences without a more rapid expansion of CCUS (Tsai et al., 2013). One of the initial estimates on the impact of CCS on the GDP was carried out for coal-fired power plants in China (Vennemo et al., 2014). They used a computable general equilibrium (CGE) model to understand the policy-cost CCS would add to the GDP. In other words, their analysis estimates the additional costs through a *de facto* tax on carbon in a variety of scenarios. They found that in the absence of international finance, CCS could lead to reduction of the GDP by 4%, which could be inhibitory for large-scale deployment (Vennemo et al., 2014). While the addition of CCS is expensive, it is imperative that it is kept in the energy mix. Analysis of into Japan's long-term mitigation policy clearly highlights that artificially limiting CCS and nuclear lead to GDP loss of 6.4% and 3.5% respectively. This is also the most influential factor affecting the GDP loss, when compared to other factors such as unavailability of low-cost renewables and nuclear phase-down. They also observed that the absence of CCS did not result in a higher use of renewable power (Silva Herran et al., 2019). An additional CGE analysis from China also showed important positive results for CCS adoption. They showed that while some GDP loss is noted for CCS adoption, it also offsets much higher GDP losses accompanying electric vehicle (EV) adoption. This is because CCS and EV adoption in tandem lead to decarbonizing the transport sector, while also reducing import dependence for crude oil (Li et al., 2017). For CCU, the contribution to the GDP is anticipated to be largely positive, though the magnitude is uncertain. This is because of the potential to create value-added products and generate foreign direct investments. CCU will also avert unemployment in the coal mining sector while also providing opportunities in green power and hydrogen production facilities.

Apart from equilibrium analysis, input-output (IO) analysis has also been used for estimating impact of CCS adoption on the gross value addition (GVA), which adjusts the GDP with the subsidies and taxes on a certain commodity. Results from an IO analysis in the Netherlands showed that the scenario with high CCS was $0.8B less than the baseline. This is particularly because the GVA uses taxes as a subtracted term, and carbon taxes accordingly lead to reduction in the GVA (Koelbl et al., 2016). However, GVA addition can be higher in scenarios creating high-value biofuels and bioproducts resulting from CO_2 capture, as evidenced by an analysis by the same group for the entire European Union (Koelbl et al., 2015). Thus, the implications of CCUS on the GDP/GVA remain uncertain and are quite dependent on the methodology followed, the co-products associated with the process, and the regional context.

In terms of employment, CCUS can provide two important contributions. First, a large number of workers are employed in the fossil fuel supply chains and a full phase-out without CCS may results in massive losses of employment. Four G20 economies – China, India, United States and Australia – employ around 7 million people in the coal mining sector alone (Pai et al., 2020). When considering the entire supply chain, a similar amount of people may be considered, especially as some jobs in the unorganized sectors may not be accounted for in the literature (Garg et al., 2022). Having CCUS in the energy mix would slow down job losses for these employees. In addition, setting up of infrastructure and equipment for CCUS could lead to additional high-wage jobs. Table 1.3 shows the preliminary analysis of such employment that could be created.

Table 3. Annual jobs created for 700 Mt-CO_2/year CO_2 capture cluster in the Great Plains in the United States

	Project jobs	Operation jobs
Industry capture		
Steel	1680 – 3030	170 – 310
Refinery	440 – 760	40 – 70
Cement	430 – 690	60 – 110
Hydrogen	175 – 300	20 – 30
Ethanol	30 – 50	5 – 10
Power sector capture		
Coal	1800 – 3350	160 – 300
NGCC	1140 – 2090	100 – 180
Transport		
Trunk Line	1,250 – 2190	8 – 20
Feeder Line	250 – 370	2 – 5

Source: (Rhodium Group, 2020)

An important benefit of CCUS is the potential ability to reduce stranded assets in the coal and gas sectors. Broadly, stranded assets may be defined as, "assets [that] suffer from unanticipated or premature write-offs, downward revaluations or are converted to liabilities" (Ansar et al., 2013). Stranded assets may create economic shocks that disrupt the macroeconomic system (Clarke et al., 2022). The IPCC AR6 states that stranded assets do not include only assets in the power sector, but also reserves of fossil fuels as well. Overall, the global value of stranded assets that may be created is \$1-4 trillion (Mercure et al., 2018). Using CCUS in the fossil sector to reduce end-of-pipe emissions and CDR to offset residual emissions could substantially bring down this high value of potential stranded assets.

Chapter 2

Global estimation of costs and risks associated with CCUS implementation

The costs associated with CCUS have been identified as one of the biggest deterrents to its large-scale implementation (Clarke et al., 2022). This section aims at providing estimates of the current CCUS costs and some future projections on how they might decline. It also elucidates some critical factors that add monetary risks to CCUS projects, with subsequent chapters discussing approaches to alleviate such risks.

Before discussing the cost estimates directly, it is imperative to understand that different metrics have been used in the CCUS literature. Because the power sector is considered critical in its contribution to large point sources, several sources have studied integrating or retrofitting CO_2 capture equipment into existing power units (U. Singh & Singh, 2016). Here, the most commonly used metric is the increase in the levelized cost of electricity. However, several G20 economies have increasingly indicated that the key form of power sector decarbonization will be in the form of renewables or nuclear power (Denholm et al., 2022). In such cases, CCUS could be more critical for so-called "hard to abate" sectors in industry (Davis et al., 2018). In those cases, the relevant metric is the incremental cost of product (e.g. steel, cement, fertilizer, etc.). These metrics are often sector-specific and inhibit comparison and prioritization. As such, most of this section deals with the metric of cost of CO_2 avoidance. The cost of CO_2 avoidance refers to the increased cost of the commodity (in the power or the industrial sector) that is required to produce the same unit quantity. Thus, in the power sector, the cost of CO_2 avoidance may be defined as follows (Rubin, 2012):

$$Cost\ of\ CO_2\ avoidance\ (\$/t-CO_2) = \frac{\left(Cost\ of\ plant\ with\ CCS, \frac{\$}{MWh}\right) - \left(Cost\ of\ reference\ plant, \frac{\$}{MWh}\right)}{\left(Emission\ factor\ of\ reference\ plant, \frac{t-CO_2}{MWh}\right) - \left(Emission\ factor\ of\ plant\ with\ CCS, \frac{t-CO_2}{MWh}\right)}$$

The use of this metric allows us to prioritize sectors or individual facilities through the marginal cost of avoidance of CO_2. It also helps us in comparing CCUS against other mechanisms of GHG reduction. For instance, some older subcritical units with efficiency of lower than 35% may be subject to renovation and maintenance. Often times, the investments in these cases are offset by the co-benefits of reduced fuel use and the costs may be lower than replacing an entire plant with a solar facility (Singh et al., 2016).

Another reason for using of the above metric is that CO_2 sequestration incentives are often awarded per tonne of CO_2 avoided. This is done to avoid any perverse incentives to inefficient plants, that may result if the total CO_2 captured is incentivized. For instance, the 45Q tax credits in the United States provide \$135/t-CO_2 for CCS on point sources and \$180/t-CO_2 for CO_2 from the ambient air (Anderson et al., 2022). Thus, if the cost of CO_2 avoidance is lower than the awarded incentive for a particular sector, it should nominally be able to operate profitably. In the following paragraphs, we separately discuss the costs of CO_2 avoidance for CO_2 capture, CO_2 storage in geologic formations (CCS) and CO_2 utilization to create value-added products (CCU).

2.1 Costs of CO_2 capture

The cost of CO_2 capture is defined as follows:

$$Cost\ of\ CO_2\ capture\ (\$/t - CO_2) = \frac{\left(Cost\ of\ plant\ with\ CCS, \frac{\$}{MWh}\right) - \left(Cost\ of\ reference\ plant, \frac{\$}{MWh}\right)}{\left(Amount\ of\ CO_2\ captured\ irrespective\ of\ energy\ penalty, \frac{t - CO_2}{MWh}\right)}$$

The costs of CO_2 capture are the most significant cost component in the CCS supply chain. For a CCS value chain involving CO_2 capture from a power plant and its sequestration in a deep saline aquifer (i.e., without any revenue from EOR/ECBM), the CO_2 capture phase likely contributes to 60-75% of the overall system costs. These costs are largely dependent on three factors:

1. The concentration of CO_2 in the flue gas
2. The scale at which the facility is operating
3. The fraction of CO_2 from the point source being captured

The first factor, i.e., concentration or purity level of CO_2 in the flue gas is by far the most important factor in determining the system costs. This is evident by the fact that most operational CO_2 capture units in the world have been from high purity sectors where the costs of capture are negligible or very low. Figure 2.1 shows the costs of CO_2 capture from various point source sectors. This is also called the “Sherwood plot” i.e., the characterization that the cost of separation of any waste product becomes higher as its concentration in the product stream becomes lower.

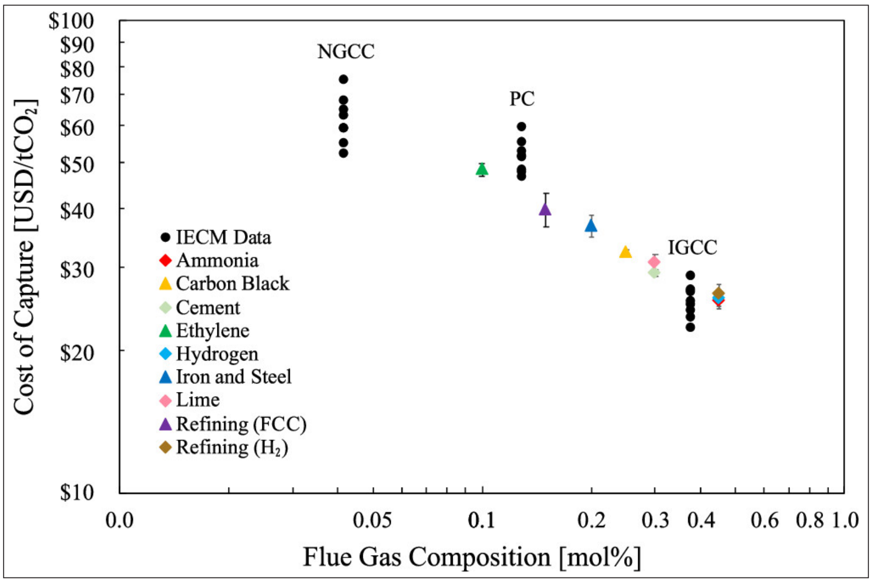

Figure 5. Cost of CO_2 capture for different large point sources plotted against the flue gas composition

Source: (Pilorgé et al., 2020) Adapted with permission from the American Chemical Society.

