ALMA MATER STUDIORUM - UNIVERSITA' DI BOLOGNA

Dipartimento di Ingegneria Civile, Chimica, Ambientale e dei Materiali

Department of Civil, Chemical, Environmental, and Materials Engineering

Corso di Laurea
Magistrale
Second Cycle Degree
In
Earth Resources Engineering

THESIS

"Circular Economy and Carbon Capture, Utilisation and Storage Technologies in Developing Countries"

PRESENTATA DA
DEFENDED BY
Heydar Ismayilli
0000844602

RELATORE
SUPERVISOR
Prof. Davide Tabarelli

Anno Accademico – Academic year 2019-2020

Table of Contents

ABSTRACT

The Earth gets warmer primarily as a result of human activity, which results in the release of greenhouse gases into the atmosphere, most notably carbon dioxide, CO_2. Increasing carbon dioxide concentration brings many problems with itself such as climate change, global warming, freshwater issues, reduced soil productivity, increasing acid rains, human health issues, extinction of species and more. And developing countries have a huge share in this increase in carbon dioxide emissions. To tackle with undesirable change, new missions and technologies are needed. In the coming decades, a carbon capture, utilisation, and storage appears to be a viable problem-solving technology. Developed countries started to use these technologies, demonstrating that although zero-emission is currently unlikely, reducing pollution is entirely feasible. Besides this, transition to renewable energy resources is one of the main circumstances. Also, there is a relation between CCUS and circular economy.

This paper mainly focus on this relationship and provide information for developing countries to shift from linear economy to circular economy. The idea of a "circular economy" (CE) is quickly gaining traction as a new model for sustainable development. A circular economy is one in which goods, gases and materials are removed, recycled, repaired, and reused rather than discarded, and waste from one manufacturing process is turned into a valuable input.

The research development scenario aims to increase the number of CCUS plants which result with decreasing of carbon dioxide emissions. The scenario says that, four factories should come together and construct one carbon capture, utilisation and storage plant. One of the main part of this idea is capturing process begins where the greenhouse gas emit to the atmosphere. Those gases absorbed by special adsorbers and transported to main pipeline by polyethylene pipelines. The main pipeline takes all the absorbed gases to the CCUS plants. By using this system, emitted carbon dioxide will be captured before mixing to air or atmosphere.

Acknowledgements

First and foremost, I would like to express my heartfelt gratitude to Professor Davide Tabarelli, my research supervisor, for allowing me to conduct research and providing invaluable guidance during the process. His dynamism, vision, friendliness, and inspiration have all left an indelible impression on me. He has shown me how to complete the study and present the research findings as clearly as possible under the circumstances. Furthermore, I would like to express gratitude to all of my professors, tutors, group mates, and friends for volunteering their time to discuss and brainstorm with me.

Finally, and most notably, I want to express my appreciation to my fiancee and her parents, as well as my sister and my parents, for their unwavering support and encouragement during my years of study and research. Without them, nothing would be possible.

List of Tables

List of Figures

Abbreviations

API - American Petroleum Institute

BAU - Business As Usual

CAPEX - Capital Expenditure

CE – Circular Economy

CCE – Circular Carbon Economy

CCF - Cyclone Converter Furnace

CCS – Carbon Capture and Storage

CCUS – Carbon Capture, Utilisation and Storage

CHEERS - Chinese-European Emission-Reducing Solutions

CSIRO - Commonwealth Scientific and Industrial Research Organisation

CTL - Coal-to-liquids

IEA – International Energy Agency

IGCC - Integrated Gasification Combined Cycle

IRP - International Resource Panel

IOGP - International Association of Oil & Gas Producers

LNG - Liquefied Natural Gas

LPG - Liquefied Petroleum Gas

MSW - Municipal Solid Waste

NGCC - Natural Gas Combined-Cycle

OPEX - Operating Expenditure

PCSP - Pilot CO2 Storage Project

1. CLIMATE CHANGE AND GLOBAL WARMING

1.1 Introduction

Last two centuries, the amount of greenhouse gases increased dramatically due to the industrial revolution. While the GHG increases worldwide, it causes the changing of the climate from north to south, from east to west. Solar energy is the primary driver of the Earth's climatic system. At present, the average incoming solar radiation is 342 Wm^{-2}. It varies by less than 0.5 Wm^{-2} on the time scale of years to a century, approximately in pace with the eleven-year sunspot cycle. About 31% is reflected in space primarily due to the high reflectivity of clouds, ice, and snow. In that sense, the presence of water in these forms tends to cool the Earth. Thus about 235 Wm^{-2} is absorbed in the atmosphere and at the Earth's surface. Note, however, that the outgoing radiation from the Earth's surface at the prevailing average temperature of about +15°C is about 390 Wm^{-2}, i.e., about 155 Wm^{-2} more than finally escapes from the Earth. This process is the result of the natural greenhouse effect [1]. In the long term, the absorbed energy is balanced by the outgoing long-wave radiation.

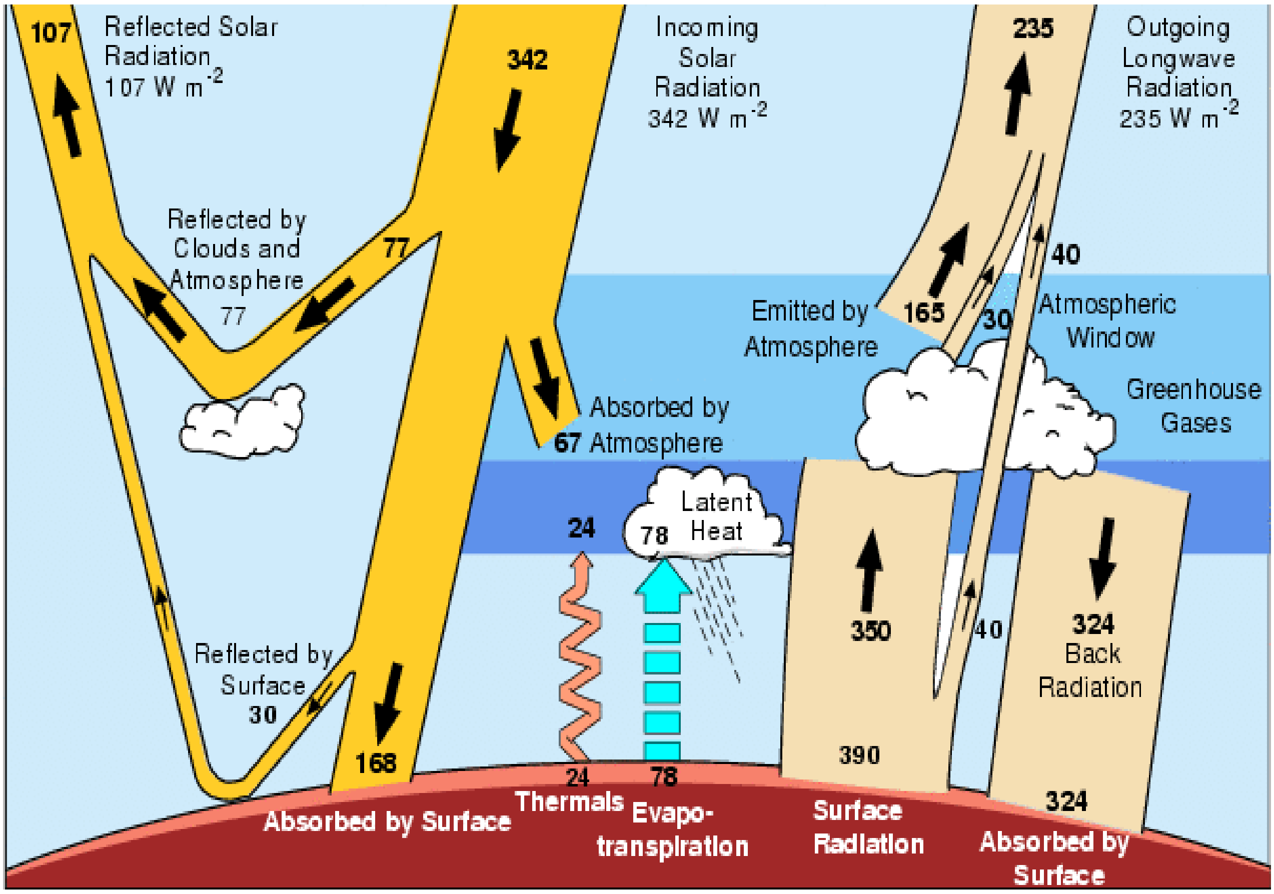


Figure 1.1 The Earth's global average annual energy balance. Fluxes are given in Wm^{-2}. Som'ce: Kiehl and Trenberth (1997)

Moreover, the earth atmosphere has a capacity to emit infrared radiation and trap some atmospheric gases such as GHGs. The greenhouse gases contain carbon dioxide (CO_2), water vapour, methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs) and ozone in the troposphere and stratosphere. The concentration of these gases is always crucial for life on Earth planet. Greenhouse gases occur naturally on the Earth for providing conservative conditions. If the concentration increases, the Earth's surface begins to absorb more infrared radiation, which causes global warming. Otherwise, the temperature would decrease and cause global cooling. It means, while man-induced disaster happens, we have to be careful about preserving the balance of temperature and GHGs in the atmosphere. In particular, carbon dioxide augments this natural greenhouse effect.

With the growing demand for energy consumption, most countries have been using coal as the primary energy source. World Coal Association Coal fact sheets show that the world's electricity is generated by coal and steel is respectively 41% and 68% [2], [3]. There is a consensus that global energy demand will continue to rise, driven primarily by continued increases in population and economic growth. At the same time, climate change from increased carbon dioxide levels (CO_2) released into the atmosphere has become a top international priority. Consequently, more energy will have to be delivered, but with far fewer emissions, to meet the international commitment to limit the increase in average Earth temperature well below 2°C compared with preindustrial temperatures [4].

Several global warming issues are unbalanced ecosystems, health problems for people, and species threatened with extinction [5]. New missions and technologies need to tackle global warming. Carbon capture, utilisation and storage system seems an acceptable problem solver technology in these decades. Developed countries began to use these technologies and proved that zero-emission is impossible for now, but decreasing the emissions is entirely possible. While the investments increase in the Research & Development of carbon capture, utilisation and storage systems, the new improvements gain speed.

Climate change policy is located at the centre point of these discussions. Advancing development goals sustainably, there are strategic interests for developing countries in addressing climate change while simultaneously addressing nationally defined development priorities [6].

1.2 Impacts of Climate Change

From the historical records, changing the climate has been detrimental effects on humanity and cultures. Besides this, all the living species have been affected by these climatic issues. While climate changes, everything needs to adapt to a new environment. However, some civilisations failed to adapt to the changing climate. Changing climatic conditions has been attributed to part of the collapse of several early civilisations, including the early Egyptian empire, the western Roman Empire, the Mayan civilisation, the Bronze Age people of Canaan, and the Norse farmers of Greenland [7].

The research emphasised that a higher concentration of carbon dioxide can create a fertilisation effect resulting in greater photosynthesis of up to 40%, and it gives countenance to faster growth for some plant species. Research also proposes that increased carbon dioxide concentrations prevent some plant species from UV-B radiation, which has detrimental effects on some plants' growth. The high concentration of CO_2 also causes increase precipitation which will enhance harvests everywhere [8].

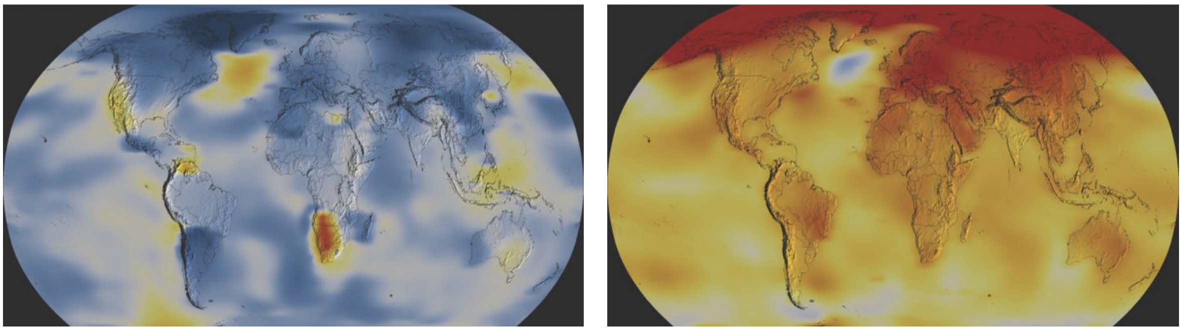


Figure 1.2 The temperature change from 1890 – 2020

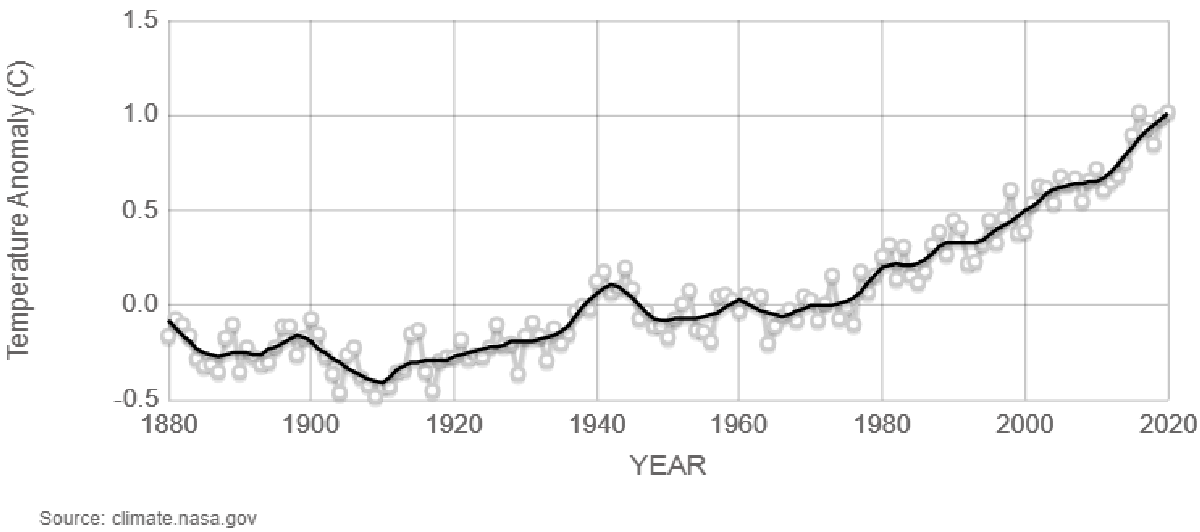
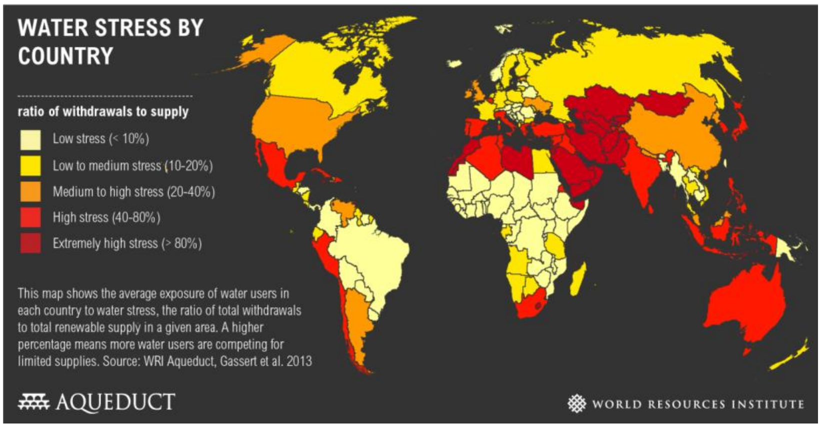


Figure 1.3 Temperature change 1880 – 2020 years

From the graph, it is visible that, in a century, global temperature on the Earth increased dramatically (Figure 1.3). One Celsius does not seem more important when we think of the local temperature of an area, but in a global increase, it breaks our ecosystem's chains.
In theory, it seems quite possible all over the globe. However, some areas may increase, which may be offset in other parts of the Earth. The causes of the negatory effects upon agriculture are multiple for some countries due to climate change. In 2003, the severe heatwave began in Europe, and the temperature increased 20 to 30 % during the summer months than the mean temperature in Celsius over other years. The maximum temperature fluctuated between 35 and 40 Celsius in those months. The highest temperature recorded in July was 38.1 Celsius in the United Kingdom. July 2003 was an abnormal climatic condition also for France, Germany, Italy and Spain.

The precipitation diminished, and evaporation increased dramatically in the Mediterranean area and South Europe, so water balance deficit of up to 380 mm [11]. France lost 20% of its grain harvest during this period, Italy lost 13% of its wheat, and the UK lost 12% of its wheat. Ukraine saw a 75% decrease in its grain harvest from average years [10]. Typically, the effects include decreases in agricultural output due to some crops being overcome by the excessive heat of more than a few degrees Celsius above current temperatures and drought [9].

Changing the climate also brings along the freshwater issue, which seems problematic and unsolved for developing countries. Southern Africa, central Asia, and countries around the Mediterranean Sea are located in high-stressed and extremely high-stressed regions where climate change could decrease groundwater recharge and streamflow (Figure 1.4). Within 5 years, the population living in water-stressed areas is projected to increase to around 5 billion [12]. An area lack freshwater will cause collective death, which is called the holocaust. The reason for tragedy can be seen as a changing climate, but the point to focus on has to be unforeseen anthropogenic mistakes. Changing of climate has begun for dozens of years and centuries.
For increasing world food production, humankind gravitates to fertilisers, pesticides and animal waste. However, for an extended period, they face freshwater problem to irrigate. Ocean and seawater are not useful for irrigation and use for a drink. There is only 3 % of fresh water on the Earth, and just 0.5 % is available to use. 2.5 % of freshwater is locked up in glacier, so far under the earth layer, which high cost to extract and use polar ice and atmosphere.



A generous portion of Earth water is salty with 97%. Howbeit, modern farming around the world pollutes the freshwater basins by the nitrate and phosphate fertilisers and pesticide residues.

Figure 1.4 Water stress by country

The reason is that nitrogen and phosphorus fertilisers are soluble in water, and they contaminate the groundwater.

In addition to this, increased heat has an undesirable impact on human health, mainly for the elder, sick and the people who do not have access to air-conditioning. In Europe, 36000 people have been killed by the heatwave in the 2003 climatic tragedy [13]. Research suggested that one degree of increased temperature causes 600 deaths over 65 years old in Japan. If the temperature increased by two degrees, the amount of death would be around 65 people per day, and a three-degree increment means 162 people per day.

Scientific researches projected that climate change has a significant impact on Poles. The Polar Regions were the enormous mass of glacial ice on Earth with 85% and 10% appropriately to Antarctica and Greenland. The melting of these ice fields changes the current of oceans.

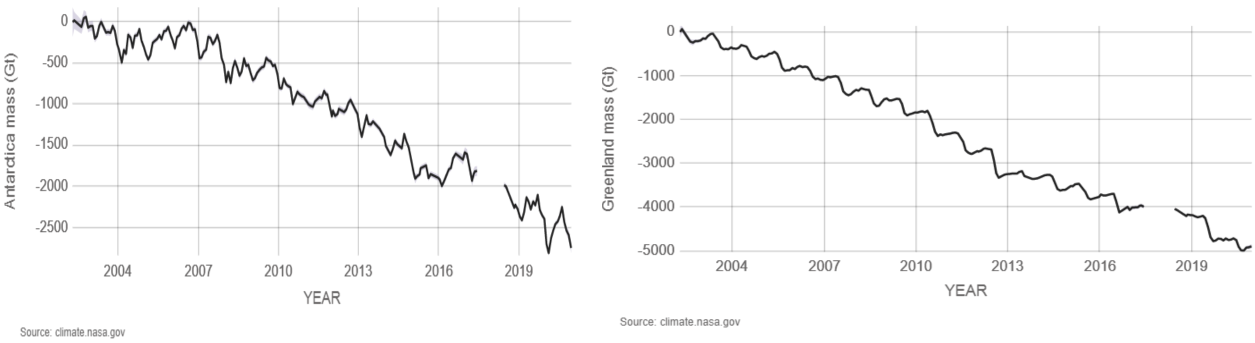


Figure 1.5 Losing mass of Antarctica and Greenland (2002- 2020)

Since 2002, both massive ice fields losing their mass dramatically, Antarctica lost 2500 Gt (gigatonne), and Greenland lost 5000 Gt (Figure 1.5). Annually, the rate of this change for

Antarctica is 150 billion metric tons, while it represents 278 billion metric tons for Greenland. Everything is interdependent in our ecosystem as a chain, and from our experience, we saw that if one of the chains gets broken, it affects all ecosystems.

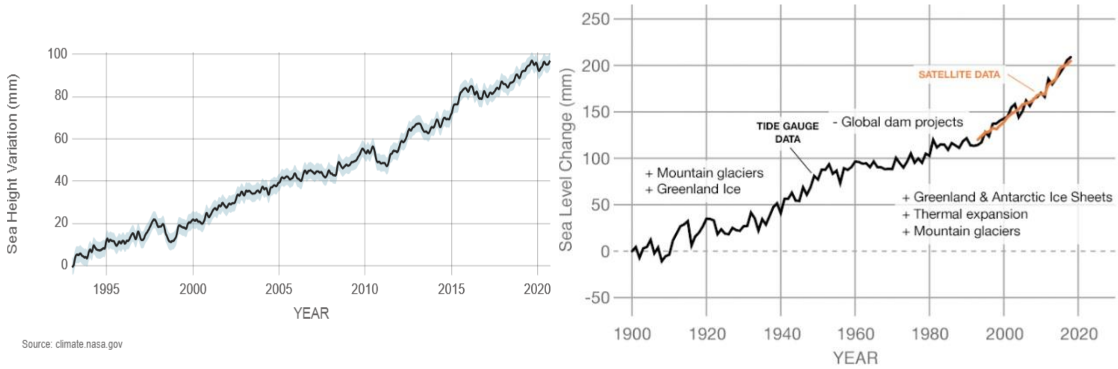


Figure 1.6 Sea height and sea-level change in the years 1995 - 2020

Ice masses are melting, and the sea level is increasing (Figure 1.6). Graphs tell us dramatic changes in the sea level began from the last century and increased more than 200 millimetres. The changing rate of sea level is 3.3 millimetres every year. It means that in the following decades, the sea-level will increase more than 33 millimetres.

