WHITE PAPER

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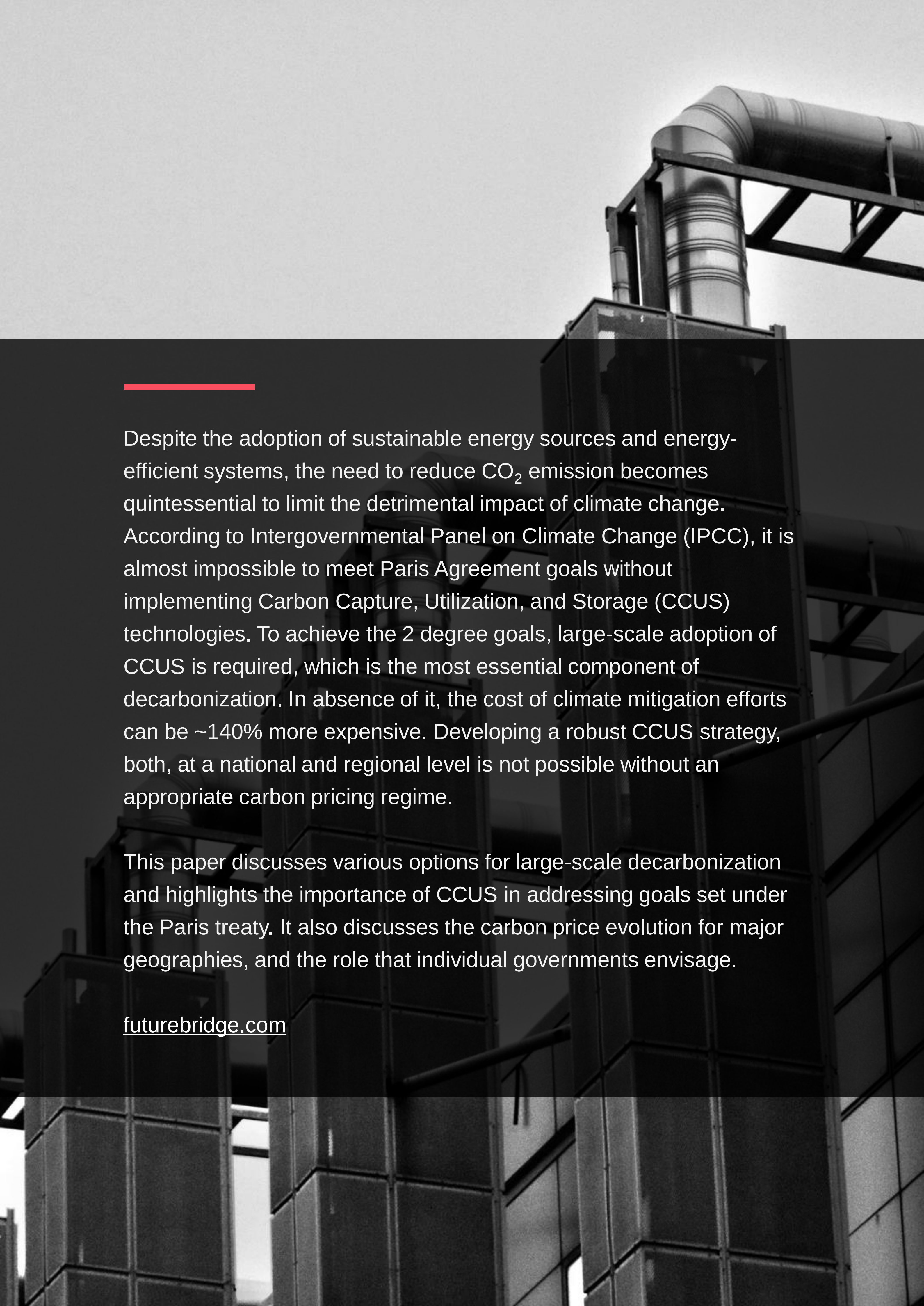
CCUS – A Game Changing Opportunity for the Industrial Sector

FutureBridge



Despite the adoption of sustainable energy sources and energy-efficient systems, the need to reduce CO_2 emission becomes quintessential to limit the detrimental impact of climate change. According to Intergovernmental Panel on Climate Change (IPCC), it is almost impossible to meet Paris Agreement goals without implementing Carbon Capture, Utilization, and Storage (CCUS) technologies. To achieve the 2 degree goals, large-scale adoption of CCUS is required, which is the most essential component of decarbonization. In absence of it, the cost of climate mitigation efforts can be ~140% more expensive. Developing a robust CCUS strategy, both, at a national and regional level is not possible without an appropriate carbon pricing regime.

