Life Cycle Analysis of Carbon Capture Storage and Utilization (CCUS) in India

A report

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ABBREVIATIONS

AR	Assessment report
CCUS	Carbon capture storage and utilization
CEA	Central Electricity Authority
CIL	Coal India Limited
CO2	Carbon dioxide
COP	Conference of Parties
EOR	Enhanced oil recovery
EPA	Environment Protection Agency
ESP	Electrostatic precipitator
FGD	Flue gas desulphurization
GHG	Greenhouse gases
GWP	Global warming potential
IEA	International Energy Agency
IEO	International Energy Outlook
IGCC	Integrated gasification combined cycle
INDC	Intended Nationally Determined Contributions
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life cycle assessment/analysis
MEA	Monoethanolamine
Mt	Million tons
NAPCC	National Action Plan on Climate Change
NTPC	National Thermal Power Corporation
OECD	Organization for Economic Co-operation and Development
PC	Pulverized coal
SCR	Selective catalytic reduction
SETAC	Society of Environmental Toxicologists and Chemists
TRL	Technology readiness level
UNFCCC	United Nations Framework Convention on Climate change

ABSTRACT

Growing population and consequently the energy demand is causing an extensive damage to health and ecosystem which can be attributed to climate change due to uncontrolled GHG emissions to atmosphere past 10 to 15 decades. According to IPCC Assessment reports, human influence on climate change is evident and hence stabilization of GHG concentrations is inevitable. Fossil fuel burning is recognized as major contributor accounting to 75% of total anthropogenic CO_2 emissions. This along with increasing energy demand and substantial share of coal to electricity production in developing country like India, necessitates deployment of emission reduction technologies. Among various options proposed, carbon capture storage and utilization (CCUS) technology is gaining extreme attention. It deals with capturing of CO_2 from its sources, transporting it and subsequently either storing or utilizing as a feedstock. Although a significant reduction in CO_2 emissions is possible, this technology requires additional energy and resources that questions the feasibility of application. Thus, developing country like India requires an extensive technoeconomic and environmental assessment before its large-scale acceptability. A well-established technique to assess environmental impacts in a systematic way is 'Life cycle assessment' (LCA). Application of LCA to CCUS is vital to determine other consequences to the environment and subsequent interpretation of risk-benefit ratio. This study therefore deals with understanding the implication and extent of GHG emission reduction due to CCUS and robust comparison of environmental consequences all through the life cycle of a reference coal fired thermal power plant without CCUS and one with CCUS in India. For comparison, conventional powerplant with all abatement technologies except CCUS has been conducted. LCA of Talcher Kaniha powerplant was carried out with 3 assessment methodologies in order to determine the suitable methodology. From the results, life cycle global warming potential is 1.559, 1.536 and 1.5703 kg CO_2 eq./kWh for CML-IA baseline, IMPACT 2002+ and ReCiPe Midpoint 2016 (H) respectively. However, some environmental impacts are same but with difference reference units among all methodologies. These results further require an extensive review which allows to compare the LCA results of CCUS equipped powerplants in our future studies.

Keywords: Carbon capture storage and utilization, Coal fired thermal powerplant, Global warming, Life cycle assessment, OpenLCA.

Chapter 1
Introduction

1.1 Introduction to global climate change

Globally, technological growth and advancements focusing on economic development and alleviation of poverty has resulted in excessive utilization of resources as well as production of huge quantity of wastes. As a consequence, burden on supply of natural resources and deterioration of environment together have started increasing at a reckless rate. Degradation of environment is more likely in the form of climate change, pollution of air, water, soil and other entities, deforestation and desertification, etc. all of which are ultimately impacting the survival of human beings on this planet earth. Climate change is one of those serious environmental concerns and refers to long-term variations in the weather and temperature caused due to the greenhouse gases emitted majorly as a result of fossil fuel combustion. Besides temperature increase, it also results in intense droughts, water scarcity, severe fires, rising sea levels, flooding, melting polar ice, catastrophic storms and declining biodiversity (URL-1). Climate change thus requires extensive mitigation efforts and long-term goals to avoid consequences on environment and humans.

In the view of ambitious efforts undertaken to combat climate change, UNFCCC's Paris agreement is a landmark international treaty adopted in 2015 by 196 parties at COP 21 whose goal is to limit global warming below 2°C (ideally 1.5°C) compared to pre-industrial levels (URL-3). Also, among 17 sustainable development goals, goal 13th stresses on immediate action essential to combat climate change and its impacts (URL-10). However, IPCC in its recent AR6, imparts that limiting global warming to 1.5°C is unachievable until there is immediate and deep emissions reductions across all sectors (URL-2). This implies the necessity of immediate control of GHG emissions to achieve long term temperature goal as well climate neutrality by mid of century.

1.2 Climate Change mitigation options

Mitigation involves stabilizing the GHG concentration in atmosphere through controlling the flow of greenhouse gases into the atmosphere released as a result of extensive anthropogenic activities and economic development past 150 years. Immediate focus on mitigation is very essential to enable both economic and social development in a sustainable manner. There are diverse impending options for controlling the GHG concentration in atmosphere. Different countries and their local governments are engaged in alleviating this problem in their own ways and also integrating the concept of sustainability and climate change mitigation in their development plans. Some of the potential emission limiting options are listed as follows: i) reducing energy consumption and enhancing less energy-intensive activities, ii) Switching to less carbon intensive fuels viz., natural gas, iii) increasing the share of nuclear power generation, iv) increasing share of renewable energy sources like biofuels, v) enhancement of biological sinks including afforestation and land management, vi) Carbon capture storage and utilization and other carbon removal technologies (URL-2)

1.3 Climate change mitigation - Indian scenario

Climate change is a global phenomenon with local consequences and hence India in its part has also committed to set pro-active ambitious targets in the view of Paris agreement which has reflected in its INDCs and NAPCC (URL-4). In India, annual CO_2 emissions have increased by 45% of 2010 value with currently 2.44 billion tons being emitted (Fig. 1-2). In the fact that, India contributes to almost 6% of total global CO_2 emissions and 3rd largest CO_2 emitter after China and USA, has committed to reduce carbon intensity by 30-33% by 2030 (Kumar et al., 2019). From Fig.1-1 it is obvious that CO_2 is a major contributor to global warming especially those released due to fossil fuel combustion and other industrial activities. It is also evident from Fig 1-4. that India's power sector especially coal fired thermal power plants are mainly responsible for half of all CO_2 emissions. Coal being the dominant source of fuel in India, its share to energy production was 55% in 2016 and is estimated to share 48-54% even in 2040 (Kumar et al., 2019). Nevertheless, according to International Energy Outlook 2021, share of coal as primary energy will still be 28-30% in 2040 in non-OECD countries (IEO, 2021). These indicate the dominance of coal in upcoming years and thus necessitates the need of CO_2 emission mitigation technologies to reduce these emissions in no time to prevent the further effects on environment and human health due to climate change.

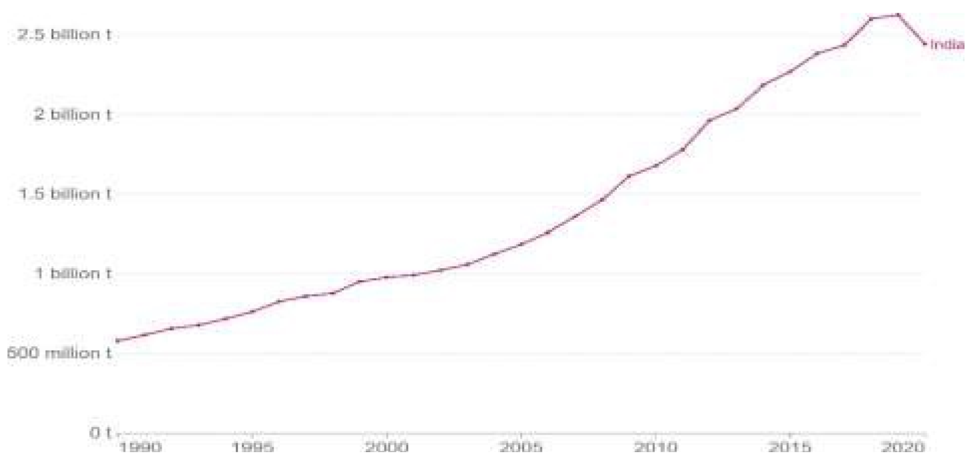


Figure 1-2. Indian annual CO_2 emissions trend (URL-6)

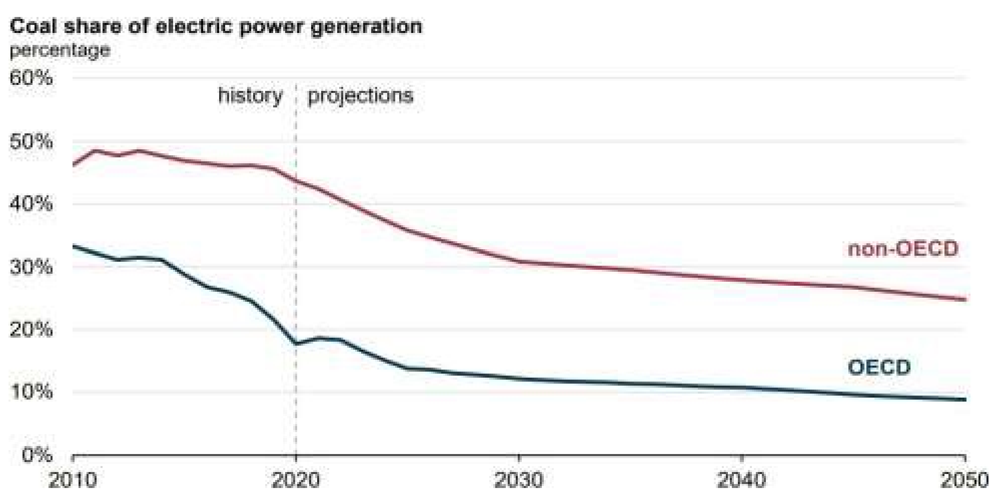


Figure 1-3. Share of coal in primary energy (IEO, 2021)

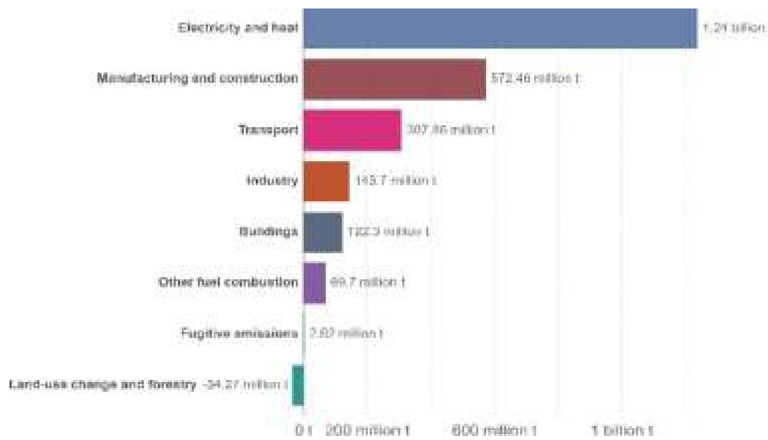


Figure 1-4. CO_2 emission by sector in India (URL-8)

In India like other nations, numerous initiatives are undertaken by the government and industrial authorities to explore ways to reduce the concentration of CO_2. Those include switching to alternative fuels and electricity production methods, improving the efficiency of coal combustion, carbon capture storage and utilization (CCU/S) etc. The renewable fuel-based energy systems are limited by current technological advances for implementation at larger scale and also coal will remain a major fuel source for electricity generation suggesting the major portion of thermal power plants for energy production in future. Along with renewables-based electrification, bioenergy, and hydrogen, the International Energy Agency's (IEA) Energy Technology Perspectives 2020 study emphasizes that CCUS must play as one of four major pillars of the global energy transition (IEA, 2020).

1.4 CCU/S and its deployment status in India

CCU/S is an emerging CO_2 abatement technology that deals with capturing of CO_2 after combustion, its compression and subsequently storage or utilization thus having capability to cut down GHG emissions by 50-85%. Globally, around 21 projects are in successful operation and many of them are in the development phase (Global CCS Institute, 2021). Unfortunately, none of the projects in India are operational nor in plan phase. Although developing nations like India emphasize on renewable energy than CCUS, the faster transition from rural to urban regions will increase the demand for energy and consequently, the emissions produced which necessitates the implementation of CCUS (Kumar et al., 2019). Also, under deep decarbonization scenarios in India, CCUS has potential to reduce 780 Mt/yr. in 2°C scenario below 60 USD/t CO_2 and additional 250 780 Mt/yr. up to 75 USD/t CO_2 in < 2°C scenario (Malyan and Ankur., 2021).

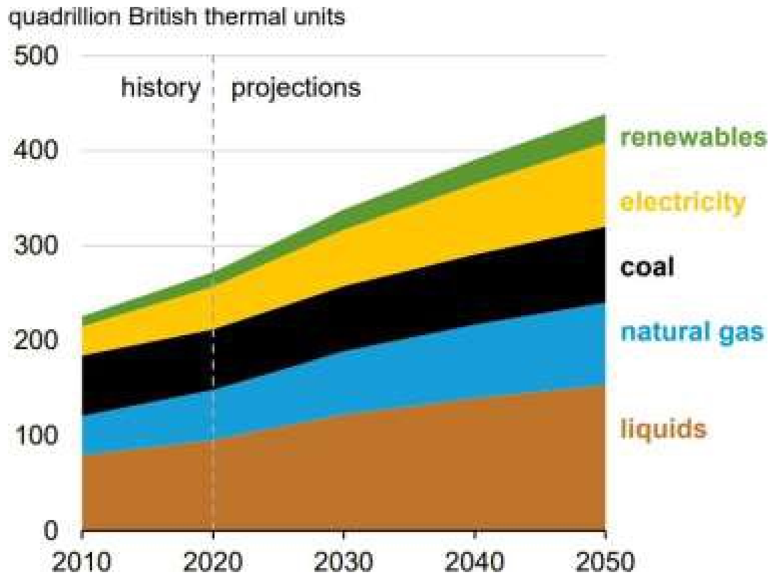


Figure 1-5. Energy consumption by fuel of non-OECD countries (IEO, 2021)

India in its 2008 National Action Plan on Climate Change (NAPCC), has mentioned the importance of CCS in Indian power sector along with the concerns regarding its high cost and storage instability. Although CCUS is crucial for sustainable development, its large-scale implementation is still under debate due to high cost induced capture processes (65% increase in base cost), requirement of extra coal to deal with reduced plant efficiency and also potential environmental impacts (Malyan and Ankur., 2021).

Despite the reduce in global warming, serious other environmental impacts are of concern and has to be assessed in order to conclude its feasibility and applicability in India. Assessment of environmental impacts involves determining impacts on air, water, soil, human health, depletion of resources, waste generation and others. Therefore, a thorough life cycle analysis on CCUS will help in determining the extent of possible environmental impacts along with reduction in global warming. Thus, this study deals with conduction of full life cycle analysis of an Indian coal fired thermal power plant equipped with CCUS to determine the possible ecological consequences and its subsequent comparison with conventional power plant.