1.3 Increasing carbon dioxide emission

Over the globe, carbon dioxide emission increases on an irrepressible scale. Each country has a notable impact on this increment. The increased concentration of carbon dioxide is caused by anthropogenic considerations. These issues are primarily due to the intervention of energy. Moreover, from the 1800s to this day, the need for energy has steadily increased and is increasing.

Furthermore, this causes the rate of carbon dioxide in the air to skyrocket suddenly. Increasing carbon dioxide does not have any benefit for the world. Nevertheless, the opposite is true. As the concentration increases, it decreases the efficiency of the ecosystem both on land and in water. This reduction brings about ecosystem degradation, air pollution, and climate implications, which we have not seen any favours until now. As humanity, today we obtain energy from fossil fuels. The rate of carbon dioxide emitted by these fuels to the atmosphere is constantly increasing. At the same time, fossil fuels are used in everyday homes, transport, workplaces, factories and many more, and we are now inundated with carbon dioxide in every part of our lives. Since carbon dioxide is a colourless, odourless gas, we cannot see it quickly, but it begins to peel and freeze as it rises to the atmosphere. As a result, it starts to create a greenhouse effect for the world.

As the temperature rises, unexpected and unusual acid rain, excessive heat or extreme cold are recorded. We can easily feel these in our daily life as humanity. Also, when we look at the issue globally and when we investigate, we see that the ecosystem started to collapse, that glaciers in oceans and seas melt and mixed into water, as well as freshwater reserves are going to end. Simultaneously, we can observe the burst fires in different regions, mainly rainforests, people and terrestrial species rapidly extinguished. We can easily observe that they lost their lives. For example, in 2003, 36000 people lost their lives due to the heat.[13].

Developed countries set out to deal with the problem in their own right and started operations with many meetings and decisions. Rio de Janeiro and Kyoto protocols can also be examples. However, as a result, the concentration of carbon dioxide continues to increase steadily, which means that when the problem is global, there is no need for discrimination like in developed and developing countries. Otherwise, any step to be taken may be fruitless.

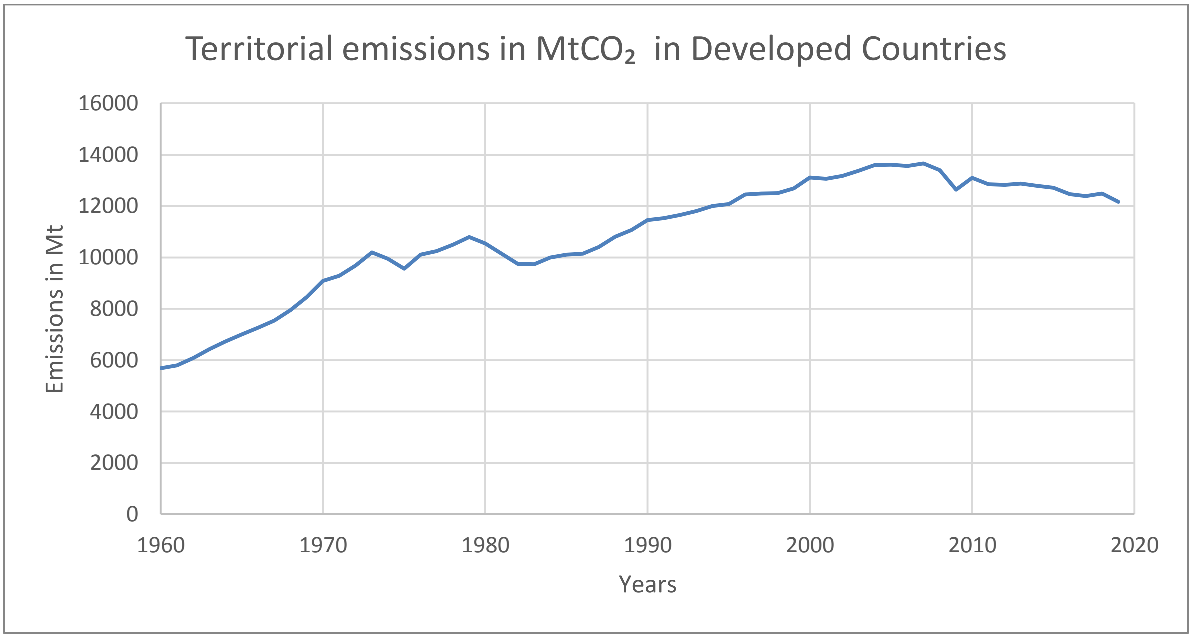


Figure 1.7 Territorial emissions in developed countries, 1960 - 2020

The rate of carbon dioxide has increased in developed countries until 2007 (Figure 1.7). However, it has been on the decline since 2007. The total rate of carbon dioxide emitted to the atmosphere by developed countries in 2019 is slightly higher than 12000 Mt. This figure was 6000 Mt per year in the early 1960s. Carbon dioxide emissions have doubled in 60 years as the growing number of people, and the energy demand increased. Undoubtedly, consuming fossil fuels so quickly would come at a price. It will be both unexpected and destructive if droughts prevail in many parts of the world and extreme cold prevails in others.

Today, the CO_2 amount in the atmosphere is over 0.03%. Although the concentration is low, the damage and effects it causes are very permanent. 99% of the gases in the atmosphere are oxygen and nitrogen gases. The other 1% is composed of greenhouse gases, carbon dioxide and inert gases. Greenhouse gases absorb infrared radiation or radiated heat. Moreover, this process continues for millions of years. However, when a carbon molecule is thrown into the atmosphere, the process extends up to 100,000 years, and this molecule goes back and forth between plants, soil, air and water, and at the end of this process finds itself in the stagnant reservoir of sediments.

We see another striking point when we look at the carbon dioxide waste graph of developed countries. Since 2007, the carbon dioxide emission released into the atmosphere has started to decrease. Namely, according to 2007 data, these countries were emitting 13656 $MtCO_2$ carbon dioxide into the atmosphere. In 2019 data, this figure decreased by 1500 $MtCO_2$ to 12163 $MtCO_2$. The reason for this decrease was in 2005, and the European Union launched an emissions trading system in 2007, which regulates 10,000 facilities with a total value of $50 billion in the international carbon market, more than 75 % of the entire world carbon market [40].

Moreover, at the same time, the Kyoto protocol, which was adopted in 1997, came into effect in 2005. The situation is different and dire in developing countries. Countries emitting 3500 $MtCO_2$ of carbon dioxide in the 1960s were now taking their pace and rising steadily. Developing countries that do not fully meet the demand for energy with fossil fuel types continue to pollute the atmosphere without considering the future.

In 2007, carbon dioxide emissions were recorded as 16970 $MtCO_2$, and there is no stopping here (Figure 1.8). By continuing to deplete fossil reserves, they brought their carbon emissions to 23585 $MtCO_2$ in 2019. If we compare it with 1960, this corresponds to almost 7 times more carbon emission. If we suddenly decide to get rid of fossil fuels today, nature can overcome such damage in hundreds of thousands of years. It is essential to save nature from thinking that this possibility will not be possible in the near future, at the same time to stop the changing climate towards damage and to reduce the temperature on the Earth.

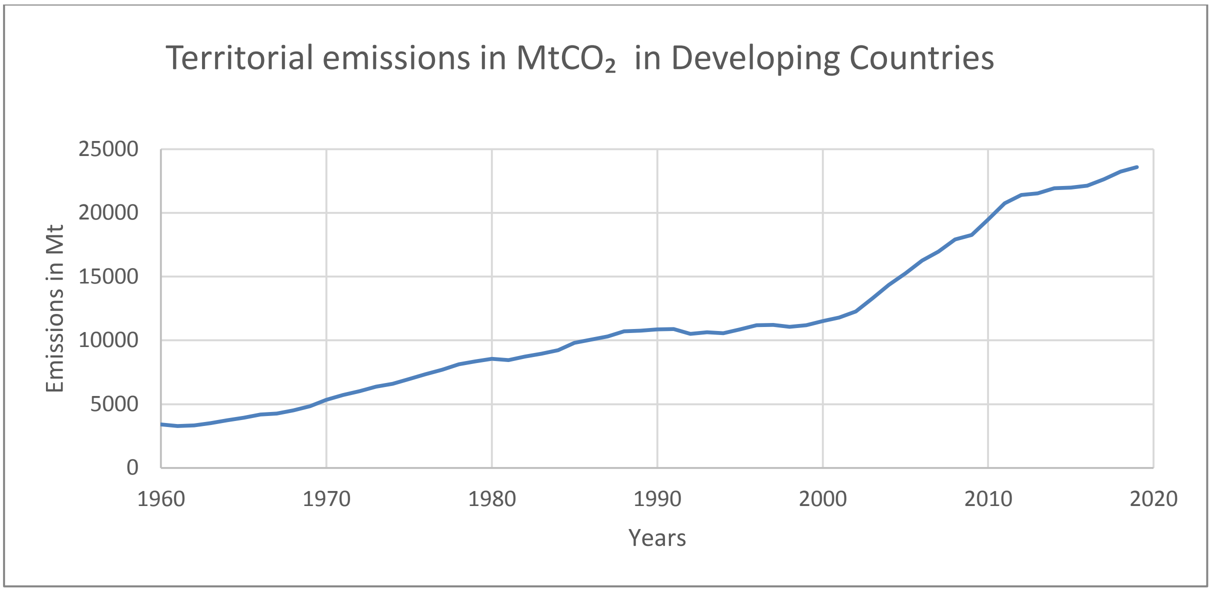


Figure 1.8 Territorial emissions in developing countries, 1960 - 2020

According to IEA data, there was no significant decrease in fossil reserve usage between 1990 and 2018 (Figure 1.9). Although fossil fuel production has an increasing trend, sustainable energy resources cannot approach these rates. For these reasons, technology is needed to reduce carbon dioxide.

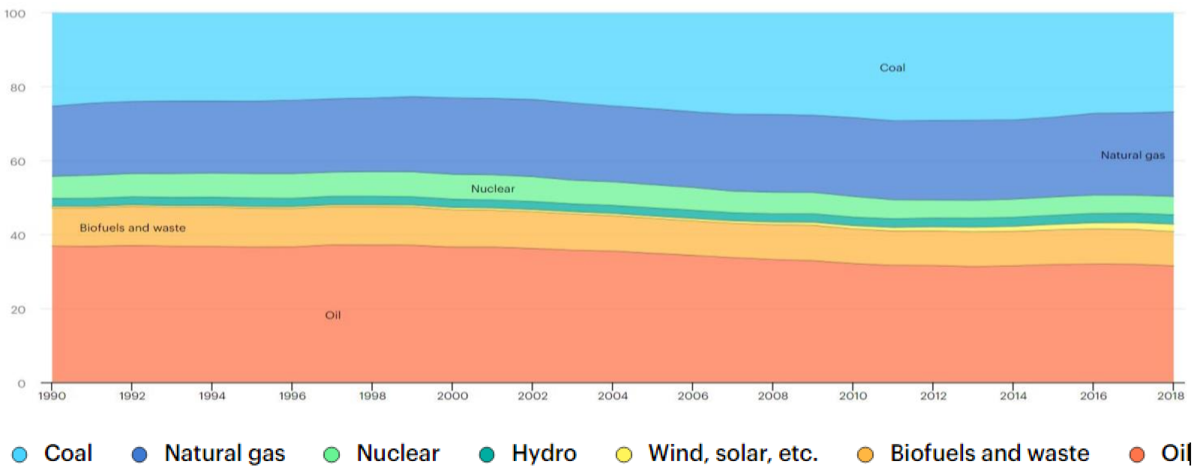


Figure 1.9 World energy balance, 1990 – 2018 [39].

Moreover, today, "CCUS" technology is used and developed to counter the increasing pollution. Some developing countries have applied CCS and CCUS technologies to adapt to a new global circular economy with strong aims for cutting emissions.

China	Strong domestic CCUS research has been conducted, as well as EOR production, several CO_2 capture pilots, industrial CCUS research and development, an IGCC with CCS plans, comprehensive bilateral cooperation with the US is currently ongoing, and a regulatory mechanism is being developed.
Brazil	The establishment of a research centre, the beginning of bilateral technical cooperation with the United States, the creation of EOR, and the study of a CCS pilot at a bioethanol plant are all underway.
South Africa	The CCS Centre has been developed, the national storage atlas and roadmap have been completed, and regulatory analysis has begun.
Indonesia	CCS project proposed under Japan's offset policy
India	Fertiliser capture and utilisation programs on a small scale are currently ongoing.

Table 1.1 A partial list of major CCUS and CCS operations in developing countries [37].

1.4 Status and outlook

Climate change is expected to have a major effect on developing countries unless serious mitigation and adaptation measures are implemented, with the vulnerable bearing the brunt of the burden. The longer severe steps are taken, the worse the consequences will be, and the potential costs will be higher. Taking steps now to mitigate and adapt to climate change would greatly minimise potential risk. To mitigate potential climate change attempts to reduce greenhouse gas emissions in the developing world should be increased.

Developing countries such as China and India should prioritise greenhouse gas emission reductions. Adaptation should be prioritised for the least developed countries. A lot can be achieved in developing countries to mitigate climate change without slowing down the economy, especially in terms of increasing energy production, reducing deforestation, and improving agricultural efficiencies. In developing countries, the knowledge base on climate change is frequently minimal. There is a shortage of data, studies, and adequately trained staff.

To reduce the potential impacts of climate change in developing countries, action must be taken immediately. The following actions should be prioritised:

- Emissions of greenhouse gases should be kept to a minimum.
- Providing support to developing countries in responding to climate change by reducing their vulnerability.
- Developing countries such as India, China, and Brazil must prioritise low-energy growth and clean energy production (Table 1.1).
- Developing countries should avoid using single-use materials
- Developing countries should change their economy from linear to circular economy, giving lots of advantages such as recycling and reusing materials.

2. Technology of CCUS

For capturing CO_2, some of the countries use CCUS technologies (Figure 2.1). The carbon dioxide increase, which continues with the start of the industrial revolution, has reached a problematic level today. Energy production based on fossil fuels has become the livelihood of the world. To counter the carbon dioxide increase in the atmosphere, it is necessary to use today's new technologies. CCUS technology is also a product developed for this purpose.

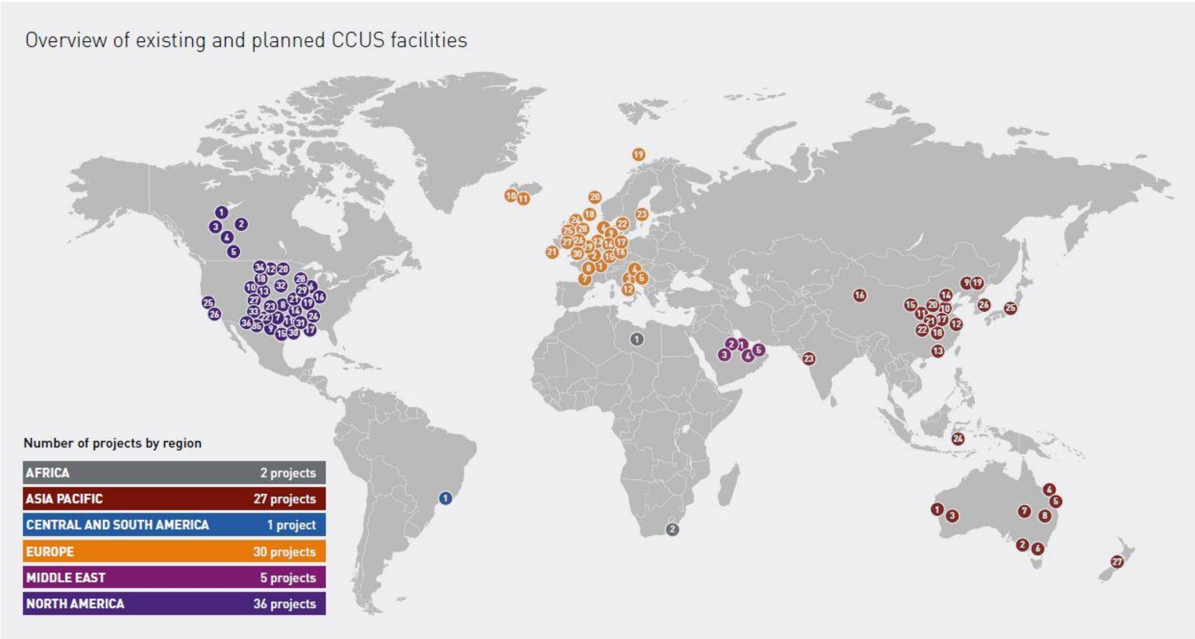


Figure 2.1 Number of projects by region (2021, Global CCS Institute and IOGP data)

The most widespread technology for reducing CO_2 emissions has three different processes: capturing the carbon, utilisation and storage. Carbon capture is designed to remove and lower the concentration of carbon in the air. After the captured carbon transports to the plants for utilisation process. The utilisation process aims to convert carbon dioxide into valuable products or a standard product for pumping and storing in the wells. The carbon dioxide storing process prevents the pumped CO_2 gas from re-entering the atmosphere [14].

Time goes by, in developing countries, the number of CCS plants should be increased. Today, most CCS plants are located in China (Table 2.1). While CCS may be appealing to some developing countries, there has been little production of demonstration projects in Africa, Asia, or Latin America, owing primarily to their high costs in the absence of anticipated revenues or substantial carbon financing [37].

CCS facilities in Developing Countries

Country	Facility Name	Facility Industry	Operational	Description
Algeria	In Salah CO_2 Storage	Natural Gas Processing	2004	In Salah CO_2 Storage facility started CO_2 injection in 2004 and completed in 2011. 3.8 million tonnes of CO_2 is successfully stored in the depleted gas reservoir near the gas processing plant. The storage site was closely monitored by In Salah CO_2 Assurance Joint Industry Project JIP, using various geochemical, geophysical, and production techniques, including satellite imaging, well monitoring, seismic monitoring and micro-seismic monitoring. No CO_2 leakage was reported during the lifetime of the project.
South Africa	Pilot Carbon Storage Project (PCSP) - Zululand Basin, South Africa	Under evaluation	2020	The PCSP is an important step forward in South Africa's CCS progress. The project will serve as a proof of concept for CCS and capacity building in South Africa, and it is an essential phase in the country's CCS roadmap. The project entails injecting 10,000 to 50,000 tonnes of supercritical CO_2 into an onshore deep saline formation and monitoring it, with the Zululand Basin as the goal.
China	Australia-China Post Combustion Capture (PCC)	Power Generation		The scope of the study includes evaluating the technological, economic, social, environmental, legal, and regulatory viability of retrofitting post-combustion carbon capture technology to a power plant operated by the Huaneng Group in China's Jilin Province. The facility could have the

	Feasibility Study Project			potential to capture approximately 1 Mtpa of CO_2.
India	Carbon Clean Solutions Solvay Vishnu Capture Project	Chemical Production	2012	Carbon Clean Solutions tested their proprietary chemical solvent at a Solvay chemical plant near Tirupati, India. The carbon dioxide capture capacity of the test facility was around 22 tonnes per day, with testing occurring between August 2012 and August 2013.
China	China Coalbed Methane Technology Sequestration Project	N/A	2004	This project aimed to test the coal seams in the north-eastern part of China as permeable and stable enough to absorb CO_2 and enhance methane production. Approximately 192 tonnes of CO_2 was injected into a single coal seam in April 2004.
China	Chinese-European Emission-Reducing Solutions (CHEERS)	Oil Refining	2022	Chinese-European Emission-Reducing Solutions CHEERS at a demonstration laboratory in Sichuan Province, China, the 2nd generation chemical-looping technology is being tested and checked. The project aims to become a 3 MWth demonstration system for decarbonising the petroleum refining industry and other energy-intensive industries by 2022.

China	CNPC Jilin Oil Field CO_2 EOR	Natural Gas Processing	2018	This facility injects CO_2 for enhanced oil recovery (EOR) in low permeability reservoirs of the Jilin oil field in northeast China. The CO_2 is captured from a nearby natural gas processing plant at the Changling gas field and transported by pipeline. After 12 years of pilot and demonstration tests, the commercial operation, as Phase III began in 2018, reaching 600,000 tonnes CO_2 per annum. Cumulative CO_2 injection of 1.12 million tonnes for pilot and demonstration-scale operation was reached in 2017.
China	CNPC Jilin Oil Field EOR Demonstration Project	Natural Gas Processing	2008	This pilot into the Jilin oil field was the first large CO_2-EOR demonstration project in China to understand CO_2 EOR mechanisms under the geological conditions in China. An accumulative injection capacity of around one million tons CO_2 in the period of 2008 to 2016.
China	Daqing Oil Field EOR Demonstration Project	Industrial Applications	2003	The facility aims to provide technical support for future enhanced oil recovery EOR activities in extra-low permeability reservoirs around the Daqing oil field in Heilongjiang Province, Northeast China. EOR has been studied since the 1980s, and the scale of CO_2 field flooding tests has been expanded since 2003. The current annual CO_2 injection rate is estimated at around 200,000 tonnes.

China	Guohua Jinjie CCS Full Chain Demonstration	Power Generation	2020	Shenhua Guohua Jinjie Energy, a subsidy of Shenhua Group, is developing a demonstration-scale CCS facility in a coal-fired power station in China's Shaanxi Province. The CO_2 collected from the Shenhua ordos CCS demonstration project will be transported by tanker truck to an existing CO_2 injection site with a capacity of 150,000 tonnes per year.
China	Haifeng Carbon Capture Test Platform	Power Generation	2018	As Stage, I of a planned program of CCS activities, two sets of carbon capture test facilities are planned to be installed at Unit 1 of the Haifeng Power Plant Guangdong area, China. One set would be designed to test amine-based capture methodology, the second membrane-based. The total capture capacity for both is estimated at around 70 tonnes per day. Operations started in December 2018.
China	Huaneng GreenGen IGCC Demonstration-scale System (Phase 2)	Power Generation	2020s	The GreenGen program to develop a large-scale CCS facility in China in the power sector in Tianjin, China, is being carried out in three phases, with the second phase including the development of a pilot-scale CO_2 capture system estimated at between 60,000-100,000 tonnes per annum. In 2016, the pilot plant's construction was finished, and commissioning activities began.