Figure 2.1 shows that the costs of CO_2 capture in the natural gas combined cycle (NGCC) plants are generally the highest (\$60-80/t-CO_2). This is because the CO_2 concentration in the flue gas is about 3.5%. The cost of capture for pulverized coal (PC) plants is somewhat less (\$50-70/t-CO_2). That said, it should be noted that a PC plant also has an emission factor of 2-2.5 higher than an NGCC plant so the overall costs per unit power depend on the net capacity of the plants. So far, two examples of CCS in PC plants have existed at the commercial scale, the Boundary Dam plant in Canada and the Petra Nova plant in the United States. In the Boundary Dam plant, the cost of CO_2 avoidance was \$65/t-CO_2 and the cost of CO_2 capture was \$40/t-CO_2. Contrastingly, the cost of CO_2 capture for the Petra Nova plant (now suspended) was about \$30/t-CO_2. The slightly lower cost was due to a different engineering design of the plant where the heat supply came from an auxiliary gas boiler (Mantripragada et al., 2019). In the power sector, the lowest costs of CO_2 capture would likely be in the case of IGCC plants where costs of capture of \$20-30/t-CO_2 may be observed. These lower costs occur due to a higher flue gas concentration of CO_2 in the flue gas at about 40-60%. Moreover, the pressure at which the CO_2 is obtained is also significant i.e., 30-40 bar (Ho et al., 2019). This renders it more usable for onsite uses, i.e., where the source and sink are located in close proximity without additional compression needs. An important example of commercial application of IGCC with CCS was in the case of the Plant Ratcliffe in the Kemper County in the United States. Here, the plant was suspended due to financial and other reasons. However, about 0.3M tonnes of CO_2 was captured during operation (Nelson et al., 2018).

As discussed earlier, most of the CCS development has occurred in the industrial sector where High-purity sources of CO_2 may be found. The lowest cost of CO_2 capture is in the ethanol bio refinery sectors. Here, the fermentation of feedstock for ethanol production yields ~99% purity CO_2. As such, the costs of CO_2 capture are considered close to zero, especially as the CO_2 is obtained at high enough pressure suitable for onsite use. Similar opportunities may also exist in the renewable natural gas sector as well. These two CO_2 sources are also biogenic, and as such, may be considered as applications of BECCS. An example of CCS in the ethanol sector is the Decatur Plant in Illinois in the United States with a capacity of 1 Mt-CO_2 captured annually (Gollakota & McDonald, 2014).

In the case of fossil CO_2, the sector with most active CO_2 capture is natural gas processing. Here, the flue gas may contain 65-99% purity levels of CO_2. Several important projects have been operating or planned in this sector at >100,000 t-CO_2/year capacity. These include the Val Verde plant in the United States, the Al Salah plant in Algeria, part of the Sleipner project in Norway and the Abu Dhabi project in UAE. In addition, high-purity CO_2 capture opportunities also exist in ammonia and fertilizer production plants. Here, the cost of process CO_2 emissions is very close to zero. Thus, key projects in Alberta in Canada and Oklahoma in the United States have emerged. That said, ammonia production is also significantly energy intensive and substantial energy-related CO_2 emissions may occur. Thus, the overall cost of CO_2 capture is ~$25/t-$CO_2$ (Figure 2.1). These costs are similar to the cost of CO_2 capture from steam methane reforming (SMR) plants producing blue hydrogen, alongside steel and cement plants. Another point source sector of interest is the refining sector which is unique because of multiple streams of CO_2. Thus, costs of capturing CO_2 from the process emissions in the catalytic converter unit is quite low. But the overall cost of CO_2 capture from the entire facility is similar to that of a coal-fired power plant (Yao et al., 2018).

Finally, capturing of CO_2 from ambient air has also emerged as a significant opportunity for achieving CDR oval from the atmosphere. This technology is particularly critical for countries where substantial emissions are transport-related, i.e. not in the form of point sources. DAC were quoted at very high levels ($600-1000/t-$CO_2$) a decade back (Socolow et al., 2011). However, accelerated R&D efforts have brought down these costs to $220-250/t-$CO_2$ when reported at a scale of 1 Mt-CO_2 annually (Keith et al., 2018; McQueen et al., 2020). With large government and private sector efforts, these costs are estimated to further come down to $100/t-$CO_2$ or so. However, the success of DAC is incumbent on provision of low-carbon electricity, failing which the overall avoidance costs may be high.

The costs of CO_2 capture are projected to come down in the future with increased technological learning and economies of scale. The exact reduction in cost trajectory is speculative as it depends on the actual level of deployment. The endogenous learning curve for any technology is commonly indicated as (Rubin et al., 2015):

$$y_i = a{x_i}^{-b}$$

where y_i is the cost to produce the ith unit, x_i is the cumulative production through period i, a is the cost to produce the first unit and b is the learning rate exponent. The quantity $(1 - 2^{-b})$ is defined as the Learning Rate (LR), which is the cost reduction taking place when the cumulative production doubles. The learning rates for capital CO_2 capture system costs are taken as 0.06-0.17. The corresponding learning rates for CO_2 capture O&M costs is 0.10-0.30 (Rubin et al., 2004).

2.2 Costs of CO2 compression

In addition to CO_2 capture, the costs of compression may also add about $5-10/t-$CO_2$ to the overall system costs (Pilorgé et al., 2020). This is largely in the form of additional electricity requirement for operating the compressor units. These costs arise when CO_2 has to be compressed to about 2000 psi, i.e. a supercritical stage. At commercial scales in the future, where transport of CO_2 is required, these costs may be assumed. These costs may not come down appreciably in the future as CO_2 compression is a relatively advanced technology.

It may be noted that some onsite uses of CO_2 do not require CO_2 compression if the source and sink are in close proximity. The most common example of this situation is in the case of algae production, where even 1 bar pressure of CO_2 is adequate (Ou et al., 2021). Other opportunities where low pressure of CO_2 may be utilized are the production of carbonated beverages, polycarbonates, methanol (and derivative products), refrigerants, metal casting and mineral carbonation (Table 2.1). These values may be compared to the product pressure emerging out of various point sources, as shown in Figure 2.2. Thus, IGCC, ammonia plants, natural gas processing plants, and SMR facilities may be key candidates for utilizing CO_2 for the aforementioned applications.

Table 4. CO_2 pressure required for various end use applications.

Application	CO_2 pressure	Total pressure
carbonated beverage	2 bar	≈2 bar
enhanced gas recovery	120 bar	≈120 bar
enhanced oil recovery	89.6–150 bar	≈90–157 bar
enhanced coal bed methane recovery	60–200 bar	≈60–200 bar
polycarbonates	1 bar	≈1.05 bar
methanol	1–3 bar	61–63 bar*
methane	0.04 bar	1 bar*
urea	121.6 atm	≈121.7 atm
algae		
refrigerant	70–100 bar	≈70–100 bar
metal castings	95 bar	≈100 bar
decaffeination agent	300 atm	≈300 atm
mineral carbonation	0.06–150 bar	≈1–150 bar

Source: *(Ho et al., 2019). Adapted with permission from the American Chemical Society.*

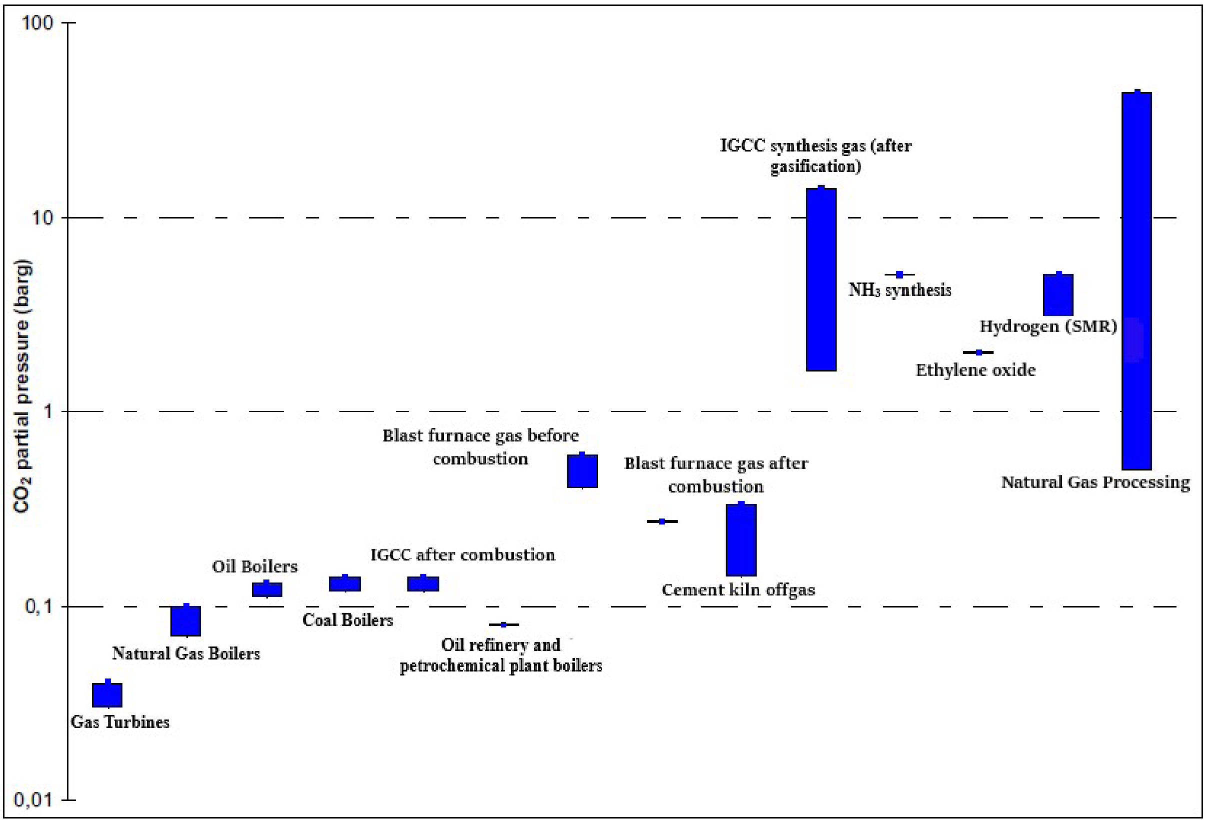

Figure 6. Partial pressure of CO2 from various point sources

Source: (Kaarstad et al., 2011). Reproduced under the CC BY-NC-ND license.

2.3 Costs of CO_2 transport

The costs of CO_2 transport via pipelines depends on scale. Pipelines may not be designed in continuous lengths. Instead, they come in specified, discrete nominal diameters – which depend on the CO_2 throughput and the length of the pipeline such that CO_2 remains in supercritical phase throughout. Figure 2.3 shows the annualized costs of pipelines as a function of the throughput and length. These costs correspond to \$0.5-1.5/t-CO_2 for a 100 km stretch of the pipeline (U. Singh, Loudermilk, et al., 2021).