This paper discusses various options for large-scale decarbonization and highlights the importance of CCUS in addressing goals set under the Paris treaty. It also discusses the carbon price evolution for major geographies, and the role that individual governments envisage.

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Summary

- FutureBridge expects Carbon Capture and Storage (CCS) to be one of the most pragmatic technologies that can be retrofitted with the existing industrial-scale plants to reap quick benefits. CCS not only creates additional jobs for the industrial sector but also provides a conduit to a cluster of technology integration options, such as hydrogen, Bio-energy with Carbon Capture and Storage (BECCS), etc.
- If implemented in a planned manner, ~14% of cumulative reductions can come from CCS driven initiatives by 2060.
  - ~2,500 large-scale facilities need to be operational to meet Paris Goals; however, only 43 such facilities exist in different stages of development.
- Geological storage is not an issue for the technology to fully materialize; instead, funding and policy hurdles need an early fix.
- In the past 12-18 months, several countries such as the US, the UK, Australia, Canada, Norway, and China have gained significant momentum on the policy front. These countries also have an added advantage of ample geological storage capacities, which help in positioning themselves at the topmost quadrants of the CCS-Storage Indicator (CCS-SI) and the CCS-Interest Indicator (CCS-II).
- Over the last decade, CCS has received significant attention from the R&D community, with patents and literature filings increasing by 2–3 folds, respectively.
  - In the last decade, the membrane technology had received significant attention from the R&D community.
  - Active research on some novel materials such as ionic liquids, aerogels, Metal Organic Frameworks (MOF), etc., reveal their ability to reduce process energy requirement; however, scalability and overall process economics still remain a challenge for such materials.
- Of ~180 CCS plants analyzed (under different stages and at different scales), >70% are functional in the utilities and chemical sectors.
  - Maximum number of CCS installations (~44) registered in the US, followed by Canada and China
  - Post- and pre-combustion capture type accounts for >80% of all CCS projects
  - >40% of plants are using absorption technology to capture CO_2

> “By far the best way to reduce the cost of CCS and profit from its benefits is to stop looking for unicorns and conscientiously progress the options we have in hand today.”
>
> – **Dr. Niall Mac Dowell**, Imperial College, London

Need for CCUS – Recalling the Paris Agreement

When global leaders met on Dec 12, 2015, for the Climate Change Conference (COP21) in Paris, the carbon capture technology had already advanced a great deal as compared to the conventional technology being used in the 1920s. The formal use of this technology was observed in the 1970s when the captured CO_2 from a gas processing facility in Texas was used to boost oil recovery from the nearby fields.

The key goal of the Paris agreement is to limit the global temperature rise well below 2°C above pre-industrial levels, thereby anticipating a reduction in the global Greenhouse Gas (GHG) emissions by 80-95% by 2050 compared to 1990 levels. There is an international consensus that Carbon Capture, Utilization, and Storage (CCUS) will play a critical role as part of an economically sustainable route to emission cuts required to limit global warming to 2°C. In 2014, the Intergovernmental Panel on Climate Change (IPCC) stated in its report that *without CCUS, the costs of climate change mitigation could increase by ~138%, and realizing a 2℃ scenario may not be possible without CCUS technologies*.

The Paris agreement holds special significance as it highlights efforts made over the past 2 decades to achieve a certain degree of substantial progress in emission reduction program, by bringing together both, emerging and developed nations (~196 parties) at a single platform. All parties had to mandatorily come forward with their Nationally Determined Contributions (NDCs) on how they would strengthen their efforts in the coming years.

- **China:** The world's largest CO_2 emitter pledged a peak in CO_2 emissions by 2030; 20% of its energy needs are from low-carbon sources. The country plans to reduce emissions per unit of GDP by 60-65% from 2005 levels by 2030.
- **United States**: On June 1, 2017, the US announced its withdrawal from the Paris Agreement, citing reasons that the treaty will undermine its economic growth; however, the country still needs to abide by the 4 years exit period.
- **European Union**: The country focuses on a reduction in emission levels by 40% by 2030, compared to 1990 levels.
- **India:** Reduction in emission intensity by 33-35% by 2030 as compared to 2005 levels; the country also aims to achieve ~40% cumulative installed power capacity from non-fossil sources.
- **Brazil:** The country focuses on a 37% reduction in emissions by 2025, compared to 2005 levels.