China	Huazhong University of Science and Technology Oxy-fuel Project	Power Generation	2020s	Huazhong University of Science and Technology HUST collaborated with industry partners to establish the world's largest operational oxy-fuel combustion demonstration facility in Hubei Province, China. The Jiuda Salt Company's captive power plant was used to build a 35 MWth oxy-fuel unit. The plant's construction was finished in 2015. Plans show that 100,000 tonnes of CO_2 will be captured every year in the future.
China	ITRI Calcium Looping Pilot	Cement Production	2013	In cooperation with the Taiwan Cement Company TCC, the Industrial Technology Research Institute ITRI has installed a calcium looping test facility at TCC's cement plant in Hualien, Taiwan. This test facility became operational in June 2013 and is the most extensive test facility worldwide for this technology, with a capacity to capture around 1 tonne per hour of CO_2.
China	Karamay Dunhua Oil Technology CCUS EOR Project	Methanol Production	2015	Carbon dioxide capture systems were retrofitted to a methanol plant located in Karamay City, China, in 2015. The facility has a CO_2 capture capacity of approximately 100,000 tonnes per annum. The captured CO_2 is transported by tanker truck to the Xinjiang oil field in the Junggar Basin for enhanced oil recovery.

China	PetroChina Changqing Oil Field EOR CCUS	Coal-to-liquids (CTL)	2017	PetroChina has been running CO_2-EOR trials in Changqing Oil Field since 2014. In 2017, the CO_2-EOR operations were scaled up to 50,000 to 100,000 tonnes per annum. CO_2 is captured from a coal-to-liquids plant. Injecting CO_2 into these reservoirs has the added benefit of enhanced oil recovery while sequestering CO_2 to reduce warm gas emissions.
China	Shenhua Group Ordos Carbon Capture and Storage (CCS) Demonstration Project	Coal-to-liquids (CTL)	2011	This is one of the largest pilot or demonstration scale CCS projects in the world to have injected CO_2 into a dedicated geological storage setting and is a pioneering project in China for evaluating CO_2 injection in such environment. It is China's first entirely coal-based full-chain CCS project. The CO_2 was sourced from the Ordos coal liquefaction plant, with the liquid CO_2 transported a short distance to the injection site. Four injection tests were performed periodically from 2011 to 2014 for a total CO_2 injection volume of approximately 300,000 tonnes.
China	Sinopec Qilu Petrochemical CCS	Chemical Production	2021	Sinopec Qilu Petrochemical CCS plans to retrofit a CO_2 capture system to an existing coal/coke water slurry gasification unit at a fertiliser plant in Zibo City, Shangdong Province, China. The initial phase of the facility is in construction with a capture unit capable of close to 0.4 Mpta CO_2. The 2021 timeframe schedules the long term target of 0.5 Mtpa of CO2 capture capacity.

				The CO_2 stream would be transported by pipeline to the Shengli oilfield for enhanced oil recovery.
China	Sinopec Shengli Oilfield Carbon Capture Utilization and Storage Pilot Project	Power Generation	2010	Approximately 30,000-40,000 tonnes per annum of CO_2 can be captured from a pilot facility at the Sinopec Shengli power plant, located in Shandong Province, China. The captured CO_2 is transported by road tanker to the Shengli oil field for enhanced oil recovery EOR. The pilot capture facility became operational in the latter part of 2010 though CO_2-EOR operations began in early 2008.
China	Sinopec Shengli Power Plant CCS	Power Generation	2020s	China Petrochemical Corporation Sinopec plans to build a post-combustion capture system to a newly built thermal power production unit as part of Phase III of the Shengli Power Plant development in Dongying City, Shandong Province, China. The CO_2 capture facilities, with a capacity of 1 Mtpa, are expected to begin operation in the 2020s. CO_2 will be extracted and transported via pipeline to the Shengli oilfield for improved oil recovery.
China	Sinopec Zhongyuan Carbon Capture Utilizatio	Chemical Production	2006	The pilot facility includes a 20,000 tonnes per annum tpa CO_2 capture facility that have been operational since 2006, an additional 100,000 tpa CO_2 capture facility was added in 2015. The CO_2 is captured from a petrochemical complex in Henan

	n and Storage			Province, China. It is then transported to the Zhongyuan oil field for enhanced oil recovery operations.
China	Yanchang Integrated Carbon Capture and Storage Demonstration	Chemical Production	Early 2020s	Yanchang Petroleum, through affiliates, is developing CO_2 capture facilities at two coal-to-chemicals plants. The smaller-scale CO_2 capture source, with a capacity of 0.05 Mtpa, has been operational since 2012, while the larger CO_2 source, with a capacity of 0.36 Mtpa, is currently under construction and may be operational in the early 2020s. Captured CO_2 would be used for enhanced oil recovery EOR in oil fields in the Ordos Basin in central China.
Brazil	Petrobras Santos Basin Pre-Salt Oil Field CCS	Natural Gas Processing	2011	Since 2011, Petrobras has developed CO_2 separation and injection systems installed in FPSO's to produce O&G fields located in the offshore Santos Basin Pre-Salt. The CO_2 associated with the natural gas is separated, then compressed and injected into gas injection wells for enhanced oil recovery. As of December 2019, the Santos Basin Pre-Salt development reached 14.4 million tons of CO_2 injected. It is projected that by 2025, 40 million tons of CO_2 would have been accumulated, contributing to technical advancement, cost savings, and demonstration of the safety of the CCUS technology.

Brazil	Petrobras Santos Basin Pre-Salt Oil Field CCS	Fertiliser Production	2009	Petrobras began injecting CO_2, around 370 tonnes per day, into the Miranga onshore oil and gas field in the state of Bahia, Brazil, in late 2009, the purpose of which was to test technologies that could contribute to the then future development projects for the Santos Basin's offshore pre-salt cluster. Press reports from around April 2011 indicated that the first phase of CO_2 injection at Miranga was completed.

Table 2.1 CCUS and CCS projects in developing countries, 2021 [22]

2.1 CO_2 Capture

Capturing and sequestration of carbon dioxide from flue gases are the main processes of CCUS technology. While modelling a capturing system, we faced several issues. Existing technologies for CO_2 capture can be physical and chemical processes such as absorption, adsorption, cryogenic, membrane and microbial processes. However, the companies which use the CCUS system needs economically attractive and feasible technology.

Factors that affect the choice of a suitable capture process include feed gas characteristics (composition, flow rate, pressure, and temperature), source type (power generation, gasification, gas upgrading, etc.), source fuel type (solid or gas), capture type (precombustion, post-combustion, and oxy-combustion), capture performance rating (CO_2 purity, recovery, energy penalty, etc.), and cost.

The ratio of carbon dioxide changes due to flue gases from various sectors. Flue gases from chemical and power plants contain CO_2, N_2, O_2, H_2O, CO, H_2, etc., compositions. Remarkably, the CO_2 content in industrial gases can be as low as 0.1% (by volume) and as high as 75% (by volume) or more. Natural gas supplied to a typical liquefied natural gas (LNG) process contains, depending on the nature of the natural gas wells, 0.1−8% CO_2. The coking process in an iron industry produces a large amount of coke-oven (CO) gas which contains only 1% CO_2. CO_2 contents are about 7% in typical refinery flue gases, 8−11% in urea, natural gas processing, upstream LNG, and fuel oil plants, 19% in cement plants, 20−24% in conventional blast furnace and Corex steel plants, and 44% in CCF steel plants. The CO_2 content from an iron and steel plant is even greater than usual if CO is converted into CO_2 using a shift reaction. Even the power plants, depending on their types, produce flue gases with significantly different CO_2 contents. While flue gases from natural gas combined-cycle (NGCC) power plants contain only 3−4% CO_2, coal-fired power plants produce post-combustion flue gases containing 12−14% CO_2. The composition of the flue gas from an oxy-combustion-based coal-fired power plant is much different. The flue gas coming from the oxy-combustion boiler has a high CO_2 content of 58− 60%, which after dehydration and O_2 scrubbing increases to 74.2−76%.

Around 84.3 % of global primary energy came from oil, gas and coal reserves in 2019 (Figure 2.2). For the coming decades, displacing them with low-carbon energy resources is one of the appropriate ways to reduce this share. In 2000, 35.2 % of global electricity production came from low-carbon energy resources, and in 2019, this percentage shows 36.7% [15]. The developing world 1.5% increase does not seem reasonable because changing climate acts more rapidly than changing to low-carbon energy resources.

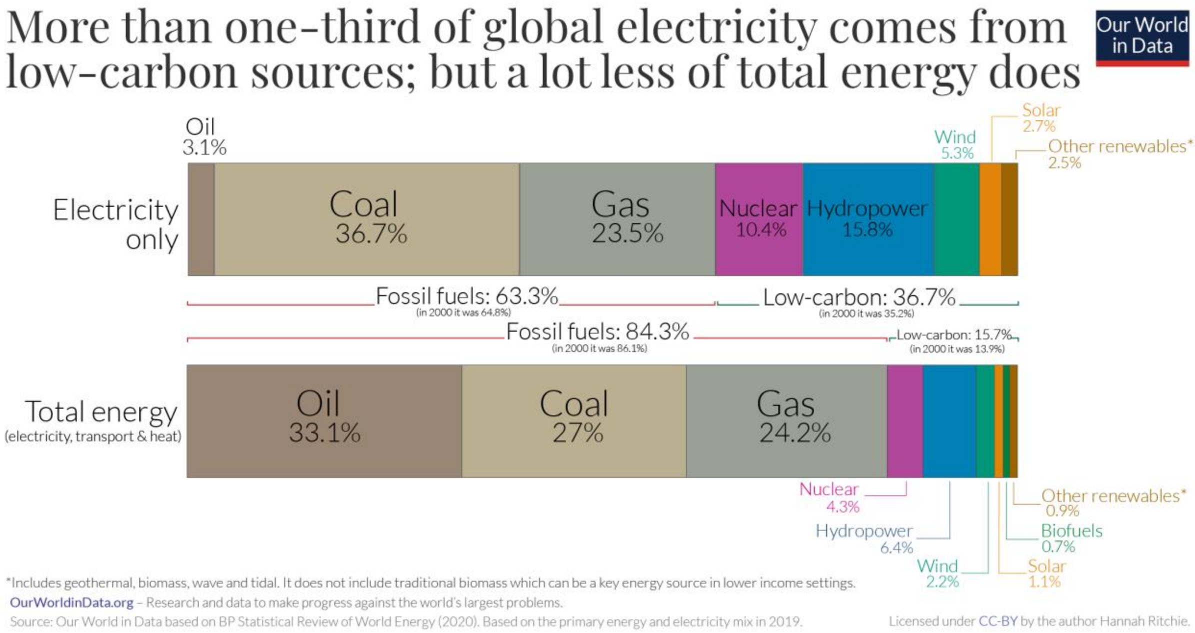


Figure 2.2 Sources of global electricity

There are three known basic systems for capturing CO_2 from the power sector, including biomass:

- Decarbonisation of the fuel prior to combustion – pre-combustion capture
- CO_2 separation from the products of combustion - post-combustion capture
- Reconstructing the combustion process to produce CO_2 as a pure combustion product, obviating the need for its separation (oxyfueling or oxy-fuel combustion)

2.1.1 Pre-combustion

Pre-combustion involves decarbonisation by gasification of the primary fuel, usually coal or biomass, to produce H_2 through a combination of partial combustion, conversion, and water-gas transition. The focus of IGCC facilities is the current development and demonstration of pre-combustion capture. In principle, the approach is equally applicable to all integrated gasification systems, such as integrated gasification fuel cell (IGFC) systems where hydrogen is the final syngas product. The separation of CO_2 and H_2 can be achieved using several technologies(Table 2.2).

H_2 and CO_2 separation technologies for pre-combustion process
• Absorption-based separation
• Adsorption-based separation
• Membrane separation
• Cryogenic separation

Table 2.2 Separation technologies for pre-combustion process

They use physical solvents such as the Selexol and Fluor processes, which are currently the most commercially developed.Besides that, there are disadvantage and advantage of the pre-combustion method (Table 2.3). The main advantage of this method is that while capturing CO_2, it uses low energy. After capturing the CO_2, by using a compressor, the gas is compressed, and this process also takes less energy than other combustion methods. It also has disadvantages such as

issues with temperature and performance associated with hydrogen-rich gas turbine fuel.

Capture option	**Advantage**	**Disadvantage**
Pre-combustion	Low energy usage for capture and compression of CO_2	Issues with temperature and performance associated with hydrogen-rich gas turbine fuel

Table 2.3 Advantage and disadvantage of pre-combustion

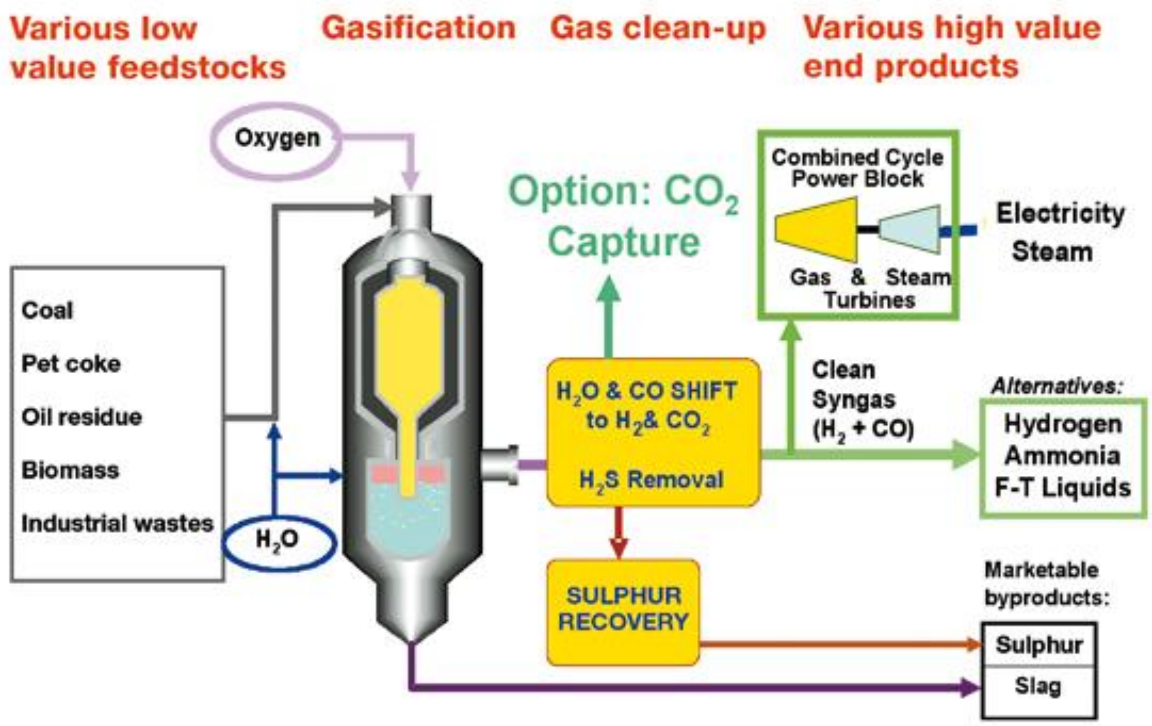


Figure 2.3 Process scheme of pre-combustion

In the pre-combustion of carbon capture, the carbon is captured before the fuel is combusted. First, fuel and steam at high temperature and pressure are fed into the gasifier (Figure 2.3). The steam has a liquefied quantity of O_2 to prevent the fuel from fully combusted. The carbon in this fuel reacts with the steam to produce hydrogen gas and carbon monoxide.

$$C_{(S)} + H_2O_{(g)} \rightarrow CO_{(g)} + H_{2(g)}$$

Solid carbon reacts with H_2O gas in this reaction. Despite the limited O_2, there is always a little bit of combustion that happens. This little bit of combustion produces small amounts of hydrogen sulphide (H_2S), carbonyl sulphide (COS), ammonia (NH_3) and hydrogen cyanide (HCN). The flue gas is then removed from the gasifier. It is first clean to particulate matter, otherwise known as the ash, which will flow mostly from combustion. Then it is scrubbed in acidic compounds. Basic materials such as $CaCO_3$, water murky, ammonia and other compounds are condensable. As a result, they are eliminated by cooling the gas stream. The substance that remains is a relatively pure mixture of carbon monoxide and hydrogen gas, also known as cyanide gas. Cyanide gas used to be known as town gas because it was used to light streetlights back in the 19th century. This gas can be used as fuel or be fearless further purified into hydrogen gas to be used in hydrogen fuel cells. For using it as a fuel cell, then gas goes into the water gas shift mechanism. This turns the carbon monoxide into carbon dioxide and more H_2. This is then purified to pull out the water H_2O and the CO_2. So the system left with just hydrogen gas which can be used in the fuel cells.

CO_2: H_2 separation is somewhat more straightforward than the post-combustion separation of CO_2 and N_2 due to the more significant difference in molecular weights and molecular kinetic diameters for CO_2 versus H_2 than for CO_2 versus N_2.
In addition to the further development of technologies related to CO_2:H_2 separation, other aspects of pre-combustion capture processes that are being addressed by RD&D efforts include:

- Development of H_2 -fueled gas turbines (addressing combustion processes, including flameless combustion, burner design, heat transfer and cooling, materials impact, and operational aspects)
- Physical, energetic, and operational integration of pre-combustion capture process into an IGCC plant
- Optimisation of gasification process — catalysts, heat integration, and adaptation for CO_2 capture, purification, and transmission [16].

2.1.2 Post-combustion

Current anthropogenic CO_2 emissions from fixed sources are mostly due to combustion systems such as power plants, cement kilns, industrial kilns and iron and steel production facilities. In these large-scale operations, direct ignition of the fuel with air in a combustion chamber has been the most economical technology to extract and use energy from the fuel. Therefore, the strategic importance of post-combustion capture systems emerges when faced with the reality of today's CO_2 emission sources. All CO_2 capture systems aim to separate CO_2 from the flue gases generated while burning fossil fuels on a large scale. A similar system for capturing can also be applied to biomass-fired combustion processes, which is much smaller scale compared to fossil fuels. Unlike pre-combustion, post-combustion needs more power for a solvent generation. Moreover, it means the capital and operational costs will be high (Table 2.4). Fuel is burned with air inside a boiler in a coal-fired power generation system. The turbine produces electricity by producing steam. The critical components of boiler exhaust or flue gas are N_2 and CO_2. Post-combustion capture is widely regarded as the best available technology, especially for coal-fired power plants.

Capture technology	Advantage	Disadvantage
Post-combustion	Fully advanced technology, commercially used in other industrial sectors at scale Opportunity for retrofit to existing plant	High parasitic power requirement for solvent regeneration High capital and operating costs for current absorption systems

Table 2.4 Advantage and disadvantage of post-combustion

Fuel is burned with air inside a boiler in a coal-fired power generation system. The turbine produces electricity by producing steam (Figure 2.4). The critical components of boiler exhaust or flue gas are N_2 and CO_2. Post-combustion capture is widely regarded as the best available technology, especially for coal-fired power plants. Currently, cutting-edge competition technology is focused on amine solvent cleaning. Scrubbing with a solvent that interacts with CO_2 is known as solvent scrubbing.

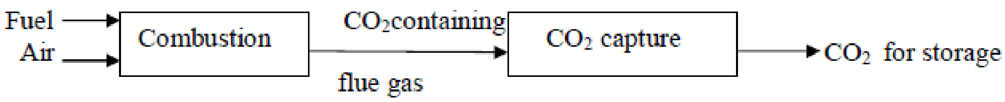


Figure 2.4 General CCS process scheme

It is trapped in the flue gas and regenerates at a higher temperature, resulting in a stream of refined CO_2 that can be compressed and stored. The current solvent regeneration heat demand is high (around 3.0 MJ/kgCO_2 for final attempts and 4.2 MJ/kgCO_2 for conventional Econamine FG treatment using MEA as solvent) and has a significant effect on the plant's overall performance. [17]

In most combustion systems, flue gases or stack gases are at ambient pressure. Vast flows of gases are emitted as a result of the low pressure, the high presence of nitrogen from the air, and the large size of the units, the most notable example being stack emissions from a natural gas combined cycle power plant with a maximum capacity of around 5 million normal $m3h^{-1}$. A range of commercially viable process methods can be used to capture CO_2 from flue gases in theory. However, comparative evaluation studies have shown that chemical solvent-based absorption processes are currently the preferable alternative for post-combustion CO_2 capture.

Several post-combustion gas separation and capture technologies are being researched, including absorption, cryogenic separation, membrane separation and microalgal bio-fixation, adsorption. The various technology choices for post-combustion CO2 capture are summarised in Figure 2.5.

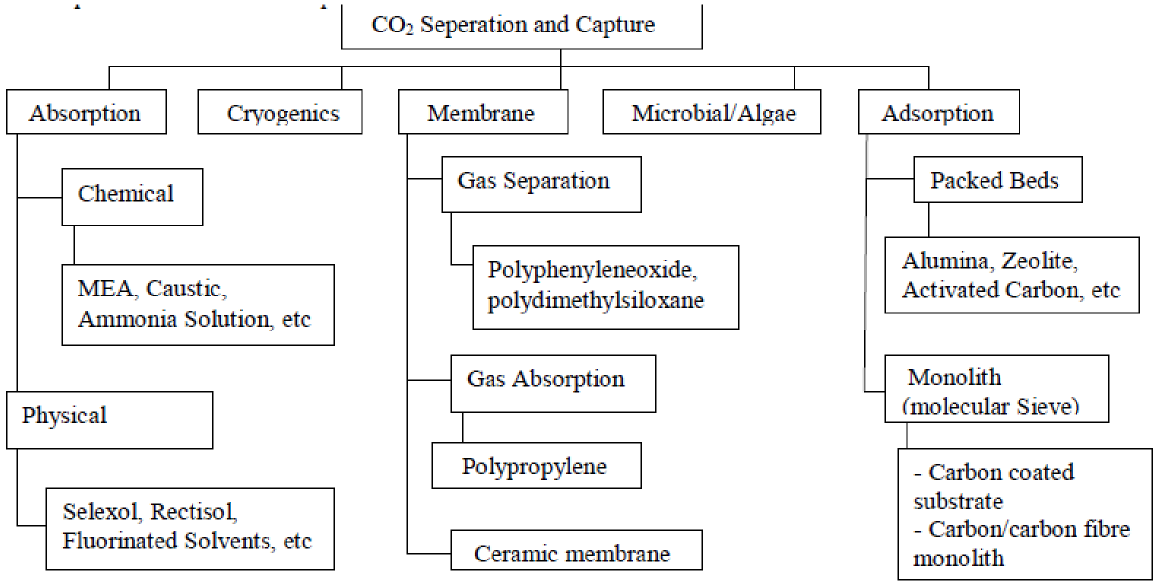


Figure 2.5. Carbon dioxide separation and capture methods [19]

Absorption: This is a well-known CO2 capture device mainly employed in the chemical and oil industries. Solvent scrubbing requires the use of a chemical solvent that reacts with the CO2 in the flue gas and is then regenerated at a higher temperature, resulting in a filtered CO2 stream that can be compressed and stored. The exhaust gas is cooled first, then purified to eliminate particulates and other impurities before being fed into the absorption column, where the amine solvent chemically absorbs CO2. The CO2-rich solution is fed into a stripper column, which raises the temperature (to about 120 C) to release the CO2. The CO2 that has been released is compressed, and the regenerated absorbent solution is recycled back into the stripper column.