Chapter 2
Literature review

2.1 Carbon Capture, storage and utilization

2.1.1 Background

IPCC, 2005 report on carbon capture and storage as an option for mitigation of climate change states that, “It is 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” (IPCC, 2005). Depending on the objective of capturing, the captured CO_2 can be either stored or utilized for the production of products, fuels, chemicals or building materials that require CO_2 as a raw material viz., methane etc. which can provide a potential revenue stream for CCU/S facilities. It is also possible to both utilize and store the captured CO_2 at the same time for example enhanced oil recovery or in construction materials where some or all of CO_2 used are being permanently stored (IEA, 2020). Thus, it contains the following elements: Capture, Transportation, Storage and Utilization, each one of which is reviewed in upcoming sections.

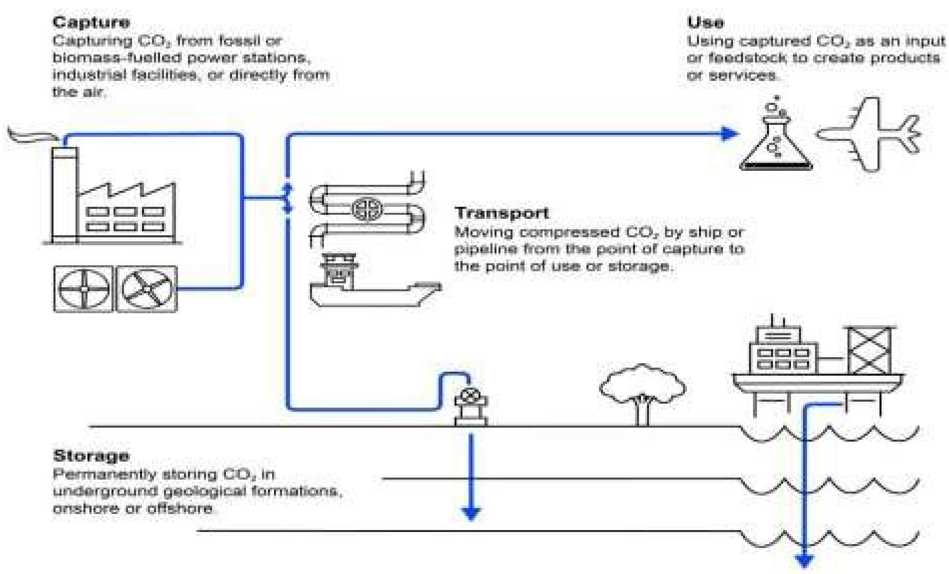
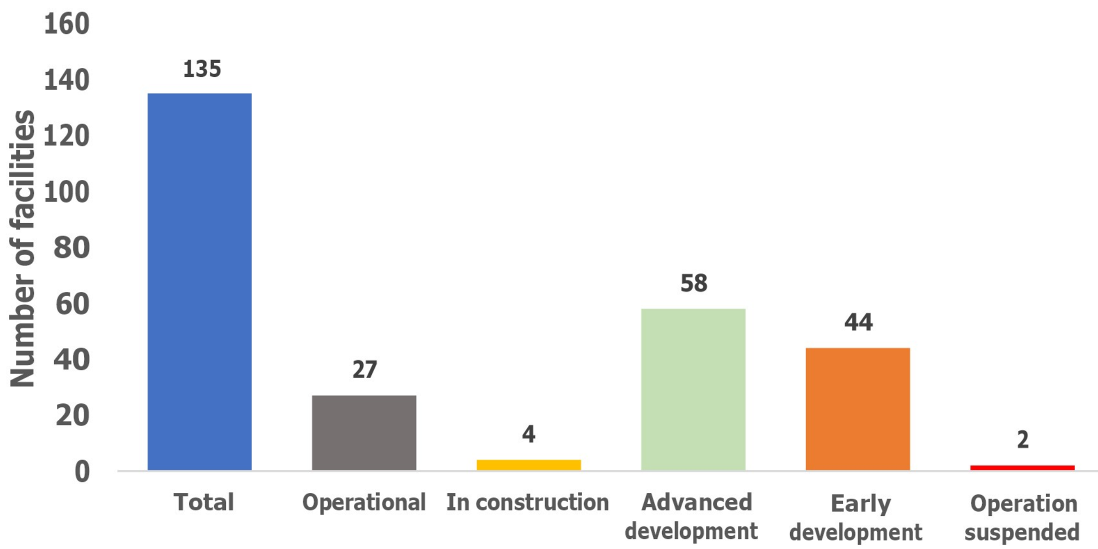


Figure 2-1. Overview of carbon capture, storage and utilization (IEA,2020)

Around the world CCUS facilities have been in operation since 1970s with a great expansion in its applications from last decade. There are currently 21 CCUS facilities having 40 Mt CO2 capture capacity with the first large-scale project commissioned in 1996 at Sleipner offshore gas field, Norway. However, on a coal-fired power generation system only two pilot scale facilities are operational (IEA,2020). Although the awareness of this technology is high on a global scale, application in India is almost zilch. It is seen that four projects are under construction where two of them are in China, 1 in Norway and 1 in United States (Global CCS Institute, 2021). Besides, several projects are in advanced and early phase of development. Unfortunately, none of the among projects belong to India.



2.1.1.1 Influencing factors, advantages and disadvantages of CCU/S

Factors influencing the CCU/S widespread application include technical maturity, capacity, overall associated costs, potentiality, diffusion and transfer of technology to developing countries and their capacity to apply the technology, regulatory aspects, storage potential environmental issues and risks, and public perception. Also, net decrease in emissions through this technology depends on fraction of CO_2 captured, increased emissions due to reduction in overall plant efficiency, leakage during transport and fraction retained in storage area over long term (IEA, 2020) and (IPCC, 2005). A detailed integrated assessment of commercial availability, economic aspects, long term usable CO_2 storage potential, ecological assessment and stakeholder analysis have to be conducted in order to understand its implications (Viebahn et al., 2014). CCUS in its share has several advantages and challenges associated that needs to be dealt and are discussed in the table below.

Table 2-2. Advantages and disadvantages of CCUS system

Advantages	Disadvantages
Source emission reduction or removal at point sources	High cost associated with capture and transportation technologies
Removal of other pollutants like SO_2, PM, NOx etc.	Problems and uncertainties associated with storage

Utilizing the captured CO_2 as a feedstock for manufacturing commercially viable chemicals and products	It involves a high energy penalty. A powerplant equipped with CCS would require 10-40% more electricity especially for capture and compression compared to a non-CCU/S powerplant
It is possible to retrofit the existing powerplants to equip the facility	Requirement of chemicals, materials, equipment and other resources
High global warming controlling capability	Has social and environmental burdens
Capable of reducing emission in those industries in which other technologies are expensive to apply	
possible to generate negative emissions by CCS in combination with bioenergy or direct air capture	

2.1.1.2 Drivers and restraints of CCU/S

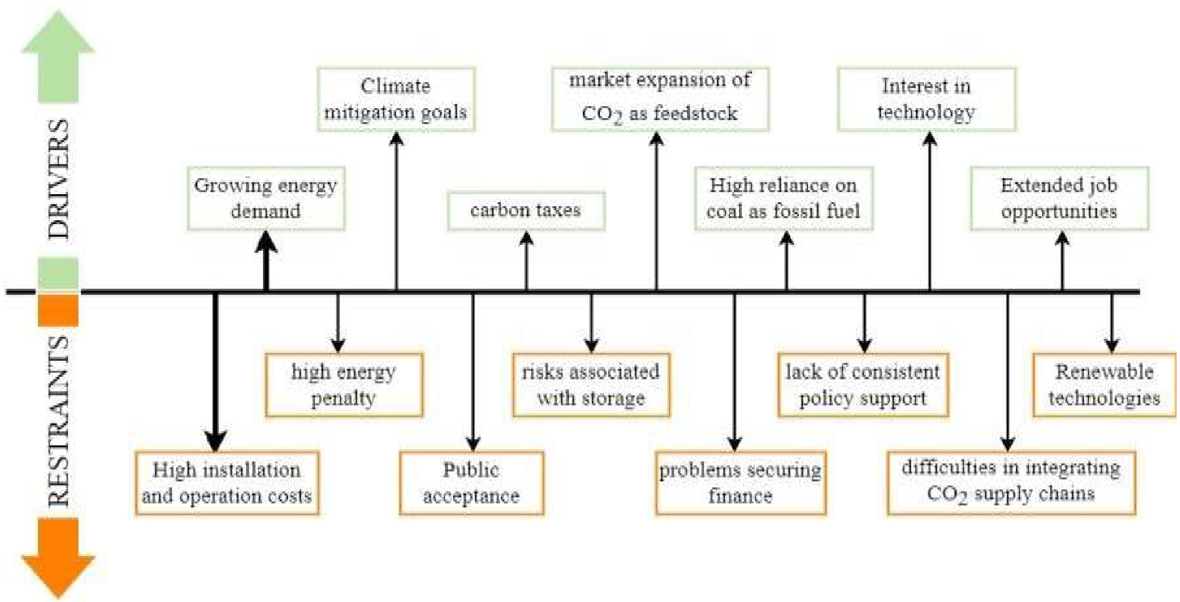


Figure 2-3. Drivers and restraints of CCU/S (Kumar et al., 2019) & (Araújo & de Medeiros., 2017)

The maturity and extent of application of CCU/S varies greatly with technology type and intended purpose (IEA, 2020). While, awareness towards CCU/S is increasing for last couple of decades, commercial considerations and lack of consistent policy support are major challenges which hinder its widespread applications. International energy agency

(IEA) in 2009 under roadmap for CCU/S had mentioned developing 100 large-scale CCU/S projects with a cumulative of 300 $MtCO_2$/year in the last decade to meet global climate change mitigation goals. Unfortunately, the actual capacity installed was around 40 Mt. Thus, major drivers and restraints of this technology as stated by (Kumar et al., 2019), and (Araújo & de Medeiros., 2017) greatly affects the deployment and are depicted in the figure 2-3.

2.1.1.3 Technical and economic aspects of CCU/S

Sustainable climate mitigation strategies are hinged on two dynamic elements i.e., technology level and economic value. As such, different technologies involved in capture,storage and utilization are at various levels in terms of its technology readiness level (TRL).It highly determines the extent of application of that technology at large scale. These technical aspects are vital to be understood to know which particular technology suits bestfor intended project. Many technologies are already mature while others are still in development phase and needs to be demonstrated at pilot scale. The status of various technology involved in CCU/S value chain are depicted in the figure no. 2-4.

Similarly, economic assessment is also a major factor on which whole deployment of CCU/S is hinged. Cost analysis allows comparison between existing technologies and aids in decision making. IPCC in its 2005 report, has performed a comparative cost analysis of CCS for power generation facility which is given below.

Table 2-3. Comparative cost analysis of CCS for power generation facility in US$/kWh (IPCC, 2005)

Power plant system	Natural gas combined cycle	Pulverized coal	Integrated gasification combined cycle
Reference plant without capture	0.03-0.05	0.04-0.05	0.04-0.06
With capture and geological storage	0.04-0.08	0.06-0.1	0.05-0.09
With capture and EOR	0.04-0.07	0.05-0.08	0.04-0.07

Another modelled study by Akash et al., 2016 on economic and environmental impacts of implementing CCS indicate that upon addition it is modelled that, the net power output decreases, water consumption increases, emissions decreases and capital cost increases. The following table gives an overview of expected implications of CCS addition in India (Akash et al., 2016).

Table 2-4. Estimated technical implication of CCS implementation in India (Akash et al., 2016)

Characteristics	Amine based system	Oxyfuel combustion
Net power output	-10%	-18%
Net plant efficiency	-3.3%	-6.5%
Makeup water requirement	+5%	+16%
CO_2 emissions	-90%	-90%
NOx emissions	-5%	-99.2%
SOx emissions	-100%	-85%
Particulate emissions	-50%	-99%
Capital cost	+47%	+55%
Cost of electricity	+49%	+69%

2.1.2 CO_2 Capture

Capturing process involves the separation of CO_2 from other flue gases and is thus categorized into different processes based on the stage of capture. Several technologies are employed according to requirement in capturing the CO_2 and are explained in table 2-5. The three approaches for capturing are illustrated in figure no. 2-5 and explained as follows:

a) Post-combustion

It involves capturing the CO_2 released after the combustion of fossil or other fuels in air i.e., mixture of N_2 and O_2. This technique has comparatively good potential to effectively capture CO_2 and can be retrofitted to existing technologies. Perhaps, the partial pressure of CO_2 in flue gas that acts as thermodynamic driving force for capturing is low and hence requires more energy and cost to deal with this challenge (Plasynski et al., 2009).

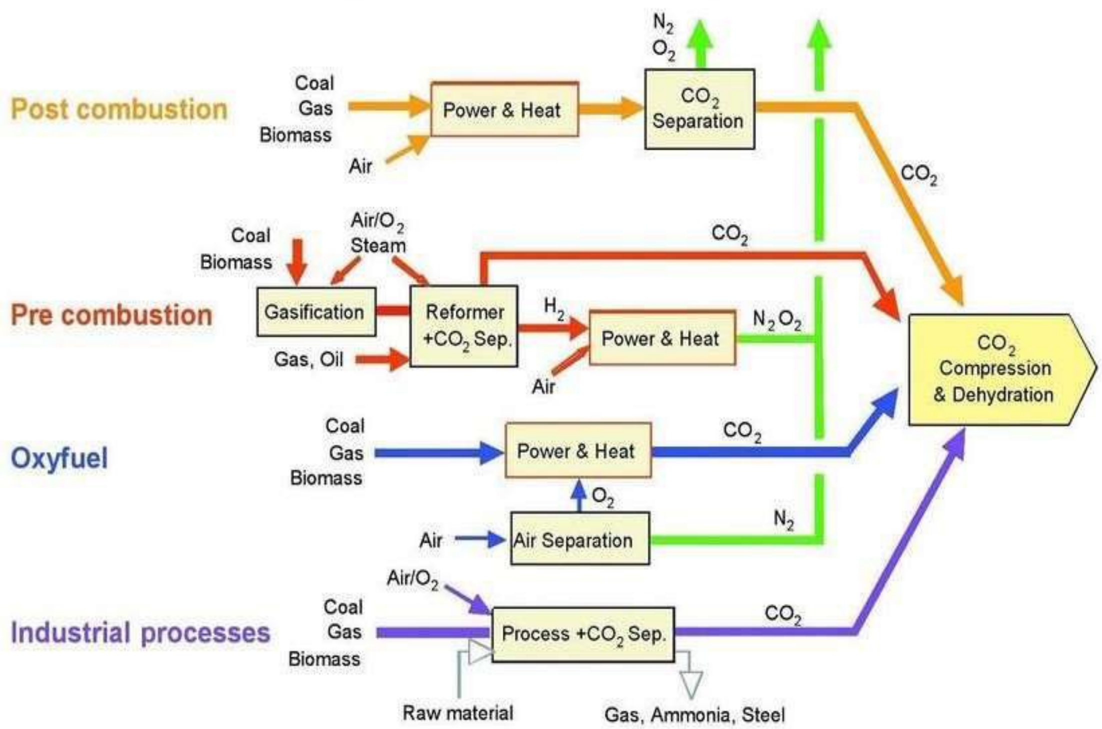


Figure 2-5. Approaches to CO_2 capture (IPCC, 2005)

b) Pre-combustion

CO_2 is captured prior to the fuel combustion. In order to overcome the problem of high cost of capturing in post-combustion due to low partial pressure of CO_2 in flue gas stream, efforts led to development of combustion technologies that exclusively produced concentrated CO_2 streams at high pressure. Gasification of fuel is one such technology that produces synthesis gas (also known as syngas), a mixture of hydrogen and carbon monoxide which upon water-gas-shift reaction converts the CO ultimately into CO_2. CO_2 is recovered from the stream and H_2 then acts as fuel which is burnt to produce steam (Plasynski et al., 2009).

c) Oxy-combustion:

It involves burning of fossil fuels entirely in pure oxygen resulting in formation of highly concentrated CO_2 and H_2O vapor in flue gas stream which can then be separated inexpensively. As, a result the volume of flue gas is decreased resulting in significant decrease in cost of capture. Along with this, lower NO_X production also poses an advantage. On the other hand, the requirement of a cryogenic air separation unit to obtain pure oxygen upsurges the cost. Based on comparative studies between convention powerplant with amine scrubber and oxy-combustion, it is concluded that latter is more economically feasible (Plasynski et al., 2009)

Capture cost holds highest share (~75%) in overall deployment cost and depends on factors like energy requirement, plant location, concentration of CO_2 etc. Since most capture systems are intended to capture between 85-90% at the point source, they have the lowest cost per ton of CO_2 captured (IEA, 2020).