- **Russia:** The country focuses on a 25-30% reduction in emission intensity by 2030, compared to 1990 levels.
- **Japan:** The country focuses on a 25% reduction in emission intensity by 2030, compared to 2005 levels.

Since, the first Conference of the Parties (COP) meeting in Berlin in 1995, there have been ~170 parties till November 2017 that have ratified the Paris Agreement in the conclusion of the Fiji COP23 meeting. As a result of the ratification, the Intended Nationally Determined Contributions (INDCs) turned into Nationally Determined Contributions (NDCs). However, mere ratification of these NDCs cannot solve the issue of CO_2 emission.

To put things in perspective, the aim to achieve a 2°C future is easier said than done due to the complex global energy systems and varying societal aspirations. The fulfillment of this goal will depend upon multiple variables that include population, economic growth, energy intensity, GHG emissions intensity, CO_2 price mechanism, etc.

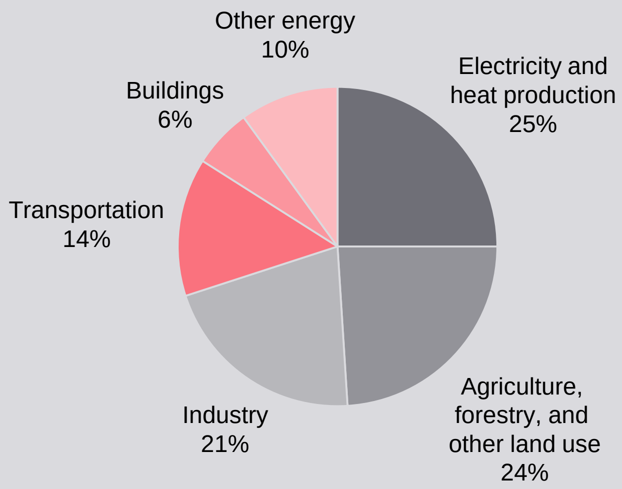
Policies and Prices need to be Concurrent

The global population remained stable during the period, 2000–10; in contrast, the level of economic activity witnessed exponential growth. The industrial sector is vital for the economic prosperity, contributing to approximately one-third of the global GDP. According to IPCC’s report on Climate Change, 2014, the industrial sector contributes to ~21% of the overall GHG emissions (*Exhibit 1*). The same report highlights some of the top CO_2 emitters, globally (*Exhibit 2*).

According to the International Energy Agency (IEA), ~14% of cumulative reductions should come from CCS driven initiatives by 2060 to achieve the ambitious target set under the Paris agreement. Furthermore, Beyond the 2°C Scenario (B2DS), IEA predicts a ~32% share of CCS for industrial decarbonization. However, for large-scale decarbonization, it is imperative to explore other options/technologies beyond CCS to meet the pre-decided goals. A few of the alternatives for CCS includes demand-side measures, energy efficiency improvements, electrification of heat, use of hydrogen (made with zero-carbon electricity) as feedstock or fuel, use of biomass as feedstock or fuel, etc.

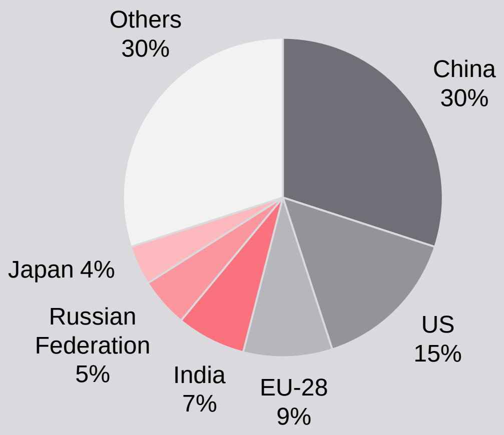
FutureBridge has discussed the impact of CCUS on achieving decarbonization through this white paper.

EXHIBIT 1: GHG Emissions by Economic Sector



Source: IPCC, 2014

EXHIBIT 2: Global CO_2 Emissions from Fossil Fuel Combustion and Some Industrial Processes



Source: US Environmental Protection Agency (EPA), 2014

Industries such as cement (3 Gton CO_2), steel (2.9 Gton CO_2), ammonia (0.5 Gton CO_2), and ethylene (0.2 Gton CO_2) account for ~45% of the CO_2 generated from industries. ~15% of the ~35 Gton of global CO_2 was generated in 2015. Therefore, CCS is the most reliable and cost-competitive technology at present for large-scale decarbonization; however, the current state of affairs presents a slow rate of CCS installation.