Cryogenics: This method employs a separation principle based on cooling and condensation. When the gas stream contains high CO2 concentrations, this process is used to catch CO2. It is currently not used on CO2 sources that are more dilute, such as conventional power plants. Separation of this strategy often necessitates a considerable amount of electricity.

Membranes: Membranes work because of variations in physical or chemical interactions between gases, and the membrane material is altered to allow one part to move through faster than the other. The membrane modules may be used as a gas absorption column or as a traditional membrane separation device. CO_2 removal occurs in the former case due to the membrane's inherent selectivity between CO_2 and the other gases involved. In contrast, CO_2 removal occurs in the latter case due to gas absorption, in which membranes, which are usually microporous, hydrophobic, and nonselective, are used as a fixed interface for CO_2 transfer. This membrane-based gas separation method is still relatively new, with low selectivity and high energy consumption.

Use of microbial/algae: Aside from physicochemical CO_2 removal methods, biological CO_2 removal methods involving algae, bacteria, and plants have also been used. For CO_2 mitigation, microalgal fixation of carbon dioxide in photobioreactors has recently reawakened interest. Insufficient illumination would limit the growth of microorganisms, reducing CO_2 removal. The use of chemoautotrophic microorganisms that remove CO_2 using inorganic chemicals rather than light energy has also been effective.

Adsorption: For gas separation, solid adsorbents such as activated carbons, zeolites and mesoporous silicates, alumina, and metal oxides have been widely used. Recently, activated carbon fibres and carbon fibre composites have been described as promising solution for gas adsorption. Structured porous monolith materials made of carbon fibres have recently been studied for their ability to adsorb gases due to their molecular sieving characteristics selectively. Monolithic carbon fibre composites minimise inter-particle voids and increase bulk density, increasing the material's adsorption potential. Although traditional wet solvent processes (used for example, in CO_2 removal on a large scale in applications such as natural gas processing) are commercially available and have been tested for capturing CO_2 from flue gas at pilot scale, this method is expensive, needs pre-treatment, produces large amounts of wastewater and sludge from the solvent processes, and has a low performance. As a result, in order to make CO_2 capture commercially feasible, new ideas and cost-effective technologies for such applications are critical. The development of carbon fiber composite adsorbents for CO_2 capture is currently looking very promising. It is a dry process, as opposed to the traditional solvent methods. Carbon fiber monolithic composite adsorbents have been produced as a single block or a cylinder. CSIRO recently developed a new form of carbon fiber composite adsorbent with several channels [19].

2.1.3 Oxy-fuel combustion capture

Oxy-fuel combustion necessitates the supply of oxygen rather than air to the combustion chamber, resulting in a near-pure CO_2 reaction product rather than a mixture that must be segregated. Oxygen can be produced in the form of a gas stream formed by separating O2 from the air or as a solid oxide produced by a chemical looping process.

Capture technology	Advantage	Disadvantage
Oxy-fuel combustion	Sophisticated air separation technologies	Significant plant impact makes retrofit less attractive

Table 2.5 Main advantage and disadvantage of oxy-fuel combustion

By combusting a hydrocarbon or carbonaceous fuel in either pure oxygen or a combination of pure oxygen and CO_2-rich recycled flue gas, the oxy-fuel combustion mechanism removes nitrogen from the flue gas. In oxy-fuel combustion capture systems, CO_2 capture performance is very close to 100 %. Impurities in CO_2 include gas components originating from the fuel used, such as SO_x, NO_x, HCl, and Hg, and inert gas components derived from the oxygen feed or air leakage into the system, such as nitrogen argon and oxygen. CO_2 is delivered as a thick supercritical phase through a pipeline. To prevent two-phase flow conditions in pipeline systems, inert gases must be reduced to a low concentration. To comply with regulations governing the co-disposal of toxic or hazardous waste or prevent operations or environmental issues associated with disposal in deep saline lakes, hydrocarbon formations, or the ocean, the acid gas components may need to be removed. To avoid water condensation and corrosion in pipelines, the carbon dioxide must also be dried, allowing traditional carbon-steel materials.

Indirect heating - steam cycle: the oxy-fuel combustion chamber heats a separate fluid through heat transfer through a surface in these systems. It can be used for process heating or power generation in a boiler with a steam cycle. Any hydrocarbon or carbon-containing fuel may be used with the indirect method.

Fluidised beds could be fired with O_2 instead of air to provide heat for the steam cycle for pulverised coal, gasoline, natural gas, and biomass combustion (Figure 2.6). Even in highly exothermic settings, the extreme solid mixing in a fluidised bed combustion system will provide excellent temperature regulation, reducing the need for flue gas recycling. There are several commercial prototypes for fluidised combustion boilers that could be converted to use oxygen in theory. Shimizu et al. proposed a circulating fluidised bed combustor with O_2 firing to produce the heat needed for $CaCO_3$ calcination [20].

Essential features of the system included (Figure 2.6): The burner configuration and gas recycle flow rate was chosen to achieve the same temperatures as air combustion (temperatures consistent with the boiler's existing materials).

- The boiler's CO2-rich flue gas is separated into three streams: one to be recycled back into the combustor, one to be used as coal feed transport and drying gas, and the third as product gas. Direct water scrubbing removes residual particulates, water vapour, and soluble acid gases, including SO_3 and HCl, from the first, recycle and the product stream. The burners receive oxygen, entrained coal dust, and the second recycle stream.

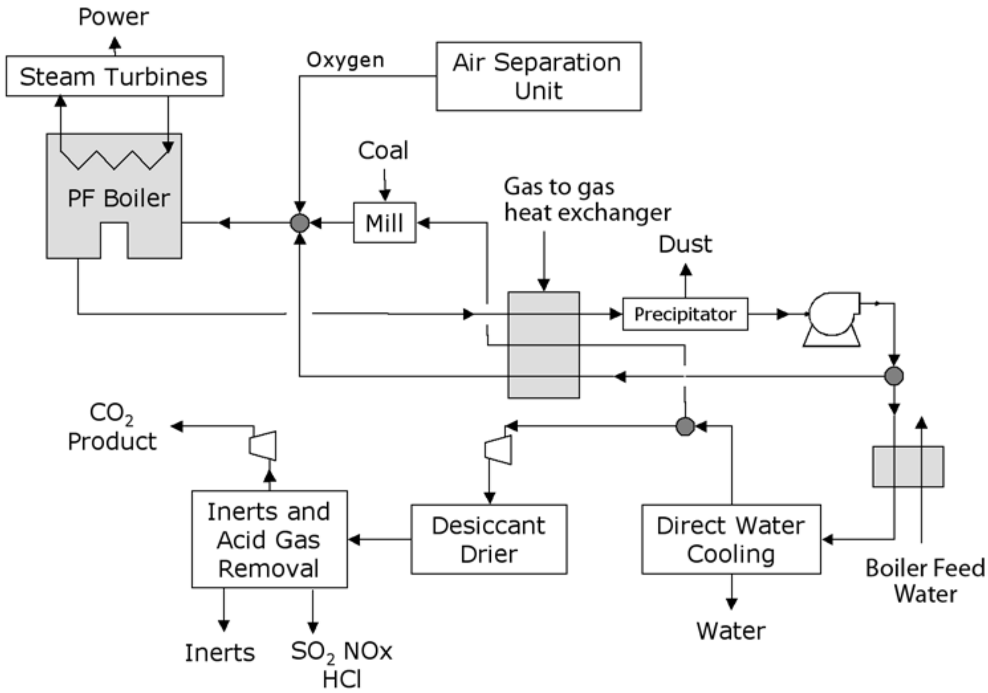


Figure 2.6 An oxy-fuel, pulverised coal-fired power plant schematic [21].

- Even if pure O_2 is used as the oxidant in the boiler, air leakage is sufficient to produce a high enough inerts level to necessitate the installation of a low-temperature inert gas removal device. In this scenario, the cryogenic oxygen plant would generate 95 % O_2 purity to reduce power consumption and capital costs.

- If high purity CO_2 is needed for storage, a CO_2 purification plant with low temperature (-55°C) integrated with a CO_2 compressor can remove not only excess O_2, N_2, argon, but also all NO_x and SO_2 from the CO_2 stream [41]. Importantly, removing these components before final CO_2 compression removes in the net flue gas drain, the need for upstream NO_x and SO_x removal equipment exiting the boiler. Higher SO_x concentrations in the boiler and lower NO_x levels arise from the removal of N_2 from the flue gas. Construction materials that are corrosion resistant must be selected.
- Since the CO_2/H_2O gas mixture in the boiler has a higher emissivity than nitrogen and provides better heat transfer in the convection component, overall heat transfer is improved in an oxy-fuel shooting. These enhancements, combined with the recycling of hot flue gas, resulting in a 5% increase in boiler efficiency and steam production.

  Running the O_2 plant air compressor and the first and final stages of the CO_2 compressor without cooling and recovering the compression heat for boiler feedwater heating before de-aeration improves overall thermal efficiency.

Due to the reuse of hot gas, these are inexpensive and relatively simple modifications that improve boiler/heater thermal performance. A coal-fired boiler's modifications are complicated [21].

2.1.4 Status and outlook

Commercially available post-combustion CO_2 capture technologies based on absorption processes are currently available. They manufacture CO_2 from flue gases in coal and gas-fired plants for food and beverage applications and chemicals processing, with capacities ranging from 6 to 800 $tCO_2\ d^{-1}$. For deployment in large-scale power plants with capacities of 500 MWe, they need to be scaled up to 20-50 times current unit capacities. When applied to post-combustion capture systems, the inherent limitations of currently available absorption technologies are well established, and their effect on system cost can be measured reasonably accurately for a given application. As a result of the dominant position of air-blown energy conversion processes in the global energy infrastructure, the availability of post-combustion capture systems is critical if CO_2 capture and storage become a feasible climate change mitigation strategy.

Since no technological obstacles to its implementation have been found, oxy-fuel combustion can be used in furnaces, process heaters, boilers, and power generation systems. Since these options require limited modification of technologies and facilities that have already been developed for the combustion of hydrocarbon or carbonaceous fuels in the air, early use of this capture technology is likely to address applications involving indirect heating in power generation and process heating. As part of the CO_2 compression and purification method, current technology advancement envisions a very high-efficiency separation of NOx, SOx, and Hg. With further process and heat integration in the power cycle, improved separation efficiencies of these pollutants are probable.

In theory, all pre-combustion systems have essentially the same conversion routes, with the exception of variations arising from the initial process for producing syngas from gaseous, liquid, or solid fuels and the subsequent need to extract impurities from the fuel feed to the factory. The syngas is then treated before being reacted with steam to create more H_2 and CO_2. These two gases can be separated using well-known commercial absorption-desorption processes, resulting in a CO_2 stream that is ideal for storage.

2.2 Transportation of CO_2

The availability of infrastructure to securely and efficiently transport CO_2 is a critical factor in CCUS deployment. The two most common methods for transporting CO_2 on a wide scale are pipeline and ship, though CO_2 can also be shipped over short distances and in limited quantities by truck or train, though at a higher cost per tonne of CO_2. Pipeline transportation has been practised for many years and is now widely used. CO_2 transportation by ship on a large scale has yet to be demonstrated, but it will be equivalent to the shipping of liquefied petroleum gas (LPG) and LNG. Nonetheless, there are numerous opportunities for innovation, especially in offshore CO_2 unloading and spillovers from the general shipping industry, such as automation and new propulsion technologies. The key considerations in choosing a CO_2 transport mode are economic factors and regulatory frameworks. Pipelines are the most cost-effective way to ship vast amounts of CO_2 onshore and offshore, based on distance and length.

The proportion of pipeline transportation in a CCUS project's overall expense varies depending on the amount shipped, as well as the diameter, length, and materials required to construct the pipeline. Other considerations include labour costs and the system's expected lifespan. Location and geography are also important factors that influence the overall cost. Transport accounts for less than a quarter of the overall expense of most CCUS programs. Pipelines in rural and sparsely populated areas cost 50-80% less than those in densely populated areas. Offshore pipelines are typically 40% to 70% more costly than onshore pipelines.

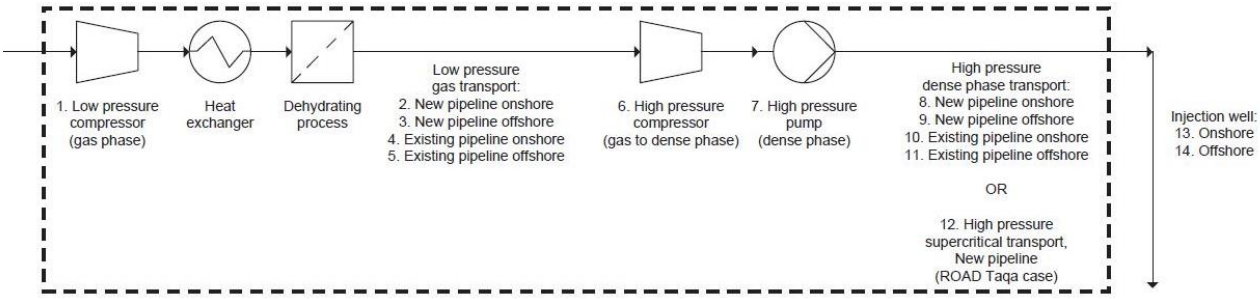


Figure 2.7 Standard CO_2 transport system

Figure 2.7 depicts a standard CO_2 transport system that is divided into two parts: low-pressure compression and high-pressure compression.

There are substantial economies of scale based on pipeline size, with unit costs dropping dramatically as CO_2 capacity increases. As new projects are built, pipeline costs are likely to vary significantly between regions. In general, the cost of new pipelines in Asia is expected to be 30% lower than in Europe [23]. Although the properties of CO_2 vary from those of natural gas, CO_2 transport by pipeline is quite similar to natural gas high-pressure transport. Wherever possible, repurposing existing natural gas or oil pipelines will be much less expensive than constructing a new one. The two key factors to consider when evaluating the repurposing of existing oil and gas pipelines are design pressure and remaining service life.

Compared to higher-pressure purpose-built CO_2 pipelines, oil and gas pipelines typically operate at lower pressure, resulting in a reduction in CO_2 transport capability. In addition, several existing oil and gas pipelines have been in use for over 20 years. A case-by-case analysis is needed to determine their remaining life, taking into account internal corrosion and remaining fatigue life in particular [24]. CO_2 transportation by ship to an offshore storage facility provides more versatility, particularly if there are many offshore storage facilities that can take CO_2. The portability of shipping will also help with the initial construction of CO_2 capture hubs, which can then be linked or turned into a more permanent pipeline network as CO_2 volumes increase. Just about 1000 tonnes of food-grade CO_2 is exported from major point sources to coastal delivery terminals in Europe each year. Interest in CO_2 shipping has grown in recent years in several regions and countries where offshore storage has been proposed, such as Europe, Japan, and Korea.

The figure covers CO_2 shipping, both port-to-port and port-to-storage, as well as port infrastructure requirements; it does not include CO_2 capture, onshore transportation, or CO_2 storage facilities (Figure 2.8). Equipment for liquefaction, temporary storage, loading/unloading, ships, and gasification are among the most critical infrastructure components.

It is important for policymakers to consider the cost-effectiveness of shipping CO_2 in a variety of scenarios in comparison to other CO_2 transport alternatives, such as pipelines. The data and knowledge obtained from collaborators, stakeholders and the literature were used to help create a CO_2 shipping costing model.

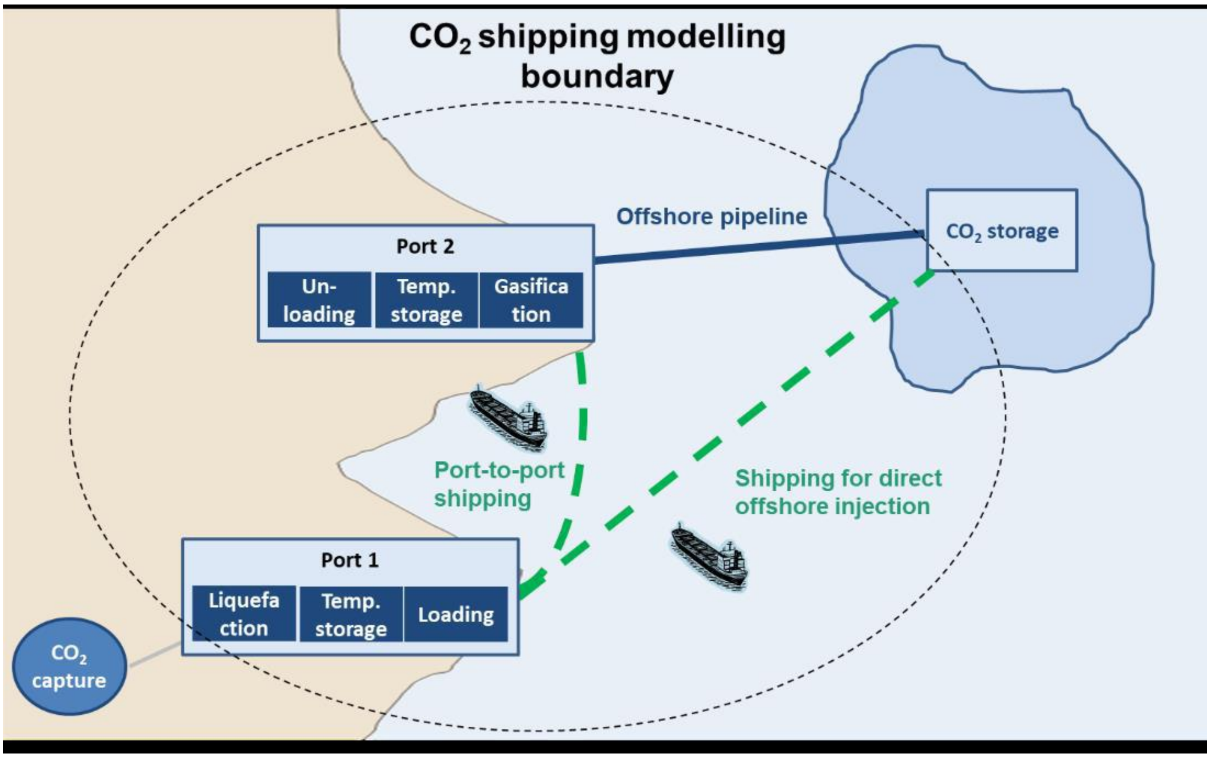


Figure 2.8 Components of the CO_2 transportation chain [42]

The figure depicts a description of the overall shipping cost breakdown, allowing an appreciation of the relative value of the various cost components (Figure 2.9). As seen, the most significant cost components of CO_2 shipping are liquefaction and ship costs, which include capital expenditure (CAPEX), operating expenditure (OPEX), and fuel. Furthermore, unlike pipelines dominated by CAPEX, shipping costs are dominated by operational and fuel costs [42].

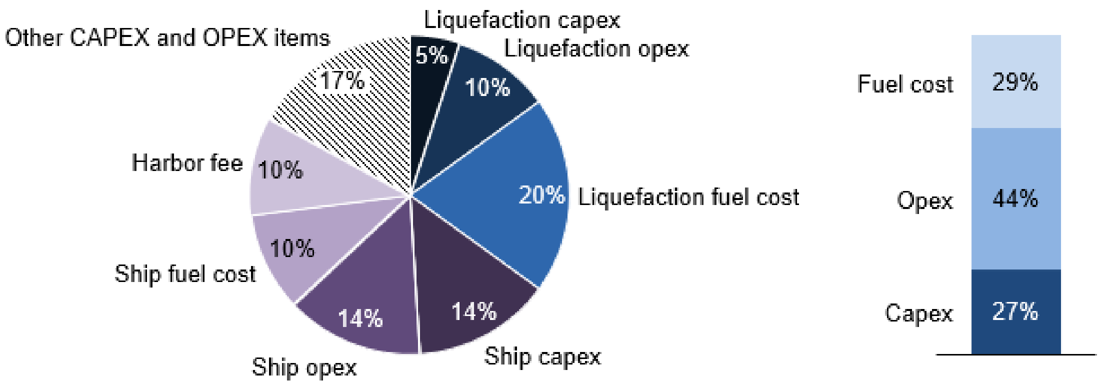


Figure 2.9 CO_2 shipping cost components [42]

CO_2 transportation on a large scale by ship is yet to be illustrated, although it will be equivalent to transporting LPG and LNG. There will be multiple phases in the supply chain: Before being loaded into ships for shipment, CO_2 will have to be liquefied and placed in tanks. Such ports or offshore storage facilities may be destinations. Based on familiarity with current CO_2 shipping operations and large-scale shipping of other gases like LPG and LNG, unloading onshore will be relatively simple. Offshore unloading, whether to an offshore platform before conditioning and injection or directly to a storage site after conditioning on a dock, is yet to be confirmed, and the procedures are less well known. For regional CCUS clusters, shipping CO_2 by sea may be a viable option. Shipping may compete with pipelines on cost in some cases, especially for long-distance transport, which may be essential for countries with limited domestic storage capacity. Pipelines have a higher share of capital in overall costs than ships so that shipping could be the cheapest method for long-distance transport of small amounts of CO_2 [25].

