Chapter 1

Overview

1.1 Coal Usage: Merits and Problems

Remarkable changes have been taking place in the world's energy supplies as the vagaries of climate change are intensifying globally, causing enormous damage to ecosystems and services and resulting in suffering for people.

The global energy demand is essentially met by fossil fuels (coal, natural gas and oil), and they will account for 78% by 2040 (Cao et al. 2020). Among them, coal is the largest energy source for electricity generation and the second-largest feedstock source of primary energy (Wei et al. 2020).

Coal is abundant and available worldwide. In India too, coal is the major fuel for producing electricity and is considered the main fuel for a few more years in the future, as the total reserves are about 150 gigatons, ranking third globally after the USA and Russia (Ashkanani et al. 2020).

Coal can provide fairly cheap energy/electricity with the necessary infrastructure developed over more than a century for generating electricity. Coal-fired power technology has developed rapidly over the last century. During that period, the power plant efficiency improved from below 10% at the beginning through 20-35% during the middle to greater than 45% at the end of the century (Fig. 1.1; credit: Stamatelopoulos et al. 2003).

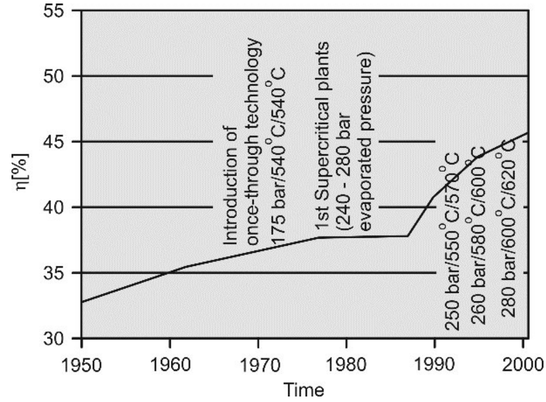

Fig. 1.1 Efficiency of steam power plants in Europe. (Source: Credit: Stamatelopoulos et al. 2003).

If the steam is generated at a pressure below the critical pressure of 221.2 bar in the pulverized coal-fired boiler, it is a subcritical process, and if operated at higher pressures, it is supercritical, which offers higher efficiencies. In 2002, a 965 MW lignite-fired power plant at Niederausseem went into operation with an efficiency of >45% (McMullan 2004) with steam pressure and temperatures of 275 bar/ 580-600°C. Research on coal-fired power generation in Europe aimed to establish that the plans could possibly operate with steam pressure and temperatures of 375 bar/ 700°-720°C resulting in efficiencies of >50% (Bailey and Feron 2005).Thus, coal-fired power generation was developed to provide a secure and stable energy supply. In developing countries, coal is still wanted for power generation as a cheap and reliable energy source and may remain so until at least the mid-century (2050s) or even beyond!

Numerous studies show that fossil fuels, especially coal, will remain central in the global energy mix for providing power to people, industries, etc., and more notably for driving the global economy (for e.g., USDOE 1999; MIT Study 2007; Morrison 2008; Herzog 2009; Aaron Larson 2022) even as renewable energy resources are increasingly deployed.

Fossil fuel is the primary source of carbon dioxide (CO_2). Every combustion process generates CO_2. From the perspective of energy security and global economic development, the use of fossil fuels will continue to dominate the world's energy consumption for a long time. CO_2 emissions from global fossil fuel combustion and industrial processes have seen a dramatic rise since the start of the industrial revolution. Fig. 1.2a shows the world's CO_2 emissions since the 1990s, which are closely related to energy consumption and maintain a similar growth tendency.

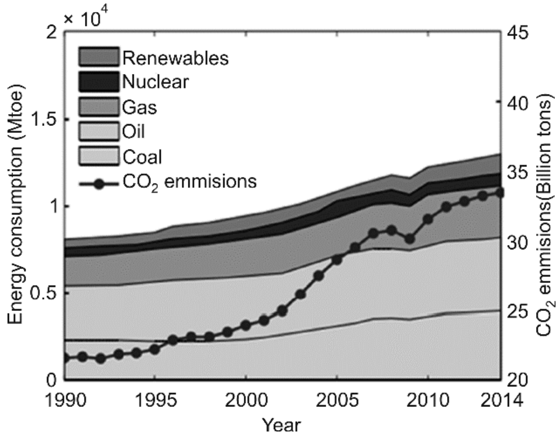

Fig. 1.2 (a) World energy consumption and CO_2 emissions (Source: Dong et al. 2018).

Direct human-induced impacts on forestry and other land uses, such as deforestation, land clearing for agriculture, and degradation of soils, can also emit CO_2. In addition, land can remove CO_2 from the atmosphere through reforestation, soil upgrading, and other activities. Agriculture, deforestation, and other land use changes are the next largest contributors of carbon dioxide.

The atmospheric CO_2 level peaked at 421 ppm in 2022, as measured at NOAA's Mauna Loa Atmospheric Baseline Observatory from pre-industrial level of around 280 ppm.

In terms of absolute values, CO_2 emissions rose more steeply from the 1950s and reached 25.23 billion metric tons by 2000. Emissions climbed 32% between 2000 and 2010; and continued to surge, adding 36.1 billion mt of CO_2 to the atmosphere in 2019. In 2020, the outbreak of COVID pandemic caused emissions to drop by 5% to 34.2 billion mt. Since then, emissions have approached pre-pandemic levels, reaching 36.3 billion mt added to the atmosphere in 2021. The global historical CO_2 emissions from fossil fuels and industry 1750 to 2020 based on data from 'Global Carbon project', are shown in Fig. 1.2(b) (Ian Tiseo 2023, Statista).