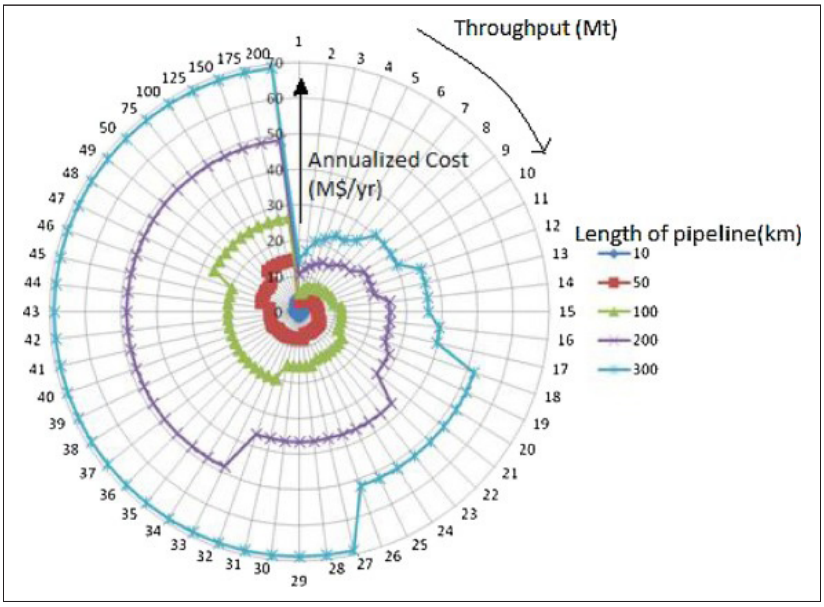

Figure 7. Radar chart depicting variation of annualized diameter costs against changes in length and throughput

***Source**: (Garg et al., 2017) Reproduced with permission from Elsevier.*

2.4 Costs of geologic storage of CO_2

The costs of geologic storage of CO_2 depend on the type of formation that is being utilized. So far, most of the operational sinks have been in the form of depleted oil reservoirs which facilitate EOR. Depending on the price of international crude, the costs of CO_2 storage in this case may or may not help offset capture costs. Assuming an international crude price of $60/bbl, a recent analysis showed that EOR-linked CCS in India might deliver revenues of $100/t-$CO_2$ for coal-fired power plants (Vishal et al., 2022). At this rate, the costs of other parts of the supply chain are largely offset. There are four key limitations associated with this strategy. First, while EOR offsets costs, it may also undercut the CO_2 captured because of the combustion of the derivative products of crude. Thus, the life cycle efficacy of EOR largely depends on the effectiveness of process (i.e. barrels of oil recovered per unit of CO_2 injected). Second, EOR also does not deliver uniform CO_2 injection. Thus, most of the CO_2 injection occurs in the initial phase of the project and the latter phases involve recycling of the co-produced CO_2 along with oil (U. Singh & Dunn, 2022). Third, the storage capacity in such reservoirs is limited and only a fraction of the actual requirement from CCS globally. Fourth, the costs are largely linked to the revenues indicated above. As such, when international crude prices decline, this financial model may be challenged.

As such, long-term geologic CO_2 storage will likely have to hinge upon injection in deep saline aquifers. The costs associated with these aquifers range from $2-30/t-$CO_2$ (U. Singh, Loudermilk, et al., 2021). This variability arises due to the differences in geologic characteristics of the sinks. If the sink is in a depth of 1000-2500m, the costs of storage are generally less than $10/t-

CO_2. However, at higher depths of 3000-4000m, the associated costs of drilling may increase exorbitantly. Another consideration associated with these costs is the porosity and permeability of these reservoir. A higher porosity facilitates easier subsurface transport of the CO_2, thus reducing the number of wells that must be drilled per unit area.

Additional costs associated with CO_2 storage may also manifest in the form of brine management and long-term monitoring, reporting and verification (MRV) costs.

2.5 Cost of CO_2 utilization

The costs of CO_2 utilization are more complicated to estimate because of the diverse set of end uses that may result. Hepburn et al. (2019) carried out an exhaustive analysis of the CCU pathways in a low-potential and high-potential scenario (also adapted in the IPCC AR6). These costs are represented in the form of the marginal abatement cost curve shown in Figure 2.4. This figure has several important features. First, it arranges all the major CO_2 utilization pathways in ascending order of the cost of avoidance. The x-axis shows the carbon avoidance potential of each pathway, while the y-axis shows the breakeven cost, i.e., the carbon price at or above which the product created via CO_2 utilization is cheaper than the incumbent. As such, the area of each rectangle shows the overall investment required annually in 2050, from that pathway. This chart may be interpreted in two different ways. If there is a maximum constraint on the carbon price, then all the potential technologies below that price may be utilized. Alternatively, if there is a minimum constraint on the CO_2 that must be abated, this graph indicates the minimum carbon price needed for that.

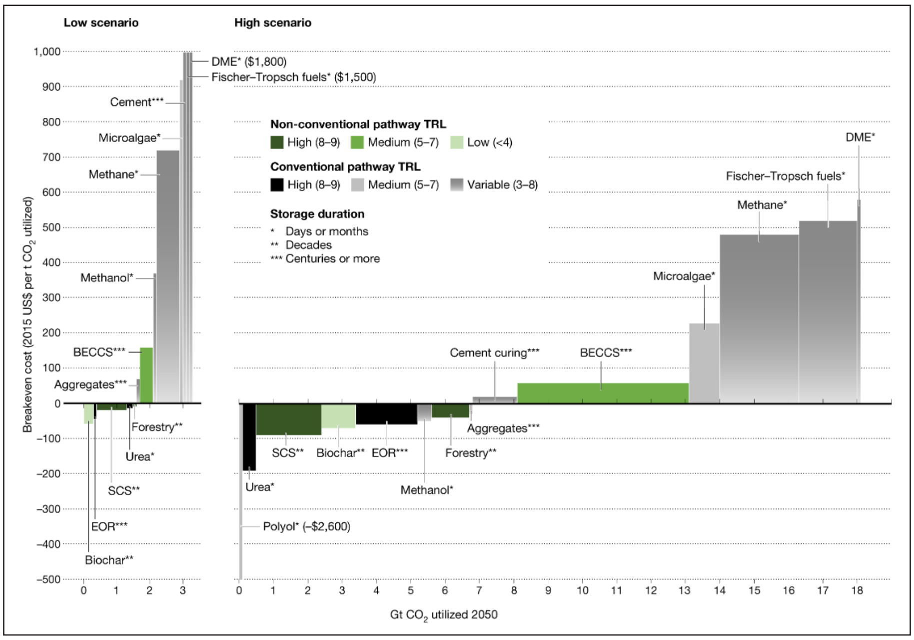

Figure 8. Estimated CO_2 utilization potential and breakeven cost of different sub-pathways in low and high scenarios

Source: (Hepburn et al., 2019)

Here, the high-potential scenario assumes that the CCU derived products will displace a greater market of the incumbent product. Thus, in the case of concrete, the high-end estimates replacing almost 70% of the current concrete market through the CCU derivative product. The negative costs of carbon avoidance here represent the cases where the CCU derivative product would be cheaper than the incumbent product. Such cases largely arise with the prevalence of free feedstock, lower discount rates and availability of excess electricity (Hepburn et al., 2019). Some places with negative breakeven costs may also be or with the provision delivering carbon sequestration by themselves (e.g. biochar, EOR or soil carbon sequestration).

The key pattern visible in Figure 2.4 is that the low scenario where only 3 Gt-CO_2 is utilized annually is reflective of much higher costs. Thus, the costs of methanol production in such a scenario are in excess of \$300/t-CO_2. Contrastingly, higher deployment of CCU are anticipated to bring down these costs. Thus, methanol production breakeven costs come down below \$0/t-CO_2. At this scale, CCU based methanol is likely to become cheaper than conventional methanol. That said, further converting methanol to methane results in a high cost (\$500-700/t-CO_2) irrespective of the scenario because of the large energy investment (Hoppe et al., 2018). The costs of production of Fischer-Tropsch fuels are currently very high (\$1500/t-CO_2) though it may come down below \$500/t-CO_2 with higher technological learning. It must be noted that such fuels are currently at a low technology readiness level and it is anticipated that these costs would further reduce as technological breakthroughs occur (Prussi et al., 2019).

A critical accounting consideration associated with CCU is the allocation of the life cycle emissions. A number of studies so far have considered the entire CO_2 reduction benefit to be allocated to the CCU derivative product. Thus, the cost of avoidance may be lower than a case where the benefits are equitably allocated to the product and the point source. It is, therefore, recommended that a consistent way of apportioning these benefits is developed to avoid costing ambiguities not otherwise present in the case of geologic CO_2 storage.

2.6 Key financial risks associated with CCUS deployment

Because of the large coordination required across the CCUS supply chain, a number of risk factors may emerge (Figure 9).

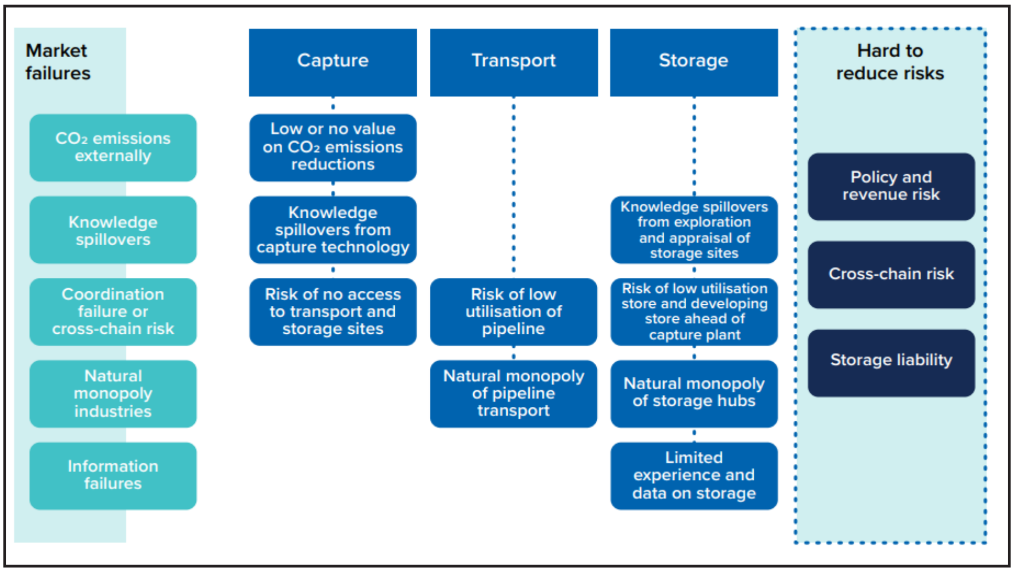

Figure 9. Market failures across the supply chain

Source: (Zapantis, 2019)

Some of these risk factors are associated with early deployment and are likely to be solved in the first five years of commercial scale deployment in a country. For instance, the first movers in a CCUS technology may not benefit from the knowledge spillover in CO_2 capture. Thus, there may be a rush to 'wait and see' in the case of large-scale projects. Some of this is alleviated through government support and/or funding for alleviating such risks (Zapantis, 2019). Another factor may be the relatively underexplored geologic sinks. Generally, most countries with prevalent fossil fuel extraction have a substantial database associated with the stratigraphy of oil, gas and coal reservoirs (U. Singh, Sharma, et al., 2021). The United States has a five-decade experience of carrying out EOR in the Permian Basin. However, sequestration in saline aquifers is relatively underexplored barring the experience of the Sleipner field in Norway. In India, the storage capacity of saline aquifers has not been carried out in substantial detail. This risk may also be averted by either using EOR/ECBM or CCU approaches for initial CO_2 capture projects.