2.1.3 CO_2 transportation

Transport of CO_2 is very critical and requires a safe and reliable infrastructure. It is categorized into offshore and onshore where the former includes transportation by ships and latter includes via pipeline and rail/trucks. The choice of transport mode is greatly influenced by regulatory frameworks, quantity of CO_2 being transported, distance between source and sink and cost of transport. Most reliable modes for long distance transport include pipeline and ships whereas trucks or rails are used for short distance transport. Pipeline system is the cost-effective whose share on overall costs is influenced by pipeline material used, dimensions, number of compressors and pumps used, labour costs and shelf life. Transportation through pipeline requires captured CO_2 to be compressed above its critical pressure to liquid and booster pump for every 100km. Offshore transportation through ships are still in demonstration phase but will be similar to LPG and LNG shipping (IEA, 2020).

2.1.4 CO_2 storage

Storing involves injecting the CO_2 into deep impermeable formations under the earth so as to prevent its escape into atmosphere. It can be stored in geological formations, oceans or can be carbonized into minerals. Potent geological formations include depleted oil and gas reservoirs, deep saline formations (offshore and onshore), enhanced oil recovery, enhanced coal bed methane recovery, deep unmineable coal seams, sedimentary basins, saline aquifers with former two having highest capacity. In order to have successful geological storage, prior site characterization, selection and performance prediction is necessary (IPCC, 2005). It is estimated that world has geological capacity to hold 100,000 Gt of CO_2 (Plasynski et al., 2009).

Different mechanisms for effective and reliable storage depend on geological conditions and thus includes structural and stratigraphic trapping, residual trapping in pore spaces and solubility trapping in water and mineral trapping to form carbonate minerals. Extensive monitoring is vital to ensure proper injection, closure and to know further movement of CO_2 underground.

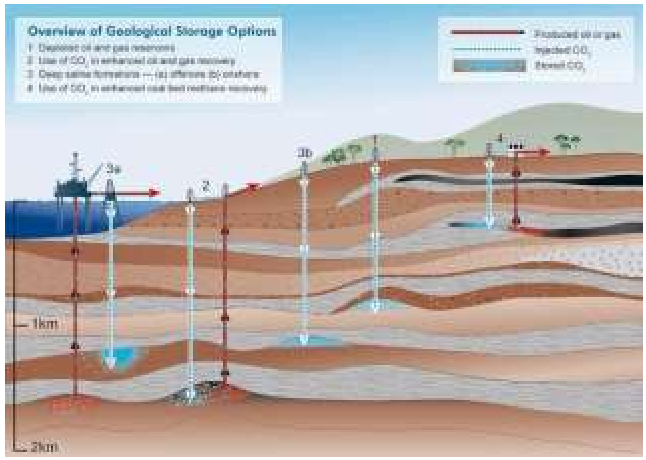


Figure 2-6. Types of geological storage options (IPCC, 2005)

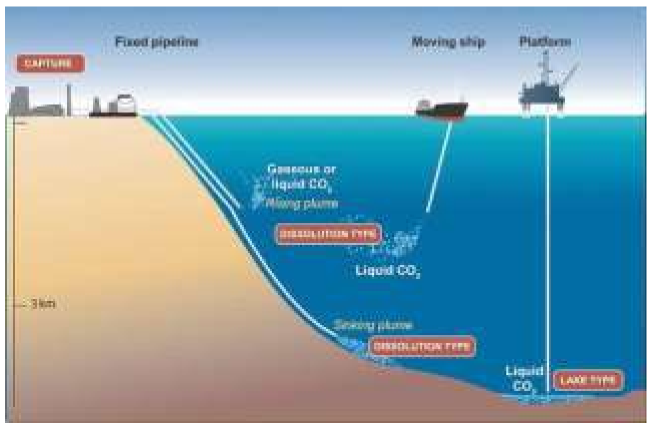


Figure 2-7. Types of oceanic storage (IPCC, 2005)

A major problem with storage is the risk of leakage of CO_2 to atmosphere and groundwater contamination resulting in public concerns and thus requires an extensive study of storage site. Also, cost of storage influences greatly and depends on injection rate, type and properties of storage reservoir and location of reservoir with cheapest being depleted oil and gas fields. However, when used for EOR, the costs are significantly reduced due to incremental revenues from oil extraction along with delivering higher climate benefits than other options (IEA, 2020). The Sleipner project in an offshore saline deposit in Norway, the Weyburn EOR project in Canada, and the In Salah project in a gas field in Algeria are 3 pilot scale storage projects currently active which captures 3-4 $MtCO_2$ that would otherwise be released to atmosphere (IPCC, 2005).

Significant research has also been done on ocean-based CO_2 storage, although interest has waned as a result of environmental, legal, and financial issues. Dispersion as tiny liquid

CO_2 droplets that disintegrate in ocean water (dissolution type) and the formation of liquid CO_2 lakes in deep ocean depressions (lake type) are two methods proposed for ocean storage (Plasynski et al., 2009)

Apart from the above storage options, mineral carbonation is another potential way of dealing with captured CO_2 which involves chemical conversion of CO_2 into solid inorganic carbonates using alkaline and alkaline earth oxides such as MgO and CaO, present naturally in rocks. This results in formation of magnesium and calcium carbonates which traps the CO_2 that cannot be released into atmosphere. These carbonates can either be disposed to silica mines or re-used for construction purposes.

2.1.4.1 Storage potential of CO_2 in India

It is very essential to identify potential and suitable storage options in order for CCU/S to be successful. This entails a detailed qualitative and quantitative assessment of storage of all types. In addition to this, assessing other modes like shipping, if no storage sites available in proximity of source must also be done. Many source-sink studies specific to India are conducted in order to understand the possibilities of storage. Initial findings indicated that the Gangetic (north, northeast), Brahmaputra (northeast, Bangladesh border), and Indus (northwest, Pakistan border) river plains, as well as the nearby offshore regions on the Arabian Sea (southwest coast) and Bay of Bengal (southeast coast), are potential storage sites (Kapila et al., 2009).

Table 2-6. Geological CO_2 storage capacity in India as estimated by different studies (Kumar et al., 2019)

Sites	Estimated storage capacity of CO_2 in Gt		
	Dooley et al., 2005	Singh et al., 2006	IEAGHG, 2008
Unmineable coal seems	2	5	0.345
Depleted oil reservoirs	-	7	1.0-1.1
Depleted gas reservoirs	2	7	2.7-3.5
Offshore and onshore deep saline aquifers	102	360	107.3
Mineralization in basalt rocks	-	200	-

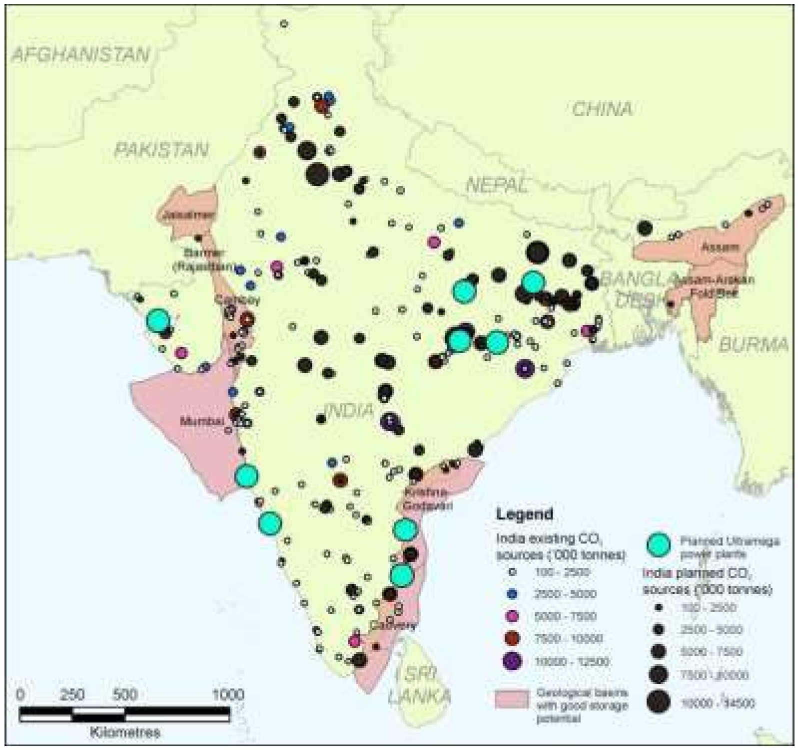


Figure 2-8. Geological storage potential in India, (Kapila et al., 2009)

2.1.5 CO_2 utilization

It is also known as 'carbon recycling'. CO_2 acts as a valuable input for many products and services. Captured CO_2 can be directly used without conversion or converted to a useful product. Currently, 230 million tons of CO_2 is utilized globally with highest as a raw material in fertilizer industry for urea manufacturing followed by oil and gas industry. Other existing and emerging pathways include food and beverage production, cooling, water treatment, greenhouses, hydrocarbon fuel, polymers like ethylene, chemicals like methanol, building materials like concrete. Apart from this, production of low carbon hydrogen is also prominent as H_2 utilization for sustainable development is increasing rapidly (IEA,2020). Utilized CO_2 must replace a product with higher emissions viz., fossil fuels to acquire climate benefits and thus requires a life cycle analysis. Given that many of the applications for these technologies are still in the early stages of development, it is very challenging to predict the future of CO_2-based goods. They are anticipated to cost significantly more than traditional and alternative low-carbon products, mostly due to their high energy intensity, hence policy assistance is essential (IEA, 2020).

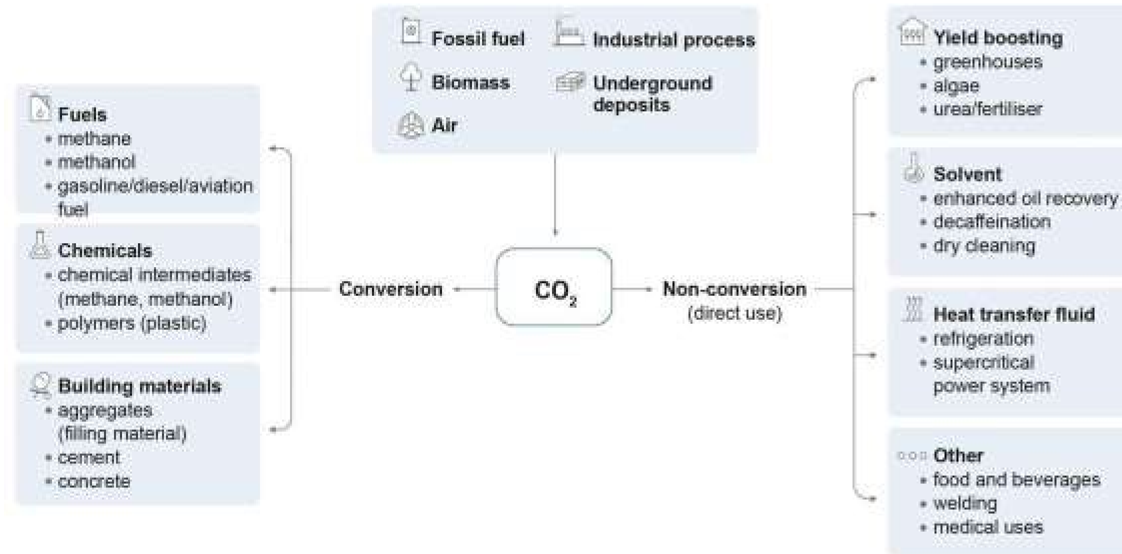


Figure 2-9. CO_2 utilization options (IEA, 2020)

2.1.5.1 CO_2-Enhanced oil recovery

CO_2 is majorly used in oil extraction for enhanced extraction because of its miscibility in crude oil. This process can either be considered as either storage or utilization option. It is inexpensive than other solvents and around 70 to 80 Mt commercially available CO_2 is used for this purpose (IEA, 2020). Instead of utilizing commercial based CO_2, captured CO_2 can be used to for oil recovery. The primary mechanism behind this involvesdisplacement of oil from rock pores after the dissolution of CO_2 in oil which causes a reduction in oil viscosity, increase in overall reservoir pressure and subsequent pushing ofoil towards the production well. The first project to demonstrate this was Boundary dam project in Saskatchewan in Canada where the captured CO_2 was injected to Weyburn oil field for EOR and approximately 63% of emissions reduction was observed over its full lifecycle. The potential climate benefits of this utilization technology can be assessed by conducting a quantitative life cycle and cost analysis considering the project specific characteristics (Duda, J. R., & Il, A. B. Y., 2010).

2.2 Life cycle assessment (LCA)

2.2.1 Background

Rapid growth in economy involved huge production of products that did not consider their impacts on environment since the focus was largely on mass production and profit. Later, as the awareness about environment increases, conventional end-of-the-pipe abatement regulations were forced to be followed which were limited only to the production phase. Nevertheless, it is observed that a product has its own ecological footprint right from the raw material extraction needed for its production till its usage and disposal. Considering these impacts is very important in modern world to attain a holistic sustainable development. Sustainable development deals with meeting the demands of present generation without compromising the ability of future generation to meet their own meets. Such a development needs assessment of impact of present generation on resources, materials and environment. Manufacturing of products require energy and resources and thus sustainable production is important to control the resource and waste management. One way to achieve this is through assessment of the process. In view of this, the Society of Environmental Toxicologists And Chemists (SETAC) along with Environmental Protection agency (EPA) framed a basic approach for conduction of cradle to grave environmental assessment of materials and products. The 1992 UN Earth Summit stressed on application of life cycle methodologies as one among the most promising tools for management of environment (Jensen et al., 1998).