Sector-wise, by 2021, about 47 % of the emissions were generated in the energy-generating (electricity and heat) sector, and around 25 % by the transport sector. The industrial sector (bigger ones like chemicals, petrochemicals, iron and steel, aluminium, cement, paper) generates about 18 % of the total CO_2 emission (IEA 2021; Liu et al. 2021; Ren et al. 2021).

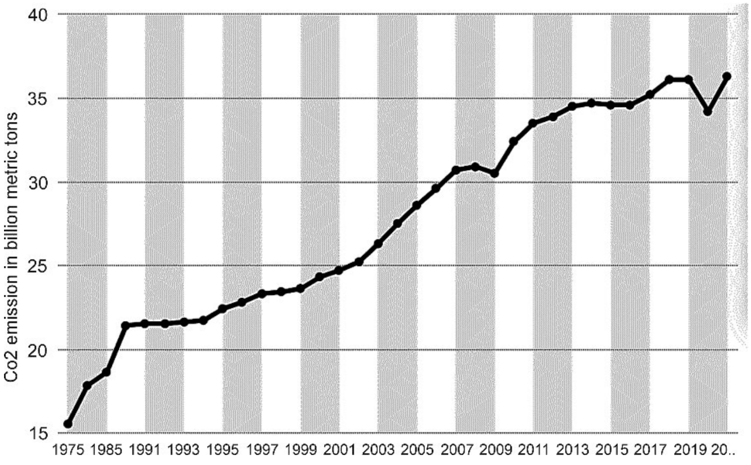

Fig. 1.2 (b) Energy related CO_2 emissions worldwide 1750–2020 (source: Ian Tiseo, Feb 6, 2023 @ https://www.statista.com/statistics/526002/energy-related-carbon-dioxide-emissions-worldwide/).

The IPCC Assessment Reports (2007, 2013) unequivocally established that carbon dioxide is the cause of global warming and the resulting climate change. Among several sources of CO_2 emissions, the coal-fired plants represent the largest set of CO_2 sources and account for more than one-third of the worldwide emissions. Globally there are about 8500 coal-fired power plants totaling over 2,000 gigwatts capacity. They generate about one third of the global electricity needs (Birol and Malpass 2021). However, air pollution from these plants causes numerous health issues and even premature deaths (e.g., Cropper M, et al., 2021; The Jakarta Post, 2022). Fig. 1.3 shows two typical coal-fired power plants that emit the highest CO_2 and other pollutant gases. The Belchatow 5400 MW lignite-fired power plant in Poland tops in Europe and globally emits 30.1 million tonnes/year (NFP, April 13, 2021@https://notesfrompoland.com/2021/04/13/polish-coal-plant-was-eus-biggest-co2-emitter-in-2020/). China is the largest greenhouse gas (GHG) emitter globally; six of the ten highest emitting plants are located in China and East Asia; two are in India and two are in Europe, including the Belchatow plant (Yale School of Environment, E360 DIGEST, July 28, 2021).

Fig. 1.3 Left: 5400 MW Bełchatów Power Station in Bełchatów, Poland, 2016, the largest emitter in the world; Right: Jiangsu Nantong power station, Jiangsu Province, China (2016).

Source: (left) - NFP, 2021 @https://notesfrompoland.com/2021 /04/13/polish-coal-plant-was-eus-biggest-co2-emitter-in-2020/) April 13; (right) - Yale School of Environment, E360 DIGEST, July 28, 2021.

As of 2020, two-thirds of the coal quantity burned was used to generate electricity (The Economist 2020A), and coal was the largest source of electricity generation at 34% in 2020. China accounted for over half of the coal-fired power generation in that year (Global Electricity Review 2021; Reuters 2021), and about 60% of the electricity generated in China, India, and Indonesia is from coal (Birol and Malpass 2021).

In 2020, coal-fired power plants of 2059 GW capacity were operational worldwide. In that year, 50 GW was commissioned, 25 GW started construction in Asia, most of these in China, and 38 GW were shut down

(Morton 2020; The Economist 2020B),mostly in the USA (Roberts 2020) and the European Union (Piven 2020; Boom and Bust 2021) (https://haas.berkeley.edu/wp-content/uploads/WP294.pdf).Coal-fired power stations emit over 10 Gt of CO_2 each year (IEA 2021), nearly one fifth of world greenhouse gas emissions.

A new 1,000 MW coal power plant using the latest conventional pulverized coal technology produces about 6 million tons of CO_2 annually (Socolow 2005). At this rate, if the proposed new additions of about 1400 GW by 2030 are installed (WEO 2006), as much as 7.6 billion metric tons of CO_2 each year will be released. This means, around 30% of increase over the 2006 annual global emissions of 25 billion metric tons of CO_2 from fossil fuel consumption (IEO 2006). Worldwide emissions from these new proposed plants between now and 2030 would be equal to about 50% of all fossil fuel emissions since the industrial revolution started around 1760, which is about 260 years from now (Socolow 2005; Berlin & Sussman 2007; Jayarama Reddy 2014).