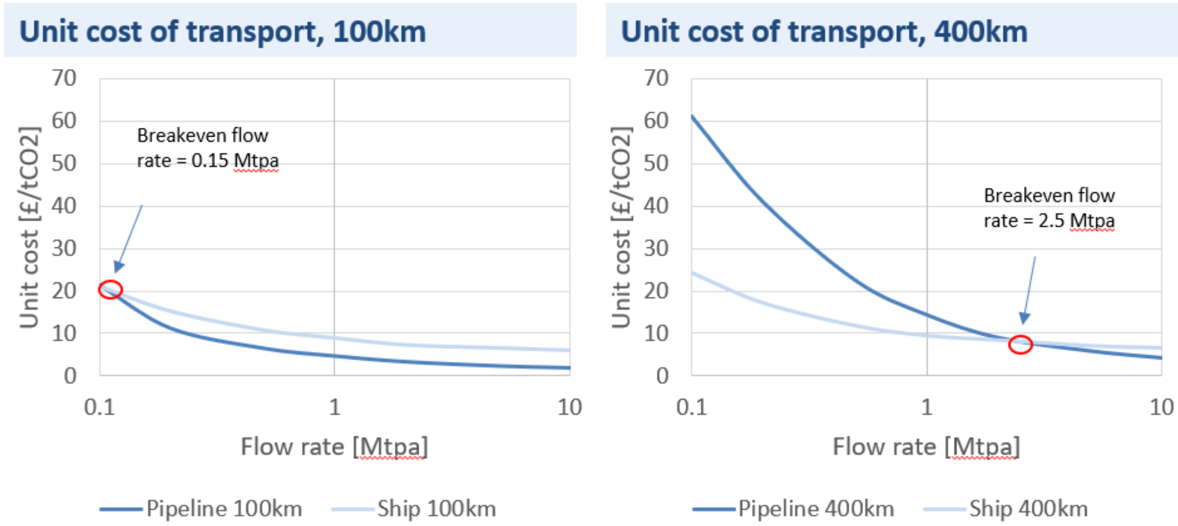


Figure 2.10 Transport breakeven flow rates for 100 and 400 km lengths [42]

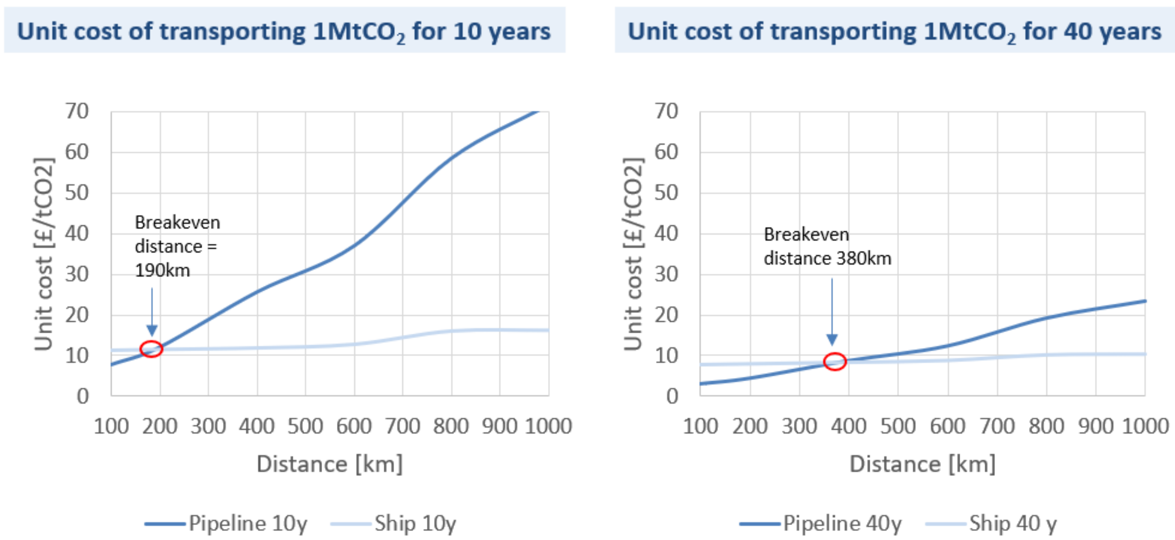


Figure 2.11 Shipping breakeven distance for 10 and 40 years lifetime [42]

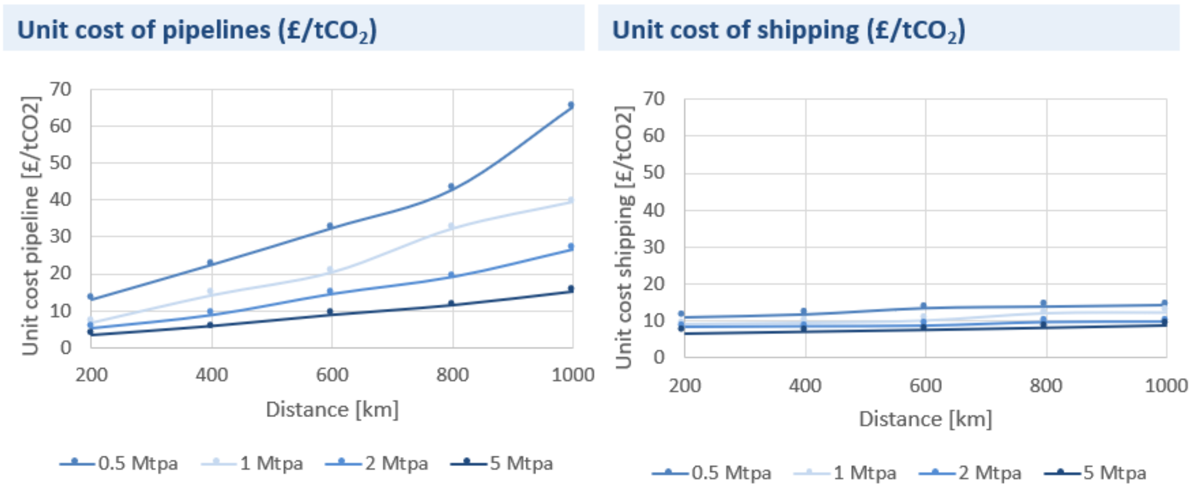


Figure 2.12 Pipeline transport and shipping unit costs for various flow rates and distances [42],[26].

2.2.1 Status and outlook

CO_2 shipping may play an essential role in CCUS support. The technological and regulatory hurdles should be resolved in order to realise the benefits of CO_2 shipping.

In some instances, the CO_2 shipping costs are smaller than the comparable CO_2 pipeline costs. However, this depends on variables such as distance, project period, pressure requirements, and CO_2 flow rate. The most expensive elements of CO_2 transport are liquefaction and ship costs (CAPEX and OPEX) (i.e. more than 70 percent). Unlike pipelines, which are dominated by CAPEX, shipping costs are dominated by operational and fuel costs. The cost-effectiveness of shipping costs is determined by the initial and transport pressure conditions; shipping costs for pre-pressurised CO_2 for liquefaction and low-pressure CO_2 transport can range from €8 to €11 / tCO_2. Sensitivity analysis revealed that, for a given CO_2 pressure state, the lifetime shipping project cost is more sensitive to the CO_2 flow rate, owing to the need for additional ships; however, since this cost is distributed over a larger quantity of CO_2, the unit cost (€/tCO_2) is less sensitive to flow rate. Shipping costs were also discovered to be responsive to project duration and ship size. Due to the high CAPEX costs, pipeline costs are much more sensitive to distance and flow rate than shipping costs. For lower CO_2 flow rates, longer distances, and shorter lifetimes, shipping costs are more cost-effective than pipelines.

CO_2 shipping will open up a variety of opportunities, including lowering the cost of early CCUS ventures, expanding CCUS economic locations, and importing CO_2 from other clusters. Gathering CO_2 from multiple locations through shipping can allow for the cost-effective deployment of several clusters in parallel. Shipping can also expand the feasibility of CCUS to clusters that do not have suitable storage sites nearby, such as countries and towns.

- When planning CCUS projects, it is necessary to consider ship transportation as a long-term transportation option.
- The countries which do not have enough storage has to consider both options, such as port-to-port and port-to-storage, to transport CO_2 to nearby countries which have CO_2 storage.
- It is an applicable business model for CO_2 transport and shipping industry. Evaluation of feasible CO_2 shipping business models, including reward structures, ownership structure (e.g., which organisations are likely to own the port vs the ship), risk management techniques, and capital financing. The cost-effectiveness of these processes, as well as the long-term viability of any business growth policies introduced, should be considered.

2.3 Utilisation of Carbon Dioxide

Carbon dioxide recovery from energy-plant flue gases can help to limit its concentration in the atmosphere. Large amounts of carbon dioxide will be required for disposal or use. This situation has piqued curiosity in determining how much the using options (technological, biological, and chemical) can be extended. This kind of analysis is useful for two reasons:

- Recycling carbon dioxide can reduce carbon dioxide emissions while still conserving primary energy.
- The utilisation may be more cost-effective than disposal.

Carbon dioxide is currently used for two primary industrial uses, either recycled from industrial processes (reforming, fermentation, ammonia synthesis, water gas change reaction, and other sources) or derived from natural wells:

- Technological application
- Fixation into chemicals

This distinction is critical since hydrogen can be a limiting factor in the operation of a device, given the scarcity of hydrogen available from water at a low "carbon dioxide emission" rate. The use of carbon dioxide in the industry is only limited to a few systems:

Synthesis of urea (ca 30 Mt y^{-1}).

- Synthesis of salicylic acid (ca 20 kt y^{-1}).
- Synthesis of Group 1 and 2-element inorganic carbonates, such as Na_2CO_3, K_2CO_3, $BaCO_3$ (a few tens Mt y^{-l}).
- Synthesis of polycarbonates from epoxides (only a few kt y^{-l}, at present).
- Additive in the synthesis of methanol (variable amounts, up to several Mt y^{-l}).

The first three methods, which have been around for a century or more, do not necessitate using a 'catalyst.' The last two, which were produced more recently, necessitate the use of a catalyst. The development of carbon dioxide conversion catalysts began after discovering the first transition metal-carbon dioxide complex, which remained a "scientific mystery" for a long time. It has only recently attained the status of "interest for industrial use."

However, owing to its molecular properties, thermodynamics, and kinetics, carbon dioxide conversion is not a simple or straightforward reaction. Despite their tremendous potential, the invention of new catalytic reactions has been stifled in recent years because there was no pressing need to alter the status quo. Despite their tremendous potential, the production of modern catalytic reactions has been stifled in recent years due to a lack of urgency in changing conventional synthetic technologies, which are primarily dependent on low-cost raw materials and intermediates. Concerns over the environmental effects of any of these developments, new carbon dioxide pollution laws, and the anticipated availability of vast amounts of CO_2 could all alter the situation drastically.

2.3.1 Phosgene Substitution

Phosgene ($COC1_2$) is commonly used in the chemical industry (6-8 Mt y^{-l}) to make urethanes, polyurethanes, isocyanates, carbonates, and polycarbonates. In the reaction of the synthesis of carbamic esters, carbon dioxide is a vital substitute.

Phosgene based route

$CH_4 + H_20 = CO + 3H_2$

$C + H_20=CO + H_2$

$CO + CI_2 = COC1_2$

$COC1_2$ + ROll + Base = ROCOC1 + BaseHCI

ROCOCI + 2 R'R"NH = R'R"NC(O)OR + R'R"NH_2CI

Carbon Dioxide based route

CO_2 + 2R'R"NH = R'R"NCOOH_2NR'R"

R'R"NCOOH_2NR'R" + RX = R'R"NCOOR + R'R"NH_2X

Side reaction

R'R"NCOOH_2NR'R" + RX = CO_2 + R'R"NH + RR'R"NHX

Amine's alkylation is a side reaction that has stopped the carbon dioxide mechanism from being used in use until now. By the way, using carbon dioxide instead of chlorine would eliminate the need for chlorine. Other alkylating agents than halogenated compounds may be used.

2.3.2 Methanol

The use of one extra mole of hydrogen in the synthesis of methanol from carbon dioxide rather than carbon monoxide:

$CO + 2H_2 = CH_3OH$

$CO_2 + 3H_2 = CH_3OH + H_20$

The synthesis of hydrocarbons can be done using methanol [27]. The production of methanol from biomass is a fascinating process. Methanol as a chemical or energy commodity may have a demand worth hundreds of millions of tons per year [28].

2.3.3 Dimethylcarbonate and Homologues, Diphenylcarbonate

In manufacturing, these compounds are commonly used as monomers for polymers, solvents, fuel additives, and alkylating or acylating agents. The existence of group R has a significant impact on thermodynamics.

$2ROH + CO_2 = (RO)_2CO + H_20$

When R=methyl or a higher alkyl, the free energy shift is negative, but when R=phenyl, it is positive. Despite the favourable thermodynamics, the synthesis of dimethyl carbonate, DMC, and higher homologues has been hampered by the low yield and selectivity [29].

2.3.4 Urea

Urea $(H_2N)_2CO$ is manufactured at a rate of a few tens of millions of tons per year and is widely used as an agrochemical and chemical intermediate. It produces carbamates and carbonates as it interacts with alcohols. To avoid conversion to ammonia and the formation of the trimer of isocyanic acid, strict control of the reaction conditions and the use of a catalyst are necessary.

$(H_2N)_2CO + ROH = NH_3 + H_2NCOOR$

$H_2NCOOR + ROH = NH_3 + (RO)_2CO$

$H_2NCOOR = 1/3\ (HNCO)_3 + ROH$

The use of urea as an intermediate has yet to be wholly explored; the chemistry of urea and carbonates can be combined to form a fascinating network of reactions [30].

2.3.5 Polymers

These materials have a long lifespan and a vast market opportunity. Only polycarbonates and polyurethanes have been synthesised from carbon dioxide to date, and only in small quantities.

Industrial exploitation can be seen in the production of propylene polycarbonate, a copolymer of carbon dioxide and propylene oxide. Under very mild conditions, new reactions have been produced that co-polymerise carbon dioxide with unsaturated amines.

2.3.6 Inorganic Carbonates

Tens of millions of tons of carbonates are synthesized from the Group 1 and 2 elements (Na, K, Ba, and others) each year, with natural calcium carbonate serving as a source of carbon dioxide, converted to calcium chloride. Instead, substituting recovered carbon dioxide for calcium carbonate will be quite interesting [31].

$2Mg_2SiO_4 + 2\ H_2O + CO_2 === H_4Mg_3Si_2O_9 + MgCO_3$
olivine serpentine

$3\ KAISi_3O_8 + H_20 + CO_2 === KH_2A1_3SiO_{12} + K_2CO_3 + 6\ SiO_2$
orthoclase muscovite

$2\ KAISi_30_8 + 2\ H_2O + CO_2 === H_4AI_2Si_2O_9 + K_2CO_3 + 4\ SiO_2$
Orthoclasc kaolin

$3\ MgCa(SiO_3)_2 + 2\ H_2O + 3\ CO_2 === H_4Mg_3Si_2O_9 + 3\ CaCO_3 + 4\ SiO_2$
diopside

2.3.7 Building Materials

CO_2 can be used in the construction industry to substitute water in concrete (a process known as CO_2 curing) or as a raw material in its constituents. Carbonates, the type of carbon that makes up concrete, are formed when CO_2 reacts with minerals or waste streams, such as iron slag. This process usually is less energy-intensive than those for fuels and chemicals, and it requires the permanent preservation of CO_2 in the materials. As compared to their traditional counterparts, certain CO_2-based building materials will outperform them [32].

The future of CO_2-based goods is difficult to predict since many technologies are still in the early stages of growth. They are likely to be much more expensive than traditional and alternative low-carbon goods because of their high energy intensity. Policy support would be critical. In the short term, the demand for CO_2-based products is expected to be limited, but it can expand rapidly in the long run. According to a high-level analysis of CO_2 usage capacity, it could hit 5 $GtCO_2$/year for chemicals and building materials and even higher for synthetic hydrocarbon fuels [33].

2.3.8 Lithium carbon dioxide battery

The lithium–carbon dioxide (Li–CO_2) battery has gotten much attention since it was first introduced in 2013 because of its beneficial dual existence as a carbon dioxide (CO_2) sequestration system and an integrated energy storage solution [34].

The electrolyte, anode and materials, diaphragm, and other components of the Li-CO_2 battery are similar to those of the Li-O_2 battery. With the need for energy conservation and environmental security, the lithium CO_2 battery has tremendous potential to capture and revive carbon resources though still in its infancy. According to the latest study, the material for battery anodes and oxygen reduction catalyst has progressed significantly. However, several challenges are still overcome, such as improving battery cycle efficiency and lowering overvoltage during battery charge and discharge [35].

Lithium-ion batteries are commonly used as electrochemical energy storage systems in consumer electronics, but higher specific energy technologies are needed for electrified transportation applications. As a result, rechargeable Li–O_2 batteries, which have a higher potential energy capacity than Li-ion batteries, have recently received much press. While several studies have identified new concepts that have attained long cycle life, Li–O_2 batteries, in general, have reduced cyclability. Despite the fact that it has gained even less interest, the Li–CO_2 battery is an alternative to Li-ion production, with a potential energy capacity of 1876 Wh $kg^{-1,}$ far exceeding that of Li-ion batteries (265 Wh kg^{-1}). This kind of battery entails CO_2 reduction and evolution reactions on the surface of a porous cathode with a lithium salts-based electrolyte during discharge and charge, respectively [36].

The energy density of the Li-CO_2 battery is 7 times higher than the Li-ion battery.

$$2Li + 3/2\ CO_2 \rightarrow Li_2CO_3 + 1/2C \qquad G = -1.33\ eV$$

The measured discharge potential of 2.9 V corresponds with the estimated thermodynamic potential of 2.90 V versus Li/Li+ for reaction.

2.3.9 Carbonated beverages

Another use of captured and separated carbon dioxide is the carbonation of beverages. Carbon dioxide can only be transported over short distances because it is a volatile substance. The cost of transporting carbon dioxide is often a large part of the final cost to the end-user. As a result, being able to manufacture high purity carbon dioxide on-site will result in substantial cost savings. The carbonated beverage industry is an example of an industry where on-site carbon dioxide processing provides significant benefits [80].

The saturation of a liquid with CO_2 gas is known as carbonation. In other terms, it is a concept for the pressure and temperature-assisted breakdown of CO_2 gas in water. It usually entails the use of cold CO_2 under high pressure. CO_2 is a nontoxic, inert gas that has almost no flavour and is widely available at a low cost. It is soluble in liquids and can exist as a solid, liquid, or gas in each of the three matter phases. This can happen naturally or by artificial means, as in most soft carbonated drinks and soda water. 8 g/L CO_2 is the highest volume of CO_2 that can be dissolved in water. When the drink is under pressure, the excess CO_2 would probably remain in the water. In other words, CBs are made by combining chilled flavoured syrups with carbonated water, with carbonation levels in colas and related beverages ranging from 3.5–5 g CO_2 per liquid volume, whereas fruity drinks are less carbonated. The dissolved gas not only adds a distinct flavour and sparkle to the beverage but also serves as an antibacterial agent. CO_2 is useful as an anti-yeast since it helps to inhibit the formation of extra CO_2 as a byproduct of sucrose to ethanol fermentation.

Furthermore, it deprives moulds of the oxygen they need to expand. Carbonation in soft drinks ranges from 1 to 5 volumes of gas per volume of liquid. Carbonated soft drinks are classified as having 3.5 or more CO_2 volumes (colas, tonics, or soda); 2.5–3.5 CO_2 volumes (lemon, lime, soda, or grapefruit); and 1.0–2.5 CO_2 volumes (strawberry, cherry, grape, orange, pineapple, or fruit punch) [81].

2.3.10 Status and outlook

In IEA 2020 report states that, in 2018, Switzerland constructed a fabric that uses CO_2 for the carbonation of beverages and annually carbon capture capacity calculated as 600 tCO_2/year. The same application has to be applied for developing countries while reducing CO_2 emissions, and they also help develop the economy.

The utilization of carbon dioxide is one of the primary ways for developing countries to shift from linear economy to circular economy, which is called circular carbon economy. It means that by using captured and treated carbon dioxide, countries can produce different maters such as in building material production, methanol production, polymer, urea, inorganic compound and lithium-carbon dioxide production.

2.4 CO_2 Storage

There are several sedimentary regions around the world that are suitable for CO_2 storage in different ways. In general, geological storage sites should have

- sufficient capacity and injectivity,
- a suitable sealing caprock or confining unit,
- a sufficiently stable geological environment to prevent jeopardising the storage site's integrity.

The criteria used to determine basin suitability are [43]

- basin characteristics (tectonic movement, sediment form, geothermal and hydrodynamic regimes),
- basin resources (hydrocarbons, gas, salt),
- industry maturity and infrastructure,
- and social issues such as level of growth, economy, environmental problems, public education and attitudes.

Their position on the continental plate partly determines the suitability of sedimentary basins for CO_2 storage. Because of their stability and structure, basins formed in mid-continent locations or near the edges of stable continental plates are excellent targets for long-term CO_2 storage. Most continents have such basins, as do the Atlantic, Arctic, and Indian oceans. Basins found behind mountains created by plate collision are likely to have good storage capacity, and these include the Rocky Mountain, Appalachian, and Andean basins in the Americas, European basins immediately north of the Alps and Carpathians and west of the Urals, and Asian basins south of the Zagros and Himalayas. Basins in tectonically active areas, such as those near the Pacific Ocean or the northern Mediterranean, may be less suitable for CO_2 storage, and sites in these areas must be carefully chosen due to the risk of CO_2 leakage [44]**.** Basins placed on the edges of plates where subduction is taking place or between active mountain ranges are more likely to be heavily folded and faulted and thus have less certainty for storage.