However, other factors are harder to abate and may arise throughout the lifespan of the CCUS project. Further sections of this report will discuss ways of reducing such risks. The first such risk is availability of revenue for the captured CO_2. As noted in Figures 2.1 and 2.4, the cost associated with CO_2 capture and several configurations of CO_2 utilization is significant. The large-scale deployment of CCUS in IAMs is often contingent on a nationwide/global carbon price. If a carbon market is established, it would be vulnerable to some price variations. This might dramatically alter the project economics of CCUS.

The second hard to abate risk pertains to coordination across the supply chain. Successful CCUS implementation requires capture of CO_2, its polishing and compression, transport and finally its uptake via geologic sinks or a saleable commodity. Often, one or more components of this supply chain may be less developed or be vulnerable to other risks. For example, CO_2 pipeline construction may have to undergo clearances from national/local governments regarding forest and ecological risks. If the captured CO_2 is being used for EOR or producing a commodity such as methanol, its business model hinges on the market price of the commodity. Particularly, in the case of EOR, the international crude price volatility is associated with some degree of risk. Thus, the Petra Nova plant in the United States was capturing close to a million tonnes of CO_2 but was integrated with EOR (Meckel et al., 2021). During the COVID-19 pandemic, crude oil prices came down to a historic low, because of which CO_2 capture operations had to be halted at this facility and are yet to reopen at the time of writing of this report. That said, standalone oil explorations have continued despite crude price volatility due to energy security priorities, in order to reduce import dependence of oil.

The third hard to abate risk is associated with storage liability. Depending on the type of CCUS configuration, the CO_2 may be sequestered for a number of years. For instance, in the case of geologic storage, 99.9% of the CO_2 may be considered to be safely stored for 100 years and 99% of it for 1000 years in well-regulated reservoirs. However, the leakage risk may be as high as 2-17% in a poorly-regulated onshore reservoir over a 100-year duration (Alcalde et al., 2018). Such risks also exist in the case of CCU. For instance, biochar may be considered to store 40-60% of the CO_2 over a time horizon of 100 years. However, this is completely re-emitted back into the atmosphere over a time horizon of 1000 years (Chiquier et al., 2022). As the time duration of the MRV process is strongly linked to leakage rates, operators may perceive a risk associated with storage liability.

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Chapter 3
Investment Outlook

The last five years have seen a significant advancement in IAM methodology, in terms of metrics being reported. An important, policy-relevant metric that has been incorporated within key IAMs is the investment required across various energy subsectors. These analyses show several important conclusions. First, the magnitude of energy investments, globally is $1800 billion/year currently. This would need to increase up to $2400-4700 billion/year in deep decarbonization scenarios converging to 1.5°C scenarios (McCollum, Zhou, et al., 2018). They also conclude that the nature of energy investments would also need to realign. Currently, the most significant investments are going to fossil fuel extraction and power plant construction. In the future, these would need to be realigned with substantial funds going to energy efficiency, renewables and transmission and distribution infrastructure. It is noteworthy that the investments required for climate action are substantially higher than meeting other societal targets such as food security and water access (McCollum, Zhou, et al., 2018), with several developing economies likely to prioritize the latter for government funding (McCollum, Echeverri, et al., 2018). This also highlights the case for finding other financial mechanisms for funding CCUS projects (Chapter 4).

3.1. Investments required for CCUS in upcoming years

We used the NGFS scenarios – as described in Chapter 1 – to estimate the investments required for CCS in power plants (coal, gas and oil), and also the transport and storage infrastructure (Figure 3.1).

The investments in the coal CCS sector remain fairly low in the 'Current Policies' and the 'NDC' scenarios. This follows from our discussion in Chapter 1, where these scenarios do not show rapid CCUS adoption in the coal sector, as they rely on policies which are either implemented or conditionally committed to by the various countries. Even in the 'Below 2°C scenarios', four out of the five model runs do not show appreciable CCUS uptake in the coal sector. The GCAM analysis does show that investments in the coal sector are anticipated to reach $0.7B in 2040, and $2B in 2050. It is notable that these results may not directly correspond with the actual action on CCUS, since coal-fired power plants are demonstrating suitable CO_2 capture feasibility at some sites. In the 'Net Zero 2050' scenario, the MESSAGE analysis does show $9.5B/year investment in the coal sector in 2030, while declining to zero by 2040. This shows that their analysis considered coal CCS as a short-term mitigation option. It is notable that a coal-fired power plant is assumed to operate for 30-60 years in a full economic lifetime, and 15-25 years even in a truncated life span (Cui et al., 2019). Thus, an investment in 2030 would result in such a facility operating until at least 2055-60. The GCAM analysis shows significant investments in the coal sector ($16 billion) in both 2040 and 2050.

The investments in the gas sector are somewhat higher than the coal sector. While no investments are seen in the 'Current Policies' scenario, the MESSAGE analysis does show $6 billion investment in 2040 and $15 billion investment in 2050. The investments in the 'Below 2°C' scenarios are low in the GCAM analysis, with investments remaining below $3B/year in 2050. However, the MESSAGE analysis shows very high investments in the gas CCS sector here, with investments starting at $10 billion in 2030 and rising up to $52 billion by 2050. Interestingly, the MESSAGE analysis shows higher investment in 2030 for the 'Net Zero 2050' scenario, followed by much lower investment compared to the 'Below 2°C' scenario. This is because gas CCS is seen as a medium-term mitigation option in this scenario with investments peaking within the next decade itself.

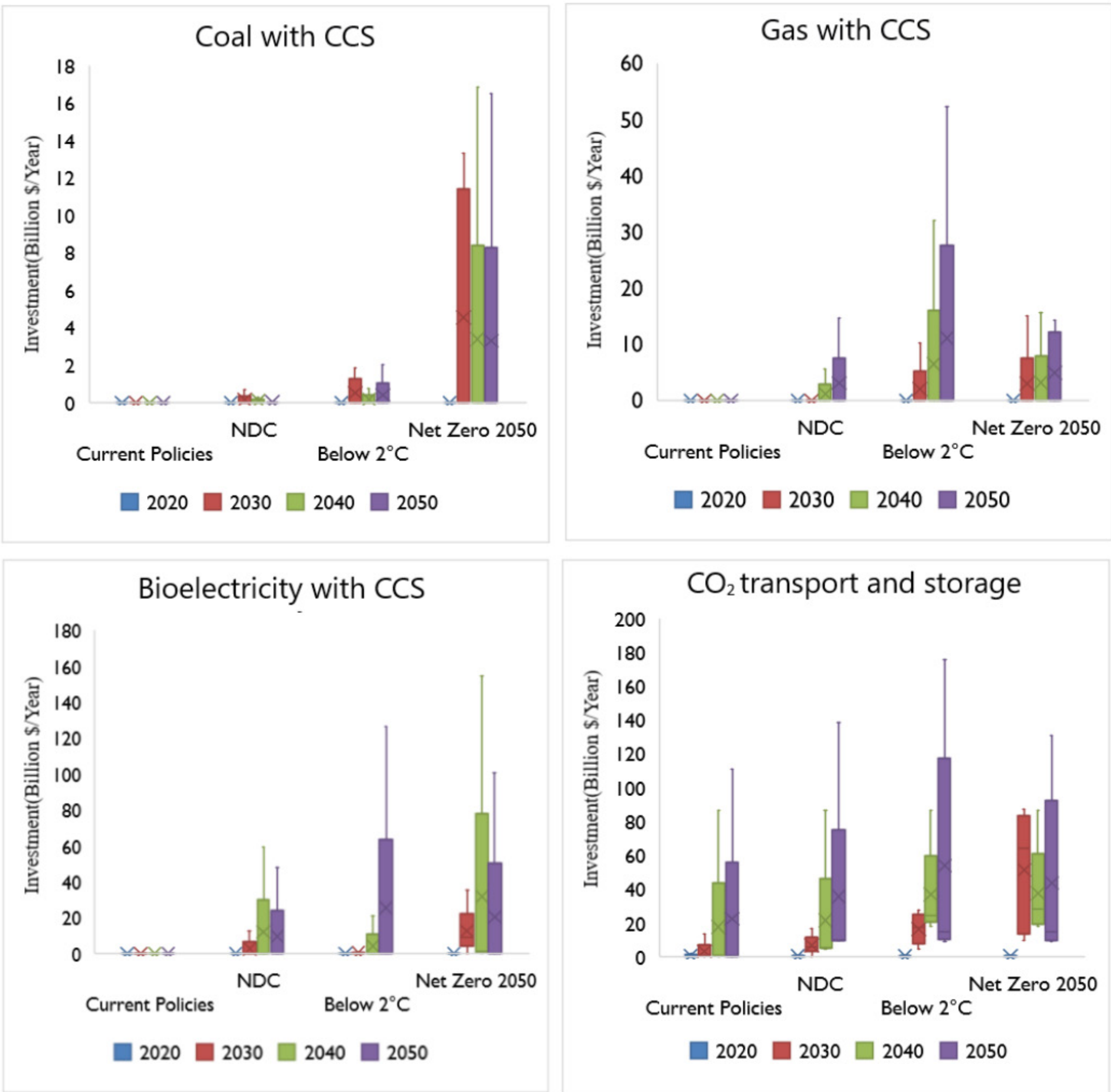

Figure 10. Investments for power plants with CCS by fuel type (coal, gas, bioenergy) as well as investments towards CO2 transport and storage infrastructure

***Source**: Authors' visualization with data from IIASA's NGFS portal.*

Investments for bioelectricity plants show interesting patterns as well. The 'Current Policies' scenarios do not have any appreciable investment. However, the GCAM analysis shows very high investments in the NDC scenario itself, reaching $60 billion/year by 2040. These investments are even higher in the 'Below 2°C' scenario ($21 billion in 2040, $126 billion in 2050) and the 'Net Zero 2050' scenario ($154 billion in 2040, $101 billion in 2050). Other models, however, do not show high bioelectricity adoption with CCS, barring some investments in REMIND in 2030, that remain below $10 billion/year.

The graph on the investments required for CO_2 transport and storage offers very useful information. This is because it shows that the cumulative investments required for CO_2 transport and storage may be much higher than the power plants with CCS. It is noteworthy that this situation arises because more substantial portions of CCS are occurring in the industry sector, where low-cost capture opportunities are present. While these opportunities do add to the investments required in the transport and storage infrastructure, they are not represented in the other panels as they are non-electricity investments.