Several European countries such as Austria, Belgium, Portugal and Sweden have already phased coal out of their domestic energy mixes. Still, there are many non-OECD countries adding new coal plants, including China and India, which are the largest and second-largest producers, consumers, and importers of coal respectively. The EIA's International Energy Outlook 2021, released in Oct 2021, reported that increases in coal-fired generation in 'other non-OECD Asia,' that includes Indonesia, Vietnam, and Thailand, among other countries but not China or India, would account for more than 75 percent of the world's coal-fired generation increases from 2030 through 2050. While renewable energy sources, largely wind and solar account for about 60% of the generation increase in the region during the projection period, coal-fired generation accounts for rest of the remaining growth. As coal-fired generation steadily increases through 2050, in 'other non-OECD Asia', coal's share of the generation mix increases from about one-third in 2020 to almost half by the end of the projection period (Aaron Larson 2022).

Some remain cost-effective because costs to people due to the health and environmental impact of the coal industry are not included in the cost of generation (Davis 2020), but there is the threat of newer plants becoming stranded assets (Harrabin 2020).

Coal-fired power stations have a high carbon intensity. On average, coal power stations emit far more greenhouse gas per unit electricity generated compared with other energy sources.

Estimation of carbon dioxide emissions from a coal-fired power plant (Wikipedia: Fossil fuel power station): The CO_2 emissions from a fossil fuel power plant can be estimated with the following formula (Global Energy Monitor 2020):

CO_2 emissions = capacity × capacity factor ×heat rate ×emission intensity × time

where ‘capacity’ is the maximum allowed output of the plant, "capacity factor" or "load factor" is a measure of the amount of power that a plant produces compared with the amount it would produce if operated at its rated capacity nonstop, heat rate is thermal energy in/electrical energy out, emission intensity (also called emission factor) is the CO_2 emitted per unit of heat generated for a particular fuel.

An example, a new 1500 MW supercritical lignite-fueled power station running on average at half of its capacity might have annual CO_2 emissions estimated as:

= 1500MW × 0.5 x 100/40 × 101000 kg/TJ × 1year

= 1500MJ/s × 0.5 × 2.5 × 0.101 kg/MJ × 365×24×60×60s

= 1.5×103 × 5×10−1 × 2.5 × 1.01−1 × 3.1536×107 kg

= 59.7 ×103 – 1 – 1+7 kg = 5.97 million tonnes.

This power plant is estimated to emit about 6 million tonnes of CO_2 each year. Similar estimates are drawn by institutions such as Global Energy Monitor, Carbon Tracker and Electricity Map.

Alternatively, it may be possible to measure CO_2 emissions, perhaps indirectly via another gas, from satellite observations (Fei et al. 2019).

Emissions reduction: So, the strategies required to achieve the reduction of emissions from fossil fuel usage become crucial to mitigate the climate change impact. A wide range of mitigation plans have been developed to reduce CO_2 emissions from different generating sources in the context of reducing the climate change effects.

The mitigation options include (a) energy saving and energy efficiency improvements (b) switch-over to less carbon-intensive fuels, renewable energy sources (c) nuclear power (d) enhancement of biological sinks (afforestation/reforestation) (e) reduction of greenhouse gas emissions other than carbon dioxide (IPCC Special report 2005) and (f) applying carbon dioxide capture and storage (CCS) or carbon capture utilization and storage (CCUS) approach.

Each approach has intrinsic advantages and limitations that controls its applicability. Adopting a single approach may not effectively meet the IPCC goal of CO_2 reduction, i.e.50–85% by 2050 from 2000 levels. Therefore, a set of CO_2 emission reduction plans needs to be developed. Amongst the different approaches, CCS can reduce CO_2 emissions (typically, 85–90%) from large point emission sources, such as power generation plants, and energy intensive emitters, such as cement kiln plants and so on. Leung et al (2014) broadly summerises these reduction strategies (Table 1.1).

Table 1.1 Summary of some emissions reduction strategies (Source: Leung et al 2014).

Strategy	**Application area/sector**	**Advantages**	**Limitations**
Enhance energy efficiency & energy conservation	Mainly in commercial & industrial buildings	Energy saving of 10% to 20% easily achievable	Extensive capital costs for installing energy saving devices
Increased usage of clean fuels	Replacing coal with natural gas for power generation	Natural gas has lower carbon content & higher combustion efficiency and emits 40-50% less CO_2 than coal; cleaner exhaust gas	Higher fuel cost for conventional natural gas; comparable cost for shale gas
Adopt clean coal technologies	IGCC*, PFBC*etc. to replace conventional combustion	Enable the use of coal with lower emissions of air pollutants	Requires significant investment to roll out technologies widely
Renewable energy (RE) usage	Well-developed Hydro, solar, wind power & bio fuels	Use of local natural resources; low/nil GHG and toxic gas emissions	Applicability depends on local resources availability and cost; solar and wind are intermittent and related technologies are not mature; more REs are costlier than conventional due to incentives
Development of nuclear power	Nuclear fission is used in US, France, Russia, Japan & China; nuclear fusion still in R&D phase	No air pollution and GHG emissions	Usage controversial citing Fukushima nuclear accident; Germany is phasing out nuclear plants
Afforestation/ reforestation	Applicable to all countries	Simple approach to create natural & sustainable carbon sinks	Restrict land use for other purposes
Carbon capture and storage (CCS)/ (CCUS)	Applicable to large CO_2 point emission sources	Can reduce considerable CO_2 quantities with capture efficiency >80%	CCS full-chain technologies are not proven affordable at commercial scale

1.2 Carbon Capture Utilization and Storage – Concept

CCS is a promising and developing technology, which has the potential to almost completely eliminate CO_2 emissions from the power plants and industrial units (IEA 2004; Herzog et al. 2001; Herzog 2001; IPCC Spl report 2005). CCS could help lower CO_2 emissions from power generation plants by 50% by 2050 (Wei et al. 2020; Wienchol et al. 2020; IEA 2008). It is recognized that the cost of reducing CO_2 emissions will dramatically increase by 140% if carbon capture and storage technologies are not considered (GCCSI 2017).