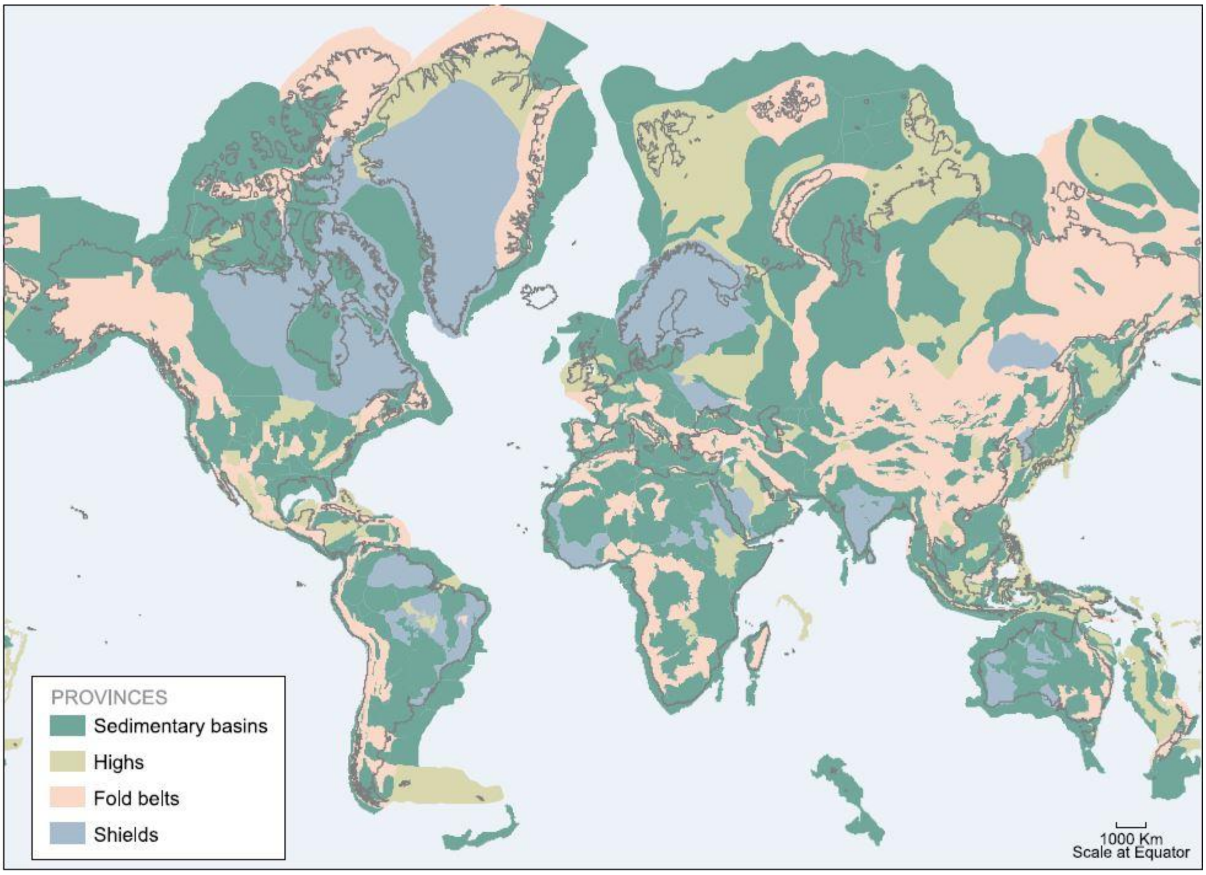


Figure 2.13 Distribution of sedimentary basins around the world [45]

Carbon dioxide can be stored in:

Oil and gas fields :

- Abandoned oil and gas fields
- Enhanced Oil Recovery
- Enhanced Gas Recovery
- Saline Formations
- Coal seams

Other Geological media :

- Basalts
- Oil and gas shales
- Salt caverns
- Abandoned mines

2.4.1 Abandoned oil and gas fields

For a variety of factors, depleted oil and gas reserves are excellent candidates for CO_2 storage. First, oil and gas deposited in traps (structural and stratigraphic) did not escape (in some cases for millions of years), demonstrating their integrity and protection. Second, most oil and gas fields' geological structure and physical properties have been thoroughly studied and characterised. Third, computer models have been developed in the oil and gas industry to predict the movement, displacement behaviour, and trapping of hydrocarbons. Finally, some of the existing facilities and wells could be used to handle CO_2 storage operations. Depleted fields would be unaffected by CO_2 because they already produce hydrocarbons, and if hydrocarbon fields are still in production, a CO_2 storage scheme can be optimised to increase oil (or gas) production. However, abandoned well plugging in many mature fields started many decades ago when wells were filled with a mud-laden fluid. As a result, cement plugs had to be strategically positioned inside the wellbore, but without regard for the fact that they could one day be relied on to contain a reactive and potentially buoyant fluid like CO_2. As a result, the state of wells penetrating the caprock must be evaluated [46]. The need to avoid exceeding pressures that harm the caprock can restrict a reservoir's capacity. Reservoirs should be less sensitive to permeability reductions caused by plugging of the near-injector area and reservoir stress fluctuations [47].

2.4.2 Enhanced Oil Recovery

Enhanced oil recovery (EOR) through CO_2 flooding (injection) offers the potential for economic benefit from additional oil output. Conventional primary production usually recovers 5–40% of the initial oil in place [48]. Secondary recovery, which employs water flooding, produces an additional 10–20 % oil in place [49]. Various miscible agents, like CO_2, have been used for enhanced (tertiary) oil recovery (EOR), with an incremental oil recovery of 7–23% (average 13.2%) of the original oil in location [50]. Oil reservoirs can need to meet additional requirements for enhanced CO_2 storage in EOR operations. In general, the reservoir depth must be greater than 600 m. For high- to medium-gravity oils (oil gravity 12–25 API), injection of immiscible fluids must frequently suffice. Miscible flooding is preferable for light, low-viscosity oils (oil gravity 25–48 API). For miscible floods, the reservoir pressure must be higher than the minimum miscibility pressure (10–15 MPa) needed to achieve miscibility between reservoir oil and CO_2, which varies depending on oil composition and gravity, reservoir temperature, and CO_2 purity [51].

Other preferred conditions for all forms of flooding to accomplish successful oil recovery include comparatively shallow reservoirs (less than 20 m), a high reservoir slope, a homogeneous formation, and low vertical permeability. The absence of a natural water supply, main gas cap, and significant natural fractures are favoured for horizontal reservoirs. The thickness and permeability of the reservoir are unimportant. The heterogeneity of reservoirs also has an impact on CO_2 storage performance. The density differential between the lighter CO_2 and the reservoir oil and water causes the CO_2 to travel along the top of the reservoir, mainly if the reservoir is relatively homogeneous and has a high permeability, which has a negative impact on CO_2 storage and oil recovery.

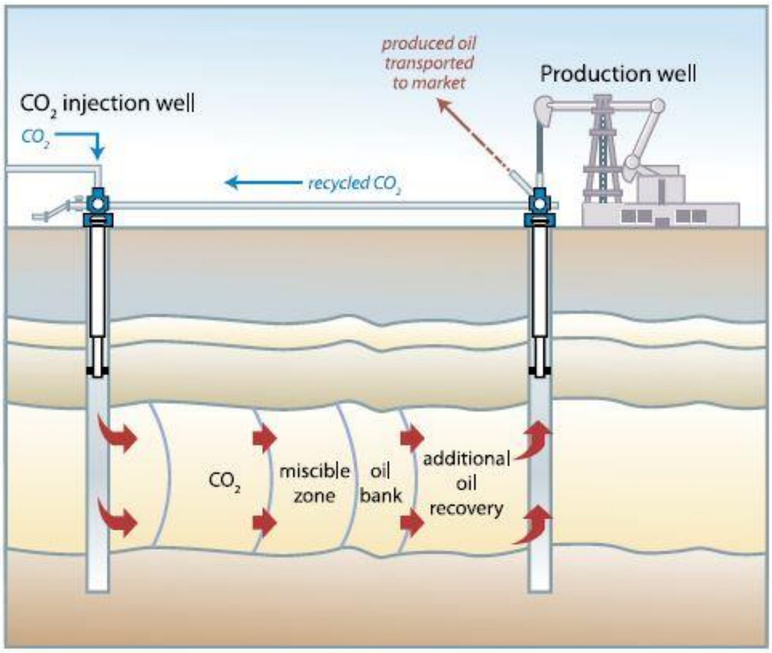


Figure 2.14 CO_2 injection for enhanced oil recovery (EOR)

As a result, reservoir heterogeneity may have a beneficial impact by delaying the rising of CO_2 to the reservoir's surface and causing it to disperse laterally, resulting in a total penetration of the structure and greater storage capacity.

2.4.3 Enhanced Gas Recovery

About the fact that up to 95 % of the original gas in place can be extracted, CO_2 could theoretically be pumped into exhausted gas reservoirs to improve gas recovery by repressurising the reservoir [52]. Enhanced gas recovery has so far only been applied at a pilot scale, and some authors have speculated that CO_2 injection could result in lower gas recovery factors, especially in highly heterogeneous fields [53].

2.4.4 Saline

Deep sedimentary rocks filled with formation waters or brines containing high amounts of dissolved salts are referred to as saline deposits. These deposits are common and provide vast water, but they are unsuitable for agriculture or human use. Locally, the pharmaceutical industry uses saline brines, and formation waters of varying salinity are used in health spas and generate low-enthalpy geothermal electricity. Potential geothermal areas will not be ideal for CO_2 storage because geothermal energy consumption is expected to rise.

The CO_2 is pumped into poorly cemented sands 800–1000 m below sea level. Secondary thin shale or clay deposits in the sandstone affect the internal flow of the injected CO_2. The primary seal is a dense shale or clay coating that extends for a long distance. The saline formation into which CO_2 is injected has a significant potential for preservation. Reservoir experiments and calculations have shown that the CO_2-saturated brine would gradually become denser and drain, removing the possibility of long-term leakage [54].

2.4.5 Coal seams

Coal has fractures (cleats) that add permeability to the structure. Solid coal has many micropores within cleats into which gas molecules from the cleats can disperse and be closely adsorbed. Coal can mechanically adsorb several gases at coal seam pressures and contain up to 25 standard m3 (m3 at 1 atm and 0°C) methane per tonne of coal. CO_2 injection into coal seams will displace methane, increasing CBM recovery. Carbon dioxide has been successfully pumped at depths higher than the CO_2 critical point at the Allison Project and in the Alberta Basin, Canada [55]. Carbon dioxide-ECBM can increase the amount of methane generated to nearly 90% of the gas, relative to the traditional recovery of just 50% by reservoir-pressure depletion alone [56].

The permeability of coal is one of several deciding factors in the choosing of a storage location. The permeability of coal varies greatly and usually declines with rising depth due to cleat closure with increasing effective stress. The majority of CBM-producing wells in the world are less than 1000 meters deep.

2.4.6 Basalt

Basalt flows and layered intrusions occur worldwide, with significant amounts present [57]. Basalt has low porosity, permeability, and pore space continuity, and any permeability is usually correlated with fractures from which CO_2 can leak unless a suitable caprock is present. Nonetheless, basalt may have some potential for CO_2 mineral trapping because injected CO_2 may react with silicates in the basalt to form carbonate minerals [57]. More research is required, but basalts seem unlikely to be suitable for CO_2 storage in general.

2.4.7 Oil and gas-rich shale

Oil or gas shale deposits, as well as organic-rich shale deposits, can be found all over the world. The trapping mechanism for oil shale is identical to that of coal beds, namely CO_2 adsorption onto organic material. Carbon dioxide-enhanced shale gas production has the ability to lower storage costs. The potential for CO_2 storage in oil or gas shale is currently uncertain, but the large quantities of shale indicate that storage capacity could be substantial. Volumes may be restricted if site selection parameters such as minimum depth are established and applied to these shales, but the very low permeability of these shales is likely to prevent the injection of large volumes of CO_2.

2.4.8 Salt caverns

CO_2 storage in salt caverns formed by solution mining could make use of technologies developed for storing liquid natural gas and petroleum products in salt beds and domes. A single salt cavern will span more than 500,000 m3. CO_2 storage in salt caverns differs from natural gas and compressed air storage in that the caverns in the latter case are cyclically pressurised and depressurised on a daily-to-annual time scale, whereas CO_2 storage must be practical on a centuries-to-millennia time scale. Since a single 100-meter-diameter cavern can only accommodate around 0.5 million tons of high-density CO_2, clusters of caverns could be constructed for large-scale storage. Salt caverns can also be used for short-term CO_2 storage in collector and distribution networks between CO_2 sources and sinks.

2.4.9 Abandoned mines

Abandoned coal mines have the ability to store CO_2, with the added advantage of CO_2 adsorption into coal that remains in the mined-out environment [58]. The rocks above coal mines, on the other hand, are highly fragmented, increasing the chance of gas leakage. Furthermore, long-term, stable, high-pressure, CO_2-resistant shaft seals have not been established, and any shaft failure may result in significant amounts of CO_2 being released.

2.4.10 Status and outlook – cost of CCS

Capture of CO_2	Cost of capture	LCOE without capture	LCOE with capture
Hard coal-fired power plant	~17 - 22 €/MWh	~ 48 €/MWh	~ € 65-70 /MWh
Natural gas-fired power plant	~20 €/MWh	~70 €/MWh	~ € 90 /MWh

Table 2.6 Cost of capturing carbon dioxide

Transportation of CO_2	Distance	Volume	Cost
Onshore pipeline	180 km	2.5 Mtpa	€ 5 /tonne
	180 km	20 Mtpa	€ 1.5 /tonne
	500 km	20 Mtpa	€ 3.7 /tonne
Offshore pipeline	180 km	2.5 Mtpa	€ 9.5 /tonne
	180 km	20 Mtpa	€ 3.5 /tonne
	500 km	20 Mtpa	€ 6/tonne
Ship	180 km	20 Mtpa	€ 11/tonne
	500 km	20 Mtpa	€ 12 /tonne
	500 km	2.5 Mtpa	€ 15/tonne
	1500 km	20 Mtpa	€ 16/tonne

Table 2.7 Cost of transportation of carbon dioxide

Storage of CO_2	Capacity	Operational cost
	200 Mt	€ 0.4 /tonne
	66 Mt	€ 1.88 /tonne
	40 Mt	€ 4.2 /tonne

Table 2.8 Cost of storage of carbon dioxide

3. CIRCULAR ECONOMY

The circular economy is a restorative industrial economy that aims to concentrate on renewable energies, reduces, monitors, and eliminates the usage of toxic chemicals, and eliminates waste by careful design. The concept extends beyond the mechanics of producing and consuming products and services in the fields it aims to redefine. The circular economy definition is based on the study of non-linear structures, especially living ones. The circular economy definition is based on the study of non-linear structures, especially living ones. The concept of optimising structures rather than modules, also known as 'design to suit,' is a significant result of drawing insights from living systems. It necessitates the careful handling of material flows [67].

As a result, the circular economy advocates for a 'functional service' model in which manufacturers or retailers gradually maintain ownership of their goods and, where possible, serve as service providers—selling the use of products rather than their one-way use. This shift has immediate implications for the production of efficient and competitive take-back systems and the spread of product- and business-model design practices that produce more resilient goods, promote disassembly and refurbishment, and consider product/service changes where necessary. According to circular economy theorist Walter Stahel, "the linear model converted services into goods that could be sold, but this throughput approach is wasteful." In the past, reuse and service-life extension were often used techniques in times of shortage or hardship, which resulted in low-quality goods. Today, they are indicators of successful resource stewardship and management' [67].

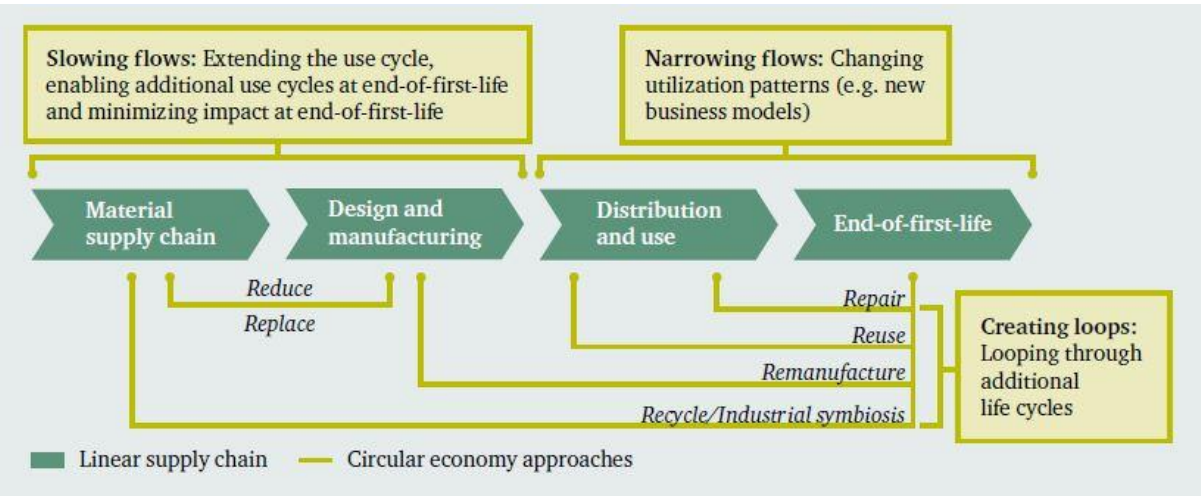


Figure 3.1 Activities related to the circular economy [68]

In practice, CE can be divided into three types of activities (Figure 3.1):

1. Creating loops – As a product reaches the end of its lifespan, it is reused, repaired, or recycled rather than discarded.

2. Slowing flows – adopting modern methods of developing and manufacturing products means that they are used for as long as possible, reducing demand for new products.

3. Narrowing flows entails transitioning to more productive product use, such as product sharing or product-as-a-service models [68].

3.1 Principles of Circular Economy

The circular economy is based on a few fundamental principles (Table 3.1).

Basic principles of circular economy	Description
Design out waste	Waste does not occur as the biological and technical elements of a product are planned for disassembly and refurbishment, with an effort to fit into biological or technical resource cycles. The biological nutritions are non-toxic and can be easily composted. Technical nutrients, such as polymers, alloys, and other artificial materials, are intended to be reused with minimum energy and maximum quality retention.
Build resilience through diversity	Modularity, flexibility, and adaptability are particular characteristics that must be prioritised in an unpredictable and rapidly changing environment. Diverse systems with multiple connections and sizes are more resilient in the face of external shocks than systems designed solely for efficiency—extreme throughput maximisation results in fragility.

Rely on energy from renewable sources	Ultimately, systems should strive to operate on renewable energy sources. According to Vestas, a wind energy company, "any circular story should begin by looking into the energy involved in the production process."
Think in 'systems	Understanding how parts affect one another within a whole and the relationship of the whole to the parts is critical. Non-linear processes are often referred to in systems thinking (feedback-rich systems). In such systems, the combination of imprecise starting conditions and feedback results in a slew of unexpected outcomes and outcomes that are not inherently proportional to the input. Instead of focusing on one or more components or the short term, systems thinking emphasises flow and interaction over time and has the ability to include regenerative conditions.
Waste is food	On the biological nutrient front, the ability to reintroduce products and materials into the biosphere through non-toxic, restorative loops is central to the concept. On the technological nutrient hand, quality changes are also possible; this is known as upcycling.

Table 3.1 Basic principles of circular economy

For this figure, we can conclude the principles with three key parts (Figure 3.2):

1. Monitor limited stocks and balance renewable resource flows to conserve and optimise natural resources – for example, substitute renewable energy for fossil fuels or using the highest sustainable yield approach to preserve fish stocks.
2. Boost resource yields by circulating goods, parts, and resources at the highest utility level at all times in both technological and biological cycles – for example, by exchanging or looping products and extending product usage cycles.

3. Enhance system efficiency by identifying and eliminating negative externalities such as water, air, and soil emissions, noise pollution, climate change, chemicals (toxins), congestion, and adverse health consequences associated with resource use. [69].

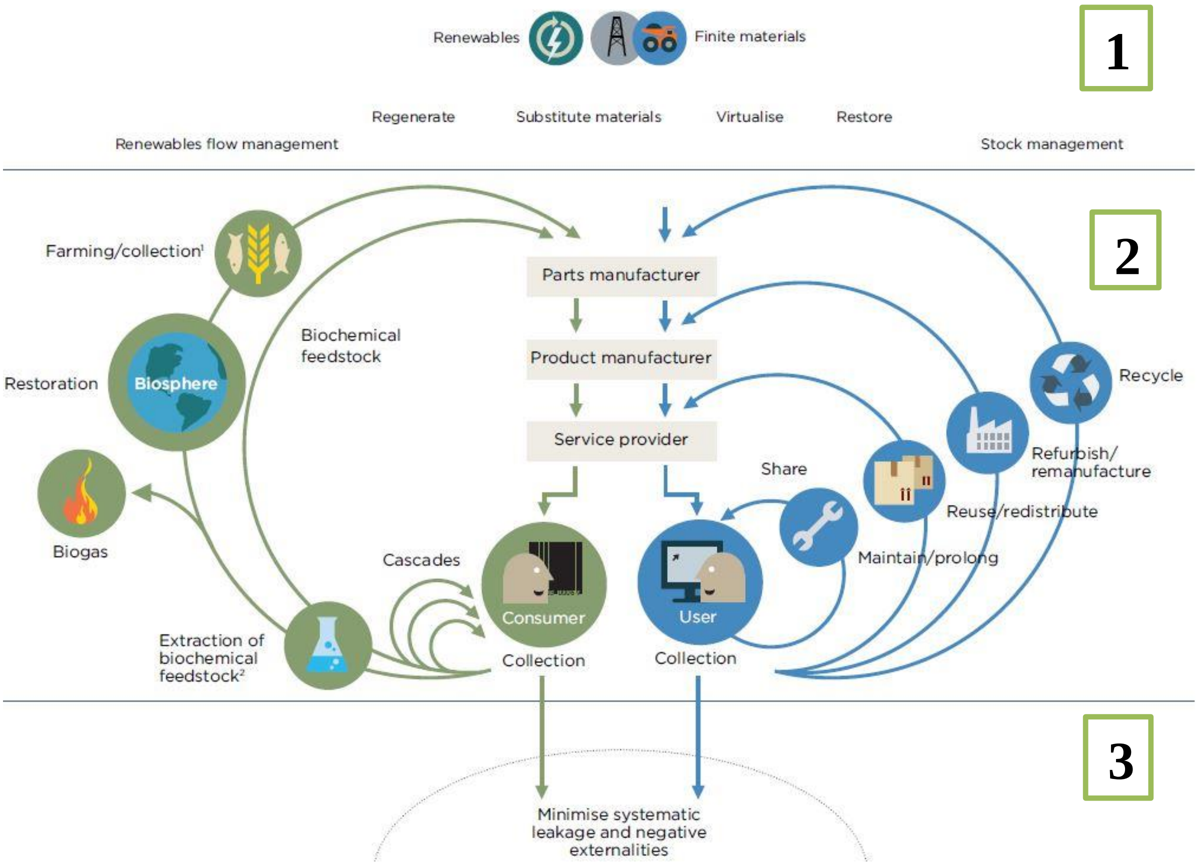


Figure 3.2 Three key principles of circular economy [69]

The simplest example is recycling waste materials while we are talking about the circular economy. For instance, in 2018, the total amount of municipal solid waste (MSW) produced was 292.4 million tons (US short tons, unless otherwise specified), or 4.9 pounds per person per day. A total of 69 million tons of MSW were recycled, with another 25 million tons composted.