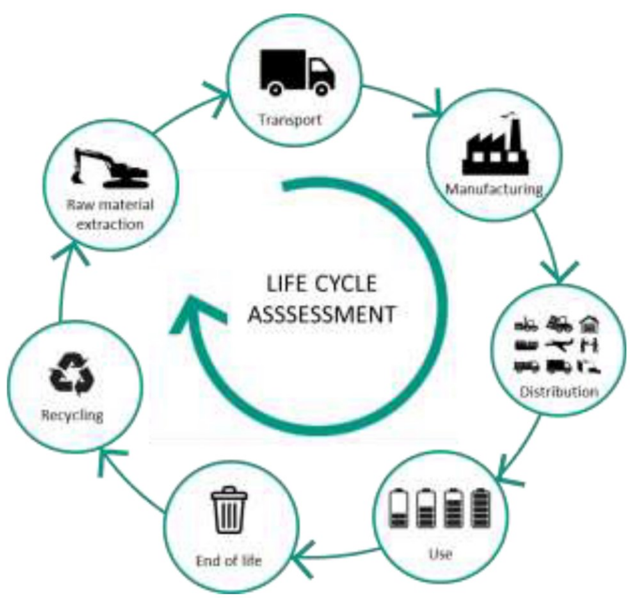


Figure 2-10. Figure depicting life cycle stages (URL-11)

Life cycle assessment involves identification and quantitative analysis of crucial environmental impacts throughout the entire life cycle of a product from raw material acquisition, manufacturing, distribution, usage till disposal with environmental interaction in every stage. It is a complicated process and hence requires a systematic analysis methodology (Lee and Inaba., 2004). It is thus an effective mathematical tool that helps to compare processes, products and services based on sustainability. Environmental impacts broadly include emissions to water, air, soil and land, waste production, land use and degradation, resource depletion etc. Hence, LCA quantifies all these impacts and links to major damage areas like human health, natural resources and ecosystem. It is used for wide range of applications like industrial product development and improvement, strategic planning and decision making, marketing purposes, policy development for ecolabelling, green production, waste management opportunities etc. (Jensen et al., 1998). LCA can either be carried out manually using standard formulas and normalization factors for impact calculation or through commercially or freely available software. Software include SimaPro, GaBi, Umberto and OpenLCA where former three are commercial whereas the latter one is open source and free. LCA is conducted in a systematic procedural manner which is discussed in the next section.

2.2.2 Methodological framework

Life cycle analysis follows a specific methodology which was standardized in 1990 by International Organization for Standardization (ISO) in series of 14040 and 14044 with constant updated and extension. The approach is basically sub-divided into four phases viz., i) Goal and scope definition, ii) Life cycle inventory analysis, iii) Life cycle impact assessment, iv) Life cycle interpretation, all of which are independent (Müller et al., 2020). A consensus framework had been established by ISO for all stages of including ISO 14040 (1997) on principles and framework, ISO 14041 (1998) on goal and scope definition and inventory analysis, ISO 14042 (2000) on life cycle impact assessment, ISO 14043 (2000) on life cycle interpretation. All the phases are discussed below in detail.

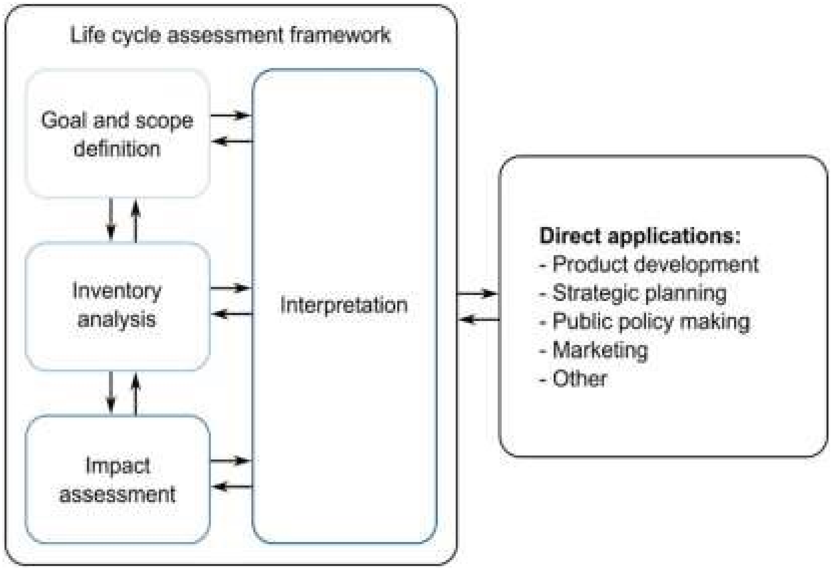


Figure 2-11. Phases of life cycle assessment (Müller et al., 2020)

2.2.2.1 Goal and scope definition:

Goal definition involves defining the purpose and is critical as it greatly influences the results of LCA. It addresses the purposes and definition of the study, target audiences, application areas and product type. It must be unambiguous and ensure the results are properly communicated to intended audience.

Scope definition should be sufficiently in line with goal and hence is complicated. It must describe all the assumptions and conditions under which the study is valid. The following must be included while defining the scope: description of system and its boundaries, functions of the system and functional unit, allocation procedures, data quality requirement, assumptions and limitations etc. Since LCA is an iterative technique, the scope can be revised based on data availability and results obtained (Jensen et al., 1998) (Müller et al., 2020). The following table provides elements to be defined in a sequential order while dealing with scope of the study.

Table 2-7. Components of goal and scope definition (ISO 14040, 1997), (Lee and Inaba., 2004) and (Jensen et al., 1998).

Terms	Definition
Product	The material chosen for LCA study
Product system	It includes all the upstream and downstream processes required for the production of product along with all the necessary inputs and expected outputs
Function	Deals with intended application(s) of the product system being studied. A system can have numerous functions out of which one is selected that is suitable to goal and scope.
Functional unit	A defined and measurable calculation reference that permits quantification of function and relationship to inputs and outputs. It forms the foundation for sound comparison of two or more product systems. Every data normalized to the basis of functional unit. Efficiency and durability of the product, performance quality standard must be taken into account when defining the functional unit
Reference flow	The quantity of product necessary to fulfil the function
System boundary	Includes all the unit processes associated with the product needed to fulfil the function. A process tree can be established indicating all collection of unit processes and their interrelationships. It is subjective and includes geographical boundaries, life cycle boundaries, boundaries between techno sphere and biosphere. Depending on the system boundary the analysis can be cradle to grave (raw material extraction to disposal), cradle to gate (raw material extraction to manufacturing), gate to gate (within the factory), gate to grave (manufacturing to disposal).
Data quality requirement	It specifies and properties to require to meet the goal and scope of the study. It includes precision, completeness, representativeness, consistency, reproducibility, time coverage, geographical coverage, technology coverage, uncertainty information etc

2.2.2.2 Life cycle inventory analysis

It involves collection of all the required data and calculation procedures required to quantify all the inputs and outputs and subsequent preparation of dataset. It is the most time and resource intensive step in LCA. For each and every process, data regarding inputs, outputs, emissions, products and by-products must be collected. Apart from data collection, it also includes refining system boundary, calculation, data validation, allocation and relating data to specific system. It also requires establishing a proper process diagram to improve the transparency of study (Jensen et al., 1998). Based on the availability, data can be classified into background and foreground data where the former includes secondary data collected from published or unpublished literature, modelling, or from a database and latter deals with data collected through experiment or on-site. On the basis of data collected, system boundaries are then refined to include, exclude or modify specific processes (Jensen et al., 1998). For each unit process, all the inputs and outputs are represented in terms of functional unit of product and based on this, reference flows have to be established (Lee and Inaba., 2004). Further, the calculation procedures are chosen based on type and amount of data to be handled. It has to be noted that data quality is maintained at every stage of analysis through continuous iterative check on data validity. The problem of not including all inputs and outputs can be resolved by either expanding the system boundary or allocating relevant environmental impacts to studied system. Proper procedures to deal with allocation and recycling has to be followed which include multi-input and output processes, open-loop recycling (sharing of product produced by other system which is not included in system boundary) (Jensen et al., 1998). The data must possess the following characteristics:

- Must be time sensitive as older data may be unrealistic
- Must be related to the geographical boundary of study system
- Representative of the population or entity
- Consistent with the goal and scope of study
- Reproducible and repeatable
- Precise and complete

2.2.2.3 Life cycle impact assessment

It is the 3rd phase of LCA and involves calculation and evaluation of significant environmental impacts by applying certain methodologies to life cycle inventory analysis results (ISO, 14040, 1997). It basically interlinks the inventory data with specific impact categories depending on goal and scope of the study. This allows quantitative and/or qualitative characterization and assessment of environmental interventions identified in data.

Based on damage extent of the impact, indicators are of 2 types. 1. Midpoint or problem-oriented indicators that focus on a single environmental problem whereas the endpoint or damage-oriented indicators are aggregation of several relevant midpoint categories to three major damage categories i.e., damage to human health, ecosystem damage, resource depletion. However, the level of uncertainty basically increases from midpoint to endpoint categories.

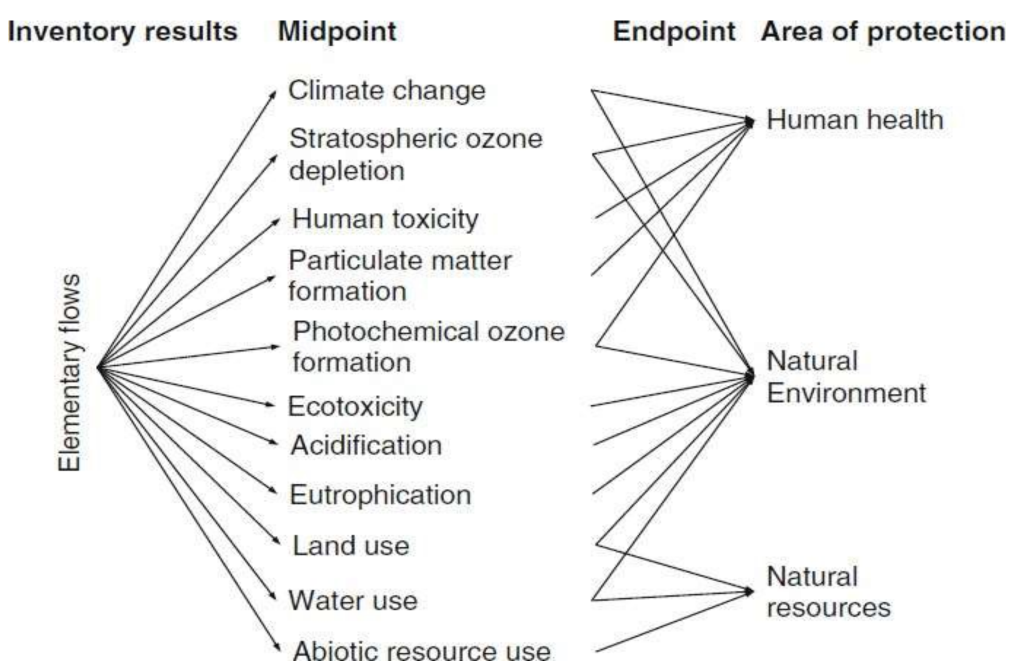


Figure 2-12. Diagram depicting relationship between midpoint and endpoint categories (Hauschild and Huijbregts., 2015)

The impact assessment phase basically includes the following elements of which initial three are mandatory and latter two are optional:

A) Category identification and characterization model selection

It requires selection of impact categories that is in line with goal and scope. Impact categories are used to describe the impacts caused by product system or process and its selection holds a prime importance as there exists various categories and multiple methods for a particular category. Various environmental impact categories exist depending on the type of assessment methodology. They must be relevant (elementary flows contribute to these categories), assessable (Proper methods are available), mutually independent and related to characterization step (Jensen et al., 1998). The impact categories must be limited to midpoint rather than endpoint because of the high uncertainty level associated with endpoint indicators (Müller et al., 2020). However, no consensus exists in single default list of impact categories till date.

B) Classification

This step qualitatively assigns the inventory input and output data to impact categories based on the scientific analysis of relevant environmental processes. Double accounting of different effects in same effect chain must be taken care (Jensen et al., 1998). According to ISO definition, assignment of LCI results to one impact category and identification those results that relate to more than one impact category is identified (Hauschild and Huijbregts., 2015).

C) Characterization

This is a quantitative step which assigns the relative contribution of each input and output to selected impact categories. Modelling categories in terms of indicators and providing a foundation for the aggregation of inventory input and output within the category are the two main components of characterization. (Jensen et al., 1998). A factor is multiplied to each elementary flow assigned to impact category using certain models which is called as characterization factor. The score is expressed in a way common to all contributions within that particular category and summed to obtain overall impact score for that category. For example, emissions of methane are expressed in terms of kg CO_2 eq. under global warming impact category and all other flows within that category (CO_2, N_2O and CH_4) are summed up (Hauschild and Huijbregts., 2015).

D) Normalization:

This is the optional step and consists of all processes required for calculating the indicator result values in reference to a particular value which allows to compare all the impact category values against a single value. It thus aids in result communication and evaluation inconsistent results by bringing down all the values to common scale for example person equivalents or person years. Different approaches exist to calculate the normalization factor (Hauschild and Huijbregts., 2015).

E) Weighting/Valuation:

It allows comparison between the values obtained for each impact category against each other. This step attempts to rank or weigh the impact category to arrive at the relative importance of these different results (Jensen et al., 1998). It is required to deal with trade-offs between results (Hauschild and Huijbregts., 2015).

