Climate Change: Emission Reduction with Carbon Capture and Sequestration and a Clean Development Mechanism

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Abstract

Climate change is a complex and protracted challenge that could have significant impacts on human society, the climate system and the world economy. Climate change is attributed to significant emissions of greenhouse gases, which are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs) and sulphur hexafluoride (SF_6). The two biggest anthropogenic contributors of CO_2 to the atmosphere are the United States of America and China.

From 1970 to 2019, China and the United States of America together produced 38% of the world's total CO_2 emissions from the combustion of fossil fuels. Continuation of these significant emissions by the two countries alone could lead to the breach of climate change targets that have been set in the Paris Agreement and Glasgow Climate Pact. The aim is to limit global warming to 1.5^0C, 1.7^0C and 2^0C respectively (with respect to the temperatures before the preindustrial era).

To meet the Paris and Glasgow climate targets the carbon budget set by the Intergovernmental Panel on Climate Change is equal to 500 $GtCO_2$, 850 $GtCO_2$, and 1,350 $GtCO_2$ respectively. As of January 2020, the world CO_2 emissions from consumption of fossil fuels were 33.63 $GtCO_2$, this is the business-as-usual scenario. Therefore, the annual estimated CO_2 emission reduction targets for the world are 27.38 $GtCO_2$, 23.04 $GtCO_2$ and 16.76 $GtCO_2$, respectively. In this thesis the two potential solutions proposed to achieve emission reduction targets of CO_2 and other greenhouse gases are: carbon capture and sequestration and a clean development mechanism supported by emission trading. In this thesis the proposed CO_2 emission reduction model is a carbon capture and sequestration approach, which estimates the potential of CO_2 emission reduction in the United States of America and China that could take place by installing carbon capture and sequestration at coal-and gas-fired plants. The clean development mechanism assessment methodology is proposed to examine and verify the authenticity of emission reductions and effectiveness of emission trading. It is a methodology of project validation that focuses on additionality.

In a business-as-usual scenario, the world emits 33.66 $GtCO_2$ per year from coal- and gas-fired power plants and industry. In this thesis the results show that the potential years of breach of world carbon budgets without carbon capture and sequestration installed in China and the United States of America is year 2034–2035, year 2043–2044 and year 2055–2056 for 1.5^{0}C, 1.7^{0}C and 2^{0}C climate targets, respectively. The potential year of breach of carbon budgets with carbon capture and sequestration installed in China and the United States of America is the year 2045–2046, year 2057–2058 and year 2077–2078 for 1.5^{0}C, 1.7^{0}C and 2^{0}C climate targets, respectively. The technology analysis shows that carbon capture and sequestration has a degree of deliverability for the United States of America. The carbon capture and sequestration ambition in China is uncertain and difficult to accomplish. The claim that carbon capture and sequestration is an essential technology does not appear to be entirely correct, as there are many technological and financial constraints that limit its role in preventing climate change.

The results of the clean development mechanism assessment methodology and emission trading show that it is possible to reduce greenhouse gases by using the clean development mechanism and emission trading. The results show that the clean development mechanism and emission trading have reduced emissions by 4.16 $GtCO_2e$. The clean development mechanism assessment methodology used to review the registered clean development mechanism projects shows that the clean development mechanism is very effective in reducing powerful greenhouse gases. The electrification of the European Union's road transport sector could reduce emissions by 0.23 Gt carbon per year by phasing out diesel and motor gasoline.

The permanent solution to the climate crisis is the installation of renewable technology for energy generation, the deployment of sustainable low carbon agriculture and a phasing out of diesel and motor gasoline from road transport. Emission trading offers a unique opportunity to develop emission reduction technologies and to create a market for renewable technologies and carbon-based financial assets.

The main conclusions of the thesis are: China and the United States of America, who are the biggest emission contributors must reduce their coal and gas-based emissions by moving their energy generation to renewables, the carbon capture and sequestration is a potential emission reduction technology and the clean development mechanism and emission trading could help in accomplishing climate targets.

At the same time the installation of carbon capture and sequestration in China and the United States of America are not adequate to meet the climate change targets and expectations. The main barriers to carbon capture and sequestration delivery are due to the cost and technology uncertainty. The clean development mechanism and emission trading can reduce emissions, but these would need to be greater than 10 $GtCO_2e$ per year in order for emission trading to have any meaningful impact and lastly the European Union can make a big contribution by electrification of its road transportation sector by removing dependency on diesel and gasoline fossil fuels.

Resumen

El cambio climático es un desafío complejo y prolongado que podría tener impactos significativos en la sociedad humana, el sistema climático y la economía mundial. El cambio climático se atribuye a las emisiones de gases de efecto invernadero: dióxido de carbono (CO_2), metano (CH_4), óxido nitroso (N_2O), perfluorocarbonos (PFC), hidrofluorocarbonos (HFC) y hexafluoruro de azufre (SF_6). Los dos mayores contribuyentes antropogénicos de CO2 a la atmósfera son los Estados Unidos de América y China.

De 1970 a 2019, China y los Estados Unidos de América juntos produjeron el 38 % de las emisiones totales de CO_2 del mundo a partir de la combustión de combustibles fósiles. La continuación de estas emisiones significativas por parte de los dos países por sí solo podría conducir al incumplimiento de los objetivos de cambio climático que se han establecido en el Acuerdo de París y el Pacto Climático de Glasgow. El objetivo es limitar el calentamiento global a 1,5^{0}C, 1,7^{0}C y 2^{0}C respectivamente (con respecto a las temperaturas anteriores a la era preindustrial).

Para cumplir los objetivos climáticos de París y Glasgow, el presupuesto de carbono establecido por el Panel Intergubernamental sobre el Cambio Climático es igual a 500 $GtCO_2$, 850 $GtCO_2$ y 1,350 $GtCO_2$, respectivamente. A partir de enero de 2020, las emisiones mundiales de CO_2 debidas al consumo de combustibles fósiles fueron de 33,63 $GtCO_2$, siendo este es el escenario habitual. Por lo tanto, los objetivos anuales estimados de reducción de emisiones de CO_2 para el mundo son 27,38 $GtCO_2$, 23,04 $GtCO_2$ y 16,76 $GtCO_2$, respectivamente. En esta tesis, se analizan dos posibles soluciones para lograr los objetivos de reducción de emisiones de CO_2 y otros gases de efecto invernadero: la captura y secuestro de carbono y un mecanismo de desarrollo limpio apoyado en el comercio de emisiones. En esta tesis, el modelo de reducción de emisiones de CO_2 propuesto es un enfoque de captura y secuestro de carbono, que estima el potencial de reducción de emisiones de CO_2 en los Estados Unidos de América y China y que podría tener lugar mediante la instalación de sistemas de captura y secuestro de carbono en instalaciones industriales que usan carbón y gas. Se propone la metodología de evaluación del mecanismo de desarrollo limpio para examinar y verificar la autenticidad de las

reducciones de emisiones y la efectividad del comercio de emisiones. Se trata de una metodología de validación de proyectos que se enfoca en la adicionalidad.

En un escenario de negocios como el actual, el mundo emite 33,66 $GtCO_2$ por año provenientes de las centrales eléctricas y la industria que funcionan con carbón y gas. En esta tesis los resultados muestran que los años potenciales de incumplimiento de los presupuestos mundiales de carbono sin captura y secuestro de carbono como consecuencia de las actividades realizadas en China y Estados Unidos de América son: el año 2034-2035, el año 2043-2044 y el año 2055-2056 para 1.5^0C, 1.7^0 C y 2^0C, respectivamente. El año potencial de incumplimiento de los presupuestos de carbono para el caso de la instalación de sistemas de captura y secuestro de carbono en China y los Estados Unidos de América es el año 2045-2046, el año 2057-2058 y el año 2077-2078 para los objetivos climáticos de 1,50C, 1,70C y 20C, respectivamente. El análisis de la tecnología muestra que la captura y secuestro de carbono tiene un grado muy alto de entregabilidad para el caso de los Estados Unidos de América. Los objetivos que se ambicionan, de captura y secuestro de carbono, para el caso de China son inciertos y difíciles de lograr. La afirmación de que la captura y el secuestro de carbono es una tecnología esencial no parece ser del todo correcta, ya que existen muchas limitaciones tecnológicas y financieras que limitan su papel en la prevención del cambio climático.

Los resultados de la metodología de evaluación del mecanismo de desarrollo limpio y el comercio de emisiones muestran que es posible reducir los gases de efecto invernadero utilizando el mecanismo de desarrollo limpio y el comercio de emisiones. Los resultados muestran que el mecanismo de desarrollo limpio y el comercio de emisiones han reducido las emisiones en 4,16 $GtCO_2e$. La metodología de evaluación del mecanismo de desarrollo limpio utilizada para revisar los proyectos registrados del mecanismo de desarrollo limpio muestra que el mecanismo de desarrollo limpio es muy eficaz para reducir los potentes gases de efecto invernadero. La electrificación del sector del transporte por carretera de la Unión Europea podría reducir las emisiones en 0,23 Gt de carbono al año mediante la eliminación gradual del diésel y la gasolina para motores.

La solución permanente a la crisis climática es la instalación de tecnología renovable para la generación de energía, el despliegue de una agricultura sostenible baja en carbono y la eliminación gradual del diésel y la gasolina para motores del transporte por carretera. El comercio de emisiones ofrece una oportunidad única para desarrollar tecnologías de reducción de emisiones y crear un mercado para tecnologías renovables y activos financieros basados en el carbono.

Las principales conclusiones de la tesis son: China y los Estados Unidos de América, que son los mayores contribuyentes de emisiones, deben reducir sus emisiones basadas en carbón y gas trasladando su generación de energía a fuentes renovables siendo, la captura y secuestro de carbono ~~es~~ una tecnología potencial de reducción de emisiones. El mecanismo de desarrollo limpio y el comercio de emisiones podrían ayudar a lograr los objetivos climáticos.

Al mismo tiempo, las instalaciones de captura y secuestro de carbono en China y los Estados Unidos de América no son adecuadas para cumplir con los objetivos y expectativas de cambio climático. Las principales barreras para la entrega de captura y secuestro de carbono se deben a la incertidumbre tecnológica y de costos. El mecanismo de desarrollo limpio y el comercio de emisiones pueden reducir las emisiones, pero estas tendrían que ser superiores a 10 $GtCO_2e$ por año para que el comercio de emisiones tenga un impacto significativo. Por último, la Unión Europea puede hacer una gran contribución mediante la electrificación de su sector del transporte por carretera. eliminando la dependencia de los combustibles fósiles diésel y gasolina.