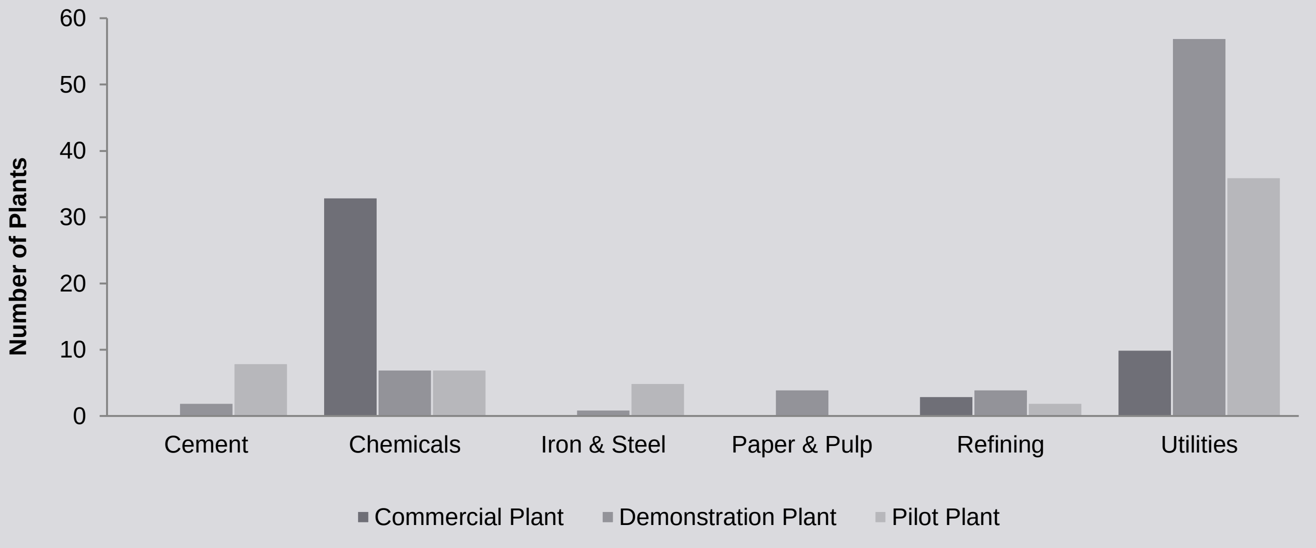
Since, the first installation of CCS plant in Val Verde County, Texas, in 1972, 43 large-scale CCS facilities have been installed that include 18 in commercial operation, 5 under construction, and 20 in various stages of development. This number is still meager as compared to the requirement of ~2,500 large-scale facilities (the size of the facility should be 1.5 million tons per annum of CO_2 capture) to be operational to achieve the Paris 2°C targets.

FutureBridge studied the regional spread of these ~180 plants (*Exhibit 3*); the US had the maximum number of CCS installations (~44), followed by Canada and China, with 17 installations, each. CCS technology holds great potential where geological storage options exist readily. A key challenge to CCS technology development has been the safe storage of captured CO_2, as transportation adds to the overall cost. Thus, storing CO_2 near industrial sites serves to be economical. Proponents of this technology have expressed their deep support against the availability of enough geological storage that exists globally. Surveys have confirmed that potential storage sites across the US, Canada, Australia, Japan, China, Europe, etc., are available and can easily store the amount of CO_2 generated by these nations. Europe alone has over 300 Gtons of storage sites available, which is sufficient to meet the Paris goals between 2019 and 2050.

It is technically proven that storage is not an issue for the technology to fully materialize. High-emitting countries score high on the CCS-Storage Indicator (CCS-SI) and relatively low on the CCS-Interest Indicator (CCS-II). While the storage indicator is usually taken from published records of geological storage available, the interest indicator is a function of multiple parameters that include the share of fossil fuel production vs. consumption, regulatory policies and their effective implementation, etc.

National policies in this regard have had a myopic view without keeping climate change at the center of sustainable development. However, with adherence to the Paris Agreement, many signatories have started to realize its long-term impact.

EXHIBIT 3: Project Type Based on Technology Readiness Level



Source: Global CCS Institute and FutureBridge Analysis

Carbon Capture and Storage Association (CCSA): “There is nothing stopping CCS but policy.”