According to 2007 MIT Study, 'CCS is the critical enabling technology that would reduce carbon dioxide emissions significantly while simultaneously allowing coal to meet the world's pressing energy needs. In IEA evaluations, CCS was shown as a cost-effective method that could play an increasing role, incentivized by stable CO_2 price (Morrison 2008).

Bulky point sources of CO_2 include large fossil fuel or biomass energy facilities, and CO_2 emitting industries. Several industrial processes produce highly concentrated streams of CO_2 as a byproduct and are good sources for capture. In the power generation and industrial sectors, many sources have large emission volumes that make them amenable to the addition of CO_2 capture technology. Ammonia manufacturing, fermentation, and hydrogen production in oil refining, and gas-producing wells are a few proper locations to carbon capture. Fuel-conversion processes offer high prospects for CO_2 capture. For instance, oil production from the oil sands in Canada is currently very carbon intensive and with the addition of CCS facility to the production process, the carbon intensity can be reduced. Other instances for CO_2 capture are producing hydrogen fuels from carbon-rich feed-stocks, such as natural gas, coal, and biomass. The CO_2 emitted would be highly concentrated (>99% CO_2) in many of these instances and the incremental costs of carbon capture would be relatively less compared to capture from a power plant.

1.2.1 CCS Potential in Confronting Climate Change

Atmospheric carbon dioxide emissions reached a historic peak average annual concentration of 412.5 ppm in 2020 (Energy Agency, 2021). The increase atmospheric CO_2 concentration levels cause the earth's mean surface temperature to rise leading to irreversible negative effects such as melting of glaciers, sea level rise and ocean acidification and so on. Therefore, effective measures need to be intensified to reduce CO_2 emissions and to restrict rise in earth's mean surface temperature.

The world governments met in 2015 in Paris and reached an Agreement to voluntarily cut down emissions so as to restrict global warming well below 2°C, preferably 1.5°C compared to pre industrial levels by 2100. CCS has been underscored during the decade or more as a practical method to remove anthropogenic CO_2 from the atmosphere at least to the level of 450 ppm (1 ppm CO_2 in global atmosphere means 2.13 Gt of carbon). Pacala and Socolow (2004) identified strategies ('wedges') to help to reduce future CO_2 emissions in order to stabilize global CO_2 emissions. A 'wedge' is a strategy or measure to reduce CO_2 emissions, which are forecast to increase in 50 years to 3.67 billion tonnes (Gt) of CO_2 per year (equivalent to1 GtC/a). Over 50 years, this represents a cumulative total of approx. 92 $GtCO_2$ (or 25 GtC). These wedges include energy efficiency, fuel shift, nuclear energy, wind energy, solar energy, bioenergy, and natural CO_2 sinks, as well as carbon capture and storage (CCS) (Fig. 1.4).

The impact of CCS in strategies for reducing GHGs has been highlighted in several studies and projections for the global energy system such as the Stern Report (Stern 2006) and the IEA's World Energy Outlook (IEA 2009, 2010, 2011). The IEA projects an increase in CO_2 emissions in a business-as-usual scenario to approx. 550 ppm, and by a mean temperature rise of 3 – 4°C by 2050 (IEA 2008). The Commission of the European communities (2007) has stated that for climate change to be limited to 2°C, developed countries must reduce their emissions by 30% by 2020, increasing to 60 to 80% by 2050, which can be reached by implementing CCS. The extent of the increase in the accessibility of CCS to achieve the above goal is enormous.

The IEA proposes two scenarios for reducing these emissions by 2050. In the ACT Map scenario, a clear reduction in CO_2 is achieved, saving some 35 $GtCO_2$ per year by 2050 compared to the Business-As usual Scenario (BAS). This would mean maintaining today's levels of CO_2 emissions in 2050, which would be equivalent to a CO_2 concentration of around 485 ppm. The BLUE Map scenario expects even further, dropping CO_2 emissions in 2050 by 48 $GtCO_2$ per year, representing a reduction of 77 % compared to the BAS. This would be equivalent to a CO_2 concentration of around 445 ppm in 2050 (IEA 2008).

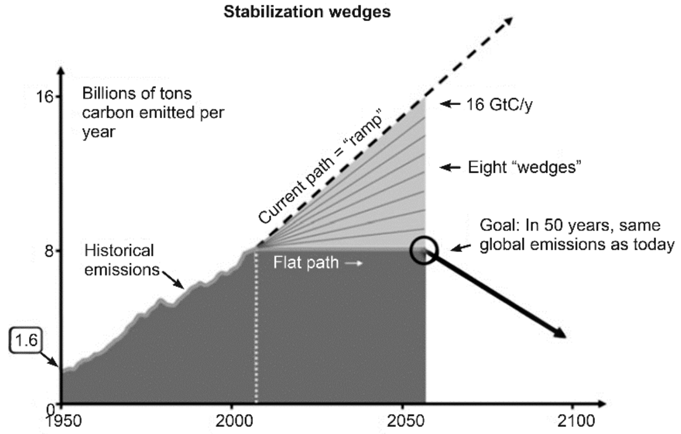

Fig. 1.4 Stabilization wedges for global CO_2 emissions (Source: Pacala and Socolow 2004; Carbon Mitigation Initiative (CMI) 2013).