As such, GCAM analysis shows very high investment in this category even in the 'Current Policies' scenarios since multiple countries are already using CO_2 capture in hard-to-abate sectors, and their analysis assumes that these investments would further increase in the future. The interquartile range for investments in the 'Below 2°C' scenarios is $22-32 billion/year in 2040 and $10-60 billion/year in 2050. This is even higher than the 'Net Zero 2050' scenario because the former has greater availability of fossil energy post-2030, while the latter has assumptions around heightened energy efficiency and renewable adoption.

For CCU, the investments have been estimated by Sick et al. (2022). They find that the investments in CCU may increase from a couple of hundred thousand dollars in 2030 to almost $4500 billion in 2050 (Figure 3.2). The highest investments are projected in the jet fuels sector, followed by concrete and animal feed (via algae-based proteins).

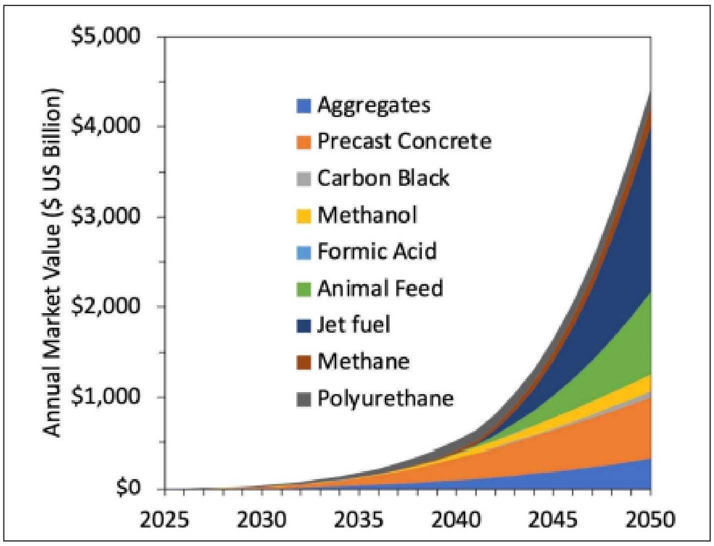

Figure 11. Market size projections for several major CO2-derived products through 2050

Source: *Sick et al. (2022)CC BY-NC-ND license.*

3.2. Reconciling bottom-up and top-down estimates

The investment statistics shown in Figure 3.1 offer useful trends and insights. However, these estimates can be categorized as top-down estimates, that have their own limitations. We categorize three limitations here.

First, the parameterization of the industry sector is much less detailed in many IAMs as compared to the power sector. As such, many models do not offer readily available investments and other details for important point sources. Lately, there has been an to better effort to incorporate technologies such as DAC into the IAMs, though results are often at odds (Fuhrman et al., 2020; Realmonte et al., 2019) and there is much less consensus as compared to power sector CCS.

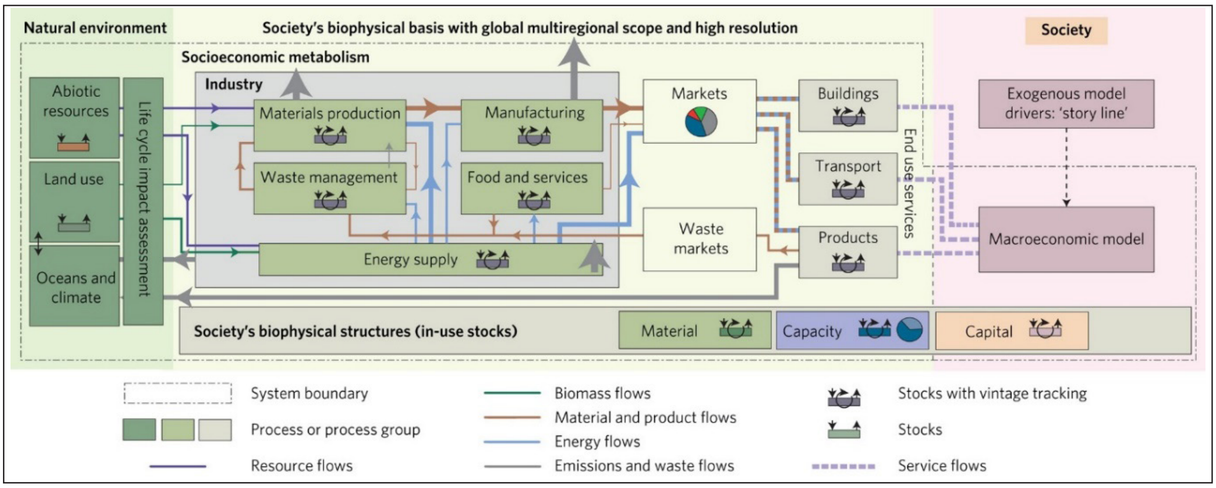

Figure 12. The industrial sectors form a network that links environmental resources to the final consumption of products and services

Source: (Pauliuk et al., 2017)

Second, the models are not adequately structured to handle CO_2 utilization as of now. Incorporating CO_2 utilization into these modeling frameworks requires a better representation of industrial ecology, where waste CO_2 may be used as feedstock for fuels, chemicals and materials (Chapter 1). Suggestions for improvements have been made, as shown in Figure 12.

Third, the models consider that the sole consideration promoting CCUS deployment is strong climate ambition. However, actual business models of CCUS deployment are much more complex. One of the critical determinants of investment willingness for on-the-ground CCUS is the availability of suitable information regarding CO_2 sinks and availability of pipeline networks for CO_2 transport. These hubs-and-clusters are not adequately represented in the IAMs, and as such, it is essential for bottom-up analyses using geospatial information systems to be softly linked with top-down analyses.

3.3. Measures to improve bankability of CCUS project

To reiterate from Chapter 2, several risks in CCUS are avoidable risks, which can be averted through detailed site characterization efforts. That said, three critical unavoidable risks have been identified.

The biggest unavoidable risk in this domain is a cross-chain risk. Because CCUS involves a diverse set of components throughout the supply chain, it is possible that the failure of even one component may jeopardize the operation or the profitability of the entire project. This risk is higher in this phase of CCUS deployment, where operations are being performed on a 'one-to-one' basis. In such a configuration, one source of CO_2 is linked to one sink. In the future, as a number of sources come up around a set of sinks, there is a possibility to forms hubs and clusters.

Clusters refer to large number of sources of CO_2 that are built around a single storage site. Because the location of storage sites is fixed, it is imperative that clusters are planned appropriately. This would entail siting the future point sources of CO_2 around close proximity of sink. There are also existing clusters of high-density of point sources, which may be suitably networked to form a CO_2 cluster. The International Energy Agency Greenhouse Gas R&D program has identified 12 large-scale clusters with emissions ranging from 7-60 Gt-CO_2 annually (P. Singh & Haines, 2014). In fact, our group's work has also identified large CO_2 clusters, all across India where the costs of capture may be below \$60/t-CO_2. Ideally in a lowest cost network, the clusters should be formed such that the sink of CO_2 is located in the Euclidean center of the sources, as weighted by their emissions (Garg et al., 2017). However, designing such a network may not be possible due to large existing facilities, as well as locations with high population densities or ecological risks. This leads to the concept of hubs. Hubs are centralized locations where CO_2 from various sources may be collected via feed lines (Vishal et al., 2022) (Table 1.2). This large volume of collected CO_2 may then be transported to the sink location via a trunk line.

Formation of hubs and clusters leads to derisking of CCUS projects in multiple ways:

- First, it brings down the costs of transport and storage, and therefore the overall costs of avoidance by introducing economies of scale. In an analysis carried out by our group for India, it was demonstrated that formation of integrated clusters across sectors (power, steel, cement and refineries), brought down the costs of CO_2 avoidance by \$10/t-CO_2, compared to a configuration where only sectoral clusters existed (Garg et al., 2017). Essentially, the cost of CO_2 transport per tonne of CO_2 is lower for pipelines with higher throughput (U. Singh, Loudermilk, et al., 2021).
- Second, it enables 'unstranding' of CO_2 sources which are in locations without adequate CO_2 storage capacity. There are several locations in the world where large urban populations have necessitated construction of high-emitting facilities. That said, these locations may not have sinks nearby. Under a high climate-stringent policy, this would effectively mean stranding of such assets. However, presence of a hub to capture CO_2 from such facilities can enable its shipping to a distant sink location at a relatively low cost.

- Third, it reduces the commercial risk associated with opening up of new storage locations. Detailed site characterization and ensuring that the proper checks are in place for a particular storage sites requires around 6-10 years (Global CCS Institute, 2016). This itself induces large risks as a number of new storage sites are planned. Instead, formation of clusters ensures that a limited number of sites would be required to be explored and greenlit for long-term sequestration.

The second major risk considered in Chapter 2 is risks associated with revenue. CCUS projects may often be incentivized for their initial capital investments. These incentives may be perceived as adequate initially but there may be cost overruns as the CCUS project evolves. Thus, a sequestration tax credit either alongside an investment credit or by itself, can enable long-term sustenance of a CCUS project for its first 5-10 years. Such an incentive would effectively incentivize actual volumes of CO_2 stored or utilized under stringent life cycle scrutiny. Thus, such incentives also avoid the risk of providing large incentives to operators who are not able to operate CCUS projects.

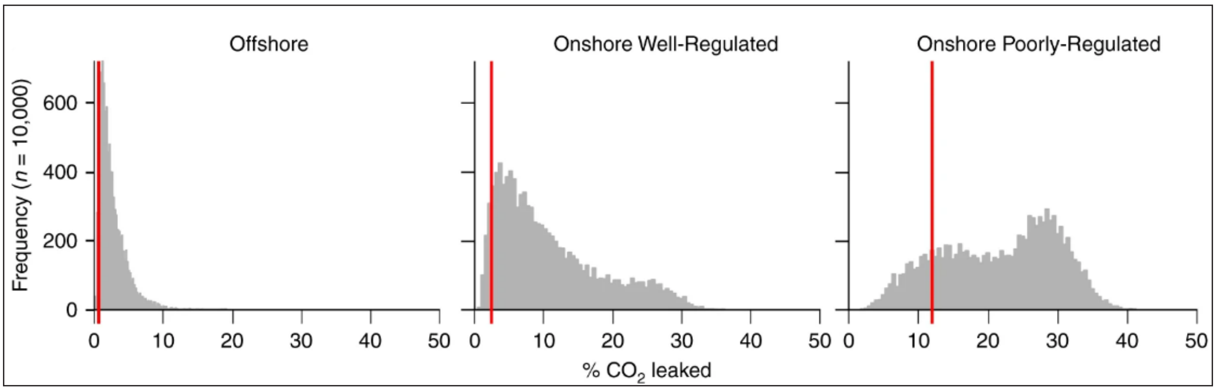

Figure 13. Histograms showing the distribution of results from Monte Carlo analysis (10,000 realizations) for each scenario; results are cumulative leakage as a percentage of the total CO2 injected at model year 10,000.