Cost and policy support are imperative for large-scale implementation of CCS technology. Policy support not only drives investments in CCS but also helps acquire investor confidence required for long-term sustainable growth, which serves to be the key to developing low-cost technologies.

Natural gas processing, and ammonia and bio-ethanol production are some of the low-hanging fruit areas where large-scale CCS projects justify economics. However, other industrial applications such as iron and steel production, and cement production could be cost-sensitive projects. Opportunities in the utilities (power) sector depend upon a variety of factors, such as share of renewable energy, investments, state subsidies, etc.

FutureBridge analysis revealed that an ideological approach to CCS could not help mitigate climate issues; it needs to be supported with a strong policy intervention by individual governments. Although, some states have progressed well in this regard, given the scale that needs to be achieved this might not be enough. Some of the policy focus areas that can boost investor confidence include:

- Setting-up nation-wide emission reduction targets at a sectoral level
- CCS deployment targets
- Capital and operational support in the form of grants and feed-in-tariffs; for instance the 45Q amendment made by the US government
- Setting-up legal and regulatory regimes that address the requirements of project life-cycles
- R&D support
- Others

Furthermore, FutureBridge indicated that a few countries, such as Canada, the United States, China, Norway, and the United Kingdom, with high fossil fuel dependency are aggressive in pursuing their CCS agenda. These nations not only have the technical potential for storage but also have a relatively well-defined carbon pricing framework.

China, with ~20 CCS ongoing projects till November 2018, has been at the forefront of deploying a suite of policy measures ranging from establishing a separate Ministry of Ecology and Environment (MEE) to creating a national carbon market for the power sector.

The United States, which withdrew its support from the Paris Agreement, ironically, has passed the Bipartisan Budget Act in February 2018. This move can potentially prove to be a game changer for increasing investments in CCS. An amendment in Section 45Q under this Act has increased the number of tax credits for geological storage of CO_2. This increases the current tax credit of captured CO_2 to be used in EOR/NG recovery from US$10/ton to US$35/ton, in addition to the tax credit for stored CO_2 in saline formation from US$20/ton to US$50/ton. It also removes the 75 Mton cap for CO_2 storage.

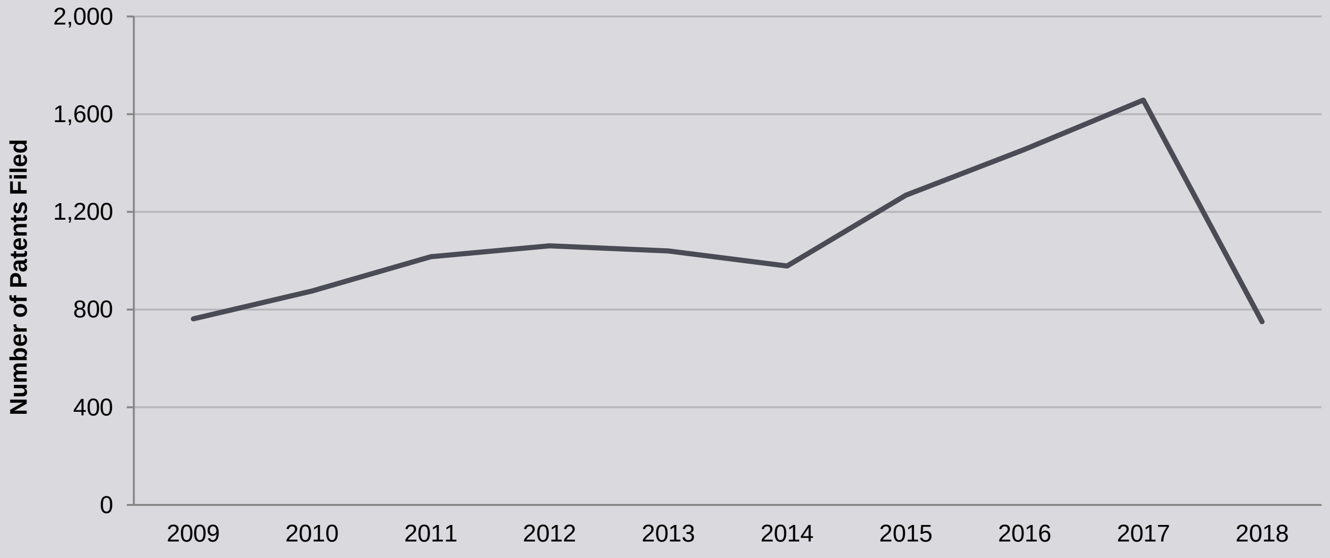
Canada's Clean Growth and Climate Action Plan mandates each federal province to set up an annual plan for carbon pricing starting from CAN$10 per ton in 2019 to CAN$50 per ton by 2022. Provinces failing to adopt such a plan will have to mandatorily follow a federal plan that automatically kicks-off in January 2019.