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Abbreviations and Acronyms

AE	abatement efficiency
AWMS	agricultural waste management systems
BAU	business as usual
BFG	blast furnace gas
BP	British Petroleum
BRT	Bus Rapid Transit
CAGR	compounded annual growth rate
CCGT	combined cycle gas turbine
CCPP	combined cycle power plant
CCS	carbon capture and sequestration
CDM	clean development mechanism
CDO	collateralised debt obligation
CDR	Direct Carbon Removal
CDMAM	clean development mechanism assessment methodology
CER	certified emission reduction
CH_4	methane
CNY	Chinese Yuan
COG	coke oven gas
COP	Conference of Parties
CO_2	carbon dioxide
CO_2ERM	CO_2 Emissions Reduction Model
CPC	Chinese Communist Party
CPI	Carbon pricing instruments
DNA	designated national authority
EAM	Emissions Abatement Model
ECPG	East China Power Grid
EEA	European Environment Agency
EERE	Energy Efficiency and Renewable Energy
EIA	Energy Information Administration
EOR	enhanced oil recovery

EU	European Union
EUETS	European Union Emission Trading System
FAR	fourth assessment report
FC	Forecast years
GDP	gross domestic product
GHG	greenhouse gas
GMSL	global mean sea level
GISS	Goddard Institute for Space Studies
GPIL	Godavari Power and Ispat Ltd.
GPP	gross primary production
GW	gigawatt
GWh	gigawatt hour
GWP	Global warming potential
HFC	hydrofluorocarbon
IEA	International Energy Agency
IEAT	industrial, energy, agricultural and transportation
IGES	Institute of Global Environmental Strategies
IPCC	Intergovernmental Panel on Climate Change
IRR	internal rate of return
kWh	kilowatts per hour
LED	light emitting diode
LNG	liquefied natural gas
LNG-CCGT	liquefied natural gas–combined cycle gas turbine
LPG	liquid petroleum gas
LULUCF	land use, land use change and forestry
MCV	market commodity value
MECS	Micro-Encapsulated CO_2 Sorbents
MIT	Massachusetts Institute of Technology
MLR	Mauna Loa Record
$MtCO_2$	Metric ton of CO_2
MRV	monitoring, reporting and verification
MW	megawatt

NASA	National Aeronautics and Space Administration
NBP	net biome production
NCV	net calorific value
NEP	net ecosystem production
NETL	National Energy Technology Laboratory
NF_3	nitrogen trifluoride
NOAA	National Oceanic and Atmospheric Administration
NPP	net primary production
NPV	net present value
N_2O	nitrous oxide
ODS	ozone depleting substance
OH	hydroxyl
PCF	prototype carbon fund
PDD	project design document
PFC	perfluorocarbon
PgC	petagrams of carbon
ppb	parts per billion
ppm	parts per million
ppmv	parts per million by volume
QOP	quotient of performance
RCP	Representative Concentration Pathways
RF	radiative forcing
SAR	sixth assessment report
SCR	selective catalytic reduction
SF_6	sulphur hexafluoride
SRES	Special Report on Emission Scenarios
TBA	Technology barrier analysis
tCO_2e	tonne of carbon dioxide equivalent
TCRE	transient climate response to cumulative carbon emissions
TCX	Tianjin Climate Exchange
UK	United Kingdom
UN	United Nations

UNFCCC	United Nations Framework Convention on Climate Change
US	United States
USA	United States of America
USEPA	United States Environmental Protection Agency
VER	voluntary emission reduction
WRI	World Resources Institute
WTO	World Trade Organization
WTOF	White Tiger Oil Field
ZERT	Zero Emissions Research and Technology

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Chapter 1 Climate Change and Greenhouse Gases

1.1 Scope and Background

During the last three decades, climate change has emerged as a significant scientific subject and a major political, economic, technological and social challenge. It is widely accepted by the scientific community that the threat of irreversible anthropogenically driven climate change is a real possibility. The scientific evidence unequivocally demonstrates that anthropogenic greenhouse gas (GHG) emissions have led to an increase in the concentrations of atmospheric GHGs. This increase has changed the natural radiation and carbon budget of planet Earth, which has led to increased positive radiative forcing (RF), creating irreversible deleterious changes to climate feedback mechanisms. The increased positive RF is attributed to significant emissions of carbon dioxide (CO_2) and non-CO_2 GHGs, namely: methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs) and sulphur hexafluoride (SF_6). These anthropogenic emissions predominantly emerge from energy generation and industrial, agricultural and transportation activities. The climate change scientific community considers that limiting global temperature change to 1.5^{0}C, 1.7^{0}C and 2^{0}C is vital for the long-term future of mankind.

The policy response to the scientific evidence and to global warming projections has been elaborate. The United Nations (UN), the European Union (EU), the United States of America (USA), the People's Republic of China and other nation states have formulated a range of climate change policies and programmes. The efforts to avoid dangerous climate change have been led by the United Nations Framework Convention on Climate Change (UNFCCC). The Conference of Parties (COP 26) recently concluded in Glasgow with a Glasgow Climate Pact, pledging to limit global temperature change to 1.5^{0}C and 2^{0}C. The projected climate change impacts will have significant impacts on human and economic development and also cause long-term damage to the natural environment.

This research and thesis examines important aspects of climate change science by reviewing the available scientific evidence and interpreting relevant data. The research identifies CO_2 emissions from major economies as the predominant driver of climate change. The majority of these emissions emerge from coal-, gas- and oil-fired energy generation plants in the USA and China. In addition, there are CO_2 emissions from transportation sectors in the EU, the USA and China.

The emphasis of this research is on carbon capture and sequestration (CCS) technology and the clean development mechanism (CDM). The research assesses the plausibility of CO_2 reduction by retrofitting CCS at coal- and gas-fired power plants in China and the USA. The research places equal emphasis on the CDM. The CDM gained prominence as a platform to generate carbon credits or carbon offsets, and 8,222 projects have been registered with the UNFCCC.

The research creates a CO_2ERM (CO_2 emission reduction model) to examine the potential of CO_2 reduction by deploying CCS and also proposes a clean development mechanism assessment methodology (CDM AM) to reform CDM carbon offset generation activities. CCS is widely being promoted by policymakers and scientists as an essential technology in order to avoid further effects of climate change.

In 2010, at the Conference of Parties in Cancun (COP 16), CCS was approved as an eligible CDM project activity technology. The CO_2ERM measures and forecasts the potential of CCS to provide a long-term and cost-effective solution to the climate change problem. In this research a CO_2ERM has been applied to China and the USA. These two countries are the greatest emitters of anthropogenic CO_2. The categorisation of these countries is based on a dataset obtained from the EDGAR database. The CO_2ERM creates business-as-usual (BAU) scenarios and emission reduction scenarios. The quantitative component of the model is supported by a detailed qualitative barrier analysis. The identified barriers to deployment of CCS include economic, energy, technology, geological and political barriers.

The CO_2ERM is a direct CO_2 emission reduction approach due to market and commercial bias towards non-CO_2 GHG reduction. Non-CO_2 reduction has largely been driven by CDM projects involving decomposition of N_2O and HFCs. The objective of a direct CO_2 emission reduction approach is to provide a 'supporting additional component' to an existing diverse climate change prevention policy. A

CO_2ERM could provide the required impetus needed for emission reduction and decarbonisation.

The proposed CDM AM measures the quality and magnitude of GHG emission reduction accomplished by registered CDM projects. The emphasis of the proposed CDM AM is on 're-characterisation of additionality' and sustainability. Unlike the UNFCCC methodology, the CDM AM introduces and applies 'sectoral additionality' to create credible carbon credits or offsets. The concept of additionality is critical to maintain scientific credibility, as CDM emission reductions – called certified emission reductions (CERs) – are being used by EU member states and companies to achieve their agreed emission reduction targets.

1.2 Scientific Background

The climate system is an essential life-supporting system, and its homeostasis is vital for the survival, environmental protection and progress of mankind. Due to advances in climate modelling and new understanding of complex climate feedback mechanisms, the scientific community has adequately demonstrated that significant emission of GHGs (e.g. CO_2 and non-CO_2 gases) into the atmosphere causes climate change due to the process of enhanced global warming. The 2022 report on climate change impacts, adaptation and vulnerability by the Intergovernmental Panel on Climate Change (IPCC) (Portner et al., 2022) states that climate change has adversely impacted human health, weather cycles and agriculture. It states that 3.3 to 3.6 billion people are vulnerable to the effects of climate change.

The GHG effect is created by the feedback mechanisms of the Earth's radiation budget. This is affected by: the incident solar radiation; the concentration of GHGs; the type of surface cover; and the amount of water vapour in the atmospheric layers. Solar energy drives the climate system through a series of complex feedback mechanisms. The most critical feedback mechanism that supports climatic homoeostasis is the radiation budgetary balance of the planet. Earth's surface and the atmosphere absorb radiation. Incoming short-wave radiation is reflected back as long-wave infrared radiation. Both incoming and outgoing radiation remain in a state of equilibrium with each other. The outgoing radiation emitted by the Earth's surface and oceans is absorbed by atmospheric gases and is radiated back to the Earth. This phenomenon is called the 'greenhouse gas effect'. The most important GHG is water vapour, followed by CO_2. The other GHGs (non-CO_2) are CH_4, N_2O, PFCs, HFCs and SF_6. The change in GHG concentrations is a key indicator of climate change (Treut et al., 2007; Cubasch, 2013; Chen et al., 2021).