CCS is an attractive option in the IAMs (Integrated Assessment Models) mitigation ranges, as it has numerous benefits. For instance, CCS can be integrated into existing energy generating systems without requiring large modifications to the system itself. Renewable energy technologies become more expensive at high installation rates because of the need for the infrastructure to take care of their intermittent nature (van Vuuren et al. 2015). Besides, CCS is a feasible choice to decarbonize emission-intensive industries like cement production (Benhelal et al. 2013). And, when combined with low-carbon or carbon-neutral bioenergy for power generation (BECCS), CCS has the potential to generate negative emissions, removing CO_2 from the atmosphere (Fuss et al. 2014), i.e., the cultivation of the feedstock biomass sequesters about as much CO_2 as is generated during the process of producing energy (bio-power or biofuels); in addition, capturing the latter leads to removal of CO_2 from the atmosphere (Kraxner et al. 2015). BECCS has twofold benefit of mitigating emissions and generating energy, enabling it favorable from the economic aspect of an IAM (Bui et al., 2018).

CCS, thus, a crucial technology to deal with global climate change, and rapid development of CCS technologies is very crucial (Blamey et al. 2010). The IEA reports that a tenfold increase in capacity is required by 2025 to be on track for achieving that target whereas the Global CCS Institute estimates that 2500 CCS facilities, each capturing around 1.5 million tonnes of CO_2 per year, would need to be operating globally by 2040 (Grantham Res Inst. 2018).

However, the status of future capture and storage of carbon dioxide for mitigating climate change depends on a number of factors, including the vital financial incentives extended for deployment, and whether the fears of storage can be effectively accomplished (IPCC Special report 2005).

1.2.2 CCS Process

The process involves capturing CO_2 either directly from the source of emissions, or directly from the air, and treating it to facilitate easy transportation either as a gas via pipeline or as liquid CO_2 by trucks and finally injecting it safely for long-time storage below impermeable rock formations (Lee and Park 2015; Chu 2009; Smith et al. 2009). A CCS unit installed at thermal power plants can efficiently capture about 85 – 95% of the CO_2 produced in a capture plant (Figueroa et al. 2008; Herzog 2001).

IPCC (2005) defines CCS as a *"process consisting of the separation of CO_2 from industrial and energy-related sources, transport to a storage location and long-term isolation from the atmosphere."* Hence, CCS consists of three basic stages: separation of CO_2; transportation and storage. (Figure 1.5). Each step of CCS – *capturing and compressing, transporting, and storing*- is very important and involves several issues. CCS refers to a group of technologies (Markewitz et al. 2012) that reduce emissions by capturing CO_2 from power plants and large industrial bases (Smith et al. 2009; Jacobson 2009) before it is released into the atmosphere, its compression into a fluid and transportation to suitable locations for storing.

CCS is also considered currently as the only practical way in sequestering the huge CO_2 amount with a 'reasonable' cost. But then, CCS has not reached the full commercial status for several reasons and also has not attained the 'acceptable' cost of less than US $20 – 30 per ton in capturing CO_2. Most significance incentives for CCS by way of carbon tax or other related methods are yet to be affected globally.

CCS technology typically requires a substantial instrumentation with a high energy price in capturing and storing facilities. Consequent to the Paris Agreement, decreasing CO_2 in every industrial sector becomes a key task; it also helps to ensure a sustainable business in the future (Yun 2017).

CO_2 capture: Carbon dioxide can be captured using different methods. But, the main approaches/ pathways are post-combustion, pre-combustion and oxy-fuel combustion processes.

Post combustion technology takes out CO_2 after combustion from the flue gas. Pre-combustion capture process involves the removal of most of the carbon content in a fossil fuel before it is combusted. Oxy-fuel technology produces CO_2 and steam by burning fossil fuels in the presence of pure oxygen. These are explained in detail in the next section 1.3

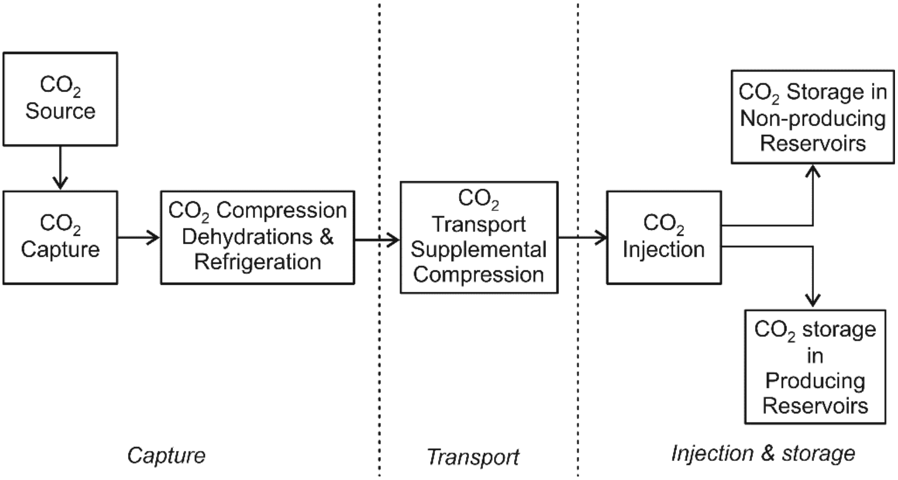

Fig. 1.5 Basic CCS Project Schematic
(Souce: Redrawn from Mike McCormick, C2ES 2012).