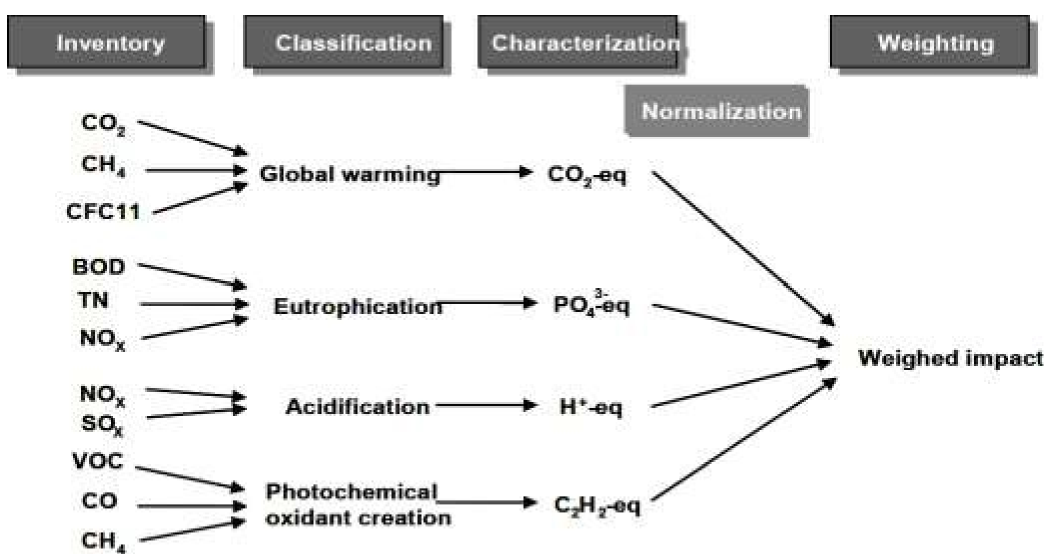


Figure 2-13. Schematic diagram depicting the elements of LCIA and their relationship (Lee and Inaba., 2004)

Based on the required impact categories, impact assessment methodologies are selected. Life cycle assessment methodologies allows to connect possible emissions and interventions quantified in inventory step to potential environmental damages on the basis of impact pathways. A detailed knowledge of impact assessment method is necessary to analyze the results accurately. Numerous assessment methodologies are available based on software and inventory databases. Selection of a particular methodology is dependent on the impact categories that needs to be included for the study and goal and scope of the study. Criteria for selection includes type of process, region of study, duration, spatial coverage reversibility, harm to human health, harm to ecosystem, probability of occurrence, exhaustion of resources and treatment alternatives (Rigon et al., 2019). They are developed based on two approaches namely midpoint (problem oriented) approach or endpoint (damage oriented) approach with high uncertainty in later one. Due to difference in cause-effect chains and extent of advancement of methods, uncertainty exists between different assessment methodologies which in practice leads to differences in LCIA results. The basis of selecting a particular methodology should be based on comparability and geographical representativeness of the data (Müller et al., 2020). A wide range of LCIA methods are available that most of commercial databases provide along with their software installation.

2.2.2.4 Life cycle interpretation

It is the final phase yet iterative in all phases of LCA and involves systematic derivation of conclusion and recommendations on identified environmental problems. According to ISO 14043, it involves 3 steps namely key issues identification, evaluation and finally conclusions and recommendations. The first step involves applying contribution analysis to determine the activities, processes, materials, components or life cycle stages that have prominent impact on overall impact of product system. If the results obtained are not matching with goal and scope of study, improvisation of inventory and assessment methods has to be carried out until completeness, sensitivity and consistency in the results are reached which marks the second step. A sensitivity and uncertainty check of results includes estimating the variations in output parameters as the input parameters are changed under different scenarios. The most widely applicable method to carry out this process is Monte Carlo simulation. Based on all these steps, third step is carried out which involves drawing conclusions and recommendations from results. Further, it involves communication of critical review of results in a way that is clear and understandable for proper decision making (Jensen et al., 1998) (Lee and Inaba., 2004).

2.3 Life cycle assessment of Coal-fired thermal powerplant

2.3.1 Background

Coal, being the highly used fossil fuel for power generation in India emits huge quantity of gases/pollutants to atmosphere that are toxic to both humans and ecosystems. Several end-of-pipe-abatement technologies are applied and being installed viz., flue gas desulfurization (FGD), selective catalytic reduction (SCR), electrostatic precipitator (ESP), carbon capture and storage (CCUS) are applied to coal fired thermal powerplants to reduce emissions of major gases like NO_x, SO_x, PM, CO_2 respectively. However, efficiency of mitigation varies quite differently from region to region and type of abatement technologies used. Therefore, life cycle assessment of such coal fired power plants is necessary in order to assess the feasibility of these mitigation technologies. It aids in developing normalization factors for various impact categories and resource utilization along with determining the influence of various powerplant parameters on final environmental impact. In such context, conducting such an assessment will allow to compare the emission trends betweena general powerplant consisting only SO_x, NO_x and PM mitigation with a CCUS equippedpowerplant (Singh et al., 2016). Though globally several literature addressing life cycle assessments of power generation is available, fewer of them were carried out for India (Singh et al., 2016), (Mallapragada et al., 2019), (Agrawal et al., 2014). Studies of LCA are either done through manual computation or using available software. Also, they have either evaluated in terms of all impact categories or considered only life cycle CO_2 emissions. Thus, upcoming sections will provide an overview of steps involved in life cycle analysis of Indian coal-fired thermal powerplants and the environmental implications obtained out of such an analysis.

2.3.2 Goal and scope definition

According to studies, the general goal of life cycle analysis is to conduct an environmental analysis over the full life cycle of coal fired thermal powerplant with and without the control technologies for NO_x, SO_x, CO_2 and PM. However, the goal may be completely defined on the basis of results to be obtained and it may differ from study to study. This phase also involves defining the assumptions, different boundaries, data collection and normalization methodology and life cycle assessment model that is being applied in the study. Further this phase involves defining function, functional units and system boundaries for the powerplant. One unit of electricity generation (1 kWh or 1 MWh) is majorly considered as the functional unit and the system boundaries involves unit processes that required for production of 1 unit of electricity. Most of the studies for life cycle approach consider unit processes as coal mining, coal transportation, coal combustion at powerplant and may include coal washing, mine commissioning and decommissioning, powerplant commissioning and decommissioning, ash handling. However, emissions from latter activities are not considered much as they tend to be relatively small when amortized over total electricity generated over lifetime of powerplant (Mallapragada et al., 2019). However, Singh et al., 2016 has considered powerplant only as the study definition area and thus it can be concluded that system boundaries differ on case-to-case basis.

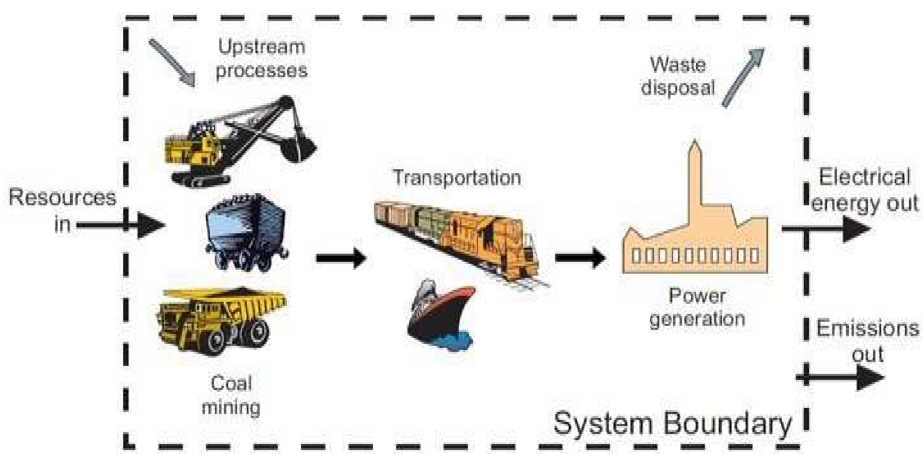


Figure 2-14. General system boundary for a coal-fired powerplant (Spath et al., 1999)

2.3.3 Life cycle inventory of powerplant

Inventory analysis involves collecting all the inputs and outputs in terms of product and elementary flows necessary for fulfilling the functional unit. It requires a complete knowledge of current scenario of powerplant operation which includes coal requirement, plant efficiency and load factor, type of plant (subcritical, supercritical, ultra-supercritical etc.), water requirement, land requirement, net power generation capacity etc. Powerplant inventories for with and without mitigation technologies can be obtained either directly from the powerplant or modelled using available software (IECM) or available databases like Eco-invent or from the published literature/organization reports, for example National thermal power corporation, India (NTPC) and Central Electricity Authority (CEA). An analytical framework established by Singh et al., 2016 for LCA of coal fired thermal powerplant. It is observed that for data that is unavailable for India, countries for which the that particular data is available is considered and normalized to Indian scenario (Singh et al., 2016). A database consisting of preliminary data like mining details, size, efficiency and capacity factor of powerplant, coal properties and requirement, gaseous emissions in terms of functional unit for different models has to be established. A brief description of the powerplant has to be provided. Coal mining related data can be obtained from the reports of Coal India Limited (CIL) and its subsidiary organizations which is responsible for >80% of Indian coal production (Mallapragada et al., 2019). Further data related to coal transportation and its mode is dependent on powerplant and mine location. Usual coal transportation options in India are by rail or road.

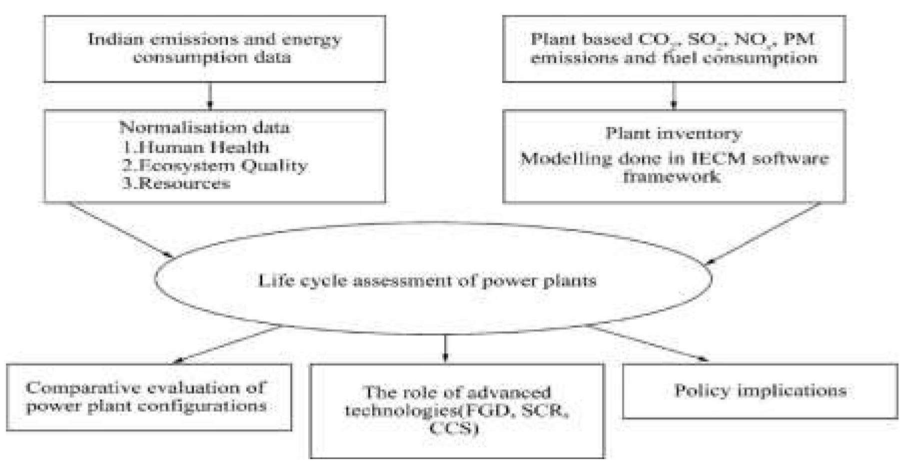


Figure 2-15. Framework for LCA of powerplants as given by (Singh et al., 2016)

Another way to collect data regarding powerplants is through modelling. Integrated Environment control model is the most widely used software for modelling powerplants developed by Carnegie Mellon University, USA. It provides a multiparameter platform for configuring coal-fired powerplant based on base plant operations, characteristics of fuel, abatement controls employed etc. It provides results in the form of plant performance, total mass of solids and gases in input and output, fuel, water & other requirements, emissions etc.

2.3.4 Life cycle impact assessment

Selection of impact assessment method greatly depends on scope of study. Many studies have majorly focused on only global warming category. Singh et al., 2016 considered Eco-indicator99 (H) as impact assessment model under 3 perspectives i.e., egalitarian, hierarchist, and individualistic and presented the result in terms of EIE (environment impact of electricity) scores which represents most dominating damage category. Another study by Agrawal et al., 2014 on LCA of imported coal powerplants, used IPCC 2001 and Eco-indicator 99 (H) in SimaPro software as assessment models for GHG emissions and human health impacts of climate change respectively for the first time in India.

2.3.4 Life cycle interpretation

Results greatly vary between the studies and can be attributed to heterogeneities in powerplant operations and assumptions made during the study. A life cycle GHG emission study on coal-fired powerplant by Mallapragada et al., 2019 reports emissions range between 0.949 – 1.368 kg of CO_2 eq./kWh with major contribution from powerplant operation (94%) compared to mining and transportation (6%). But this study completely relied on CEA database for all data.

Inferences from Agrawal et al., 2014 showed that for an imported coal powerplant, a total GHG emission of 1.129 kg CO_2 eq./kwh and human health impacts due to climate change of 2.94E-07 DALY/kWh are observed. It is also seen that emissions varied greatly with plant efficiency and negligibly with plant load factor. It also suggested that with the aid of CCS, GWP is decreases along with trade-offs in terms of other environmental impacts

Different perspective LCA by Singh et al., suggested that using of SO_2 and NOx mitigation technologies is imperative in all scenarios due to significant decrease in EIE score whereas adoption of CCS largely was unfavourable, neutral and favourable in egalitarian, hierarchist and individualistic perspectives respectively which is in line with actual situation of CCS implementation. This indicates the influence of various stakeholders like government, industry and academia on CCS and decrease in energy penalty and high costs of implementation can increase the adoption rate of CCS. However, the main drawback of this study was not considering mining and transport operations under system boundary. Due to uncertainty and variability in inputs associated, conducting sensitivity analysis of results by changing the data set values between 5th and 95th percentile of input distribution and uncertainty analysis using Monte-Carlo simulation are recommended (Mallapragada et al., 2019).

2.4 Life cycle assessment of CCU/S powerplant

2.4.1 Background

Carbon capture storage and utilization is one of the promising CO_2 emission reduction technologies and is currently being applied in a large scale globally. CCU/S are applied to fossil fuel power generation owing to the fact that they are large emitters of CO_2 and other gases to atmosphere. However, it is observed from several literature that compared to fossil fuel-based energy production systems without CCS, CCS systems require more energy for their operation, resulting in increased consumption of primary materials and fuel for energy production for CO_2 capture, compression, transportation, and storage per unit of electricity generated. To determine the various environmental advantages and drawbacks of CCS, a thorough, life cycle-based environmental assessment that can trace environmental discharges to multiple environmental compartments (air, water, and soil) across all of the stages in the CCS life cycle is necessary. Such assessments have been largely conducted in US, Europe and other countries with a notable one being LCA of CCUS on Boundary dam power station, Saskatchewan, Canada.

Generally, goal of CCUS system will majorly involve analysing environmental performance over full life cycle of CCUS. Defining the scope for CCUS equipped powerplant is similar to conventional powerplant along with addressing the CCUS system. Apart from the goal it also includes defining functional unit i.e., one unit of electricity produced, establishing system boundaries depending on the involved unit processes. Life cycle inventory involves complete collection of involving raw materials, chemicals, materials and other resources required for CCUS equipped powerplant operation and outputs in the form emissions and waste has to obtained.

2.4.2 Literature studies

Manuilova et al., 2014 has extensively conducted the LCA of post combustion CO_2 capture and CO_2-EOR at Boundary dam power station, Canada under two scenarios, one equipped with electrostatic precipitator (ESP) for particulate removal and other involving flue gas desulphurization (FGD) for SO_2 removal, CO_2 capture, transport, CO_2-Enhanced oil recovery, oil refining and refined product use along with ESP. The system boundary included the use of extracted oil from Weyburn oil field using captured CO_2, functional unit was taken as GJ of energy produced. In addition to this, a detailed information along with schematic diagram of powerplant and utilization activity has to be provided. This study, has extensively included necessary inventory data through organization and academic reports, GaBi software datasets, literatures and manual calculations require to model powerplant, CO_2 capture and transport operations, CO_2-EOR, refining and use operations. TRACI methodology was used as impact assessment models which consists of 12 midpoint categories. The main aim of the study was to account for all environmental categories except for global warming and resource depletion.