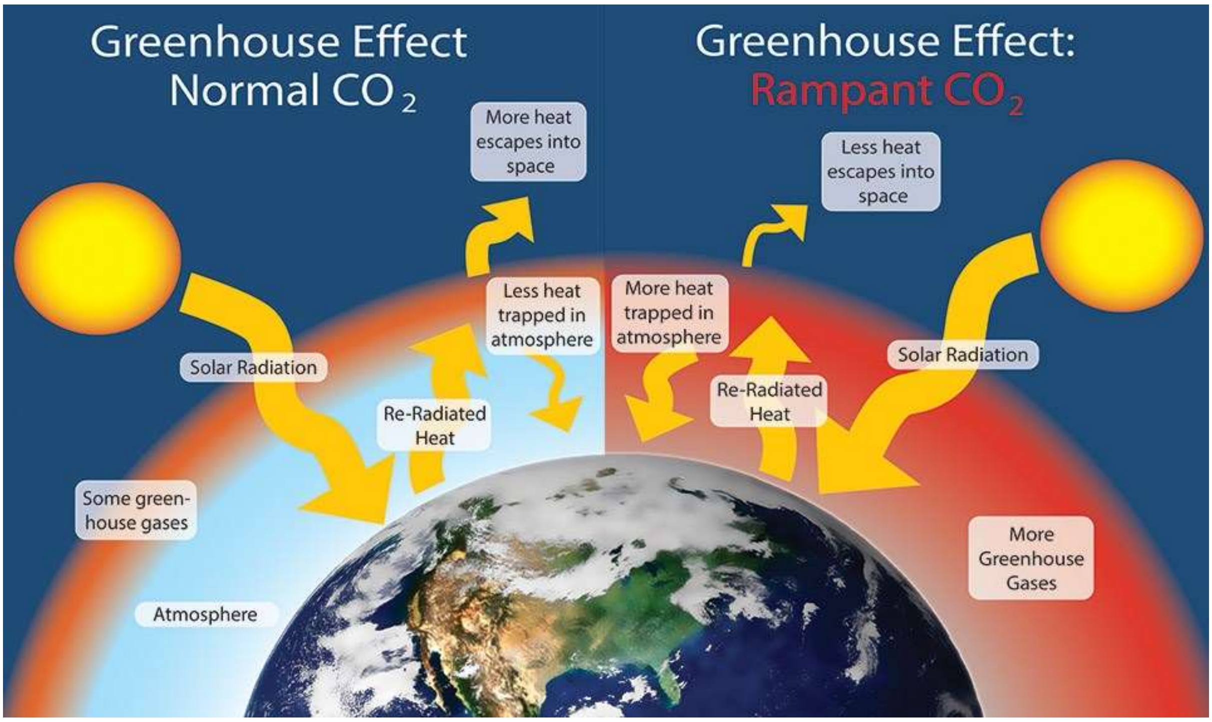

Figure 1.1: Natural and anthropogenic GHG effect

Source: Elder (2020)

The composition of atmospheric gas is dominated by nitrogen and oxygen, comprising 78% and 21% respectively (NASA, Earth Fact Sheet, 2021). CO_2 is a naturally present atmospheric trace gas and is also a GHG emitted by the combustion of fossil fuels and natural bio-geochemical processes. All GHGs are present in trace quantities in the atmosphere. For example, in 1744 (the preindustrial era), CO_2 concentration in ice cores was 276 ppmv (parts per million by volume) (Neftel et al., 1994), while in 2021, atmospheric CO_2 concentration has increased to greater than 411 ppm (Keeling et al., 1958; Scripps CO_2 Program, 2021).

Whilst GHGs are not a major component of the atmosphere, they are responsible for trapping the reflected solar heat and making life on Earth possible. In the absence of the GHG effect, life on planet Earth would probably not exist, as the average temperature of the Earth would be nearly -18°C (Masters and Ela, 2008). The IPCC Fourth Assessment Report clearly states that the warming of the climate system is unequivocally, evident from global observations of average air and ocean temperature increases, the melting of ice/snow and rising sea levels (Bernstein et al., 2007). The report states that the 'average Arctic temperature has increased at almost twice the global average rate' in the past 100 years. Additionally, the report claims that for the period 1970 to 2004, GHG emissions have increased by 70% and CO_2 represents 77% of the total world anthropogenic GHG emissions. The Sixth Assessment Report (SAR) states that global surface temperature was 1.09^0C higher in 2011–2020 than in 1850–1900 (Masson-Delmotte, 2021). The SAR points out that global oceans have warmed; it attributes warming of 0.28–0.55 yottajoules to climate change as well as the consequent increase in global mean sea level (GMSL) of 0.20 metres.

There is a linear relationship between cumulative carbon emissions and global warming. In the decade of 2010–2019, fossil fuel-based CO_2 emissions were responsible for emission of 9.6 PgC (1 petagram of carbon, 1 PgC = 1 gigatonne carbon or 1 billion tonnes), which is 86% of cumulative anthropogenic emissions (Canadell et al., 2021). The key challenge for climate change risk management is to remain within the carbon budget. Based on transient climate response to cumulative carbon emissions (TCRE), the remaining carbon budgets (from January 2020) for limiting warming to 1.5^0C, 1.7^0C and 2^0C are estimated to be 500 $GtCO_2$, 850 $GtCO_2$ and 1,350 $GtCO_2$, respectively (Arias et al., 2021). These estimates are based on the 50^{th} percentile.

1.3 Policy Background

This section provides an overview of climate change policy evolution and the development of institutions that are working to prevent dangerous anthropogenic climate change. Climate change policy started evolving in the mid-1980s and has continued to mature in order to adapt to the changing scientific evidence. Under the political mandate of the UN, climate change prevention policy has been devised based on the principles of intergenerational equity and common but differentiated historical responsibility between countries. Over the last three decades, many attempts have been made to arrive at an international GHG reduction framework in order to avoid the possibility of dangerous climate change. On 18 December 2009, all countries agreed to the Copenhagen Accord. The Accord accepted that climate change is the greatest challenge to mankind and accepted the scientific view that the increase in global temperature should be restricted to below 2°C (UNFCCC, COP 15, 2009). In 2010, the Cancun Agreement declared that Annex 1 countries (developed countries as per the Kyoto Protocol) as a group would reduce emissions by 25–40%, below 1990 levels, by the year 2020. The agreement approved the use of CCS as a CDM project activity technology (Morgan et al., 2010). An important milestone was reached in the Paris Agreement in 2015. It declared the goal to limit the increase in global temperature to less than 2°C (UNFCCC, Paris Agreement, 2015). In 2021, the parties at COP 26 agreed on the Glasgow Climate Pact, which reaffirmed the pledge to limit climate change to 1.5°C and 2°C.

The most important step in addressing the issue of anthropogenic climate change has been the formation of the UNFCCC. The UNFCCC coordinates international efforts to arrive at a political consensus and has contributed significantly to agreement between parties. After complicated and protracted negotiations, the UNFCCC established the Kyoto Protocol at COP 3. The Protocol entered into force on 16 February 2005 (UNFCCC, Kyoto Protocol, 2005) and is based on the principles of convergence, equity and differentiated historical responsibility between parties. It places the responsibility of addressing the issue of climate change on developed countries (also called Annex 1 countries) by setting binding targets for the majority of the Annex 1 countries. There are 192 parties to the Protocol (UNFCCC, Kyoto Ratification, 2010). The main objective of the Protocol is to prevent anthropogenic climate change by reducing and stabilising the concentration of atmospheric GHGs. The Protocol is a GHG emission reduction treaty, is legally binding and requires Annex 1 countries to reduce their GHG emissions by 5% below 1990 levels (1990 is the baseline year for the Protocol). The important milestones in climate change policy are provided in Table 1.1.

Table 1.1: Climate change policy milestones

Event and location	Year	Description
COP 1 Berlin	1995	Created the Berlin Mandate to address climate change using the available economic tools
COP 2 Geneva	1996	Accepted the IPPC Second Assessment Report and called for legally binding targets
COP 3 Kyoto	1997	Created the Kyoto Protocol, introduced legally binding emission reduction targets and created flexible mechanisms and international emission trading
COP 6 Bonn	2001	Created the CDM and carbon sink management policy
COP 7 Marrakech	2001	Created procedures for the CDM and created a Kyoto compliance system
COP 11 Montreal	2005	Agreed to extend the life of the Kyoto Protocol beyond 2012
COP 13 Bali	2007	The Bali agreement provided structured negotiation for a post-2012 agreement
COP 14 Poznan	2008	Agreed to create a fund for poor countries to adapt to climate change
COP 15 Copenhagen	2009	Accepted that change in global temperature should be below 2^0C and agreed to create the Green Climate Fund
COP 16 Cancun	2010	Agreed that the CDM will continue to be available for meeting Annex 1 targets and approved CCS as an eligible CDM technology
COP 21 Paris	2015	Agreed to limit global warming to below 2°C and 1.5°C compared to preindustrial levels
COP 26 Glasgow	2021	Reaffirmed the goal to limit global warming to below 2°C and 1.5°C compared to preindustrial levels and called on parties to scale up clean energy deployment

Source: UNFCCC COP 1–26 2021.

The Kyoto Protocol took into account six anthropogenic GHGs: CO_2, CH_4, N_2O, PFCs, HFCs and SF_6. To support climate change policy, all major countries/parties have created national climate change policies. This is as a result of their legal obligation to comply with the Kyoto Protocol and also to support international efforts to prevent dangerous climate change.

The national policies created to support GHG reduction are based on the principles of environmental and financial sustainability. These policies promote renewable energy generation using solar energy technologies, the deployment of wind farms, and biomass and hydroelectric power generation. In addition, nuclear energy generation is now promoted as a cost-effective option in order to reduce dependence on fossil fuels. The developed countries, especially the USA and EU member states, have developed advanced programmes of energy efficiency that reduce demand-side energy consumption. The EU has provided leadership in unifying its political agenda with climate change policy and has also created the first legal carbon trading mechanism through the European Union Emissions Trading System (EU ETS). The World Bank and the Asian Development Bank (ADB) are also active participants in GHG emission reduction projects. The World Bank created a Prototype Carbon Fund (PCF) to support emission trading within the Kyoto Protocol.

The most significant policy innovation to reduce the cost of GHG reduction has been the use of carbon emission trading. The Kyoto Protocol supported emission trading through the CDM and joint implementation (JI) projects and carbon trading mechanisms. These two project mechanisms are independent of each other and are supported in international carbon trading by the EU ETS. Carbon trading has emerged as a sophisticated tool to achieve cost-effective emission reduction. It was initiated in 2001 and has gained significant momentum. At the time of writing in 2021, there are 64 carbon pricing instruments (CPIs) in operation that cover 21.5% of GHG emissions (World Bank, 2021). Emission trading and carbon pricing is now in operation in the USA, China and the EU. In 2019, carbon pricing revenues raised $45 billion, with the price of carbon ranging from $1/tCO_2e$, to $119/tCO_2e$ (World Bank, 2020). The direct response to climate change has led to installation of renewable energy plants across the world. For example, the total renewable energy capacity in 2010 was 1,223 gigawatt (GW) and by 2019 it had increased to 2,532 GW. The total renewable energy production was 4,202,026 GWh in 2010 and it had increased to 6,586,124 GWh in 2019 (IRENA, 2020).