Source: (Alcalde et al., 2018). Reproduced under the terms of Creative Commons Attribution 4.0 International License

The third major risk considered in Chapter 2 pertains to storage liability. CO_2 storage must be safe and reliable, ensuring minimal leakage. However, the amount of leakage depends on the time duration as well (Figure 12). Even a well-regulated onshore reservoir may involve the risk of 2.5% or more after 10000 years of injection due to presence of natural faults, abandoned wells nearby, etc. (Alcalde et al., 2018). Thus, establishing appropriate storage liability norms is essential, which specifies minimum rates of permanent sequestration, methods of measurements and time duration under which the operator would be held liable for any leakages.

Chapter 4

Policy interventions and international cooperation for enabling CCUS

This chapter discusses several existing policies (both financial and otherwise) that have been instituted for advancing research, development and demonstration projects in CCUS. Financing mechanisms are particularly necessary because projects in developing countries may not be financed solely using government aid. These financing mechanisms may be in the nature of monetary or non-monetary support/ interventions. These are discussed below:

4.1. Non-monetary intervention

A dedicated fund, like a clean technology fund, is critical to scale up investment in CCUS projects commercially. At an early stage, MDBs can take the lead in creating a dedicated fund for financing CCUS projects. For technical assistance and demonstration of CCUS projects, EMDCs need mainly grant-based funding to deal with technology risk and prepare the ground for commercial deployment of CCUS projects. Various international financial instruments that a specialized fund can adopt to finance CCUS projects are as under:

1. **Green Bonds–** Green bonds are primarily issued to fund a specific green project to further climate action. To facilitate and prioritize climate financing through green bonds, many entities, mainly the European Union (EU) and the Climate Bond Initiative (CBI), have issued a taxonomy of green activities. Subject to specific screening criteria, CCUS has been included in the EU and CB''s taxonomy. Considering the enormous investment required to fund CCUS projects, green bonds can be instrumental in accessing large funds. Since Green Bonds also attract altruistic investors willing to forego some returns for the greater good of society, yields of green bonds can be lower than similar traditional bonds.

    - With regards to CCUS, there can be two ways to deploy Green Bonds: Ie project developer of CCUS directly issues green bonds in the market.
    - By taking advantage of their highest credit rating, MDBs can create a dedicated facility and issue Green Bonds to raise a relatively large amount to fund project developers of CCUS in recipient countries through concessional loans. The strategy here is to leverage the balance sheet of MDBs (especially callable capital) to crowd in private investment globally.

    Many renewable power companies in developing countries as well as some of the large financial intuitions have raised finances for their renewable projects through green bonds, which have been subscribed by various PE funds, pension funds as well as sovereign wealth funds.

    Case example – The largest private sector bank of Egypt, the Commercial International Bank (CIB), issued green bonds worth US$ 100 million in 2021 to invest in various climate action projects such as energy efficiency, renewable energy, and green buildings.

These green bonds were completely subscribed International Finance Corporation (IFC). (*IFC Invests in Egypt's First Private Sector Green Bond to Help Boost Climate Finance, Drive Green Growth*, 2021).

2. **Outcome-based sustainability debt (Bonds/Loans)–** Outcome-based sustainability debt allows project developers to link interest rates with predefined specific goals. In the case of CCUS projects, this instrument can be issued by linking the reduction of carbon emissions with the rebate in interest rates. This instrument helps in managing technology and greenwashing risk for investors.

   Case example– Tata Power in India borrowed US$ 320 million through outcome-based sustainability loans from foreign investors and initially saved 25 bps on the borrowing cost. If Tata Power increases renewable electricity generation by 1.5-2 GW and does not expand fossil fuel-based power generation capacity, Tata power would get an additional waiver of 8bps in the interest rates (Das, 2022).

3. **Syndicated Loans (Co-financing)–** A syndicated loan (co-financing) is a financing instrument that allows multiple lenders to form a syndicate for investing in a climate action project. Through co-financing, risks associated with the CCUS projects can be diversified to multiple lenders. With risk diversification and the presence of multiple lenders, co-financing allows project developers to access larger funding at a lower cost for a relatively longer tenor. In the case of co-financing, the strategy is to leverage financial resources and expertise of project financing and project monitoring of MDBs (other similar financial institutions) to mitigate the adverse risk perception associated with Emerging Markets and Developing Countries (EMDCs). A syndicate may consist of a single MDB or more than one MDBs and a single private investor or more than one private investor.

Grants may also be provided by the donors/MDBs, which can also be clubbed to de-risk the investment and improve the scale of the investment amount. By forming a syndicate, private investors can also benefit from preferred creditor status, and immunities usually accorded to MDBs, thereby mitigating the default risk for private investors. Syndicated loans can be instrumental in improving the viability of CCU projects. There are mainly three ways to structure syndicated loans:

a. **'A/B' Loan Structure –** In this structure, loan A is provided by MDBs/DFIs, and loan B is provided by private investors, who generally do not reside in the country where the climate action project is proposed to be taken up. MDBs/DFIs function as a lender of record on behalf of the syndicate. Loan B provided by foreign investors usually helps countries with limited domestic financing capacity to access international finance and scale up investment in climate action projects.

b. **The complementary Financing Scheme or 'A/C' Loan Structure** – A/C Loan Structure is like the A/B loan structure. However, private investors that provide C loans generally reside in the country where the project is proposed to be taken up. This is mainly done for projects where there are significant domestic sourcing components, as the loans in the domestic currency will remove the currency risk to that extent. This structure also improves the investment capacity of domestic investors to support large projects (such as CCU) domestically,

c. **Parallel Loan** – MDBs act as arrangers. But all the financing institutions of the syndicate sign separate financing/loan covenants with the project developers/borrowers. But private investors do not enjoy the privileges and immunities accorded to MDBs. This structure allows the syndicate to onboard foreign and domestic investors to provide funding in hard and local currencies, respectively. Further, these are generally availed by larger corporates with good credit ratings.

   Case example – In May 2019, ADB approved a syndicated loan of US$ 222 million to finance the Riau Natural Gas Power Project in Indonesia. The tenor of the loan is 20 years. Out of the total Loan Amount, ADB A and ADB B provided US$ 70 million and US$ 82 million, respectively. Launching Entrepreneurs for Affordable Products fund, an ADB-administered fund, contributed US$ 20 million. At the same time, IFC contributed US$ 50 million. ADB also agreed to cover risks to private investors of 'DB B's portion by providing a partial risk guarantee (breezy, 2021).

4. **Guarantees –** MDBs and OECD countries can also guarantee investment in CCUS projects to lower the cost of capital. The private investor will get their investment back in the event of the occurrence of certain events, such as default, technology failure, and political risk. Depending upon the project characteristics and country profile, guarantees can be structured in the following manner to lower the cost of funding to CCUS projects.

   a. Partial Credit Guarantee – All risks are covered, but the investment is protected partially

   b. Partial risk guarantees – Some of therisks are usually covered, but the investment may be covered fully or partially

   c. Political risk guarantees – Only political risks are covered, but the investment may be partially or fully covered

   d. Private Equity Fund Guarantee – Guarantee to private equity investment

   e. Projects-based Guarantees – Provided guarantees to specific projects such as CCS and CCU

   Case example – AP Renewables, Inc. acquired the Tiwi and MakBan Geothermal Power Green Bonds Project in the Philippines by issuing green bonds to the tune of US$ 200 million (tenor of 10 years) in local currency. ADB provided A loan of US$ 40 million. ADB provided a partial credit guarantee to cover 75% of both principal and interest of the green bond in the local currency (mmojica, 2020)

5. **Collective investment vehicle (Structured Equity Funds) –** To de-risk the investment in CCUS projects, blended finance instruments can be a mechanism to allocate risk to various categories of funding entities by creating a waterfall structure. Tier 1 is funded through grants from OECD countries and donor funds. MDBs and other Development Financial Institutions provide funding to Tier 2 (Mezzanine capital). Institutional investors (private equity, hedge

funds, etc.) provide Tier 3 funding. The figure below depicts the funding structure of the Collective investment vehicle. Tier 1 de-risks the investment of Tier 3 and Tier 2, and Tier 2 de-risks the investment of Tier 3. De-risking through the waterfall structure allows Tier 3 investors to provide funds with the expectation that future returns will be lower due to decreased risks.

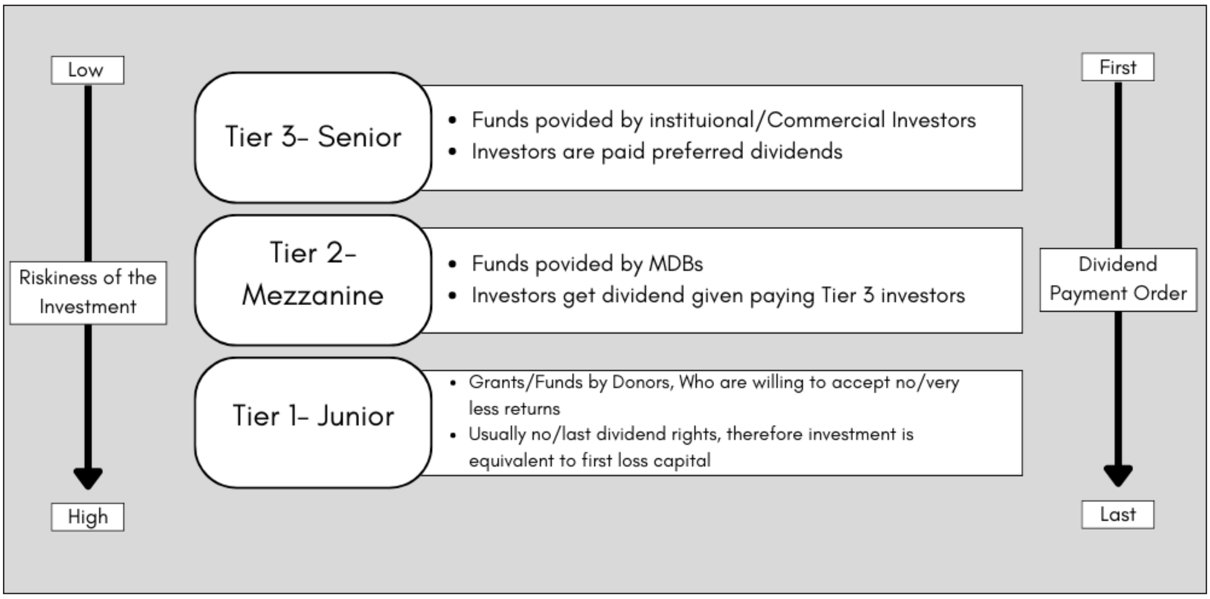

Figure 14. Typical structure of Collective Investment Vehicles

Source: (Evaluating Blended Finance Instruments and Mechanisms, 2021)

Case example – Climate Investor One (CI1) facility has been created to fund renewable energy projects such as wind, solar, and run-of-the-river hydro. Climate Investor One (CI1) facility has instituted a Construction equity fund, which is a 3- tier collective investment vehicle. Tier 1 equity capital (junior tranche) amounting to US$ 160 million has been provided by donors such as the Green Climate Fund (GCF), the European Union (EU), the Nordic Development Fund (NDF), the Directorate General for International Cooperation (DGIS) within the Ministry of Foreign Affairs of the Netherlands and USAID via PowerAfrica. Tier 2 equity capital (mezzanine tranche) amounting to US$ 320 million has been provided by Commercial investors and development finance institutions (DFI). The institutional investors have provided tier 3 equity capital (senior tranche) amounting to US$ 320 million. The Climate Investor One (CI1) facility aims to provide funds for the project's whole life cycle. Funds in the form of development loans and technical assistance will support the development phase. Construction equity funds support the construction phase and refinancing. Fund in the form of senior debt funds operation phase (*Funds – Climate Fund Managers*, n.d.). Climate Investor One (CI1) has funded Ampyr I Balenahalli wind power project of Ampyr Energy Pvt. Ltd. In India. CI1 provided US$ 3.14 million of development funding and US$ 37.90 million of construction equity (*Ampyr I Balenahalli – India | Wind – Climate Fund Managers*, n.d.).