CO_2 transport: Once the CO_2 is captured, it is compressed into liquid state and transported by pipeline, or ship or road. The technologies for CO_2 transport are well established especially pipeline transport. Globally there are several hundred km of CO_2 pipelines including on-shore and off-shore, most of them are connected with EOR operation in the US. For details, refer to IEAGHG, Dec 2013. The technology for CO_2 transport with ships is also relatively mature (Brownsort 2017). These transport technologies having reached 'Technology Readiness Level (TRL)'of 9, are currently being used in commercial applications (Bui et al. 2018).

CO_2 storage: Storage comprises geological storage of CO_2 which requires monitoring in the long term (Keith, 2009; Goeppert *et al.* 2012; Kuramochi *et al.* 2013). Deep saline aquifers, deep coal seams and spent reservoirs of hydrocarbon are three routes for geological storage of CO_2 with deep saline aquifers believed to have the largest capacity (Schrag, 2007; Faisal *et al.* 2015). Saline formations have been used for CO_2 storage at commercial level projects that include Sleipner CO_2 Storage, Snohvit CO_2 Storage and Quest (on-shore and off-shore). In contrast, CO_2 storage by EGR (Enhanced Gas Recovery) (Gou et al. 2014), and storage in depleted oil and gas fields have not reached commercial-scale operation and are at the demonstration status. Ocean storage and mineral storage are still in the early stages of development.

Underground sources need to store CO_2 for such a time that it takes the Earth's natural carbon cycle to lower atmospheric CO_2 levels to close to preindustrial levels. As more CO_2 is injected and underground reservoirs fill, it is essential to monitor leakage rates. Therefore, an extensive underground monitoring program is needed covering the wide variety of geological formations available. Besides, it will check whether appropriate geological environments are accessible to be able to offer effective storage for injected CO_2 (Schrag, 2007; Buckingham et al. 2022). Therefore, storing large amounts of CO_2 has also issues, mostly monitoring leakages and the limited global geological capacity.

Besides storing, captured CO_2 has been looked at as an asset and efforts have been made to utilize the gas. For instance, the electrochemical reduction of CO_2 is a promising technology. In this technology, short-chain hydrocarbons such as methane, ethane and ethanol are derived and these are high-value commodity feed-stocks. Producing such molecules, helps in incentivising carbon capture financially as well as significantly reduce dependence on fossil fuels (Hamdy et al. 2021; Jiang *et al.* 2010).

Consider electricity produced in excess from renewable energy sources like solar and wind is beyond current demand in a day. It is necessary to consider energy storage strategies for the excess power produced for later use in times of demand (Jayarama Reddy 2022). This excess electricity, for example, can be used to produce green H_2 through water electrolysis, which in turn can be utilised directly as a fuel either for combustion or in hydrogen fuel cells, or converted to other fuels or chemicals such as synthetic methane, methanol or dimethyl carbonate. This is referred as Power-to-Fuels (P-to-F) and Power-to-Chemicals (P-to-C) processes, which are based on the reaction of H_2 and CO_2 through the Sabatier reaction/ process. The Sabatier reaction produces methane and water from a reaction of hydrogen with CO_2 at elevated temperatures (~ 400°C) and pressure (perhaps 3 MPa) in the presence of a catalyst such as nickel.

$$CO_2 + 4H_2 \longrightarrow CH_4 + 2H_2O \qquad .....(1)$$

This approach is referred as Carbon Capture and Utilization (CCU) (Koytsoumpa et al. 2018), and it provides an opportunity to obtain economic and environmental incentives (Leonzio 2018; ENTSO 2014; Magro et al 2019; CISO 2014; EASE/ EERA 2013).

The combination of both approaches (storing as well as utilization) is called *Carbon Capture Utilization and Storage (CCUS),* which is a recognized technology to meet the requirement set in the 2015 Paris Climate Agreement (Figure 1.6).

CCUS include pipelines for transportation, injection in geological formation for storage and final utilization for fuel, chemical or material production. CCUS has the potential to reduce about 19 % of global CO_2 by 2050. This corresponds to increasing the CO_2 capture to 4000 Mt until 2040 (Koukouzas et al. 2020, 2021) (Garcia et al. 2022).

CO_2 utilisation: With increased research in the last decade, utilisation of CO_2 is rapidly growing. The conversion of CO_2 to higher-value products is a significant effort for utilizing some of the captured CO_2. Production of green hydrogen and using it as fuel or to produce valued chemicals is one promising approach as described above. Many commercial-scale CCS projects already use CO_2 in 'enhanced oil recovery (EOR)'; and there is a substantial amount of existing experience and knowledge, which has enabled CO_2-EOR to reach highly matured level (Bui et al. 2018).

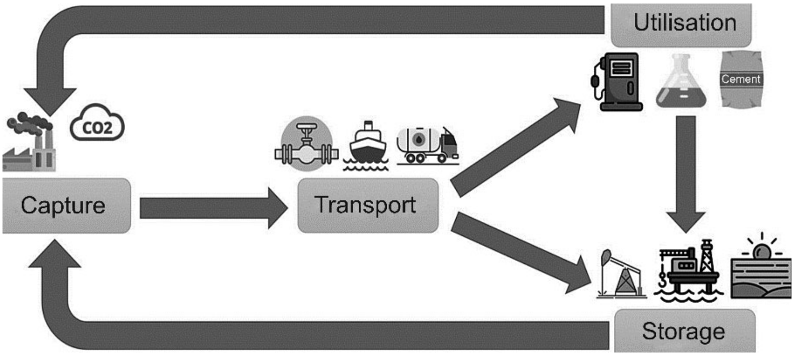

Fig. 1.6 Representation of CCUS technology
(source: Hong 2022).