Climate change policy and politics is an important matter in global politics today. The countries negotiate at COPs on the basis of common national and regional political objectives. Political positions during climate change negotiations are based on national, regional, economic and political interests, with the USA being the single most important party that continues to determine the result of the negotiations.

1.4 Climate Change and the Carbon Cycle

The carbon cycle runs between autotrophic photosynthesis, heterotrophic respiratory pathways and CO_2 exchange between the atmosphere and the ocean systems. The principal driver of the carbon cycle is the exchange of CO_2 between land- and ocean-based ecosystems and the atmosphere. CO_2 is fixed by photosynthesis, converted into organic material (i.e. terrestrial and non-terrestrial biomass) and is returned to the atmosphere by several respiratory pathways. The amount of atmospheric CO_2 fixed by photosynthesis is referred to as gross primary production (GPP). Terrestrial GPP is 120 PgC/yr (petagrams of carbon per year). Net plant growth is referred to as net primary production (NPP). Annual NPP (plant growth) is 60 PgC/yr. The difference between NPP and respiration determines the net ecosystem production (NEP) or the carbon balance of the ecosystem. Global NEP is approximately 10 PgC/yr (Houghton et al., 2001). The carbon accumulated is called net biome production (NBP). The fundamental principle in a natural carbon cycle is that NPP is the carbon input and respiration is the carbon output. There is a 10- to 30-year lag between respiration and NPP (Houghton et al., 2001). A continuous increase in NPP produces positive NBP and as a result a terrestrial ecosystem acts as a carbon sink. The SAR states that in the last decade (2010–2019), fossil fuel-based CO_2 emissions were responsible for the emission of 9.6 PgC (petagrams of carbon), which is 86% of cumulative anthropogenic emissions (Canadell et al., 2021). The combustion of fossil fuels and land use changes made from 1750 to 2019 has resulted in the release of 700 PgC (Arias et al., 2021).

The marine ecosystems (e.g. oceanic systems) act as the largest CO_2 sinks available, as CO_2 dissolves in ocean waters. The molecular diffusion between oceans and the atmosphere is approximately 90 PgC/year (Houghton et al., 2001) and is driven by the differences in partial pressure of oceanic and atmospheric ecosystems. CO_2 is highly soluble and is very reactive due to its high rate of dissociation. CO_2 in ocean waters is present as dissolved CO_2, bicarbonate and carbonate. All three forms comprise dissolved inorganic carbon (DIC). As the atmospheric CO_2 concentration rises, the DIC increases correspondingly and the majority ends up as bicarbonate. The increase in CO_2 concentration reduces the rate of CO_2 uptake, to the detriment of the ocean system's sink capacity. CO_2 solubility is temperature dependent, with cold surface water driving CO_2 uptake and warm surface water causing the release of CO_2. The NPP of oceans is approximately 45 PgC/yr (Houghton et al., 2001). The added CO_2 is stored as the waters sink, and a new steady state is created. The rate of exposure of the interior waters is dependent on the rate of mixing of old waters at the surface (Prentice et al., 2001). Climate change has increased the surface temperature of oceans on average by 0.88^0C from 1850–1900 to 2011–2020; 0.60^0C of this warming has occurred since 1980. Furthermore, the heat content of the oceans has increased from 1970 and will continue to increase until 2300 (Fox-Kemper et al., 2021).

1.5 Climate Change Evidence

Climate is a statistical representation of weather, and the complexities of the climate system emerge from direct and indirect interrelationships between different components of the climate and weather systems. The critical components of a climate system are: the ocean systems; terrestrial ecosystems; the cryosphere; and the solar system. The climate system in its entirety is driven by solar energy, which drives bio-geophysical processes that maintain the energy balance of the planet and are necessary to maintain life. As the age of the Earth is 4.5 billion years (Newman, 2007), the climate system has also evolved and changed through 4.5 billion years of biophysical evolution.

Climate change is a multidimensional economic, political and social challenge that threatens the welfare of mankind. The multidimensionality of the potential impacts associated with significant global warming makes adaptation to changing climate very challenging. Potential impacts of global warming include: the loss of human life due to flooding and cyclonic storms; the loss of life-sustaining ecosystems; reduced access to clean water and food; significant infrastructure damage; loss of geo-political dominance and political conflict; and the impact on economic productivity and political instability due to a potential influx of environmental refugees across different countries. The regional impacts will create sea level changes, leading to the inundation of inhabited coastal areas, extreme weather changes and loss of ocean biodiversity. A brief literature review of climate change evidence and impacts is provided below.

1.5.1 Surface temperature change

The global mean temperature (averaged over land and ocean surfaces) warmed by 0.76°C ± 0.19°C between the first 50 years of the instrumental record (1850–1899) and the last five years recorded (2001–2005). Surface temperature data records are available from the GISS (GISTEMP and Lenssen, 2019).

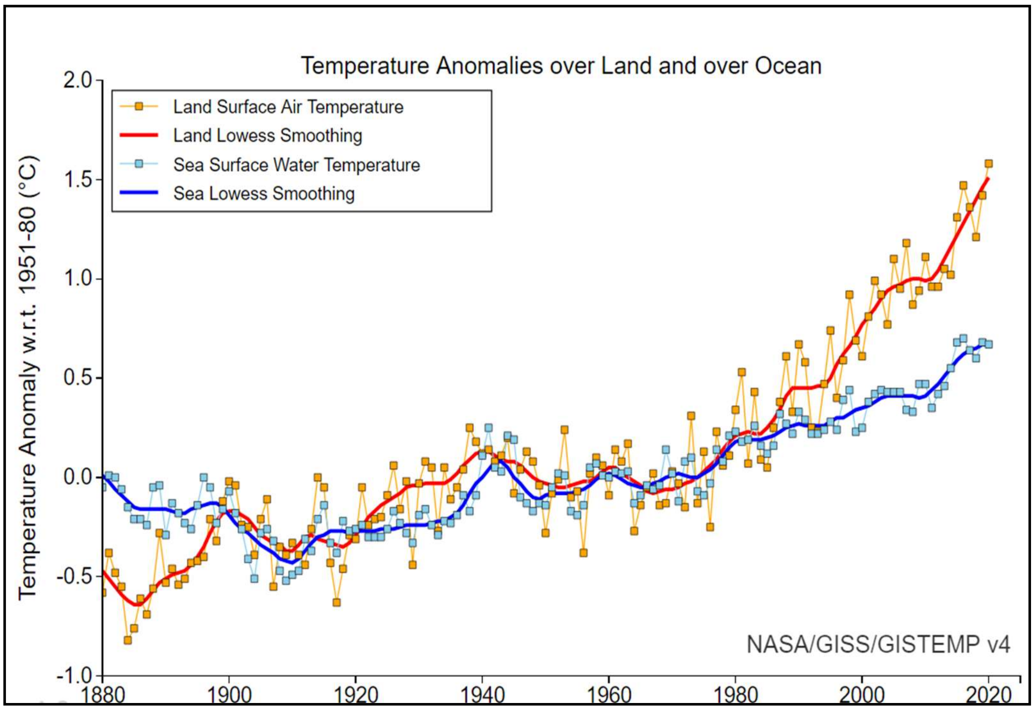

Figure 1.2: Surface temperature record

Source: GISS dataset and graph for Global Land-Ocean Surface Temperature Anomaly (GISTEMP and Lenssen, 2019)

The supporting graph about land and ocean temperature change from GISS is shown in Figure 1.2; it shows temperature anomalies over land and ocean. The annual mean temperature in the GISS dataset for the year 1882 is -0.23 °C and for the year 2006 is 0.54 °C. The GISS concludes that 2016 is likely the warmest year in the last 139 years (1880–2018) with 87% certainty (Lenssen et al., 2019).

1.5.2 Extreme weather

Several recent hurricanes and extreme rainfall in the USA, South East Asia and Europe – including the active North Atlantic hurricane seasons of 2004 and 2005, the unusual development of a cyclonic system in the subtropical South Atlantic that hit the coast of southern Brazil in March 2004 and a hurricane close to the Iberian Peninsula in October 2005 – raised public and media interest relating to the possible effects of climate change. There have been several high-profile extreme weather events that have generated scientific and political interest in climate change. In some cases, these events have been attributed to climate change and increased global warming. For example, storm surge inundation heights produced by Hurricane Michael in 2019 were estimated to be 9–12 ft above ground level (Bevan et al., 2019). GHG-driven climate change is the dominant cause leading to temperature extremes, and it is likely the frequency of extreme weather events will increase. The hydrological models used in SAR (Seneviratne et al., 2021) project an increase in flooding in the western Amazon, the Andes and parts of Asia.

There is much literature available that demonstrates the potential of climate change-induced extreme weather events. For example, in high GHG emission scenarios, heat extremes that break records are two to seven times more probable in 2021–2050 and three to 21 times more probable in 2051–2080 compared to the last three decades (Fischer et al., 2021). Impacts of climate change can be serious and unpredictable. For example, one case study shows climate-induced extreme weather events will affect demand and supply of energy and cause a 16% drop in energy supply in Sweden (Perera et al., 2020).

In sub–Saharan Africa, global warming of 4^{0}C could lead to a loss of 12% GDP (Baarsch et al., 2020) by 2050 and 80% loss of GDP by 2100.

1.5.3 Cryosphere changes

The cryosphere is the second largest component of the climate system in terms of its mass and heat sink capacity. Cryosphere changes are considered the critical indicator of climate change due to global warming. In the IPCC assessment report, ice sheet mass balance analysis carried out for the East and West Antarctic regions revealed a loss of 24–25 Gt/year of ice mass (Lemke at al., 2007). Further work carried out by IPCC attributes increased summer melting to climate change. The rate of loss of ice was 243 Gt/year (Fox-Kemper et al., 2021). The US space agency, NASA, runs the Gravity Recovery and Climate Experiment (GRACE), and the main observation of the programme is that between 2002 and 2020, Greenland shed approximately 280 gigatons of ice per year, causing the global sea level to rise by 0.03 inches (0.8 millimetres) per year (GRACE, 2020). There is also adequate historical evidence about the rise of GHGs in the atmosphere. For example, the Siple ice core data from occluded air samples within ice core highlights that CO_2 concentration in the year 1744 within the ice core was 276.8 ppmv and in the year 1953 was 312.7 ppmv (Neftel et al., 1994). Atmospheric concentrations of CH_4 before about 1750 A.D. ranged from 676 to 716 ppb (parts per billion); after about 1750 A.D., concentrations began to increase to their present value of more than 1700 ppb (Etheridge et al., 2002). The atmospheric growth rate of CH_4 from 2008 to 2017 is 7 ppb per year (Canadell et al., 2021). Similarly, atmospheric concentrations of N_2O and SF_6 have also increased.