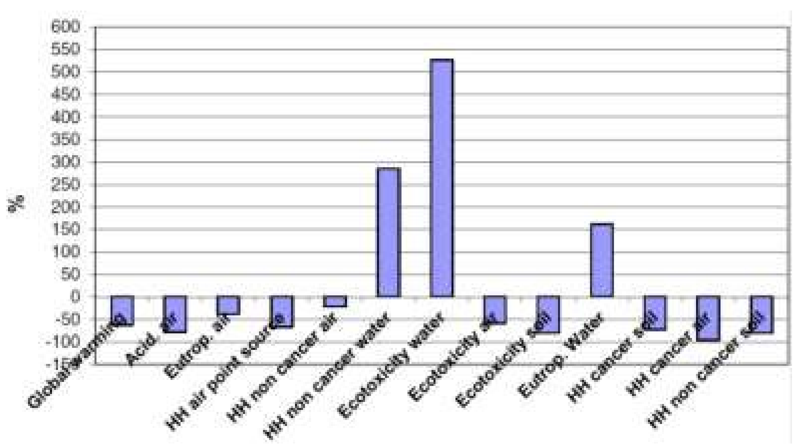


Figure 2-16. Results of LCA of Boundary Dam CCS-CO2-EOR operation (Manuilova et al., 2014)

The results are represented as change in percentage in environmental impact categories from no capture to with capture and utilization scenario. It was concluded that although global warming impact due to CCUS is reduced, there were significant increase in other categories such as water pollution, smog and NOx emissions due to use of MEA (monoethanolamine). In addition to this, electrical efficiency of powerplant decreased owing to high coal consumption. However, decrease in acidification of air and air point source impact was observed due to SO_2 and PM removal. The study also provided effective recommendations like to efficiency of all unit processes.

Sl. No	Environmental impact category	Contributing unit process		% Decrease	% Increase
		No capture	Capture		
1	Global warming – CO_2, CH_4, N_2O, HFCs, CFCs, SF_6	Electricity generating station operations		63%	
2	Acidification air and Human health air-point source	Electricity generating station operations	Product use stage	78%, 68%	
3	Cancer air, non-cancer air and eco-toxicity air - heavy metals and VOCs	Electricity generating station operations and refinery operations		95%, 22%, 59%	
4	Human health cancer and non-cancer water and ecotoxicity water	Coal mining and refinery operations		-	1320%, 286%, 527%
5	Human health cancer and non-cancer ground surface soil and ecotoxicity ground surface soil	Electricity generating station operations		73%, 80%, 80%	
6	Eutrophication – NO, N_2O, NO_2, NH_3	electrical generating station operations and refined products use life cycle stages (NOx)		38%	
7	Ozone depletion – halogenated organics	coal mining and refinery operations		21%	
8	Smog air – CO (~95%) and organic (4.7%) emissions to air	refined products Use and refinery operations		-	9076%

Table 2-8. Results of LCA of Boundary dam CCUS project (Manuilova et al., 2014)

Cuéllar-Franca et al., 2015 in their study have reviewed environmental impacts of several CCU and CCS equipped powerplants (pulverized coal, combined cycle gas turbine and Integrated coal gasification combined cycle) in a life cycle perspective. The system boundaries considered were consistent in all studies which consisted extraction and transportation of fossil fuels, power plant operation, CO_2 capture, compression, transport, injection and storage. The functional unit in all studies considered were 1 kWh/MWh/TWh of electricity produced. All the LCA studies reported GWP along with other impacts that varied widely from one study to other depending on goal, scope and impact assessment methodology. The average GWP of Pulverized coal (PC) powerplant without CCS is 876 kg CO_2 eq./MWh whereas it decreased to 203 kg CO_2 eq./MWh and 154 kg CO_2 eq./MWh in CCS with post combustion MEA capture and oxyfuel combustion CCS systems. It has reported that CCS has potential to reduce the GWP from powerplants by 63-82% in oxyfuel combustion mode. It can also be observed that GWP significantly decreased with CCS in IGCC systems compared to PC systems. Moreover, main contributor to GWP are fuel supply (53%) and CO_2 emissions from powerplants (28%) However, GWP reduction for CCU varies depending on utilization option. Apart from GWP, studies reported increase in other environmental impacts such as abiotic depletion potential (ADP) by 2–53%, ozone depletion potential (ODP) by 17–35%, eutrophication potential (EP) 1–173%, freshwater aquatic ecotoxicity potential (FAETP) by 9–135% in CCS scenario. Increase in ADP and ODP can be attributed to extra coal required to compensate the loss in electricity production efficiency. Also, increase in EP is attributed to high utilization of ammonia in the form of MEA for capturing process and increase in FAETP is due to trace metal discharge to water. For plants with CCS, reports showed both larger (9-150%) and lower (28-270%) photochemical oxidant production potentials (POCP) which is attributed to volatile MEA emissions to the atmosphere whereas this can also be mitigate by removing NOx and SO_2 emissions. Among different capture technologies assessed, post combustion capture via MEA contribute to lesser GWP of 70-80 kg CO_2 eq./MWh compared to cryogenic separation, membrane separation and pressure swing adsorption. This paper also provided a detailed comparison of different CCU technologies and their impacts to environment.

Another extensive review on CCS is conducted by Zakuciová et al., 2016 which presented a comprehensive overview on all environmental impacts of different combustion technologies. The study reported a GWP reduction by 74%, 78% and 76% in post, pre and oxyfuel coal combustion technologies respectively with CCS compared to a non-CCS system. It also suggested that use of MEA for capturing process results in increase in certain categories due to high energy penalty and production of chemical solvents. A comparative analysis of different combustion technologies suggests higher GWP reductions in PC powerplant with oxy-fuel combustion and in plants with IGCC-MEA results increase acidification and eutrophication potential and can also react with SO_2 and NO_2 to form heat stable salts thus leading to solvent losses by reducing CO_2 absorption capacity of solvent. This paper also presents factors affecting environmental impacts and uncertainties of CCS which includes the following:

• Type of coal combusted especially lignite having lowest efficiencies and highest CO_2 emission factors

• Lower plant efficiency and high capture rates results in more CO_2 to be captured thus influencing CO_2 transport and storage

• The injection depth and storage site impact the energy demand where depleted gas field of 2500m deep require higher energy compared to saline aquifer of 800m deep

• Infrastructure development of facilities influences various toxicity potential categories

Korre et al., 2010 studied LCA of 500MW with post combustion CO_2 capture technology and 1 MW of electricity generated as functional unit. A comparative LCA was modelled for with and without CCS systems and employed CML 2001 as the impact assessment methodology. It broadly described the methodological framework for developing life cycle models for CO_2 capture in power generation systems. The LCI results for combustion process are calculated manually through mass balance equation and emission factors are attained from USEPA AP-42. Like Zakuciová et al., 2016, this paper also suggested GWP is highly influenced by type of coal with lignite coal having higher GWP of 998 kg CO_2 eq./MW and lowest being bituminous with cyclone boiler type (845 kg CO_2 eq./MW). Different boiler configurations for without CCS systems were also analysed for their contribution to impacts. For CCS systems, different solvents for chemical absorption were analysed. According to LCIA results, life cycle GWP impact was significantly reduced to 179 kg CO_2 eq./MW in MEA capture along with reduced human toxicity and photo-oxidation formation impacts. Abiotic resource depletion and ecotoxicity impacts increased in all capture scenarios which can be related to energy consumption. This paper strongly implies that 80% reduction in GHG emissions can be achieved through post combustion CO_2 capture systems without significant increase in other life cycle environmental burdens compared to systems without CO_2 capture. Moreover, human toxicity impacts are shifted to ecotoxicity impacts as CO_2 capture results in reduced fly ash content further disposal of it to water or soil.

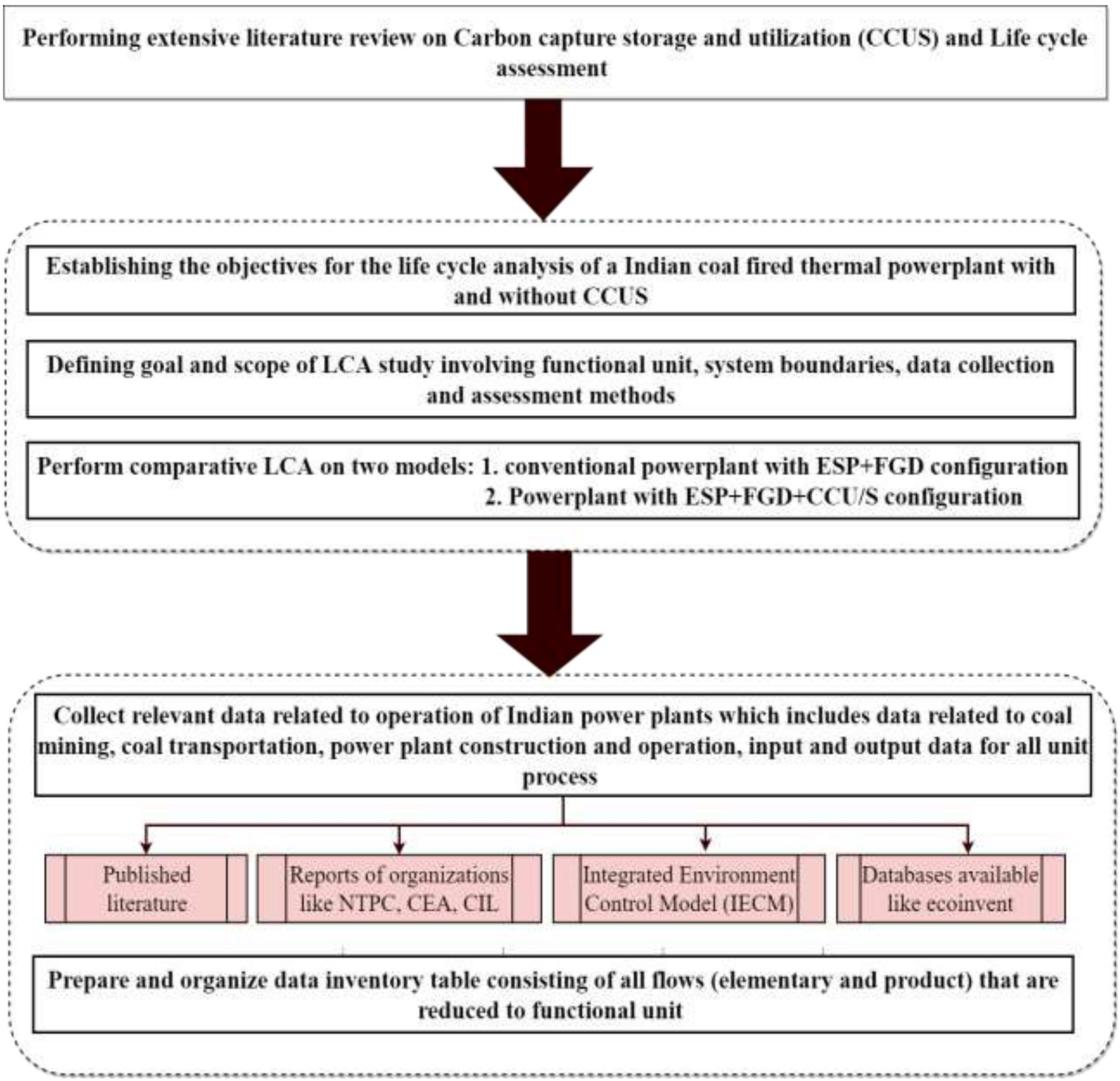
2.5 Literature gap

The following literature gap exists in the available studies and can be focused in our study:

- Lack of Indian specific LCA studies on CCUS equipped thermal powerplants. Data regarding only modelled techno-economic assessment is available.
- Broader impact categories including fossil fuel depletion, air, water and other pollutions etc. other than global warming are not considered
- Most of the studies have reported only life cycle CO_2 emissions rather than total GHG emissions