Technology State of Affairs

The ongoing R&D publication trend demonstrates a healthy growth in patent and literature filings in the CCUS space. While the number of patent filings has almost doubled during 2009-17 (*Exhibit 4*), literature filings have nearly tripled during the same period (*Exhibit 5*). As discussed earlier, the problem is not technological, rather, political and commercial. The cost of capturing and transporting CO_2 can range from US$30/ton to US$200/ton, depending on the technology used, source, and concentration of CO_2 from exhaust gases. Similarly, the cost of transportation and storage of CO_2 can range from US$7/ton to US$35/ton, based on the distance from the capture site. Lower the percentage of CO_2 in exhaust streams, higher is the cost of capture. Based on the concentration range (3%-20%), IPCC ranked certain industries as favorable targets for CCS deployment [ranked as highest to lowest]; these industries include cement, iron and steel, coal-fired power plants, other power plants and refineries, petrochemicals, and natural gas processing. The amine process is considered as a standard absorption technology for such industries; however, there are many novel processes being tested for improving the efficiency, regeneration ability, and cost of various CCS technologies currently under research.

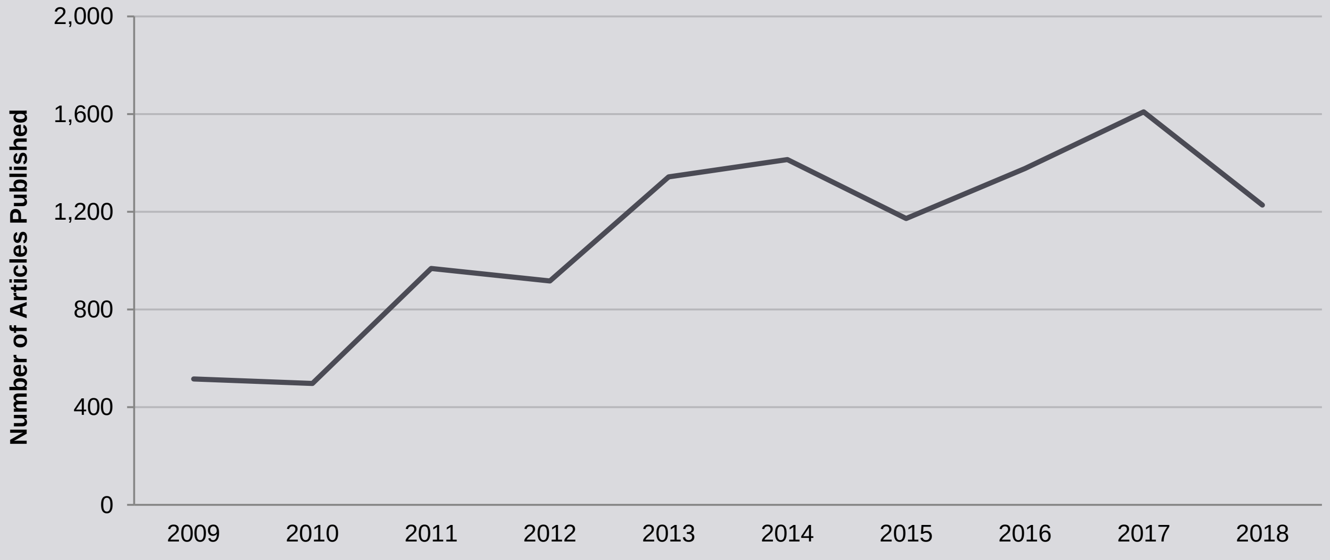
Predominantly, CO_2 capture technologies can be classified into post, pre and oxy-fuel combustion (*Exhibit 6*), but, there are many other emerging technologies under R&D which are being tested for their cost-effectiveness, energy efficiency, scale-up issues, integration with existing fuel conversion systems, etc.