In 2019, the IPCC published a major report (Portner et al., 2019) on cryosphere changes. It stated that permafrost temperature changes have increased by $0.39^0C \pm 0.15^0C$ in the Arctic and by $0.37^0C \pm 0.10^0C$ in the Antarctic. It posits that the disappearance of near-surface permafrost in the Arctic is as a result of global warming.

1.6 Major Emitters (1990–2019) and Effective Emission Reduction

This section highlights the significance of CO_2 and non-CO_2 GHG emissions for and their relationships with climate change. The section identifies the effective emission reductions required to avoid climate change and stay within the carbon budgets.

1.6.1 Net addition of carbon

There is a mathematical relationship between anthropogenic CO_2 emissions, the net addition of CO_2 to the atmosphere, the consequent net addition of carbon and global warming. To reveal the relationship between the concentration of atmospheric CO_2 and the net addition of anthropogenic CO_2, molecular weight methodology is used by researchers. Molecular weight methodology is also used by the IPCC (Denman et al., 2007). This methodology calculates that 1 ppm CO_2 = 2.12 GtC. The calculations are provided in Box CO_2 below.

Box CO_2

If the atmosphere is at a standard temperature and pressure, the density would be 1291.8 g/m^3 and the atmospheric mass would be $5.12*10^{21}$ g (Masters and Ela, 2008).

$$1 \text{ ppm } CO_2 = \{(1 \text{ m}^3\ CO_2/\ 10^6 \text{m}^3 \text{ air}) *(44.61 \text{ mole/ m}^3\ CO_2) *(12 \text{ gC/mole}) *(5.12*10^{21} \text{ g air}/1291.8 \text{ g air/m}^3 \text{ air}) *(10^{-15} \text{ GtC/gC})\}$$

Therefore 1 ppm CO_2 = 2.12 GtC

*The present concentration of CO_2 is 411 ppm; the total amount of carbon in the atmosphere is 871 GtC (411*2.12)*

1 ppm CO_2 = 2.12 GtC (a conversion factor)

1 GtC = 1/2.12 =0.471 ppm CO_2

1 tC (tonne of carbon) = 3.66 tCO_2 (3.66 is the ratio of molecular weight of CO_2 to carbon)

Therefore 1 tCO_2 = 1/3.66 = 0.273 tC (0.27 is a conversion factor)

Hence 1 GtCO_2 = 0.27 GtC

1 GtCO_2 = 0.273/2.12 = 0.128 ppm of CO_2

Emission of 1 GtCO_2 should add 0.128 ppm of CO_2, which does not account for sink removal of emitted CO_2

Source: Author and Masters and Ela (2008)

Results show that anthropogenic emission of 1 GtCO_2 is equal to 0.128 ppm concentration of CO_2 in the atmosphere, without taking into account the sink feedback mechanism.

1.6.2 Top emitters of CO_2 and non-CO_2 GHGs

To identify the top emitters of GHGs, original data from the EDGAR database was used. The EDGAR v5 (Olivier and Peters, 2020) dataset covers emissions of all countries and provides GHG emission data per source (1990–2019). It also provides CO_2 emissions from fossil fuel combustion from 1970 to 2019. The CO_2 emissions in the EDGAR dataset are calculated from fossil fuel combustion for energy generation, using the IPCC sectoral emission measurement approach.

The emissions of important countries are illustrated in figures 1.3 and 1.4.

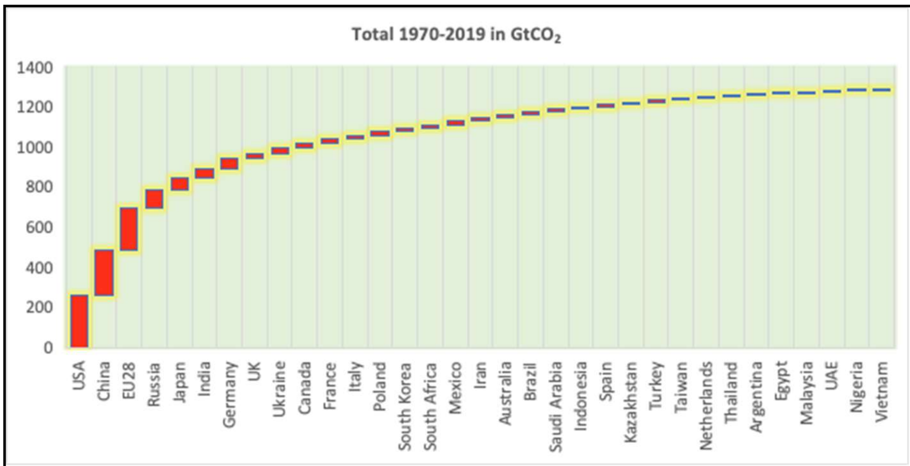

Figure 1.3: CO2 from fossil fuel combustion (1970–2019)

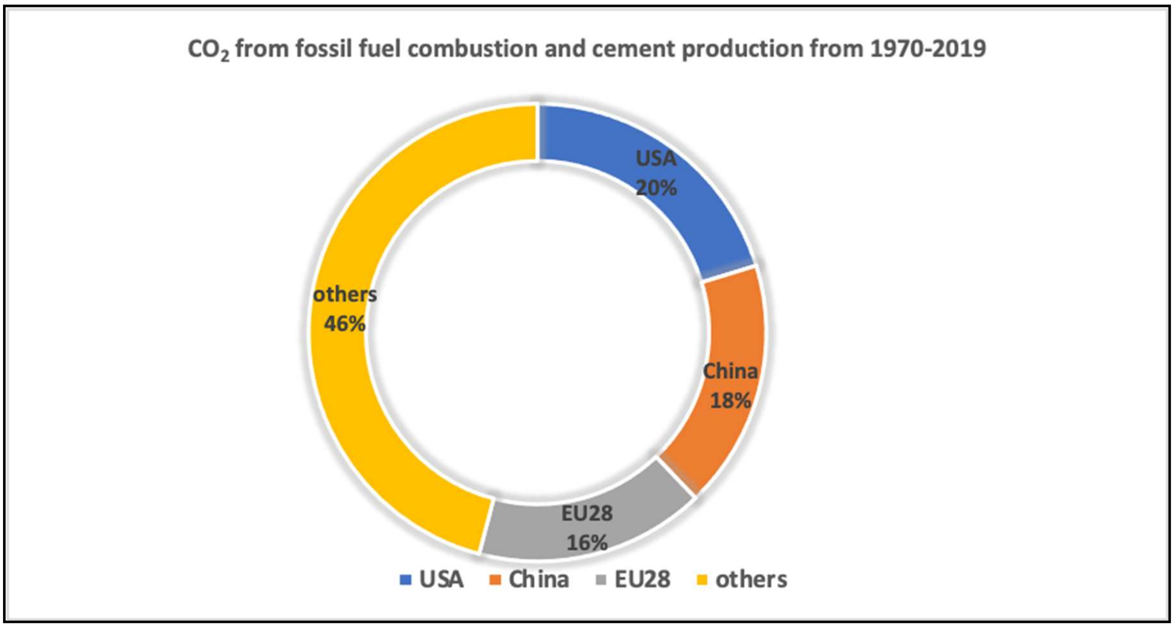

Figure 1.4: Percentage of CO2 from fossil fuel combustion (1970–2019)

Therefore, the biggest direct contributors of CO_2 to the atmosphere are the USA, China, the EU28, Russia, Japan, India, Germany, and the United Kingdom.

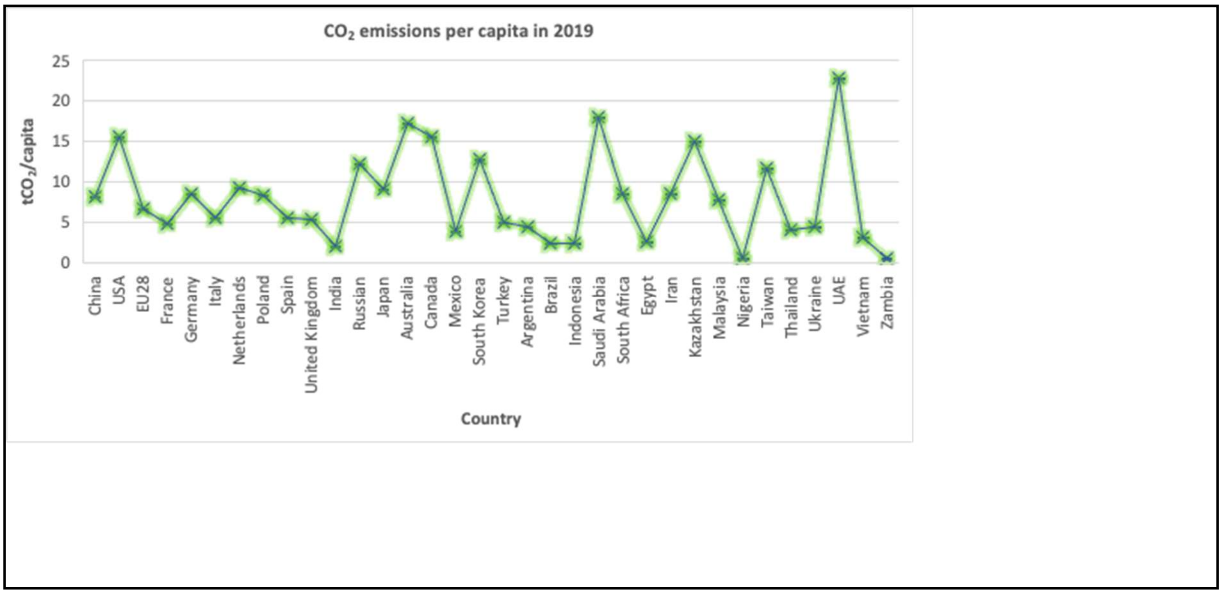

Figure 1.5: CO_2 emissions per capita in 2019

Figures 1.4 and 1.5 highlight the most recent evidence about the increase in atmospheric CO_2 concentrations. From 1970 to 2019, China and the USA produced 38% of total CO_2 emissions from the combustion of fossil fuels. In the last decade

(2009–2019), China's CO_2 emissions increased from 8.43 $GtCO_2$ to 11.6 $GtCO_2$. During the same time period, emissions from the USA decreased from 5.33 $GtCO_2$ to 5.11 $GtCO_2$. The EU member states emitted 16% and the rest of the world emitted 46%. Figure 1.5 points out the emerging picture. The highest CO_2 emissions/capita from the combustion of fossil fuels in 2019 were from the United Arab Emirates (UAE), which emitted 22 tCO_2/capita. In 2019, China and the USA emitted 8 tCO_2/capita and 15 tCO_2/capita, respectively. In 2019, the highest per capita CO_2 emitters were the United Arab Emirates, Saudi Arabia, Australia, Canada, and the USA. The lowest per capita CO_2 emitters were Zambia, Nigeria, and others.