A number of industrial facilities that touched matured level, TRL 9, utilise CO_2 for various applications. These facilities are mostly in the food and beverage industry and a few in chemical production (e.g., urea, methanol) (GCCSI 2017). Several projects utilise CO_2 for mineral carbonation, for example, Searles Valley plant in the US. In Saga City, Japan, CO_2 capture from waste incineration is utilised for the cultivation of crops and algae (GCCSI 2016). The CO_2 for these projects is mainly obtained from industrial processes such as fertiliser production, ammonia production, and ethylene glycol plants, but some projects utilise the CO_2 captured from power plant flue gas (GCCSI 2017).

Moreover, CO_2 may be used in algae bio refineries or directly in bacterial CO_2 fermentation (Pérez-Fortes *et al.* 2016). It is worth noting that during the product's lifetime, the CO_2 consumed during its synthesis will typically be released to a certain extent, and within a specific timeframe, depending on how the product is used. Product life-cycles need to be considered when assessing the true capability of CCU for global reduction in CO_2 emission and CO_2 capture must be globally applied to be able to design circular processes for carbon containing products (Pérez-Fortes *et al.* 2016; Buckingham et al. 2022).

1.3 CO_2 Capture Pathways and Technologies

In many industrial processes such as natural gas treatment and the production of hydrogen, ammonia and other industrial chemicals, capture of CO_2 has been executed for a long time. In most of the cases, the captured CO_2 stream is simply emitted to the atmosphere; and in a few cases used in the manufacture of useful chemicals (IPCC 2005). Also, CO_2 has been captured from a portion of the flue gases released at coal-fired or natural gas-fired power plants, and is sold to industries such as food processing. Table 1.2 lists 5 different CO_2- containing gas streams likely to be considered for CO_2 capture.

Table 1.2 Five different gas streams considered for CO_2 capture (Source: Garcia et al. 2022).

Composition→ Gas stream ↓	**CO_2**	**O_2**	**N_2**	**H_2**	**H_2O**	**CH_4**
Dry air	0.042 %	20.9 %	78.1 %	--	--	--
Std. flue gas	9.5 %	--	71.5 %	--	19.0 %	--
Oxy-fuel flue gas	60.0 %	--	--	--	40.0 %	--
Biogas	40.0 %	--	--	--	--	60.0 %
Hydrogen	20.0 %	--	--	80.0 %	--	--

As mentioned in the earlier section, the basic pathways or approaches available to capture carbon dioxide are: (1) post-combustion, (2) oxy-fuel combustion, and (3) Pre-combustion (Yang et al. 2008; Fout and Murphy 2009; Cuellar-Franca and Azapagic 2015). These are shown in Figure 1.7.

All three pathways have in common, the process of capturing the CO_2 from the other major constituents in the flue gas or syngas into a form that can be transported and geologically stored or used in several ways, including enhanced oil recovery (EOR), improving the growth of plants and algae (Ghiat et al. 2021) or as a raw material in the production of fuels, chemicals, or building materials (IEA 2020), while the basic difference is the difference in the concentration of CO_2. Each process has its advantages, disadvantages, and applicability.

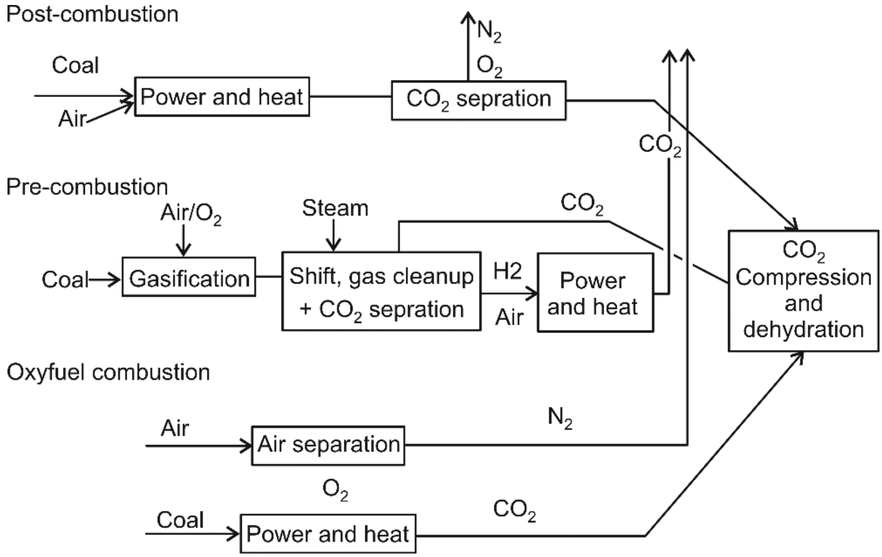

Fig.1.7 Technical pathways for CO_2 capture from coal-fired power plants (Source: Redrawn from GCCSI 2012a).