6. **Credit Default Swaps (CDS) –** CDS is primarily an insurance instrument that mitigates the default risk of debt instruments (bonds/loans). Due to information asymmetry and perceived risk, many global private investors resist investing in EMDCs. CDS allows private investors (debt providers) to secure against default risk on their investments by paying a periodic premium to CDS sellers. In the event of default, CDS sellers pay the default sum to private investors (CDS buyers). MDBs or any other funding agency can create a specialized mechanism for CCUS projects by pooling grants and donor' funds to purchase CDS on behalf of private investors (debt providers) and support CCUS projects globally. The strategy is to leverage grants and donations to crowd in private investment in urgent and critical climate action projects such as CCUS. Since projects will be located globally, there will be a kind of natural diversification of country risk and technology risk for CDS sellers, thereby allowing them to charge lower premiums from MDBs. The figure below depicts the financing mechanism using CDS.

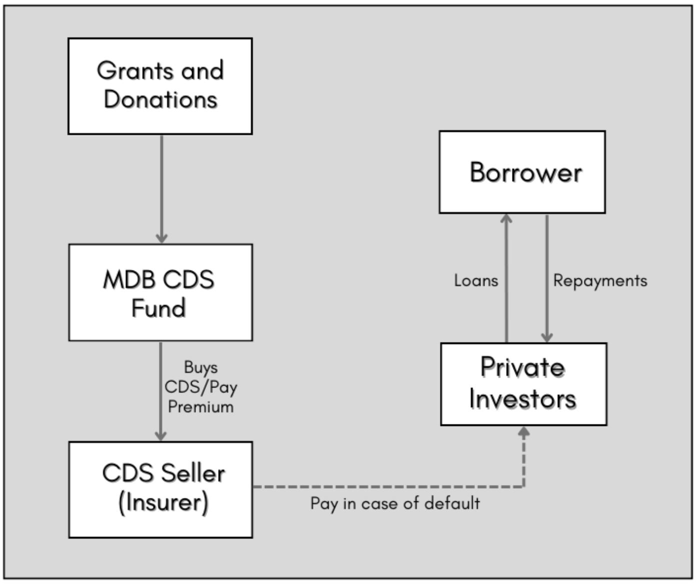

Figure 15. Typical structure of Credit Default Swaps

Source: *Author's own compilation*

4.2. Monetary intervention

In the short term, viability gap funding by MDBs, DFIs and other global funds can be a potent mechanism to improve the bankability and viability of CCUS projects globally, especially in EMDCs. If CCUS projects are part of the strategy to achieve goals laid down in the Nationally Determined Contribution (NDC) and Long-Term Strategy (LTS) of a country, viability gap funding should be provided to project developers of CCUS projects in all such countries. Since the cost of CCUS technologies required for undertaking CCUS projects is still very high, viability gap funding will facilitate technology transfer globally. Smoothness in the process of technology transfer through viability gap funding will obviate the need to reinvent the wheel and invest in the R&D of CCUS technologies, which have already been developed in other countries. Viability gap funding will improve the risk profile of CCUS projects and reduce the cost of capital on the balance capital needed. Viability gap funding will also provide sufficient time for countries with no carbon markets to develop well-functioning carbon markets and assess the revenue-generating abilities of CCUS projects.

Depending on the project profile and country's requirement, viability gap funding can be prioritized for various components of CCUS projects, such as carbon capture technologies, transportation and storage infrastructure, and carbon utilization technologies. One of the ways to provide viability gap funding is to facilitate the creation of a common infrastructure related to the transportation and storage of CO_2 to reduce overall capital costs and operation and maintenance costs. Since many countries lack sites to store captured CO_2, the cost of transportation and storage of CO_2 can be very high to render CCUS projects completely viable. Various developed countries have policies to support the CCUS project. The USA offers tax credit in the form of 45Q credit; the EU has a cap-and-trade carbon trading system. But many EMDCs lack the financial and market capability to implement such strategies in the short term. Therefore, viability gap funding led by MDBs and other global funding institutions can help EMDCs to start implementing CCUS projects at the scale required to meet net zero emissions in the next 30 to 50 years.

4.3. International cooperation

Overall, the purpose of all funds is to de-risk investment in climate action projects by deploying blended financing instruments to crowd-in private investment. Grants, concessional loans provided by MDBs, and other funds are being leveraged to attract private investors by improving the viability of projects. However, the capital resources of existing funds are not enough to fulfill current climate financing requirements to meet the Paris Agreement targets and Net zero emission. Due to the development needs and precarious macroeconomic situation, many EMDCs cannot deploy public funds to climate action projects. Public funding of climate action projects will lead to a high debt-to-GDP ratio, thereby increasing interest rates. An increase in the interest rate will crowd out private investment, leading to an adverse impact on economic growth. Since many climate action projects are capital-intensive and require low-cost financing to improve the viability of projects, capital resources of existing funds (especially MDBs) are needed to be scaled up significantly.

One of the ways the cost of CCUS projects can be reduced is to facilitate access to low-cost international financing through MDBs and public funds from OECD countries. The strategy to attract low-cost financing is to understand the risks associated with CCUS projects EMDCs and allocate each risk to market participants who are best suited to manage it through an appropriate instrument. For example, if technology risk is in the case of CCUS projects, guarantees from MDBs to cover technology risk can be a mechanism to de-risk the investment. Therefore, a risk management-based strategy to mitigate and transfer risks associated with climate action projects in developing countries should be adopted to attract low-cost financing. In the context of CCUS projects, financing can be divided into two phases. First, capacity, technical assistance, and demonstration phase of different CCUS technologies to assess market readiness for large-scale commercial deployment in various countries. Second, commercial deployment of viable CCUS technologies in power plants and industries. Since the first phase is riskier and the capital requirement is less than the second phase, the financing mechanism should be different.

Dedicated financing of projects related to low-carbon and resilient development is indispensable to meet the Paris Agreement targets. The world needs investment to the tune of US$ 3 trillion to US$ 6 trillion per year to fund climate change mitigation and adaptation projects, while the current investment is around US$ 630 billion (*How to Scale Up Private Climate Finance in Emerging Economies,* 2022). At the same time, EMDCs should at least invest US $1 trillion per year till 2030 in energy infrastructure projects related to climate change mitigation (*Global Financial Stability Report,* October 2022). It is evident that due to the investment gap, the goal of the Paris agreement to limit the global temperature increase to 2°C will not be achieved, let alone restrict the temperature increase to 1.5°C. As per the OECD database, more than 90 funds (Multilateral, Bilateral, Donor, and Private Sectors) are currently active in financing projects related to climate change mitigation and adaptation, capacity-building, disaster risk reduction, REDD, clean energy, technical assistance, and technology transfer (*Climate Fund Inventory Database*, n. d). Multilateral Development Banks (MDBs) are trying to fund projects related to climate actions through various de-risking and blended finance low-cost instruments. Primary modes of climate financing have been through concessional loans (including co-financing), grants, guarantees, policy-based and outcome-based financing, line of credit, and equity investment. However, even after the existence of many funds, the investment gap in climate financing persists.

In terms of accessing funds from private investors, various entities and project developers have been primarily accessing funds through debt-based instruments such as green bonds, sustainability bonds, and sustainability-linked bonds. However, the share of green bonds and other bonds issued from EMDCs after excluding China has been relatively low compared to OECD countries and China (*Global Financial Stability Report,* October 2022). It is also noted that OECD countries and China were able to issue significant volumes of green bonds in local currencies. At the same time, EMDEs (except China) could raise funds through green bonds and other bonds in foreign currency. Overall, more than US$ 2 trillion worth of green bonds have been issued till now, and in 2022, green bonds worth US$ 395.5 billion have been issued to date (Climate Bonds Initiative, n.d.). To finance projects related to climate change, equity funds have also been formed by pooling resources from Private investors, Venture capital firms, Private equity firms, and Hedge Funds.

At the same time, many market participants have started initiatives such as the Glasgow Financial Alliance for Net Zero (GFANZ) and the Network of Greening the Financial Systems (NGFS). GFANZ is the coalition of more than 550 financial institutions from 50 countries to promote the transition to a low-carbon economy and achieve net zero by 2050 (*Glasgow Financial Alliance for Net Zero*, n.d.). And NGFS is the coalition of central banks and supervisors to share best practices related to climate financing and risk management to mobilize finance projects related to low-carbon and climate-resilient development (*NGFS, n.d.)*. In financial markets, fund managers have also started offering and promoting ESG-focused funds to attract climate-conscious investors to support the transition to a low-carbon economy.

As per the Climate Fund Update website, twenty-seven (27) funds are actively involved in financing various aspects of climate financing (*Climate Fund Inventory Database*). Capital to the tune of US$ 43.2 billion has been pledged to these 27 funds. Some of the major funds involved in climate financing are discussed further.

1. **Green Climate Fund** – Green Climate Fund (GCF) was created under the UNFCCC framework to finance climate change mitigation and adaptation projects in equal proportions in developing countries, with a special focus on the adaptation need of Least Developed Countries (LDCs), and Small Island Developing States (SIDS). For climate action projects, initial capital amounting to US$ 10.3 billion was pledged until 2019. Additional funding to the tune of US$ 10 billion was pledged and confirmed in the first replenishment cycle (GCF-1) for the period 2020-2023. As per the portfolio dashboard of GCF[1], GCF has committed to invest US$ 11.4 billion in 209 projects in 128 developing countries. GCF was able to arrange additional co-financing to the tune of US$ 31.4 billion. GCF funded approved projects mainly through five instruments: Grants (US$ 4.6 billion), Concessional Loans (US$ 4.8 billion), Equity (US$ 1.0 billion), Result-based payments (US$ 496 million), and Guarantees (US$ 348 million) (Fund, G.C., 2021).