1.6.3 Effective emission reduction of CO_2

As mentioned in section 1.1, the remaining carbon budgets (from January 2020 to 2100) for limiting global warming to 1.5^0C, 1.7^0C and 2^0C are estimated to be equal to 500 $GtCO_2$, 850 $GtCO_2$ and 1,350 $GtCO_2$, respectively (Arias et al., 2021). These budgets are based on 50^{th} percentile TCRE estimates. The EDGAR data (Olivier and Peters, 2020) shows cumulative CO_2 emissions in 1970 from fossil fuel combustion for energy were 13.93 $GtCO_2$ and in 2019 were 33.66 $GtCO_2$; the total emissions during these 49 years were 1,138 $GtCO_2$. To identify effective emission reduction, the emissions of 33.66 $GtCO_2$ in 2019 is considered the business-as-usual (BAU) scenario. If this prevailing scenario (33.66 $GtCO_2$ as the BAU scenario) does not reduce significantly, the total CO_2 emissions from fossil fuel combustion for energy generation for the next 80 years (2020–2100) could potentially be a total of 2,692 $GtCO_2$. Table 1.2 portrays this scenario and its potential consequences. The table highlights the risks of running out of the allowed carbon budget in 2035, 2045 and 2066.

Table 1.2: BAU CO_2 emissions and carbon budget

<table>
<tr><th>Projected temperature increases for 2020–2100</th><th>Carbon budget allowed by IPCC for 2020–2100</th><th>BAU scenario 2020–2100</th><th>Year of carbon budget overshoot for 2020–2100</th></tr>
<tr><td>1.5^{0}C</td><td>500 $GtCO_2$</td><td>33.63 $GtCO_2$ per year</td><td>Allowed budget runs out in 15 years, around 2035</td></tr>
<tr><td>1.7^{0}C</td><td>850 $GtCO_2$</td><td>33.63 $GtCO_2$ per year</td><td>Allowed budget runs out in 25 years, around 2045</td></tr>
<tr><td>2^{0}C</td><td>1,350 $GtCO_2$</td><td>33.63 $GtCO_2$ per year</td><td>Allowed budget runs out in 40 years, around 2060</td></tr>
<tr><td colspan="4">Total available budget for 1.5^{0}C, 1.7^{0}C and 2^{0}C targets = 500 $GtCO_2$, 850 $GtCO_2$ and 1,350 $GtCO_2$, respectively

BAU CO_2 emissions/year = 33.63 $GtCO_2$

Allowed CO_2 emissions per year for 1.5^{0}C, 1.7^{0}C and 2^{0}C targets = allowed carbon budget for the target/time period for target (2020–2100), which is 6.25 $GtCO_2$, 10.62 $GtCO_2$ and 16.87 $GtCO_2$, respectively

CO_2 emission reduction targets per year = (BAU CO_2 emissions per year - allowed CO_2 emissions per year), which is 27.38 $GtCO_2$, 23.04 $GtCO_2$ and 16.76 $GtCO_2$, respectively</td></tr>
</table>

Source: Author

The expert assessment for projected CO_2 emissions in 2100 ranges from 54.4 to 71.4 $GtCO_2$ (Schwalm et al., 2020). The elicitation of different emission scenarios varies widely in the literature. For example, to avoid a 2°C overshoot, it is argued that global emissions of 780 $GtCO_2$ can be emitted from 2018 to 2100 (Warner and Glen, 2019). The IPCC special report highlights that an overshoot of the 1.5°C thresholds can occur after 2030. The current Paris Agreement pledges for emission reduction will overshoot the 1.5°C thresholds. To limit warming to 1.5°C, a net-zero CO_2 needs to be reached by 2050. At the same time, emission reduction of non-CO_2 gases, especially methane, is needed (Rogelj et al., 2018).

To avoid overshoot or breach of the carbon budget, the installation of CCS in coal- and gas-fired power plants is portrayed as an effective emission avoidance or reduction technology. To stay within the carbon budget, the application and deployment of CCS is needed particularly in China and the USA, which are the top two emitters. The effectiveness of the CCS scenario in China and the USA is portrayed in detail in chapter 2. In addition to these contributions to meet the carbon budget targets, sector-based emission reductions are needed, for example, transportation, agricultural and industrial decarbonisation. To portray these scenarios, emission reductions in EU transport and through the CDM in developing countries are explained in chapter 3. Transport CO_2 emissions within the EU have increased substantially, and there is a need to avoid these emissions. For example, road transport emissions from diesel and gasoline within the EU increased from 2000 to 2018 (Bhat and Garcia, 2021). Annual EU road transport emissions are 0.24 $GtCO_2$ and the net zero energy requirement in the road transport sector for the EU exceeds 3,000 TWh per year.

To effectively prevent climate change, it is clear from table 1.2 that emission reduction of 27.38 $GtCO_2$, 23.04 $GtCO_2$ and 16.76 $GtCO_2$ is needed per year to limit climate change to 1.5^0C, 1.7^0C and 2^0C targets, respectively.

1.7 Objectives of Research

The aims and objectives of the research are outlined below:

- The research aims to examine whether CCS can help avoid dangerous climate change by direct CO_2 reduction (through capture and storage) at coal- and gas-fired power plants. The aim is to offset the annual increase in CO_2 concentration, which is driven by anthropogenic activities, and to determine the technological feasibility, magnitude of potential emission reduction, geological feasibility and political acceptability of deploying CCS in the top two emitters. The CO_2ERM is a method/model approach to check the potential of emission reduction and is explained in chapter 2.
- The CDM is a unique emission reduction programme run by the UNFCCC. This programme generates certified emission reductions (CERs) that are used in emission trading programmes. The CDM is introduced in chapter 3, and the CDM AM is proposed to examine and verify the authenticity of certified emission reductions. The CDM AM is a screening methodology which examines the effectiveness of the CDM project mechanism. The

credibility of the CDM is vital for the carbon markets. Moreover, the CDM AM differentiates between different types of abatement (e.g. gas specific).

- The project also measures the contribution from carbon markets and carbon emission trading in creating net GHG emission reduction.

1.8 Research Methodology

The project researches the challenge and problem of climate change. It identifies anthropogenic activities that play a vital role in increasing atmospheric concentration of GHGs. The project determines and quantifies the emission reduction required to offset the increase in atmospheric CO_2 concentrations per year. The most exhaustively used literature is: the IPCC Third, Fourth and Sixth Assessment Reports; IPCC scientific evidence on climate change; the IPCC Report on CCS; IEA publications; the National Oceanic and Atmospheric Administration (NOAA) State of the Climate reports; Tyndall Centre research publications; Pew Centre on Global Climate Change publications; the World Resources Institute (WRI); and UN departmental publications. The project also relies on policy documents from the European Environment Agency (EEA), the Centre for European Policy Studies (CEPS), the UK Climate Change Committee and the World Bank carbon market reports. The primary data sources are: the Energy Information Administration (EIA); UNFCCC CDM datasets; carbon market datasets; and IEA country-specific energy statistics. The secondary CDM dataset was acquired from the Institute of Global Environmental Strategies (IGES) and is used to measure GHG-specific emission reduction.

1.9 Research Contribution

The main contributions of this research are aimed at the climate change research community, energy policymakers and sustainability specialists; these are:

- Estimation and identification of the potential of CCS in reducing CO_2 emissions from coal and gas combustion in China and the USA.
- Examination of the effectiveness of the CDM and emission trading to deliver credible carbon emission reductions that accomplish emission

reduction targets in the industrial, energy, agricultural and transportation sectors.

- To show how the transportation sector in the European Union (EU) can be decarbonised by electrification and the phasing out of diesel and gasoline fossil fuels.

The work carried out by the author has been peer reviewed and has been published in *Applied Sciences*. This work was published in July 2021. The paper is titled: 'Sustainability and EU Road Transport Carbon Emissions from Consumption of Diesel and Gasoline in 2000 and 2018' by Arshad Bhat (corresponding author) and Javier Ordóñez Garcia (co-author). This paper is available online at Applied Sciences | Free Full-Text | Sustainability and EU Road Transport Carbon Emissions from Consumption of Diesel and Gasoline in 2000 and 2018 (mdpi.com).

1.10 Structure of Thesis

The thesis is structured into two sections. In the first section, climate science is reviewed and CCS-based emission reduction is the proposed solution. In the second section, the CDM and emission trading are examined and CDM case studies are reviewed.

Chapter 1 identifies the drivers of climate change using historical GHG data. The research identifies an increase of net additional flux in the global carbon cycle due to anthropogenic GHG emissions. Chapter 2 proposes the CO_2ERM to reduce emissions using CCS. The fossil fuel datasets used to create the CO_2ERM scenarios were acquired from the EIA. In chapter 3, the CDM AM is used to carry out a detailed analysis of CDM projects and carbon emission trading markets. More than 100 CDM projects were assessed. However, as projects are repetitive, only fewer CDM projects were used to validate the CDM AM. The CDM AM is proposed in order to reform the CDM and to enhance its role in global emission reduction and in reforming the carbon trading market. The primary data used in the CDM AM has been acquired from CDM project design documents (PDDs), project investment analysis spreadsheets and baseline methodology documents. The CDM AM has been created with qualitative and quantitative components. The combined qualitative and quantitative scores enable the project to be categorised as an efficient or a non-efficient CDM project. In chapter 4, a critical analysis of the research as well as methods, results and conclusions are presented. The workflow of the thesis and research carried out is illustrated in figure 1.6.