Nearly 94 million tons of MSW were recycled and composted, for a 32.1 percent recycling and composting average. Other techniques were used to treat an additional 17.7 million tons of produce. Animal feed, bio-based materials/biochemical processing, co-digestion/anaerobic digestion, donation, land application, and sewer/wastewater treatment are examples of other food management pathways. Furthermore, almost 35 million tons (11.8 percent) of MSW were combusted with energy recovery, while over 146 million tons (50 percent) were landfilled. [70].

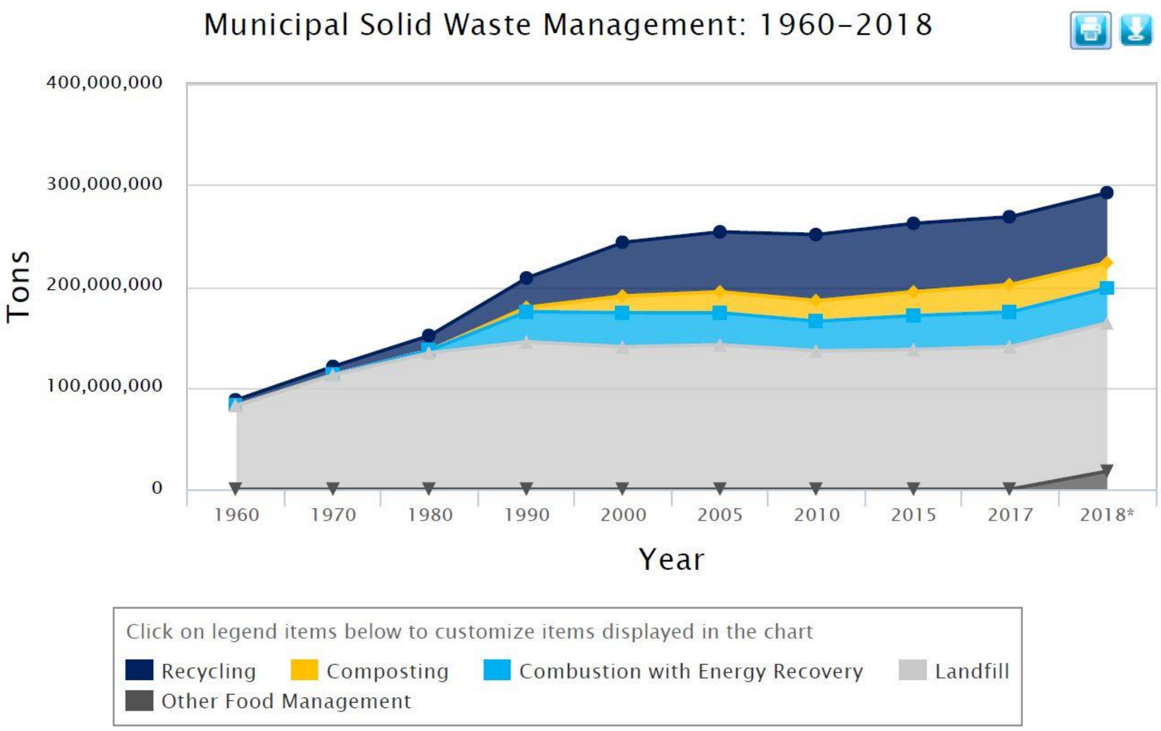


Figure 3.3 Municipal solid waste management, 1960 – 2018 [70]

3.2 Benefits of the Circular Economy in Developing Countries

A shift to a circular economy will result in long-term benefits such as a more innovative, resilient, and efficient economy. The CE's performance in developing countries will be crucial to global efforts to ensure long-term development. Developing countries are now global development hubs and are poised to become global consumption engines. Success in incorporating circular concepts into economic growth and infrastructure development strategies will help meet the needs of rising and urbanising communities while militating against a continued increase in primary resource usage, related emissions, and environmental pollution. Much of the CE's appeal stems from its ability to address some key political agendas simultaneously [68],[69]:

- Balance-of-payments support - Substantial net material savings
- Supply chain resilience
- Climate change mitigation and adaptation
- Increased innovation and job creation potential [68],[69]

Increased innovation and job creation potential - Circularity has proven to be an effective 'rethinking system,' capable of sparking innovative solutions and stimulating creativity. In the Growth Within the report, an academic meta-study of the relationship between employment and the circular economy discovered a positive impact on jobs in situations where the circular economy is applied [69].

Balance-of-payments support - As imports rise to meet increased demand for goods from expanding populations, developing country governments must look for ways to avoid balance-of-payments deficits. According to a number of reports, the potential scale of savings from switching to a circular economy in developed countries calculated as in the billions and trillions of dollars [68]. A McKinsey report for the Ellen MacArthur Foundation (EMF) estimated material cost savings of up to $630 billion per year in EU manufacturing sectors by 2025 [71]. Similar advantages could be available in developing countries.

Supply chain resilience - Substantial net material savings Fears of resources' running out' have subsided as resource prices have fallen. However, market uncertainty provides an essential incentive for both resource-importing and exporting countries to follow less resource-intensive economic paths. Furthermore, there have been increasing questions about the dependence on essential material inputs for advanced technologies in recent years. These resources are concentrated in a few producer countries, many of which lack appropriate resource governance mechanisms to mitigate the environmental and social risks associated with mineral extraction [68].

Climate change mitigation and adaptation - According to the International Resource Panel (IRP), more resource-efficient activities could be crucial to meeting the Paris Agreement's commitments. CE practices, such as more effective use of water and energy resources, better management of land ecosystems to reduce climate-induced yield losses, and creative approaches to disaster-ready building and infrastructure development, can all help with climate adaptation and resilience. With middle- and lower-income countries projected to bear the brunt of the impact of climate change in the short to medium term, capitalising on the synergies between CE and climate mitigation and adaptation would be critical to meeting global commitments under the Paris Agreement while lowering the costs of developing climate-resilient infrastructure and industry.

3.3 Relation between Circular Economy and Carbon Capture, Utilisation and Storage. Circular Carbon Economy

Major global developments ranging from population growth to economic growth shifts to breakthroughs in clean energy production and consumer innovations have resulted in a rise in international demand for natural resources and raw materials. Confronted with challenges such as climate change, natural resource depletion, and an emerging waste crisis, a primary priority for decision-makers in many countries, particularly in the aftermath of the Paris Agreement, is the promotion of technological advances that will pave the way for a low-carbon economy and the realisation of a circular economy. Germany is leading the way in replacing traditional fossil energy resources with renewable energy in its power generation, heating, and mobility sectors through its Energy Transition initiative ('Energiewende'). The aim is to reach carbon neutrality ('Treibhausgasneutralität') by 2050 [65]. To meet this lofty goal, other carbon-intensive industries, such as the chemical and waste management sectors, which rely on carbon feedstock for production/operation, are under increasing pressure to reduce their CO_2 emissions. Simultaneously, end-user demands for sustainably manufactured goods and increasingly tighter legislation to minimise primary carbon resource usage through increased use of secondary waste materials are providing momentum for a shift from a linear economy to circular carbon economy [66].

The circular carbon economy is an evolution of the concept of a circular economy, but it focuses on energy and carbon flows while maintaining the circular economy's material, energy, water and financial flows. The objective of the circular carbon economy in the second half of this century is to provide carbon equilibrium (carbon balance) or net zero emissions. The 'three Rs' of reducing, reuse and recycle are one of the organizational concepts of the circular economy. These values are used in the circular carbon economy, and a fourth R is added to "remove." The basis for carbon management in the circular carbon economy is these four Rs. Reduce decreases fugitive carbon directly. Reuse and remove assistance to turn fugitive fuel into sustainable carbon, and recycle raises live carbon and sustained carbon.

The first cycle (1) refers to CO_2 utilization through fuel conversion. The second cycle (2) concerns the use of CO_2 through conversion to chemical substances. Moreover, the third cycle (3) is the capture and storage of carbon dioxide [76].

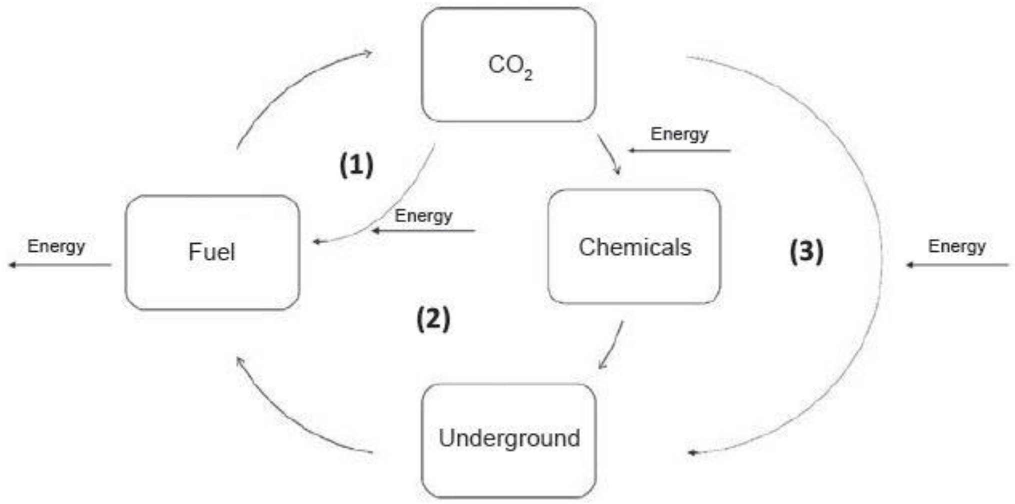


Figure 3.4 CCUS within the circular economy concept [76]

3.3.1 Reduce

The goal of reduce is to decrease the amount of fugitive carbon to achieve a carbon balance or net-zero emissions. Energy conservation is a vital way to do this. Reducing energy consumption reduces carbon dioxide entering the atmosphere. Furthermore, this can lead to a reduction in carbon dioxide emissions that must be stored and reused. Other key factors for reducing emissions are avoided using nuclear energy, non-biomass renewable and fossil fuels. Besides these, carbon capture, utilisation and storage (CCUS) technologies aim to reduce CO_2 emissions emitted to the atmosphere. The IEA concludes in the CCE Guide's “Reduce: Energy Efficiency” study that “implementing the full spectrum of currently available, economically feasible efficiency technologies will result in lower emissions in 2040 relative to today, even with an estimated doubling in the size of the global economy.” While the potential for energy efficiency is substantial – accounting for up to 40% of the abatement needed to meet the Paris Agreement – its implementation has slowed in recent years [78].

3.3.2 Recycle

Recycling in the circular carbon economy refers to the cycle of natural carbon in which the carbon is converted to bioenergy by way of photosynthesis. If the carbon emissions from bioenergy are emitted into the environment, the cycle results in no additional net carbon to the atmosphere as long as new biomass growth replaces what was harvested. As bioenergy replaces hydrocarbons, the amount of carbon that enters the atmosphere remains constant, but the amount of carbon accumulating in the atmosphere decreases by the amount of hydrocarbon-based carbon that is replaced by bioenergy. The explanation for this is that carbon from bioenergy is recycled repeatedly and does not contribute to atmospheric stocks. If carbon from bioenergy can be directly captured and processed, an additional volume of carbon can be removed from the atmosphere.

3.3.3 Remove

The residual carbon trapped in the atmosphere must be captured by capture methods of CCUS such as post-combustion, oxy-combustion, precombustion and removed or reused as durable carbon. Direct air capture technology is another way to remove carbon from the air. While using those technologies, we need to use energy to continue the process. As an environmentally friendly solution, we have to provide energy from renewable energy resources. In this way, we can break the hydrocarbon energy chain. The GCCSI states in "Remove: CCS and DAC" that 20 large-scale CCS facilities are currently operational, three are under construction, and 36 are in progress. Each facility can store hundreds of thousands to millions of tonnes of CO_2 each year. The GCCSI reports that 260 megatonnes of CO_2 ($MtCO_2$) have been permanently deposited in geological formations to date [79].

3.3.4 Reuse

After carbon dioxide captured and separated by different methods, it can be stored in geological storage, or it can be utilized in the chemical industry, Li-CO_2 battery making, building material industry, or making carbonated beverages. IEA 'Reuse: Carbon utilisation' report states that to increase CO_2 usage from the current 230 million tons of CO_2 utilized annually, new technologies that convert CO_2 to fuel, chemicals and building materials are required [77].

3.4 Status and Outlook

– Multiple studies have consistently shown the positive impacts of the circular economy on a global scale – using various methodologies and conducted across different sectoral and regional scopes – increasing GDP by 0.8–7 percent, creating 0.2–3.0 percent employment, and lowering carbon emissions by 8–70 percent [69].
– According to the Waste and Resources Action Programme (WRAP) report studied in 2015, switching to a CE could result in up to 3 million additional jobs in Europe by 2030. In developing countries, where a significant number of young people join the labour force

each year, ensuring sufficient job prospects would be critical to fostering economic development and political stability [68].

– According to an Arup report, also for the EMF, a large-scale transition to the CE in China could save businesses and households RMB 70 trillion ($10.4 trillion) by 2040, which is equal to 16% of China's projected real GDP [72]. EMF estimates that the CE will generate $218 billion in opportunities in India alone by 2030.

– A change down the cost curve for raw materials will be a natural result of net material savings. If applied to a significant portion of the material flow, global net materials savings for steel could total more than 100 million tonnes of iron ore in 2025 [69].

– According to a recent study by Material Economics, a Swedish consultancy, transitioning to a CE could reduce EU emissions from heavy industry by up to 56% by 2050 compared to a baseline scenario [74].

– According to the IRP, resource management approaches could reduce greenhouse gas emissions by 60% by 2050. Individual resource savings can be even more significant: processing aluminium from scrap reduces energy inputs and greenhouse gas emissions by 90–95 percent [75].

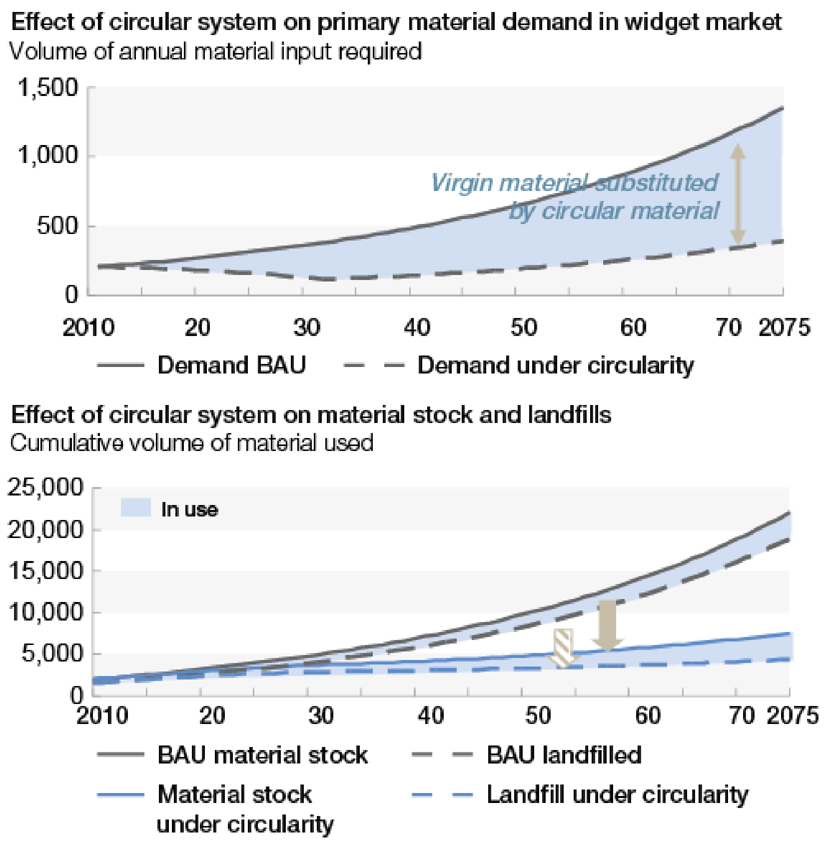


Figure 3.5 Effects of a circular system to primary material demand, material stock and landfill[67]

From the research of Ellen MacArthur Foundation, we can observe that:

- The need for virgin material extraction would be significantly reduced (Figure 3.5). The effect of a circular setup on the need for virgin material extraction is essential. This is not a passing effect; the widening gap between the two lines persists even after rising collection rates and reuse/refurbishment rates reach a plateau [67].
- As a consequence of these substitution results, landfill growth and demand for the overall material stock will be reduced (Figure 3.5). Most notably, the growth rate will not resume at the same rate as in the BAU example since product substitution would save more raw material than a comparable product made from virgin material. The underlying run rates are reduced as a result [67].

Some recommendations:

- CO_2 capture, utilisation and storage were hampered by a lack of economic incentives.
- Rather than filling the land, we have to focus on the new ways, new usage of the materials. Biological wastes easily mix with soil, and as time goes by, they are a part of the soil. However, technical materials and chemicals do not mix with soil, and they begin to kill the effectiveness of soil. Besides that, those materials also pollute groundwater which we know as freshwater resources. Remanufacturing and reusing those materials could be one of the best options.
- For carbon mitigation, renewable energy has to be combined with carbon capture, storage and utilization.
- Additional studies must be carried out in order to find an appropriate CO_2 reuse solution.

4. CASE STUDY – AIM TO REACH ZERO EMISSION IN DEVELOPING COUNTRIES

4.1 Introduction to Net Zero Emission

The phrase "net-zero emissions" has become synonymous with meeting the Paris Agreement target of restricting global temperature rise to 1.5°C. The Zero Emission Technology and Innovation Platform (ZEP) published a study earlier this year on the role of Carbon Capture, Utilization, and Storage (CCUS) in a 2°C scenario. The report concludes that CCUS is an essential component of the most cost-effective path to net-zero emissions and is particularly important for reducing emissions in difficult-to-mitigate sectors such as process industries and distributed heating [59].

Net zero-emission is a term that, in principle, is close to climate neutrality. The idea arose from the desire to avoid the worst effects of climate change. It refers to the system of achieving net-zero emissions of carbon dioxide (CO_2), methane, and other greenhouse gases in the atmosphere by eliminating all artificial greenhouse gas emissions from the atmosphere by mitigation steps (natural and artificial sinks), compensating for emissions with carbon removal from the atmosphere (carbon-offsetting), or simply not emitting to achieve net-zero. This is feasible if public and private entities, as well as people, act to eliminate as much CO_2 from the environment as they emit. The aim is to achieve total carbon neutrality, which results in a zero-carbon footprint. To compensate for its greenhouse gas emissions, an industrial organization may, for example, embark on an afforestation program and finance other projects for an equal amount of carbon savings in a different location around the world. There is also an increase in the number of energy-efficient buildings that produce their energy needs on-site and/or off-site from renewable sources. The term "net zero-emission" refers to a solution in which the amount of CO_2 and other GHGs released into the atmosphere equals the amount removed.

$$CO_2 \text{ emitted} = CO_2 \text{ removed}$$

Zero-emission is often used interchangeably with carbon neutrality and net-zero carbon footprint, both of which apply to achieving net-zero emissions by combining carbon emissions and other greenhouse gases (GHGs) estimated in terms of carbon dioxide equivalence.

The word "zero-emission" is the root phrase from which the phrase "net-zero emission" is derived. Despite the fact that both terms are fundamentally aimed at achieving the objective of global climate balance, they are conceptually distinct. To achieve net-zero emissions by 2070, steps must be taken to increase the widespread deployment of renewable energy sources to replace fossil fuels, as well as to reduce atmospheric CO_2 and overall energy demand through increased energy efficiency and improvements in consumer behaviour. For this report, we are going to focus reduction of atmospheric CO_2 by CCUS technologies in developing countries.

To achieve net zero emissions, policy orientation must shift at all levels, technical growth must be adapted to international climate targets, and corporate and individual behavior must adjust to protect the environment. However, there are three key ways to reach net zero emissions:

1- Emission offsetting is the reduction or avoidance of CO_2 or other GHG emissions in one industry to compensate for emissions made elsewhere. This can be accomplished by investments in energy conservation, renewable energy, and other low-emission technologies.

2- Carbon removal/sequestration: the removal and long-term storage of atmospheric CO_2 to offset the effects of global warming. Carbon sequestration happens naturally as well as by artificial processes such as using carbon capture technologies. CO_2 is naturally extracted from the environment by biological, chemical, and physical processes and deposited mainly in green plants and trees, soils as organic debris, inactive geologic formations, and the oceans.

3- Emission reduction: this refers to reducing CO_2 and other GHG emissions by changing manufacturing, agricultural, and other practices, such as the use of renewable energy sources (such as solar and wind energy) and energy-efficient processes [60].

4.2 CCUS and Net Zero Emission

Carbon Capture Utilisation and Storage (CCUS) is not a silver bullet solution for climate change but a vital tool for reducing industrial emissions and enabling clean hydrogen production, argues Graeme Sweeney [59]. CCUS is an effective technical choice for reducing CO_2 emissions in the energy sector, and it will be critical to achieving the target of net-zero emissions. CCUS will play four key roles in the net-zero transition: addressing emissions from existing energy assets; acting as a solution for industries where emissions are challenging to reduce; serving as a conduit for renewable hydrogen production, and eliminating carbon from the environment to offset emissions that cannot be directly abated or prevented [32].

CO_2 emission - in 2019	**$MtCO_2$**
China	10174
India	2616
Russian Federation	1678
Iran	779
Indonesia	617
Saudi Arabia	582
South Africa	478
Brazil	465
Mexico	438
Turkey	405

Table 4.1 Top 10 developing countries related to CO_2 emission, 2019 [61]

In 2019, the total carbon dioxide emission emitted by developing countries calculated as 23585 $MtCO_2$ (Table 4.1). Furthermore, in developed countries, the total CO_2 emission is calculated as 12164 $MtCO_2$. It means, in 2019, 66 % of annual emissions are produced by developing countries. Increasing atmospheric CO_2 caused global warming and climate crisis. The IPCC released their main 15th special report on 'Global Warming of 1.5°C,' which states that "Global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate" [59]. Current strategies aimed at eliminating, or at least slowing the growth of, CO_2 and other greenhouse gas emissions would affect future warming.

As seen in the graph, current environment and energy policies will minimize warming compared to a world with no climate policies in place (Figure 4.1). This chart depicts potential greenhouse gas emissions scenarios under various assumptions: if no climate policies were implemented; if current policies were maintained; if all countries met their current future pledges for emissions reductions; and necessary paths consistent with restricting warming to 1.5°C or 2°C this century.