   In terms of investment needs, (EMDEs) require at least to invest US$ 1 trillion per year till 2030 in energy infrastructure projects related to climate change mitigation. As mentioned in section 3.1 of this report, CCUS projects require an investment of at least US$ 10 billion per year to achieve the 2^{o}C rise. Therefore, capital funding provided to GCF to undertake climate action projects (more specifically, CCUS projects) is grossly insufficient and achieve meaningful progress in reducing GHG emissions.

2. **Global Environment Facility** – Global Environment Facility (GEF) was instituted just before the 1992 Rio Earth Summit to finance projects related to various international conventions and agreements such as United Nations Framework Convention on Climate Change (UNFCCC), Convention on Biological Diversity (CBD), United Nations Convention to Combat Desertification (UNCCD), Minamata Convention on Mercury, Stockholm Convention on Persistent Organic Pollutants. Projects approved by GEF are executed through various agencies (Annexure 1). GEF primarily provides grant-based funding along with additional mobilization through co-financing. Since its inception, 5200 projects have been approved by GEF, and GEF provided US$ 18.57 billion through grants and mobilized US$ 112.38 through co-financing. After 8 phases of replenishment since 1991, the total contribution from donor countries has been US$ 30.08 billion. In the last replenishment cycle (GEF) for 2022-2026, donors provided capita resources to the tune of US$ 5.33 billion (GEF Funding, 2022). However, considering the scale of financing required for CCUS projects, it is observed that the last replenishment of US$ 5.33 billion for five years (2022-2026) is grossly inadequate to achieve any impactful outcome.

[1] See https://www.greenclimate.fund/projects/dashboard

3. **Climate Investment Funds –** Climate Investment fund (CIF) is one of the largest dedicated multilateral trust funds. Developed countries provided initial capital funding to the tune of US$ 10.3 billion. UK and Spain provided initial capital. Other developed countries provided capital through loans and grants. CIF created specialized trust funds for financing projects related to clean technology, climate resilience, forest preservation, renewable power in low-income countries, and technical assistance. Funds are being disbursed through six designated MDBs as implementing partners. MDBs associated are the Asian Development Bank, the European Development Bank, International Finance Corporation, the Inter-American Development Bank, and the African Development Bank. To de-risk and lower the cost of capital, CIF deploys funds through and by blending instruments such as grants, concessional loans, equity, guarantees, and contingent grants (Annual Report 2021, 2022). As per the annual report of the CIF for 2021, the status of each specialized fund is shown in table 5.

Table 5. Break up of Climate Investor Fund in different specific trust funds

Name of Fund	Contributed resources (US$ billion)	Worth of approved projects (US$ billion)	Expected co-financing for approved projects (US$ billion)
Clean Technology Fund	7.1	5.3	55.8
Pilot Program For Climate Resilience	1.2	0.98	2.3
Forest Investment Program	0.75	0.60	1
Scaling Up Renewable Energy Program in Low Income Countries	0.78	0.57	2.9
Technical Assistance Facility	0.04		
Renewable Energy Integration	0.32		
Total (Climate Investment Funds)	10.2	7.5	62.0

Source *(Annual Report 2021)*

Clean Technology Fund (CTF) is the most suitable for implementing CCUS projects. But considering the scale requirement of climate financing, CTF's capital funding to the tune of US$ 7.1 billion is not even enough for all clean technology projects, let alone supporting CCUS projects. However, creating a specialized fund for CCUS projects within the ambit of MDBs may be instrumental in arranging low-cost funding.

4. **Carbon Capture and Storage Fund** – Asian Development Bank (ADB) has created a dedicated fund for the CCS project with the support of Australia and the UK. Only four countries (China, India, Indonesia, and Vietnam) are eligible to receive funds. The purpose of this fund is to support capacity development, conduct geological investigations to find appropriate storage sites, and take up community awareness programs. Since funding, scope, and countries supported are somewhat limited, and this fund cannot provide funding for large-scale commercial deployment on a global scale.

5. **Funding by Multilateral Development Banks (MDBs)** – As per the joint report on multilateral development 'anks' climate finance for the year 2021, eight major MDBs[2] (AfDB, ADB, AIIB, EBRD, EIB, IDBG, IsDB, WBG) provided climate financing to the tune of US$ 50.66 billion and US$ 31.05 billion to low- & middle- income economies and high-income economies respectively in 2021. The table 6 depicts the total climate financing by eight major MDBs in 2021. Total climate financing, including co-financing, was US$ 182.01 billion. MDBs provided climate financing to the tune of US$ 81.71 billion. Total climate financing for low- & middle- income economies and high-income economies was US$ 94.26 billion and US$ 87.75 billion, respectively. Instruments adopted by MDBs primarily include investment loans, grants, guarantees, equity, result-based financing, policy-based financing, and line of credit (2021 MDB Joint Report | Publications, 2022).

Table 6. Financing breakup of major MDBs for 2021

Finance Type	Low- and Middle-Income Economies (in US$ billion)			High-Income Economies (in US$ billion)			Total (Global, in US$ billion)
	Mitigation Finance	Adaptation Finance	Total	Mitigation Finance	Adaptation Finance	Total	
MDB Climate Finance	33.05	17.61	50.66	29.47	1.57	31.05	81.71
Co-financing	28.84	14.75	43.60	56.03	0.66	56.70	100.30
Total	61.89	32.36	94.26	85.50	2.23	87.75	182.01

Source: (2021 MDB Joint Report | Publications, 2022)

Considering the global financing requirement of US$ 3 trillion to US$ 6 trillion per year, financing of only US$ 182.01 billion is grossly inadequate to have any impact. Similarly, financing of US$ 94.26 is not enough for low- and middle-income economies. The percentage of co-financing in low- and middle-income economies was less than in high-income economies due to the possibility of the high risk associated with low- and middle-income economies. Therefore, low- and middle-income countries need more instruments to de-risk climate financing to attract private investors. Also, unless there are viable CCUS projects, the investment gap will persist. For example, to improve the viability of CCS projects, identification of a sufficient volume of sinks are the first requirement, then only the cost of drilling, cost of compression, cost of pipeline and cost of monitoring, etc., can be ascertained to attract investment from MDBs, especially in EMDCs.

It should be noted that the domain of international cooperation in the case of CCUS goes well beyond financing. Simultaneously with the Paris Agreement, the Mission Innovation was also launched which is a partnership of 23 countries and the EU to accelerate progress towards net-zero. Subsequently thereafter, the Mission Innovation pertaining to CCUS was launched by Saudi Arabia and the United States. The Mission Innovation CCUS challenge aims to facilitate cross-

[2] Asian Development Bank (ADB), African Development Bank (AfDB), Asian Infrastructure Investment Bank (AIIB), European Bank for Reconstruction and Development (EBRD), European Investment Bank (EIB), Inter-American Development Bank Group (IDBG), Islamic Development Bank (IsDB), World Bank Group (WBG)

border networks between private and public sectors. This program supports CCUS projects at multiple levels of technological readiness. For instance, it is funding applied research and laboratory projects of several hundred thousand dollars (DST, 2020). At the same time, it is also helping in development of much larger projects such as the Shell Quest facility in Canada which captures 1.2 Mt-CO_2 annually. Similar efforts have been announced in the Clean Energy Ministerial where sharing of CO_2 capture knowledge will be facilitated, along with development of tools, models and evaluative methodologies. This kind of knowledge transfer is necessary because intellectual property for CCUS equipment and sorbents may be concentrated in some G20 countries. For instance, the United States and China have 27% and 25% of the CO_2 compression patents (Liu and Yu, 2016).

G20

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Chapter 5

Concluding remarks and Recommendations

Since capacity building, technical assistance, and demonstration of different CCUS technologies are indispensable; the following recommendations are suggested to be adopted to support CCUS projects.

1. Grant-based financing through a specialized fund by pooling public funds from OECD countries and other donors must be created to scale up the deployment of CCUS projects. The scope of the ADB CCS fund is very limited. Grants-based funding for capacity building and technical assistance will immensely benefit EMDCs in assessing the technical feasibility of CCUS technologies. Therefore, the creation of specialized funds should be done under the aegis of a global MDB such as the WBG. GEF, CIF, GCF, and other funds can direct grants through this specialized fund, so that recipient countries do not have to apply to each fund separately, thereby reducing transaction costs and documentation requirements.

2. MDBs can also provide guarantees to deal with technology risks associated with CCUS demonstration projects, especially CCU projects. Equity and debt investments in CCU demonstration projects can be fully or partially guaranteed in EMDCs so that project developers can assess the viability of large-scale commercial deployment and test the technical suitability per the country's domestic conditions.

3. Research efforts into CCU must be diversified given its prospects and large public acceptability. This includes better inclusion of the chemicals and materials sector into modelling frameworks, developing better catalysts and reagents for facilitating individual CO_2 utilization pathways and improved global market assessment for such products.

4. Existing and planned financing mechanisms should incorporate CCU, where relevant. Accounting for the net GHG benefits in such projects must be subject to rigorous inventory practices. For instance, GHG emissions for incumbent products must be specified based on the *status quo*, such that inflation of baseline does not take place.

5. While financing mechanisms have been discussed for the next decade for initial projects, it is essential that CCUS is brought within the ambit of carbon markets in the medium-to-long term. The Doha summit of the UNFCCC has included CCUS within CDM, though the actual deployment of projects remains limited. While the EU Emission Trading Scheme and some other markets include CCUS, it should be considered whether the geographical boundary of such projects may be outside such that carbon mitigation credits may be traded across G20 countries.

6. Technical assistance should be provided to G20 countries where an effective assessment of sink potential is not present. For instance, Singh et al. (2021) have made the case that the storage capacity in saline aquifers in developing countries may not have been assessed

properly because such reservoirs have not been explored for any commercial reasons. On the other hand, stratigraphic data for depleted hydrocarbon reservoirs and coal seams may be available but it has not been fully utilized to estimate sink availability. It is recommended that requisite funds may be provided to explore this area such that future large point sources of CO_2 are sited around sinks with high readiness.

7. Finally, the motto of the 2023 G20 Presidency is One Earth, One Family, One Future. In this vein, it is recognized that many countries outside the G20 would also emerge as hubs of economic and industrial development over the next three decades. While their GHG emissions are currently low, it is imperative that primary-level screening of CCUS opportunities is carried out here. G20 can facilitate these funds for G77 countries as part of developing CCUS knowledgebase and databases globally.

Annexure

Annexure 1. Agencies executing GEF approved projects

- African Development Bank
- Asian Development Bank
- Brazilian Biodiversity Fund
- Conservation International
- Development Bank of Latin America
- Development Bank of Southern Africa
- European Bank for Reconstruction and Development
- Food and Agriculture Organization
- Foreign Economic Cooperation Office, Ministry of Environmental Protection of China
- Inter-American Development Bank
- International Fund for Agricultural Development
- International Union for Conservation of Nature
- United Nations Development Programme
- United Nations Environment Programme
- United Nations Industrial Development Organization
- West African Development Bank
- World Bank World Wildlife Fund - US

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