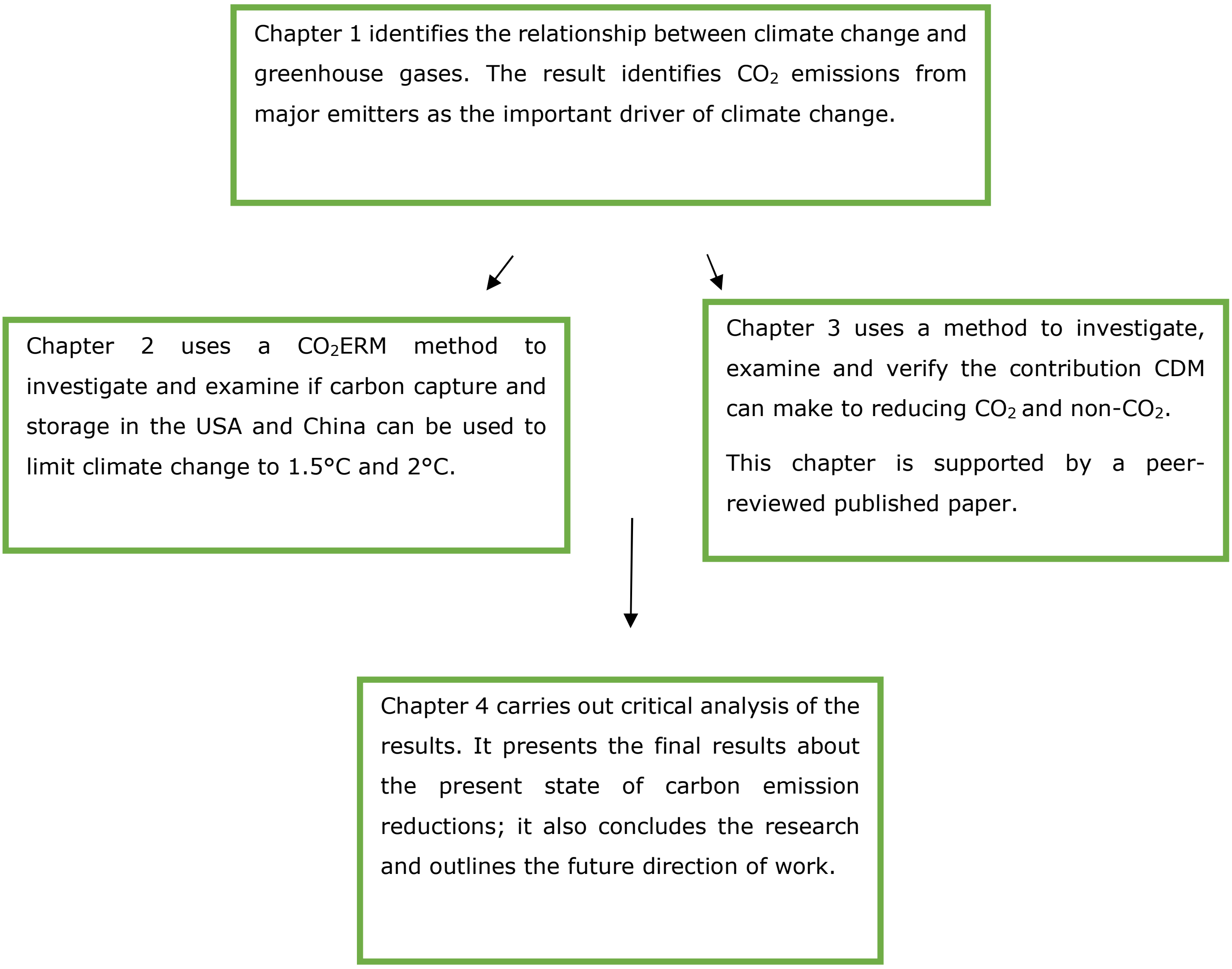

Figure 1.6: Flow chart of the research and thesis

Chapter 2 CO_2 Emission Reduction Model

2.1 Introduction

In this chapter, a theoretical CO_2ERM is proposed as a solution to help attain the 1.5^{0}C, 1.7^{0}C and 2^{0}C budgets. There is a need to stop the CO_2 emission crisis, which is driven by energy generation in the top three emitters. The top three emitters are the USA, China, and the EU. The EU is a political group of 27 separate countries. EDGAR data shows these three emitters together emitted 54% of the world's CO_2 total emissions from 1970 to 2019 (Olivier and Peters, 2020) and they have the highest CO_2 emissions per capita. In 2019, the USA, China and the EU28 (then included the United Kingdom) emitted 20 GtCO_2 of the total 33.66 GtCO_2, which is 59% of total emissions from energy generation. This BAU scenario is outlined in table 1.2 and will lead to an overshoot of the 1.5^{0}C, 1.7^{0}C and 2^{0}C carbon budgets in 15 to 40 years.

The top CO_2-emitting countries in 2019 were China and the USA: they emitted 49% of the world's emissions. In their mitigation pathways report for the 1.5^{0}C budget, the IPCC highlight the need for direct carbon removal (Rogelj et al., 2018). The recently published Synthesis Report on Nationally Determined Contributions (NDCs) under the Paris Agreement (UNFCCC Synthesis Report, 2021) estimates that taking into account all measures agreed in the Paris Agreement, the total world emissions in 2030 will be 51–58 GtCO_2e (carbon dioxide equivalent). The need to reduce or avoid CO_2 emissions from energy generation is vital to overcome the challenge of climate change and hit the targets for the 1.5^{0}C, 1.7^{0}C and 2^{0}C carbon budgets. It is the CO_2 emissions from the energy services of the USA and China that could cause an overshoot or breach of carbon budgets and consequent temperature increase.

To elucidate and elicit the role CCS could play in reducing and avoiding CO_2 emissions from fossil fuel combustion, the proposed CO_2ERM solution assesses the plausibility of creating CO_2 emission reduction at coal- and gas-fired power stations in China and the USA. The proposed CO_2ERM could offset and avoid a constant increase of atmospheric CO_2 concentration. The linkage between a continuous increase in CO_2 concentration and energy generation from fossil fuel-fired power plants needs to be de-coupled. The Global Status of CCS Report 2020 (Page et al.,

2020) highlights that there are 65 commercial CCS facilities in the world, and these CCS facilities are operational in areas of gas- and coal-fired power generation, cement production and natural gas processing.

The principal objectives of the proposed CO_2ERM are:

- To estimate the potential of CO_2 emission reduction in the USA and China.
- To assess the plausibility of creating CO_2 emission reduction in the USA and China.
- To carry out economic, technological, geological and political barrier analysis to CO_2 emission reduction using CCS at coal- and gas-fired power stations.

The supporting arguments in favour of CCS technology are:

- CCS technology can be installed at coal- and gas-fired power plants without compromising energy and economic security.
- CCS is the only technology that can capture CO_2, and there will be no disruption to the security of electricity and energy supply.
- CCS can be useful in producing low carbon hydrogen to supply to the energy, steel and cement industries.
- CCS can be installed in the cement and steel industries and at any stationary installation that combusts coal and natural gas.
- The IPCC Special Report on CCS estimates that 4.7-37.5 $GtCO_2$ can be reduced by the year 2050 (Metz et al., 2005). The IPCC acknowledges that 30 $MtCO_2$ (de Coninck et al., 2018) is captured annually in all CCS projects.
- As a chemical process, CCS replicates the natural process of sequestration of carbon. Carbon sequestration works efficiently in nature due to the interrelationship between photosynthesis (an energy-producing process) and respiration (an energy-consuming, CO_2-emission process).

- According to the IEA, CCS is an important low-cost CO_2 reduction technology. In the absence of CCS, the cost of halving CO_2 emissions by the year 2050 will rise by 70% (Carbon Capture and Storage Roadmap Targets, 2010). However, this roadmap does not elaborate on how the cost of halving CO_2 emissions will increase in the absence of CCS deployment. The Boundary Dam CCS project in Canada and the Petra Nova project in the USA are providing vital information about cost management of CCS. The cost of reduction is reported at \$45/tCO_2 (CCUS in Power, 2020), and its capture capacity is 1.4 MtCO_2. The Petra Nova project in Texas, USA, is a post-combustion project in a coal-fired power plant (CCUS in Power, 2020). The captured CO_2 is used in enhanced oil recovery (EOR) to extract non-recoverable oil, which in turn causes more CO_2 emissions.
- A CDM and carbon emission trading plan to install CCS at the White Tiger Oil Field (WTOF) in Vietnam was proposed. The project was rejected at the consultation stage. The rejection took place due to the lack of a transparent baseline assessment carried out by the project developer. The rejection was not on technological grounds (UNFCCC, White Tiger Oil Field Carbon Capture and Storage, 2006).
- Many scholars support use of CCS in emission reduction. For example, Socolow and Pacala recommend that by 2054, CCS can be installed at 800 GW of base load coal-based plants or at 1600 GW of base load natural gas-fired power plants (Socolow and Pacala, 2004). It is understood that they mean 800 and 1600 GW of total installed capacity.

Figures 2.1 and 2.2 illustrate the most recent total energy supply position for China and the USA.