Chapter 3
Methodology

3.1 Proposed Methodology



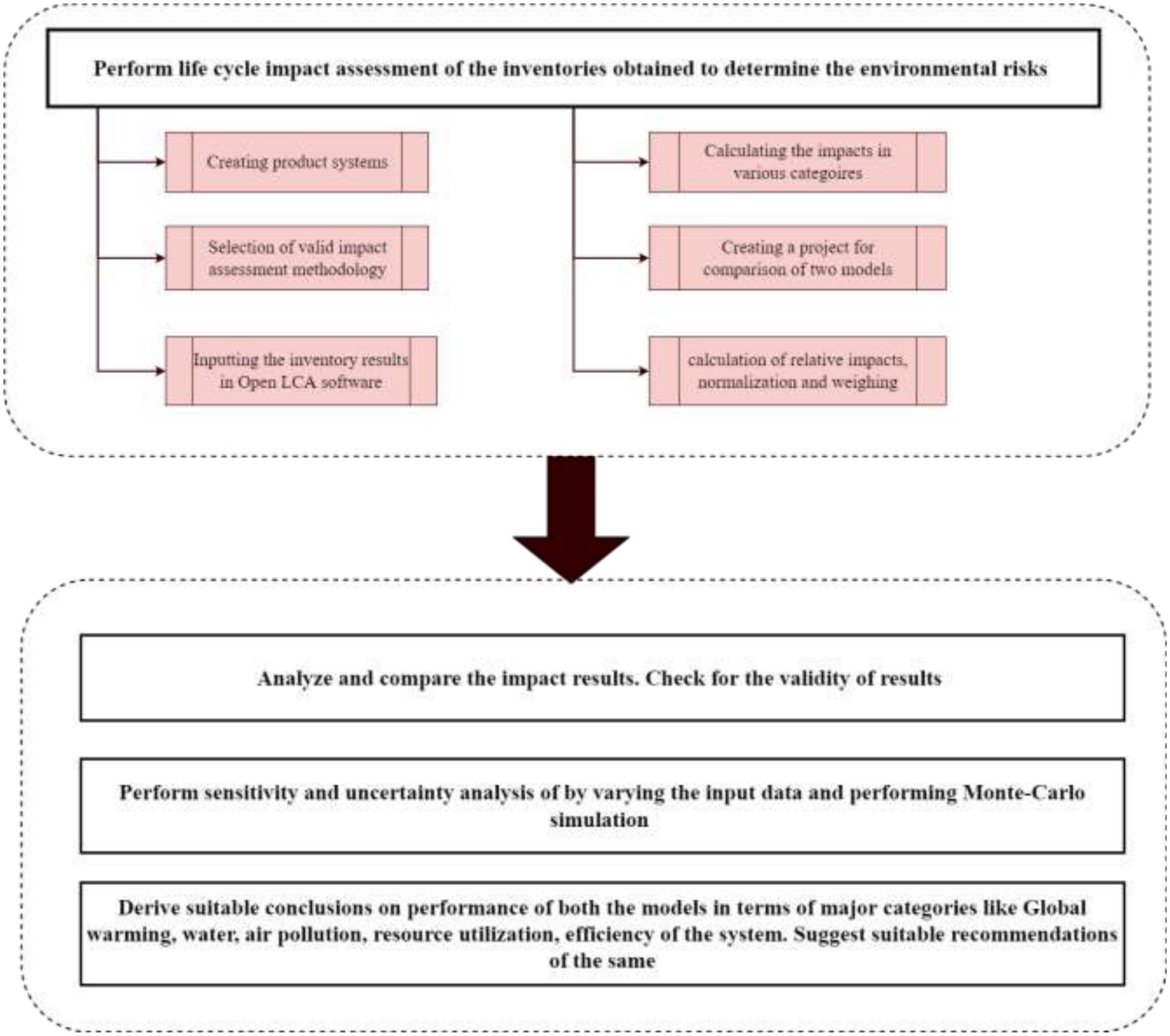


Figure 3-1. Flowchart representing the steps involved in proposed methodology

The above flowchart represents the proposed methodology for conducting LCA of Carbon, capture storage and utilization. Initial step is to perform an exhaustive literature review on all aspects including coal fired powerplants in India, CCU/S technology, need of its deployment in India, its principles and technologies involved, Life cycle assessment and its methodological framework, application of life cycle assessment to coal fired powerplants and CCU/S. The scope of LCA is divided into two scenarios, 1. LCA of conventional coal fired powerplant equipped with all abatement technologies (FGD+ESP) except CCU/S and 2. LCA of coal fired powerplant equipped with FGD+ESP+CCU/S. It also involves to select suitable impact assessment methodology for calculation of life cycle environmental impacts among the available methodologies. The project initially involves collecting necessary inventory of Indian coal fired powerplant currently in operation for conducting life cycle analysis. It must consist all relevant elementary and product flows within the considered system boundary. It is done in three ways viz., literature or reports, IECM modelling and using already existing unit processes in commercially available (Eco-invent) database. The plant inventory is then inputted to OpenLCA and suitable impact assessment methodology is selected in order determine impacts. The obtained results are then used to comparison. The second scenario involves collecting inventory for modelling powerplant equipped with FGD+ESP+CCU/S. A similar approach used earlier for conventional powerplant is used for this scenario and the inventory is obtained on the basis of system boundary which can be then inputted to OpenLCA software. Subsequently impacts are calculated by applying the same assessment methodology. The results obtained in both scenario 1 and 2 is compared against each other and analysed. All the impact categories have to be compared and significant change from scenario 1 to 2 has to calculated. The change in impact either increased or reduced allows to make informed decision on the potential environmental consequences other than global warming. The feasibility of CCU/S on Indian powerplants can thus be concluded based on analysis of the obtained information.

3.2 LCA of Talcher-Kaniha coal-fired powerplant

Indian electricity production is dominated by coal fired thermal power plants. Coal is used as the primary fuel which results in emissions of various pollutants in atmosphere. It is very important to control the emissions of these gases in order to have meet the electricity demands of the country. This work analyses the life cycle environmental implications of Indian power plant and thus allows to compare the consequences with a CCUS equipped powerplant.

3.2.1 Description of powerplant

Talcher Kaniha powerplant is considered for the study which is situated in Angul district, Orissa and commissioned between 1995 – 2005. It is sponsored and operated by NTPC and is also found to be the most suitable plant for CCS installation by Singh et al., 2017 which focused on gauging the prospects of CCS deployment on seven Indian powerplants. It consists of 6 units each of 500 MW capacity supplying power to Indian states of Orissa, Andhra Pradesh, Telangana, Karnataka, Bihar, Pondicherry and West Bengal. Unit 4 of 500 MW capacity is considered for life cycle analysis. The detailed parameters of the powerplant without CCS used for performing the analysis are listed below in the table3-1

Table 3-1. Talcher Kaniha super thermal powerplant details

<table>
<tr><th>Powerplant name</th><th>Talcher Kaniha Thermal Power Station</th><th>Reference</th></tr>
<tr><td>Sponsored by</td><td>NTPC</td><td rowspan="5">Singh et al., 2017</td></tr>
<tr><td>Unit</td><td>IV (Stage – II)</td></tr>
<tr><td>Gross capacity</td><td>545.9 MWg</td></tr>
<tr><td>Net power capacity</td><td>500 MW</td></tr>
<tr><td>Boiler efficiency</td><td>85.59%</td></tr>
<tr><td>Coal source</td><td>Eastern coal fields and Mahanadi coal fields (Talcher coal field Lingaraj block)</td><td rowspan="2">URL-13</td></tr>
<tr><td>Transport of fuel from source</td><td>Indian railways/MGR (Merry-go-round)</td></tr>
</table>

3.2.2 Goal and scope of the study

The goal is to study the environmental performance (emissions and wastes, energy and material use) over the full life cycle of a coal fired thermal power plant in India. The data were collected in 3 ways i.e., 1. Integrated environment control model which helps to configure a power plant based on its base operating parameters 2. Standard literature and NTPC reports 3. Eco-invent database. Thus, both modelled data and background data is used for the study. The following table provides details that are included under scope of the study:

Table 3-2. Components of goal and scope definition for LCA of Talcher Kaniha powerplant

Life cycle approach	Cradle to gate (Electricity production at powerplant i.e., end use of electricity is not considered)
System boundary	It consists of processes which includes coal mining, coal transportation and combustion involving particulate and SOx removal technologies
Function	Electricity production
Functional unit	1 kWh of electricity produced. All the inputs are normalized to functional unit
Assumptions	No coal is imported Pit head powerplant
Life cycle impact assessment methodology	Three methodologies are used to compare the results: 1. CML-IA Baseline 2. Impact 2002+ 3. Recipe midpoint 2016 (H)
Transport distance	Road transport distance is considered

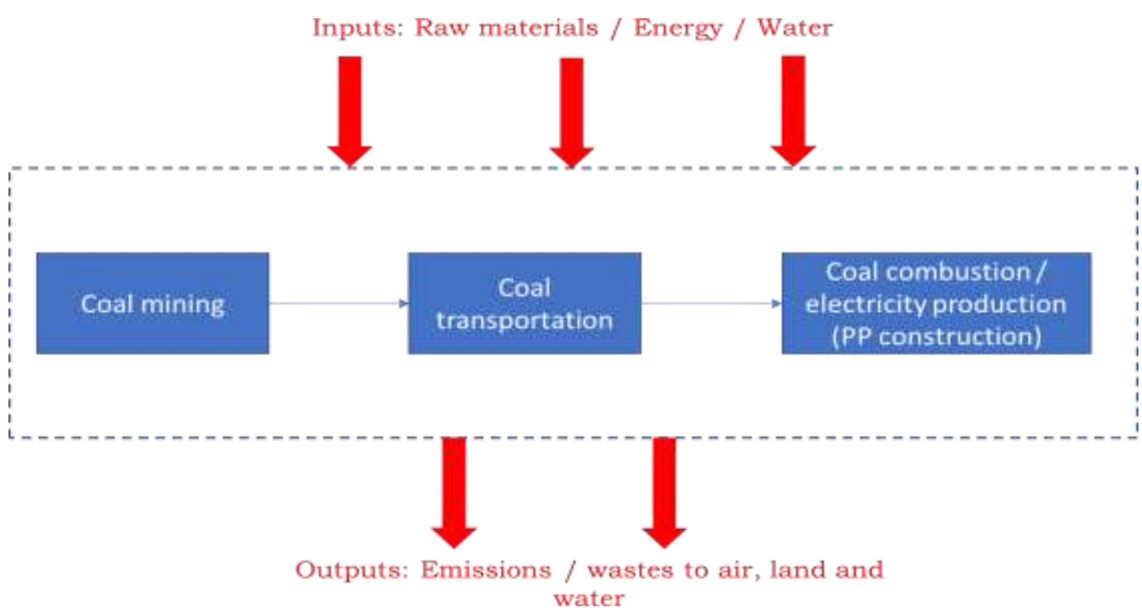


Figure 3-2. System boundary considered for study

3.2.3 Life cycle inventory

As discussed in the scope, data was collected and compared against each other for accuracy. Following provides information on how the data was collected from different methods.

1) **OpenLCA software:** This software consists commercially and freely available databases. For our study, Eco-invent database which is paid database was used. However, a free version is available for non-OECD countries. This free version was accessed, downloaded and restored into OpenLCA software. This database already consisted established processes which included all unit processes considered under system boundary of the study. The processes available in Eco-invent database is presented in table below:

Table 3-3. Data available in Eco-invent database

Process Name	Geography	OpenLCA provider name	Description
Electricity production	India - Orissa	electricity production, hard coal | electricity, high voltage | APOS, U	It represents 1 kWh of high voltage electricity production in an average hard coal power plant in India – Orissa. It includes coal mining, hard coal power plant construction, water requirement, use of fuel oil for start-up, particle removal, desulfurization and denitrification, cooling and loss of feed water. It doesn't include transformation of electricity produced and non-recycled ashes disposal Specific coal consumption: 0.73 kg/kWh
Transportation through freight railways	India	transport, freight train, diesel | transport, freight train | APOS, U	It represents transport of 1 metric ton.km of freight in India and includes entire transport life cycle including production and maintenance of locomotive, goods and wagons, transportation of goods and

			construction, operation, maintenance and disposal of railway track, diesel consumption Amount: 0.73 kg of coal * 27.9 km of distance

2) **IECM Modelling and Literature:** For IECM modelling, NTPC data for Talcher Kaniha powerplant was used. It requires to input certain data such as coal calorific value, coal composition, required configuration, result specifications, plant location, efficiency of control technologies utilized. Under 'GET RESULTS' tab in IECM the results of modelling can be obtained which is presented in table 3-5. A modelled study from the literature (table 3-4) is also considered to compare the data obtained from modelling.

Table 3-4. Powerplant details from literature and NTPC report

Parameter	(Singh et al., 2017)	NTPC report
Plant load factor (%)	81.6	86.88
Gross calorific value of coal (kcal/kg)	3910	3058
Specific coal consumption (kg/kWh)	0.64	0.8
Net plant efficiency (%)	34.34	-
Type of cooling system	-	Closed cycle
Water consumption ($m^{3)}$	-	$7.47*10^7$

Table 3-5. Results of IECM modelling

GENERAL DETAILS		
Plant Configuration		ESP+FGD
Cooling system		Wet cooling tower
Unit specified		Annual avg
Gross electrical output	MWg	552.10

Net plant electrical output	MW	500.00
Plant load factor	%	86.80
Primary fuel Input	MBtu/yr	36150000.00
Total Plant Input	MBtu/yr	36150000.00
Gross plant heat rate	Btu/kWh	8598.00
Net plant heat rate	Btu/KWh	9494.00
	KJ/KWh	10016.88
	kcal/KWh	2394.03
Annual operating hours	hr	7616.00
Annual power generation	BkWh/yr	3.81
Net plant efficiency	HHV, %	35.94
Base plant electricity use	MW	
	Base plant use	30.59
	Wet FGD	11.71
	Cold-side ESP	2.91
FUELS AND CHEMICALS - INPUT		
Coal	t/yr	3286000.00
Specific coal consumption	kg/kWh	0.86
Lime / Limestone	t/yr	24980.00
OUTPUTS		
Bottom ash disposed	t/yr	394800.00
Particulate emissions to air	tons/yr	542.30
Fly ash disposed	t/yr	920000.00
Wastewater discharge	t/yr	3027000.00
Water evaporated	t/yr	7921000.00

3.2.4 Life cycle impact assessment

This study was carried out using OpenLCA software. ReCiPe midpoint (H) 2016, CML IA baseline and IMPACT 2002+ are used as the impact assessment methodologies. Under ReCiPe midpoint, three perspectives viz., Egalitarian, Hierarchist and Individualistic are available. Hierarchist approach is selected as it based on long-term perspective of impacts as well as assumption of avoiding damages through good management. A comparative assessment of these studies is conducted in order to determine the single assessment methodology applicable for our study. The following table consists of differences between each of the methodology:

Table 3-6. Comparison between impact assessment methodologies (URL-11)

CML-IA BASELINE	IMPACT 2002+	RECIPE 2016
It restricts quantitative modelling to early stages in the cause-effect chain to limit uncertainties. Results are grouped in midpoint categories according to common mechanisms (e.g. climate change) or commonly accepted groupings (e.g. ecotoxicity).	It suggests a feasible implementation of a combined midpoint/damage approach. Also involves comparative assessment of human toxicity and eco-toxicity	Provides harmonized implementation of cause-effect pathways for calculation of both midpoint and endpoint categories. can be seen as a fusion of the two methodologies, taking the midpoint indicators from CML and the endpoint indicators from Eco-indicator.
Follows mid-point or problem-oriented approach	Follows both midpoint and endpoint / damage approach	Some characterization factors represent global scale
Most widely used with main environment impact of global warming followed by acidification	Considered long term effects for around 500 years' time horizon	Involves 3 approaches – Hierarchist, individualist and egalitarian where
Consists of 11 impact categories	Consists of 14 midpoint categories linked to 4 end point categories	Consists of 18 midpoint categories linked to 3 endpoint categories
Does not consider depletion of water as a resource	Does not consider marine ecotoxicity	Provides a broad analysis of the problem

Chapter 4
Results and discussions

4.1 Preliminary results

Table 4-1. LCIA results per kWh for non-CCUS Talcher Kaniha powerplant

CML-IA Baseline			IMPACT 2002+			ReCiPe Midpoint 2016 (H)		
Impact category	**Reference unit**	**Values**	**Impact category**	**Reference unit**	**Values**	**Impact category**	**Reference unit**	**Values**
Abiotic depletion	kg Sb eq.	3.67E-07	Aquatic acidification	kg SO_2 eq.	6.85E-03	Fine particulate matter formation	kg PM2.5 eq.	4.10E-03
Abiotic depletion (fossil fuels)	MJ	1.84E+01	Aquatic ecotoxicity	kg TEG water	1.35E+02	Fossil resource scarcity	kg oil eq.	4.23E-01
Acidification	kg SO_2 eq.	6.46E-03	Aquatic eutrophication	kg PO_4 P-lim.	2.88E-04	Freshwater ecotoxicity	kg 1,4-DCB	2.51E-02
Eutrophication	kg PO_4--- eq.	2.91E-03	Carcinogens	kg C_2H_3Cl eq.	4.28E-03	Freshwater eutrophication	kg P eq.	7.71E-04
Fresh water aquatic ecotox.	kg 1,4-DB eq.	5.75E-01	Global warming	kg CO_2 eq.	1.54	Global warming	kg CO_2 eq.	1.57

Global warming (GWP100a)	kg CO2 eq.	1.56	Ionizing radiation	Bq. C-14 eq.	4.30E-01	Human carcinogenic toxicity	kg 1,4-DCB	6.80E-02
Human toxicity	kg 1,4-DB eq.	6.03E-01	Land occupation	m2org.arable	4.48E-03	Human non-carcinogenic toxicity	kg 1,4-DCB	1.39
Marine aquatic ecotoxicity	kg 1,4-DB eq.	2.88E+03	Mineral extraction	MJ surplus	1.75E-03	Ionizing radiation	kBq Co-60 eq.	2.54E-03
Ozone layer depletion (ODP)	kg CFC-11 eq.	7.53E-09	Non-carcinogens	kg C_2H_3Cl eq.	3.27E-02	Land use	m_2a crop eq	8.52E-03
Photochemical oxidation	kg C_2H_4 eq.	2.38E-04	Non-renewable energy	MJ primary	1.94E+01	Marine ecotoxicity	kg 1,4-DCB	3.50E-02
Terrestrial ecotoxicity	kg 1,4-DB eq.	1.49E-03	Ozone layer depletion	kg CFC-11 eq.	7.53E-09	Marine eutrophication	kg N eq.	4.72E-05
			Respiratory inorganics	kg $PM_{2.5}$ eq.	3.35E-03	Mineral resource scarcity	kg Cu eq.	2.92E-04
			Respiratory organics	kg C_2H_4 eq.	1.71E-04	Ozone formation, Human health	kg NOx eq.	3.62E-03
			Terrestrial acid/nutria.	kg SO_2 eq.	2.47E-02	Ozone formation, Terrestrial ecosystems	kg NOx eq.	3.64E-03

Terrestrial ecotoxicity	kg TEG soil	3.13E+01	Stratospheric ozone depletion	kg CFC11 eq.	2.98E-07
			Terrestrial acidification	kg SO_2 eq.	5.24E-03
			Terrestrial ecotoxicity	kg 1,4-DCB	9.91E-01
			Water consumption	m^3	2.74E-03

The above table includes the comparison of LCA results for Talcher Kaniha coal fired powerplant obtained from life cycle impact assessment step in OpenLCA software. It consists of different impact categories under different impact assessment methodologies i.e., CML-IA baseline, IMPACT 2002+ and ReCiPe 2016 midpoint (H). All the impacts are represented per 1kWh of electricity produced. The results are further discussed under the life cycle analysis discussion section.