Chemical looping processes are considered another approach to capture carbon dioxide. The idea in this process is to split the combustion of a hydrocarbon or carbonaceous fuel into separate oxidation and reduction reactions. A solid oxygen carrier, mostly a metal oxide, is used to transfer oxygen from air to the fuel. The advantage of this concept compared to normal combustion is that CO_2 and H_2O are inherently separated from other components of the flue gas, requiring no extra energy for CO_2 separation (Abanades et al. 2015). However, developing a good oxygen carrier, providing high fuel conversion ratio, high oxygen transport capacity and good stability are the issues yet to be fully understood (Sifat and Haseli 2019).

In the post combustion capture, several processes that include most common chemical absorption are used (Gibbins and Chalmers 2008; Rochelle 2009). The CO_2 removed from the absorption solvent is then dried and compressed to reduce its volume before being transported to a safe storage site.

The pre-combustion capture of CO_2 is based on the ability to gasify all types of fossil fuels with oxygen or air and/or steam to produce a synthesis gas (syngas) or fuel gas composed of carbon monoxide and hydrogen. Additional water (steam) is then added and the mixture is passed through a series of catalyst beds for the water–gas shift reaction to approach equilibrium converting CO into CO_2, after which CO_2 is separated leaving a hydrogenrich fuel gas. This hydrogen can be sent to a gas turbine-generator to produce electricity or used in hydrogen fuel cells used in transportation vehicles. Although the energy requirements in pre-combustion capture systems may be of the order of half that required in post-combustion capture, the pre-combustion process requires more water for the water–gas shift reaction.

In the oxy-fuel capture, pure oxygen is used for combustion instead of air and gives a flue gas mixture of mainly CO_2 and condensable water vapor, which can be separated and cleaned relatively easily during the compression process. Each of these capturing processes carries both an energy and economic expense, contributing significantly to the total costs of a complete CCS system. The CO_2 capture step represents about 75-80% of the total cost of CCS (Davison, 2007).

The IPCC has estimated that the increase in energy required to capture CO_2 is between 10% and 40% depending on the technology - the NGCC requiring the least and pulvarised coal-fired requiring the most (IPCC 2005). The fraction of output power used in the capture as a function of base power plant efficiency is shown in Figure 1.8 (Morrison 2008). Higher the efficiency of the power plant, lower the output power utilized for CO_2 capture.

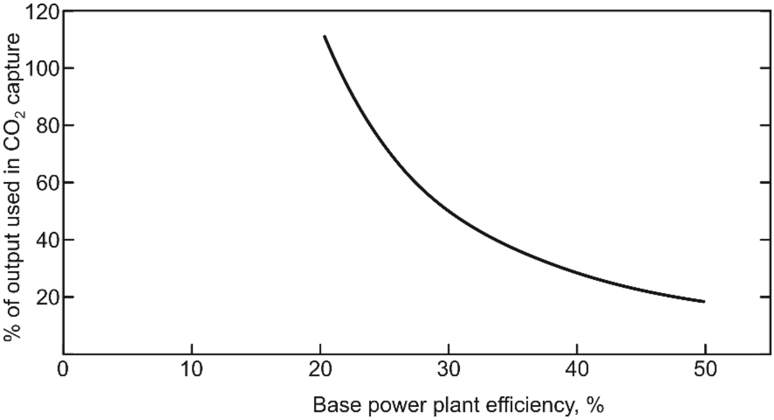

Fig.1.8 Percent of plant power used in CO_2 capture
[Source: Redrawn from RWE power, Morrison 2008].

In essence, for carbon capture systems, the most important attentions include possible improvements in efficiency, the influence of the purity of CO_2, the flexibility of system operation, and the retrofitting of coal-fired power plants.

Overall costs: The additional costs for the implementation of CCS compared to the conventional conversion of fossil fuels into electricity are reflected in the internalization of CO_2 costs. CCS systems are characterized by high capital expenditure and long-term capital tie-up, which means that each investment decision must justify the long-term profit potential. The implications of policy decisions related to climate change, energy systems and technology must be considered here, together with the growth prospects of competing technologies. Further, the way in which society views energy and climate-friendly technologies in general and CCS in particular is very crucial (ETP ZEP 2011; Global CCS Institute 2011; IEA 2007, 2010; IPCC 2005; McKinsey 2008). Social acceptance is considered as an important prerequisite for testing and implementing CCS (Kuckshinrichs, Chap.1. CCSU, Springer 2015).

1.4 Technology Readiness Level (TRL)

The technology readiness level is a system used to estimate the maturity of a technology. TRL that represents the development stage is based on a scale 1 to 9, with 9 representing the most matured technology.

Technical readiness level, TRL-1 represents the observing of basic principles. If it has reached TRL-9, it shows the actual system has proven through successful operations, and TRL-6 indicates that the system or subsystem has reached prototype demonstration in an appropriate environment.

In CCS technologies, the TRL development from TRL-1 to TRL-9 takes around 10–15 years (Chauvy et al 2019; Chauvy and de Weireld 2020; Naims 2016). It means that CCS technologies which are at TRL-6 in 2020 can be expected to be ready for implementation in 2030. Currently, the CO_2 capture technologies with TRL-6 are chemical looping, membranes for post-combustion application and calcium looping. In addition, DAC, oxy-fuel combustion, IGCC, membrane for pre-combustion application, and physical adsorption have a TRL of 7, and chemical absorption by amines and cryogenic capture presents a TRL of 9. Therefore, it can be safely assumed that several CCS technologies could be ready by 2030 and 2050 (Garcia et al. 2022).