EXHIBIT 4: Patent Literature Trend (2009–18)



Note: Includes CPC code (Y02C 010*) and IPC code (B01D 053*) that denote carbon capture, utilization, and storage
Source: Patent Database – Questel Orbit and FutureBridge Analysis

EXHIBIT 5: Scientific Literature Trend (2009-18)



Note: Includes different types of articles (research, conference & review papers) related to carbon capture, utilization, and storage
Source: Web of Science (WOS) Database and FutureBridge Analysis

EXHIBIT 6: CO_2 capture options classification

POST-COMBUSTION	PRE-COMBUSTION	OXY-COMBUSTION
Separation of CO_2 from waste gas streams after the conversion of the carbon source to CO_2 – E.g. combustion of fossil fuels or digestion of wastewater sludge	**Capturing of CO_2 generated as an undesired co-product of an intermediate reaction of a conversion process** E.g. production of ammonia	**Fuel is burned with pure oxygen to produce flue gas with high CO_2 concentration, free of nitrogen and its compounds (NO and NO_2)** E.g. power generation and cement
Absorption	Absorption	Oxy-kiln
Adsorption	Adsorption	Oxy-boiler
Membranes	Membranes	Oxy-turbine
Anti-sublimation	Pressure/Temperature/ Electric	Oxy-FCC
Liquefaction	Hybrid	Chemical Looping
Non-conventional		

Source: FutureBridge Analysis

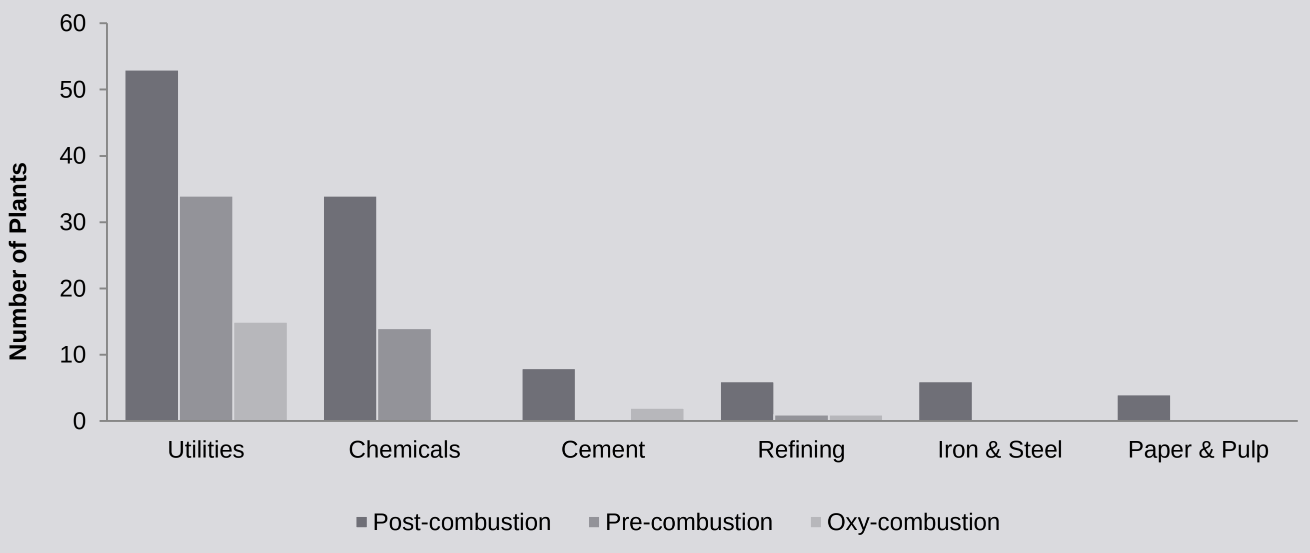
Adsorption and absorption are the most commonly used/tested processes in both, pre- and post-combustion technologies. Adsorption processes are relatively simple, with no chemical emissions. On the other hand, absorption processes are commercially available and have the advantage of scalability for large-scale carbon capture operations. Research proves that adsorption processes offer various benefits; however, they are yet to prove their cost-competitiveness with respect to the amine absorption process.

Active research conducted by academicians and industry leaders on the membrane-based process is still in its pilot stage (TRL: 5-7). This process is still far from providing a feasible option to carbon capture as compared to chemical absorption. Over the last decade, active research on membrane has exceeded solvent-based technology, signifying that R&D on synthesizing new materials is being pursued. Presently, the membrane-based process is faced with several challenges, such as the need for large surface areas and gas recovery. This process is used in applications where low recovery and selectivity are required, such as natural gas processing.