4.2 Discussion

4.2.1 IECM modelling

As per the data requirement for conducting LCA, specific coal consumption is required. As calculated from the model, specific coal consumption is 0.86 kg/kWh. However, in the IECM modelling study carried out by Singh et al., 2017 on Talcher Kaniha powerplant specific coal consumption reported to be 0.64 kg/kWh and as per NTPC report the value is 0.8 kg/kWh for the year 2016-17. The difference between modelled value obtained in literature and current modelled value can be attributed to time-frame of calculation and assumptions considered in their study. On the other hand, there is no much difference in the value as per NTPC report and value obtained in our study. However, in the Eco-invent database, the already established unit process i.e., Electricity production in Orissa, India considers coal consumption to be 0.73 kg/kWh. This difference also represents the year the data was collected. As per OpenLCA software, the production year is reported to be 2012-13. However, this is only the initial study OpenLCA value used for further calculations. Thus, results obtained by IECM modelling and Eco-invent database are subject to further review. This ambiguity in data can be solved by collecting foreground data i.e., collect all powerplant related data directly from concerned organization. Background data can also affect the time-frame and representativeness of actual system.

4.2.2 Life cycle analysis

A brief analysis of the results was carried out on the basis of different assessment methodologies. Focusing on GWP, it has been observed that the values of GWP slightly varied among the different assessment methodologies. As evident from literature, this variation can be attributed to complexity of cause-effect chains and advancement in the framework of methodologies. The values obtained for impact categories are presented in the table 14. A GWP potential of 1.559, 1.536 and 1.5703 kg CO_2 eq./kWh was obtained for CML-IA baseline, IMPACT 2002+ and ReCiPe Midpoint 2016 (H) respectively. The values that have been obtained from the literature are slightly less compared to the current obtained value. This can be due to inclusion (powerplant commissioning) or exclusion (coal washing) of different unit processes under the system boundary. A systematic review of life cycle analysis of thermal power generation system in India by Malode et al., 2022 reports life cycle GHG emissions in the range of 0.898 to 1.1.29 kg CO_2 eq./kWh It also reports that powerplant efficiency, capacity factor, heating value of coal and distance of powerplant from coal mine highly effects the results and are cause of differences between the studies. Some studies based on literature review have not considered powerplant construction whereas some have not considered the transportation. However, a study by Whitaker et al., 2012 on systematic review of LCA of utility scale coal-fired electricity generation system showed that GWP can range between 0.675 to 1.68 kg CO_2 eq./kWh for subcritical PC, IGCC, fluidized and supercritical PC combustion systems. This value represents the global scale and not India specific.

In case of other environmental impacts, it is observed that some of the impacts are common in all the 3 methodologies but the reference units are different for example., eutrophication is considered in all methodologies however the reference unit is kg PO_4 eq., kg PO_4-P eq., kg P eq. in CML-IA baseline, IMPACT 2002+ and ReCiPe midpoint 2016 (H) respectively. This variation can also change the values of a particular impact category. Since the reference units are different, it requires further LCA steps of normalization and weighting to be carried out in order to compare between the impact categories within and among the methodologies.

Selection of suitable impact categories for the study is very important as it reflects the overall collection of ecological impacts of considered product or process. For selection of suitable assessment methodology, based on earlier comparative analysis between 3 methods, ReCiPe Midpoint 2016 (H) with 18 midpoint impact categories is considered to be more suitable since this study is mainly focusing on all impacts other than global warming. It also calculates water footprint or water consumption per functional unit considered since water is as important resource as other environment resources. It provides broad analysis of the problem as it consists of both midpoint and endpoint approach. Further refinement of data is required to obtain accurate results. Within this methodology, the extent of contribution of different processes to global warming potential was studied where by it is observed that carbon dioxide emissions are majorly (92%) released from powerplant activities whereas coal mine operations contribute to only 8% of total GWP. However, it is to be observed that coal mining operations also contribute to methane emissions. The results of the contribution of unit process to GWP are tabulated and graphically represented below.

Table 4-2. Contribution of different unit operations to GWP (kg CO2 eq.)

GWP, kg CO2 eq.	Carbon dioxide, fossil	Methane
Electricity production	1.35	0
Hard coal mine operation	0.0909	0.03522

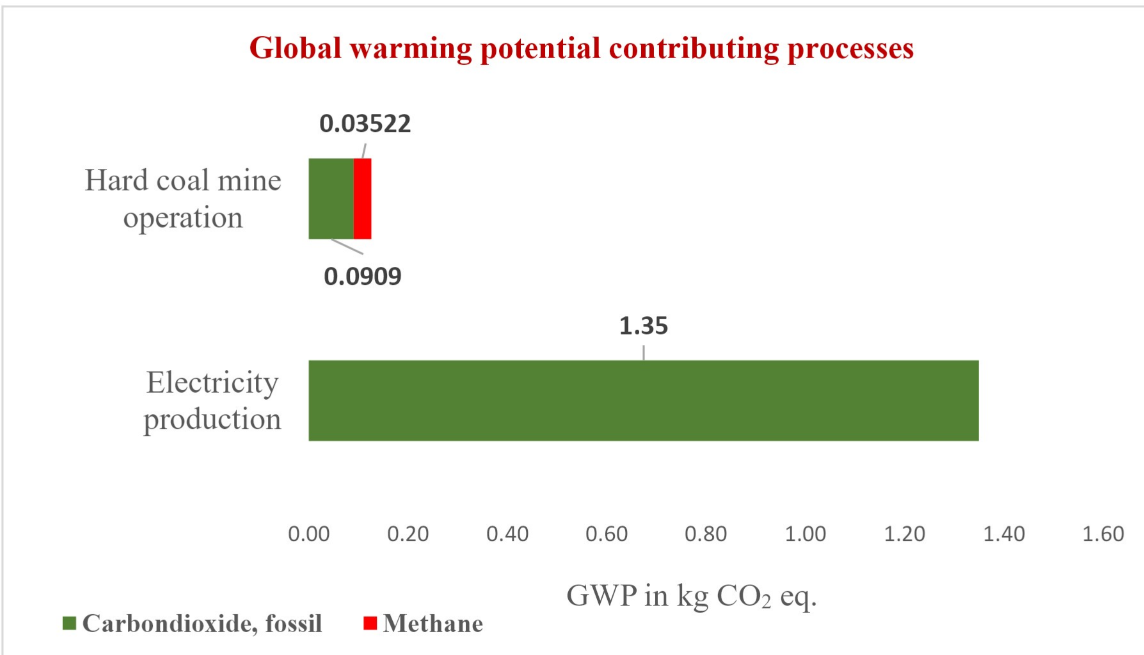


Figure 4-1. Graphical representation of contribution of different unit processes to GWP

Further, the following table provides detailed information of highly contributing processes to different impact categories, pollutants or factors involved in each category and the damage category to which each of the impact category belong to for ReCiPe midpoint 2016 (H).

Table 4-3. Process and pollutant contributions to different impact categories under ReCiPe midpoint 2016 (H) methodology

Impact category	Reference unit	Result	Emission or impact category	Contributing factors or pollutants	Highest contributing processes	Damage category
Fine particulate matter formation	kg PM2.5 eq.	4.10E-03	Emissions to air	$PM_{2.5}$, SO_2, NOx, NH_3	1) Electricity production 2) Hard coal mine operation	Damage to human health
Fossil resource scarcity	kg oil eq.	4.23E-01	Resource in ground	Coal	1) coal mining operation 2) coal washing and preparation	Damage to resource availability
Freshwater ecotoxicity	kg 1,4-DCB	2.51E-02	Emissions to ground and surface water	Zinc, Nickel, Copper, Vanadium, Chromium	1) Treatment of coal slurry 2) Treatment of coal spoil from mining operation 3) treatment of hard coal ash	Damage to ecosystems
Freshwater eutrophication	kg P eq.	7.71E-04	Emissions to ground and surface water	Phosphate	1) treatment of coal spoil from mining operation 2) treatment of hard coal ash	Damage to ecosystems
Global warming	kg CO2 eq.	1.57E+00	Emission to air	CO_2, CH_4	1) Electricity production 2) Hard coal mine operation	1) Damage to ecosystem 2) Damage to human health
Human carcinogenic toxicity	kg 1,4-DCB	6.80E-02	Emissions to water	Chromium VI, Nickel, Arsenic	1) Treatment of coal slurry 2) Treatment of coal spoil from mining operation 3) treatment of hard coal ash	Damage to human health

Human non-carcinogenic toxicity	kg 1,4-DCB	1.39E+00	Emissions to water	Zinc, Arsenic, Vanadium, Mercury, Lead	1) treatment of coal spoil from mining operation 2) treatment of hard coal ash 3) hard coal import 4) electricity production 5) treatment of coal slurry	Damage to human health
Ionizing radiation	kBq. Co-60 eq.	2.54E-03		Radon-22, Actinides, Polonium-210, Lead-210, Carbon-14	1) treatment of tailings 2) electricity production 3) treatment of low-level radioactive waste	Damage to human health
Land use	m2a crop eq.	8.52E-03	Resource / Land		1) Land for mine construction 2) road construction 3) industrial area construction 4) railway track	Damage to ecosystems
Marine ecotoxicity	kg 1,4-DCB	3.50E-02	Emissions to water	Zinc, Nickel, Copper, Chromium, Arsenic	1) Treatment of coal slurry 2) Treatment of coal spoil from mining operation 3) treatment of hard coal ash	Damage to ecosystems
Marine eutrophication	kg N eq.	4.72E-05	Emissions to ground and surface water	Nitrate	Treatment of spoil from coal mining operation	Damage to ecosystems
Mineral resource scarcity	kg Cu eq..	2.92E-04	Resource in ground	Iron, Nickel, Aluminium, Gallium, Copper, Molybdenum, Silver, Selenium		Damage to resource availability
Ozone formation, Human health	kg NOx eq.	3.62E-03	Emissions to air	NOx, NMVOCs	1) Electricity production 2) Blasting operation during demolition	Damage to human health
Ozone formation, Terrestrial ecosystems	kg NOx eq.	3.64E-03	Emissions to air	NOx, NMVOCs	1) Electricity production 2) Blasting operation during demolition	Damage to ecosystems

Stratospheric ozone depletion	kg CFC11 eq.	2.98E-07	Emissions to air	N_2O	1) Electricity production 2) Nitric acid production	Damage to human health
Terrestrial acidification	kg SO2 eq.	5.24E-03	Emissions to air	SO_2, NOx, NH_3	1) Electricity production 2) Hard coal mine operation 3) Blasting operation during demolition	Damage to ecosystems
Terrestrial ecotoxicity	kg 1,4-DCB	9.91E-01	Emissions to air	Copper, Zinc, Mercury, Nickel, Lead, Vanadium, Selenium	1) Electricity production 2) treatment of brake wear emissions 3) copper smelting	Damage to ecosystems
Water consumption	m^3	2.74E-03	Resource / Water		1) Water collection and treatment 2) Mine operation 3) wastewater treatment 4) water for electricity production	1) Damage to ecosystem 2) Damage to human health

Chapter 5 Conclusion

Climate change and its mitigation is evident and hence adoption of appropriate technology for achieving it in upcoming years is very essential. Among several clean technologies, carbon, capture, storage and utilization has tremendous potential to control the GHG emissions especially in the power generation sector. From the literature survey, although fewer projects around the world have implemented this technology, many studies and projects are interested towards adopting this emerging technology. Global policies and regulations towards abatement of climate change include CCUS as most feasible technology. In light of this, India's power generation sector is extremely recommended to install this technology due to its highest contribution to GHG emissions among all other sectors. However, this technology encounters several barriers/issues in terms of cost, risk and other sustainability notably the environmental impacts that restricts its wide scale implementation. It is resource, energy and cost intensive as well as can cause other environmental implications. Therefore, from the literature review it is evident that, a systemic technological, economic and environmental investigation of CCUS is necessary for its feasible application in India. This is to ensure that climate change is not mitigated under the expense of other detrimental factors or challenges. Detailed research in the field of environmental assessment is required to optimize CCU/S operation and thus can be dealt using life cycle assessment approach. LCA is a powerful tool and consists of 4 major steps established by ISO 14040, each of which has to be followed while dealing with the framework. Life cycle inventory stage is very crucial and quality of data obtained plays a major role as it effects the end results. Data must be representative, consistent and reproducible with the goal and scope of study. Along with this, suitable impact assessment method has to be selected. LCA helps to track various environmental outflows other than GHG emissions including solid wastes, toxic substances, air pollutants as well as resource (water, land and minerals) use. Validity of the results obtained can be determined by comparing with results obtained on LCA of a conventional coal-fired powerplant without CCU/S. This comparison will help us to determine the percentage GHG reduction from non-CCU/S to CCU/S scenario along with evaluation of all other environmental impacts. The current study thus involves applying LCA approaches separately to a non-CCUS and CCUS powerplant using specific assessment methodology.

From the LCA study conducted on Talcher Kaniha coal-fired thermal powerplant in India, the GWP per unit of electricity is obtained. Among three assessment methodologies, ReCiPe 2016 midpoint (H) is considered for our study so as to focus on all impacts other than global warming. Under this methodology, the global warming potential was observed to be 1.5703 kg CO_2 eq./kWh. in which powerplant operation contributed to 92% of global warming while the rest of emissions are from mining process which included methane emissions also. Different environmental impacts, their highest contributing process and pollutants or factors involved under each category obtained from impact assessment are also analysed.

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