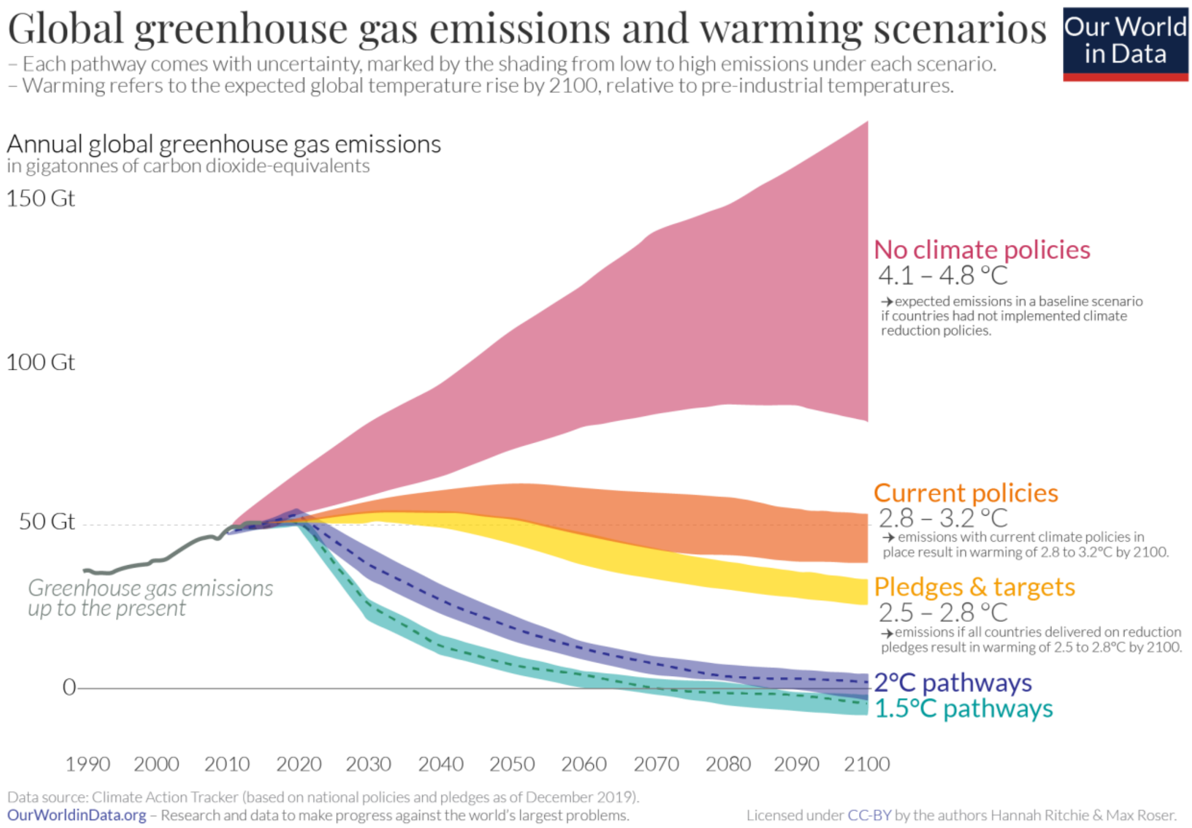


Figure 4.1 Global greenhouse gas emissions and warming scenarios [62]

If countries fulfilled their current 'Pledges,' this would be a much more significant step forward. The planet is making some strides in this regard. However, if our goal is to restrict warming to "well below 2°C," as stated in the Paris Agreement, we are obviously on the wrong track.

Robbie Andrew, a senior researcher at the Center for International Climate Research (CICERO), mapped out the global emission mitigation scenarios needed to keep global average warming between 1.5°C and 2°C. These mitigation curves, based on the IPCC's Special Report on 1.5°C and Michael Raupach's work reported in Nature Climate Change, show that immediate and rapid reductions in emissions are needed to meet either goal. Moreover, the longer we wait for a peak in pollution, the more severe these cuts would have to be. We may be making slow strides in comparison to a world without climate policies, but we are still a long way from meeting international goals.

CCUS is regarded as a critical measure for meeting corporate climate commitments, especially in the oil and gas and manufacturing sectors. More than 20% of global oil and gas output is protected by net-zero commitments by 2050, with CCUS projected to play a role in all cases.

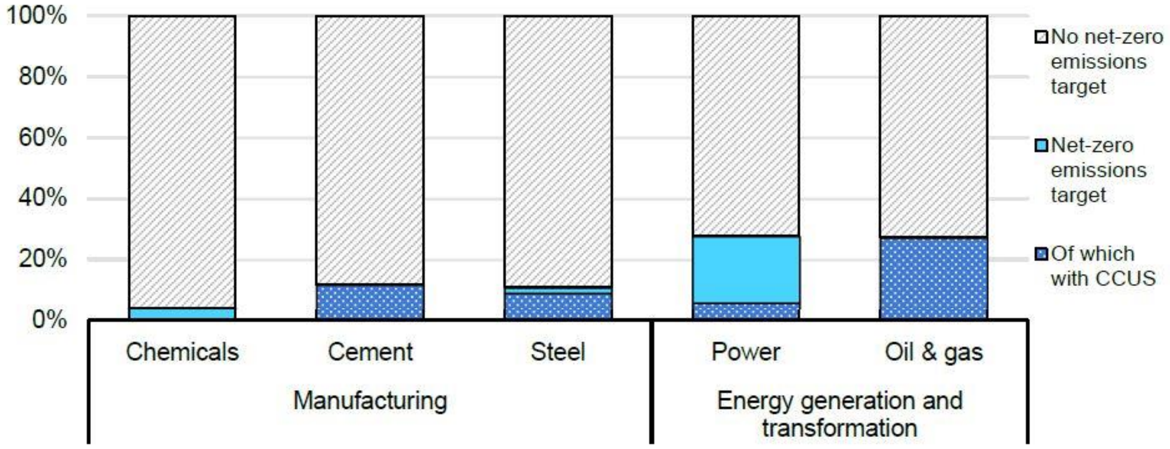


Figure 4.2 Share of operation covered by carbon-neutral corporate goals in specific industries, with CCUS playing a role [32]

4.3 Research Scenario

In our development scenario, the contribution of CCUS to reducing global energy sector CO_2 emissions evolves over the prediction period, with three distinct stages. In the first step, which will last until around 2030, the focus will be on construction of CCUS plants and capturing pollution from existing power plants and factories. About 85 % of all CO_2 emissions collected in this decade come from plants retrofitted with CO_2 capture equipment in the power and industry sectors: coal-fired power units, gas-fired power units, chemical plants, cement factories, and iron and steelworks [32]. Besides this, developing countries need to change energy production from fossil fuels to renewable energy sources.

Let us consider four oil refineries, and these refineries are jointly building one CCUS plant. By using adsorbers and polyethylene (PE) pipelines, greenhouse gases are being transported to main pipeline. This main pipeline connects all the refineries to the CCUS plant. In accordance with refinery type, we choose carbon capture methods such as post-combustion, pre-combustion and oxyfuel to proceed. The procedure continues with separation techniques which are chosen during the construction of the plant. At the end of the separation, according to the product (such as pure CO_2 or a mixture of CO_2 and H_2 etc.), we have several options to utilize. Depending on the agreements between the companies, the product can be transported to the chemical industry for methanol production, phosgene substitution, using for making inorganic carbonates, or building materials, or making Li-CO_2 batteries. The last procedure is, the residual CO_2 is transported for storing in an oil and gas field, saline, basalt, oceans, etc. And the annual profit from utilization and transport will cover the investment cost while constructing the plant. And this profit will be divided into four. In this way, the companies may begin to invest in CCUS systems because they also share the risks. When the risk is shared and seems low, it attracts more investor.

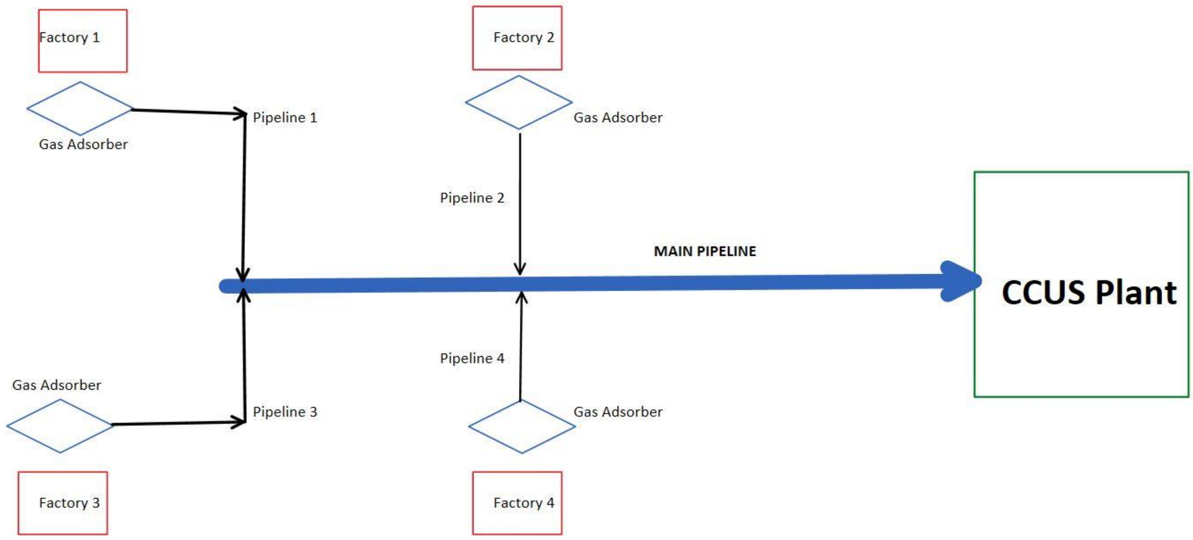


Figure 4.3 A scheme related to the scenario

4.4 Conclusions and Recommendations

Development scenario calculation for oil refinery:

Depending on the complexity of the refinery, a refinery may use 1.5 to 8% of the feed as fuel. This would result in CO_2 emissions ranging from 0.8 to 4.2 million tons of CO_2 per year for a modern world-scale 300,000 barrel per day refinery. CO_2 emissions from refineries can come from a variety of sources [63].

The calculation for Development Scenario		
app. Production of one oil refinery daily	300000	barrel
app. CO_2 emission of one oil refinery annually	0.8 - 4.2	Million tons CO_2
CO_2 capture capacity of one CCUS system annually	1.0 - 8.4	Million tons CO_2
Scenario: production of 4 oil refinery daily	1200000	barrel
Scenario: CO_2 emission of 4 oil refinery annually	3.2 - 16.8	Million tons CO_2
Scenario: CO_2 capture capacity of CCUS for 4 oil ref.	4.0 - 33.6	Million tons CO_2

Table 4.2 Development scenario calculation for oil refinery

If an oil refinery produces 300000 barrels of oil per day, 4 oil refineries produce 1200000 barrels of oil per day (Table 4.2). Based on this information, we can calculate the annual carbon dioxide emissions of these oil refineries. It is calculated that 0.8-4.2 million tons of carbon dioxide annually emitted into the atmosphere by the refinery, which produces 300000 barrels of oil per day. Thus, the carbon dioxide emission amount of the four refineries will be minimum of 3.2 and maximum of 16.8 million tons annually. And from the different sources such as table 4.2, we know that a CCUS and CCS technologies have carbon capture capacity of around 1 to 8.4 $MtCO_2$ per year. Moreover, the Century plant has the capacity to capture 8.4 million tonnes of carbon dioxide a year, the single largest CCS facility in the world [64].

If we consider the maximum annual CO_2 emission for 4 refineries which is 16.8 $MtCO_2$, and the average CO_2 capture plant for one refinery, which captures 4 $MtCO_2$ in a year. Then these 4 refinery can construct one CCUS refinery with a capacity of 16 $MtCO_2$.

REFERENCES

[1] Kenneth J. Arrow and Michael D. Intriligator (1994) - Handbooks in Economics

[2] WCA - Word Coal Association (2013) - Coal Matters https://www.carvaomineral.com.br/arquivos/Coal_Matters_Divestment_Future_Role_Coal.pdf

[3] WCA, "Coal Facts," Word Coal Association https://www.worldcoal.org/coal-facts/

[4] United Nations Framework Convention on Climate Change Paris Agreement, http://unfccc.int/2860.php. Accessed April 2018

[5] J. Hansen, P. Kharecha, M. Sato, V. Masson-Delmotte, F. Ackerman, D. J. Beerling, P. J. Hearty, O. Hoegh-Guldberg, S.-L. Hsu, C. Parmesan, J. Rockstrom, E. J. Rohling, J. Sachs, P. Smith, K. Steffen, L. Van Susteren, K. von Schuckmann, and J. C. Zachos (2013) - Assessing dangerous climate change: required reduction of carbon emissions to protect young people, future generations and nature

[6] Aaron Cosbey (2009) - Developing Country Interests in Climate Change Action and the Implications for a Post 2012 Climate Change Regime

[7] Mason, B (2002) - Egypt Felled By Famine

[8] IPCC (2001) - Climate Change 2001: Impacts, Adaptation and Vulnerability

[9] Anderson, I. (1988) - Greenhouse Warming Grips American Corn Belt

[10] [Vidal, J. (2003) - Heatwave Devastates Europe's Crops

[11] COPA COGECA (2003) - Assessment of the impact of the heat wave and drought of the summer 2003 on agriculture and forestry. EU-JRC 2003: The European Forest Fires Information System (EFFIS) results on the 2003 fire season in Portugal to the 20th of August.

[12] IPCC. (2001). Ibid. 4

[13] A. De Bono, G. Giuliani, S. Kluser, P. Peduzzi (2004) - UNEP, GRID Europe

[14] Mission Innovation (2017)**-** Carbon Capture, Utilisation and Storage Experts'Workshop report

[15] Hannah Ritchie and Max Roser (2017) - Fossil Fuels https://ourworldindata.org/fossil-fuels

[16] Stephen A. Rackley (2010) - Carbon capture and storage

[17] S.N Pandey, Sanjeev Kumar Gupta, Abhishek Tomar, Arun Kumar (2010)- Post Combustion Carbon Capture Technology

[18] IEA – International Energy Agency (2002)- GHG

[19] S.N Pandey, Sanjeev Kumar Gupta,Abhishek Tomar And Arun Kumar (2010) - Post Combustion Carbon Capture Technology - National Conference On Eco Friendly Manufacturing For Sustainable Development

[20] T. Shimizu, T. Hirama, H. Hosoda, K. Kitano, M. Inagaki, K. Tejima (1999) - A Twin Fluid-Bed Reactor for Removal of CO_2 from Combustion Processes, Chemical Engineering Research and Design,

[21] Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer, Working Group III of the Intergovernmental Panel on Climate Change (2005) - IPCC, 2005: IPCC Special Report on Carbon Dioxide Capture and Storage.

[22] International Assoociation of Oil and Gas producers, 2021 - Global CCUS projects

[23] World Bank (2015) report

[24] Kapetaki Z., Miranda Barbosa E. (2018) - Carbon Capture Utilisation and Storage Technology Development Report 2018

[25] IEA - International Energy Agency (2020) - Special Report on Carbon Capture Utilisation and Storage CCUS in clean energy transitions

[26] IEA – International Energy Agency (2020b) **-** IEAGHG

[27] Inui et al. 1996, Lee et al. 1996

[28] Steinberg 1996

[29] Ko et al. 1995, Wagner at al. 1995

[30] Aresta and Quaranta, 1996

[31] (CARBON DIOXIDE UTILISATION IN THE CHEMICAL INDUSTRY. M. Aresta and I. TOMMASI.) 1997 Elsevier Science Ltd

[32] Special Report on Carbon Capture Utilisation and Storage, IEA 2020

[33] IEA – International Energy Agency (2019)

[34] Robert Pipes, Amruth Bhargav, Arumugam Manthiram (2019) - Phenyl Disulfide Additive for Solution-Mediated Carbon Dioxide Utilisation in Li–CO_2 Batteries

[35] Lu Huaiyu1, Qu yanping1, Cao lei (2019) - The development and prospect of lithium carbon dioxide battery

[36] Alireza Ahmadiparidari, Robert E. Warburton, Leily Majidi, Mohammad Asadi, Amir Chamaani, Jacob R. Jokisaari, Sina Rastegar, Zahra Hemmat, Baharak Sayahpour, Rajeev S. Assary, Badri Narayanan, Pedram Abbasi, Paul C. Redfern, Anh Ngo, Márton Vörös, Jeffrey

Greeley, Robert Klie, Larry A. Curtiss,* and Amin Salehi-Khojin (2019)- Long-Cycle-Life Lithium–CO_2 Battery with Carbon Neutrality
[37] Almendra, F. et al. (2011) - CCS Demonstration in Developing Countries: Priorities for a Financing Mechanism for Carbon Dioxide Capture and Storage
[38] Sauter, R., 2010. CCS in the EU: the CCS and ETS directives. IEA CCS Regulators Networking Meeting, January 2010, Paris; UNFCCC Subsidiary Body for Scientific and Technological Advice (SBSTA), 2010. Carbon dioxide capture and storage in geological formations as clean development mechanism project activities: recommendation of the SBSTA. SBSTA thirty-third session, 30 Nov to 4 Dec
[39] IEA – International Energy Agency (2020) - World Energy Balances

https://www.iea.org/subscribe-to-data-services/world-energy-balances-and-statistics

[40] Capoor and Ambrosi, 2008
[41] Wilkinson et al., 2003b
[42] Emrah Durusut, Michael Joos (2018) - Shipping CO_2 – UK Cost Estimation Study, Final report for Business, Energy & Industrial Strategy Department
[43] Bachu, 2000, 2003; Bradshaw et al., 2002

[44] Chiodini et al., 2001; Granieri et al., 2003

[45] Bradshaw and Dance, 2005; and USGS, 2001a

[46] Winter and Bergman, 1993

[47] Kovscek, 2002; Bossie- Codreanu et al., 2003

[48] Holt et al.1995

[49] Bondor, 1992

[50] Martin and Taber, 1992; Moritis, 2003

[51] Metcalfe, 1982

[52] van der Burgt et al., 1992; Koide and Yamazaki, 2001; Oldenburg et al., 2001

[53] Clemens and Wit, 2002

[54] Lindeberg and Bergmo, 2003

[55] Gunter et al., 2005

[56] Stevens et al., 1996

[57] McGrail et al., 2003

[58] Piessens and Dusar, 2004

[59] Graeme Sweeney (2018) - CCUS is essential to reach net-zero emissions

https://www.euractiv.com/section/energy/opinion/ccus-is-essential-to-reach-net-zero-emissions/

[60] Saheed Matemilola , Hammed Adeniyi Salami (2020) - Net Zero Emission

[61] Global carbon atlas (2019)

http://www.globalcarbonatlas.org/en/CO2-emissions

[62] Hannah Ritchie, Max Roser (2020) - CO_2 and greenhouse gas emissions

https://ourworldindata.org/CO2-and-other-greenhouse-gas-emissions

[63] Jiri van Straelena, Frank Geuzebroeka, Nicholas Goodchildb, Georgios Protopapasa, Liam Mahony (2009) - CO_2 capture for refineries, a practical approach

[64] Simon Evans (2014) - Around the world in 22 carbon capture projects https://www.carbonbrief.org/around-the-world-in-22-carbon-capture-projects

[65] Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety (BMUB) (2016) - Climate Action Plan 2050 https://www.bmu.de/fileadmin/Daten_BMU/Pools/Broschueren/klimaschutzplan_2050_en_bf.pdf

[66] Roh Pin Lee, Florian Keller and Bernd Meyer (2017) - A concept to support the transformation from a linear to circular carbon economy: net zero emissions, resource efficiency and conservation through a coupling of the energy, chemical and waste management sectors

[67] Ellen Macarthur Foundation (2013) - Towards The Circular Economy, Economic and Business Rationale for an Accelerated Transition

[68] Felix Preston, Johanna Lehne and Laura Wellesley (2019) - An Inclusive Circular Economy Priorities for Developing Countries

[69] Ellen Macarthur Foundation (2016) - Intelligent Assets: Unlocking The Circular Economy Potential

[70] EPA (2018) - National Overview: Facts and Figures on Materials, Wastes and Recycling

https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials

[71] Ellen MacArthur Foundation and McKinsey Center for Business and Environment (2015) - Growth Within: A Circular Economy Vision for a Competitive Europe https://www.mckinsey.com/business-functions/sustainability-and-resource-productivity/our-insights/europes-circulareconomy-opportunity

[72] Exchange rate of RMB1(2019) https://uk.reuters.com/business/currencie

[73] Ellen MacArthur Foundation (2016) - Circular Economy in India: Rethinking Growth for Long-Term Prosperity https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Circular-economy-in-India_5-Dec_2016.pdf

[74] Material Economics (2018) - The Circular Economy – a Powerful Force for Climate Mitigation http://materialeconomics.com/publications/the-circular-economy

[75] Paul Ekins, Nick Hughes (2017) - Resource Efficiency: Potential and Economic Implications, UN Environment Programme (UNEP) https://europa.eu/capacity4dev/unep/documents/resource-efficiency-potential-and-economic-implications

[76] Ilies Tebbiche, Julien Mocellin, Lan Tran Huong, Louis-César Pasquier (2021) – Circular Economy and Carbon Capture, Utilization, and Storage

[77] International Energy Agency (IEA) (2020) - Reuse: Carbon Reuse file:///C:/Users/Heydar/Downloads/04-IEA-Reuse.pdf

[78] International Energy Agency (IEA) (2020) – Energy Efficiency 2020 https://www.iea.org/reports/energy-efficiency-2020

[79] Global CCS Institute (GCCSI) (2020) – Remove: Carbon capture and storage https://www.globalccsinstitute.com/wp-content/uploads/2020/11/Remove-Carbon-Capture-and-Storage-6.pdf

[80] Soft Drinks International (2011) - Carbon caprure: developing a sustainable business model

https://union.dk/media/64034/Advanced-Amine-Technology-for-Carbon-Capture.pdf

[81] Ibrahim M. Abu-Reidah (2020) - Trends in Non-alcoholic Beverages, Carbonated beverages

https://doi.org/10.1016/B978-0-12-816938-4.00001-X

[82] Zep emissions platform, European Technology Platform for Zero Emission Fossil Fuel Power Plants (2019) - The Costs of CO_2 Capture, Transport and Storage

https://zeroemissionsplatform.eu/wp-content/uploads/Overall-CO2-Costs-Report.pdf