FutureBridge assessed ~180 CCS plants based on the type of technology deployed (*Exhibit 7*). Some of the key takeaways are listed below:

- Post- and pre-combustion capture type accounted for >80% of all CCS projects
- >40% of CCS plants are using absorption technology, and >10% are using liquefaction technology
  - >30% of CCS plants using absorption process fall under the post-combustion technology type
  - >10% of CCS plants using absorption process fall under the pre-combustion technology type
- Some of the leading technology providers include Alstom, Mitsubishi Heavy Industries (MHI), BASF, Shell, Clean Energy Systems, Linde, Air Liquide, Honeywell, etc.

EXHIBIT 7: Projects Based on Capture Methods



Source: Global CCS Institute and FutureBridge Analysis

What to Watch-out for in Carbon Capture Technologies

The global implementation of projects for varied application areas proves that CCS technologies have moved beyond the basic and applied research phase. However, to break the barriers of the development stage increased capex subsidies and a strong political will are required.

FutureBridge analyzed certain technologies that can create an impact in the carbon capture space. Some of these technologies are depicted below (*Exhibit 8*):

EXHIBIT 8: Projects Based on Capture Methods

Solvents	Sterically Hindered Amine	Ionic Liquids for Carbon Capture	Piperazine	Aminosilicone	Bioenzymes
Adsorbents	Graphene	Metal Organic Frameworks (MOFs)	Zeolites	Oxidation-stable Amine-containing Adsorbents	Aerogels
Other Methods	Membranes	Chemical Looping	Calcium Looping	Carbonates	Cryogenics
[1]Negative Emissions Technology	Direct Air Capture (DACs)	Bio-energy with CCS (BECCS)	Algae	Ocean Fertilization	Enhanced Weathering

[1]**Negative Emissions Technologies (NETs):** These technologies act as an offset to the already existing carbon emissions. Theoretically, this means that the amount of CO_2 removed from these technologies can generate credit for emissions elsewhere. Most of these technologies are at research/lab scale, and for NETs to achieve success, it has to be, both, scalable as well as cost-effective.

Source: FutureBridge Analysis

Slow but Steady may not Always Win the Race: Investment Approach

Investments in CCS are imperative for the Paris Agreement to materialize; however, very few countries are actually committing themselves to achieve this goal. In 2016, IEA estimated US$850 billion worth of global investments in low carbon energy—US$297 billion was invested in renewable energy technologies, US$231 billion in energy efficiency, and US$1.2 billion in CCS. This is certainly not enough considering the ambitious targets set under the Paris Agreement.

A comparative investment assessment for the period 2010-16 revealed that renewables received ~US$2.3 trillion vs. ~US$10 billion for CCS, as cumulative investments. However, it will not be fair to compare both the scenarios due to the involvement of multiple other parameters. Considering the role of CCS in CO_2 abatement and beyond, cumulative investments need to increase significantly over the next decade.

Most technologies discussed in the earlier section are still in the TRL 2-7 range. These projects are required to effectively adopt the “learning-by-doing” principle. Needless to mention, the fast deployment of projects will lead to a steep learning curve for under-research technologies with a potential for further cost reduction.

Outlook

The progression into a more complicated world with diverse energy sources and even more diverse utilization options has propelled the need to critically evaluate what sustainable living means. A large percentage of energy sources used today emit emissions. While renewable installation has progressed significantly in many parts of the world, there is still a long way to go before it can create the required impact on emission levels at a global scale. One of the most pragmatic technologies that encompass the ability to curtail CO_2 emissions immediately is CCS. It can be retrofitted to the existing industrial plants, without having to shut-down or switch to alternate/expensive fuel sources. Moreover, CCS and renewables move simultaneously in achieving the same goals.

A majority of technology options that exist today are still in the early stages of development. The commercial implementation of novel materials, such as ionic liquids aerogels and MOFs, outperform the current state-of-the-art materials in many areas, which, in turn, will decrease the energy requirements of both, capture and utilization processes. However, cost-effectiveness is the ultimate factor determining the feasibility of the adoption of emerging CCUS technologies. Long-term stability of materials used in most CCUS methods is an important consideration that not only impacts the system performance but also affects the economics of the process.

In 2018, countries such as the United States, China, the United Kingdom, Norway, and Australia, among others had shown remarkable progress in the development of policies for CCUS. However, the key challenge remains to maintain this momentum and to ensure the proper flow of funds. FutureBridge analyzes that in addition to policy developments, certain concrete steps required to facilitate legal and regulatory framework that imbibes CCS technologies will be crucial to address Paris Agreement goals. Despite these developments, the long-term debate on whether emerging or developed countries are responsible for CO_2 emission is still ongoing.

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