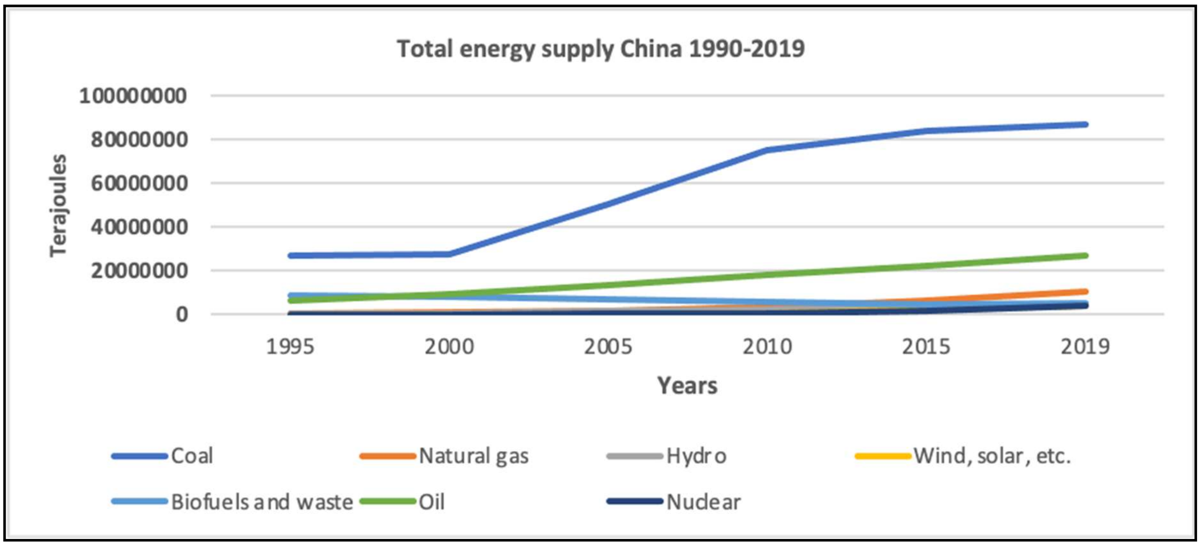

Figure 2.1: Total energy supply (TES) by source for China

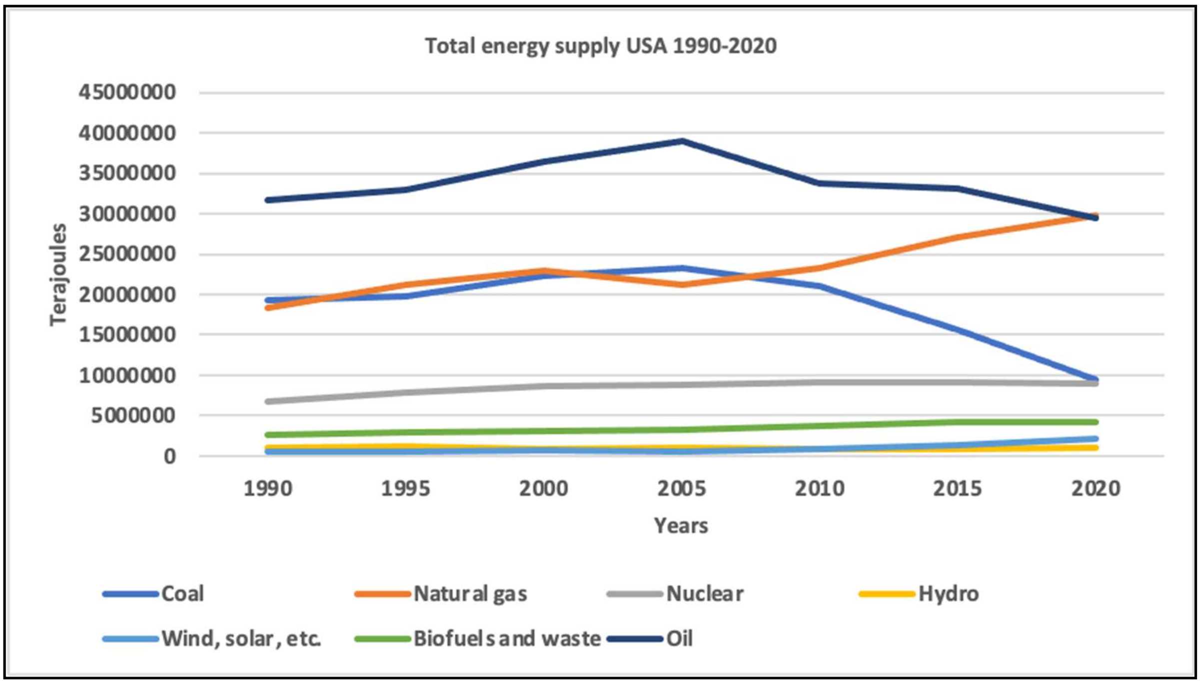

Figure 2.2: Total energy supply (TES) by source for the USA

As can be seen in figures 2.1 and 2.2, which are based on recent IEA data (World Energy Balances China and the USA, 2020), coal and natural gas are predominant fossil fuels in the total energy supply of China and the USA.

2.2 CO_2ERM Concept and Principles

The emission reduction caps in the Kyoto Protocol were applicable to Annex 1 countries (i.e. developed countries) that ratified the Protocol. The constant rise in GHG emissions and the Kyoto experience demonstrate that emission reduction caps do not achieve significant CO_2 emission reduction. As can be seen, this approach has led to a potential scenario that could lead to breach of allowable carbon budgets.

The CO_2ERM model is specific to a BAU CO_2 emission scenario for China and the USA. It hypothetically substitutes the traditional concept of emission reduction targets or caps, which do not appear to be successful. There is evidence that the Kyoto targets promoted non-CO_2 emission reduction for the carbon market and did not deliver CO_2 emission reductions in China and the USA. The emission cap is predetermined, but the nature of emission reduction carried out is driven entirely by market forces, which prefer non-CO_2 emission reduction. Consequently, non-CO_2 emission reduction project developers adopt low-cost and high-volume GHG emission reduction pathways; it is a classic demand and supply scenario.

The term 'legally binding emission reduction targets' has a unique political significance in the USA and China. It has led to resentment and unwillingness to create CO_2 emission reductions. The emphasis on legally binding caps has not created the required momentum to deal with the climate change challenge. The emission reductions caps in the USA and China are widely perceived as interfering with national sovereignty.

In contrast to emission reduction caps, the CO_2ERM model aims to offset the annual increase in CO_2 concentration without the need to comply with politically determined emission reduction targets. The introduction of the CO_2ERM model specifically to CO_2 emissions from coal- and gas-fired power stations will help overcome policy barriers and will generate a momentum to adopt a realistic and credible CO_2 emission reduction strategy. The model is specific to CO_2 emissions from coal- and gas-fired power plants. Non-CO_2 GHG reduction can be delivered by the markets.

The CO_2ERM model creates a national concept to reduce emissions of CO_2. At this stage, there is no national and/or international legislation in place that specifically targets or requires coal- and gas-fired power plants to curb their CO_2 emissions. The CO_2ERM model transfers the burden of emission reduction to the emission sources. CO_2 emission reduction can be made flexible and distributed among the most competitive players in order to achieve cost-effective CO_2 emission reduction by exploiting the fuel mix and thermodynamics of the power stations in China and the USA.

The CO_2ERM model encapsulates total negative externality emerging due to combustion of coal and gas. It reflects the cost of managing the negative externality created by the emission of anthropogenic CO_2. The CO_2 emission reductions can also be achieved by installing renewable energy technology, although the problem with this policy is that renewable energy will not be able to displace high-density coal BAU consumption in the immediate future. Continuous CO_2 emissions will lead to overshoot of the carbon budgets for 1.5^0C, 1.7^0C and 2^0C temperature changes. The CO_2ERM model for China and the USA communicates the urgency required to address the challenge of climate change. The CO_2ERM model assesses the plausibility of CCS as a critical CO_2 emission reduction technology in China and the US. The plausibility of technology deployment is determined by conducting qualitative and quantitative analyses. The CO_2ERM offers significant potential to attain equilibrium between energy generation and carbon budget limitations.

China and the USA both emit more than 1 $GtCO_2$ annually through fossil fuel combustion for power generation. In addition, they create GHG emissions from industry, manufacturing, transportation, land use change and agriculture. The emission trading markets are biased towards the reduction of long-lived GHGs (e.g. fluorinated gases and nitrous oxide). The emission reduction of these gases requires direct point source decomposition. For example, if the market value of 1 tCO_2 is \$16, a reduction of 1 tCO_2 has a market financial value of \$16. The reduction of 1 tonne of SF_6 has a financial value of \$432,000; therefore, the global warming potential (GWP) of SF_6 is 27,000 times more than CO_2. If the reduction of long-lived GHGs can be achieved through point source emission reduction, the reduction of CO_2 emissions can also be achieved at point source. A CCS-based

CO_2ERM model offers a potential solution. CO_2 emission reduction is an economic, technological, political and scientific challenge, and the CO_2 emission crisis at this stage requires a direct approach. The Kyoto Protocol did make significant progress on the issue, but a new approach is required to stabilise the atmospheric concentration of GHGs, especially CO_2.

The CO_2ERM model offers the potential to create additional, credible and verifiable CO_2 emission reduction to support global climate change efforts. It also offers a solution that concentrates global emission reduction efforts on coal- and gas-fired power plants. Unlike the Kyoto multi-gas emission reduction model, the proposed model will not create diverse multi-sectoral emission reduction: the CO_2ERM offers a single gas and energy sector emission reduction solution. The multi-gas model is biased towards reduction of high GWP gases; the proposed CO_2ERM model corrects market bias. The proposed model offers a new approach to the climate change challenge. The supporting arguments are:

- The model targets high-density coal- and gas-based high CO_2 emission BAU scenarios in China and the USA.
- The model focuses on CO_2, without aiming for a binding target.
- The model creates a way forward to integrate China and the USA into world CO_2 emission reduction efforts.
- The model offers unbiased political and geological assessment as part of the solution.
- The model integrates CO_2 emission reduction with stabilisation of atmospheric concentration of CO_2 and the allowable carbon budgets.

The underlying rationale of the model is that large-scale CO_2 emission reduction cannot be delivered by the Kyoto Protocol, Paris Agreement or the Glasgow Climate Pact nor by manipulating carbon emission trading mechanisms. The single-gas model will have automatic additionality as it will be based on CO_2 emission reductions created through avoiding CO_2 emissions from China and the USA only. Automatic additionality emerges from the nature of emission reduction created.

The single-gas model addresses the structural imbalances of the carbon market created by multi-gas abatement mechanisms, i.e. the CDM and the European Union Emissions Trading System (EU ETS). The single-gas model will not be driven by market-based demand and supply constraints but by the allowable carbon budgets for 1.5^{0}C, 1.7^{0}C and 2^{0}C temperature changes.

The single-gas model is independent of the price of carbon, unlike for example in case of Certified Emission Reductions (CERs) in the CDM market. The price of CERs plummeted from $27 to $15–$11 due to the financial meltdown in 2008. During December 2019, the average settled price of CERs by the European Climate Exchange (ECX) was less than 30 euro cents (FairClimateFund, 2019). The model is based on the four principles of atmospheric stabilisation of CO_2 concentrations:

1. **Source Emissions and Source Reduction Equilibrium**

   Emissions occurrence and concurrent reduction should be a complementary process in equilibrium to maintain the homeostasis of atmospheric CO_2 concentration. The annual rise in atmospheric CO_2 concentration due to anthropogenic activities should be stopped.

2. **Irreversible and Additional Reduction**

   The CO_2ERM achieves irreversible and additional emission reduction. As the CCS is deployed, the emission reduction achieved is long term. The emission reduction is additional and cannot take place in the absence of the model. The model achieves strong additionality.

3. **Non-Emission Trading**

   The model is a non-emission trading model. The participating countries cannot trade the emission reductions as a commodity. CO_2 is treated as a non-trading commodity.

4. **Stationary Emission Reduction**

The model creates emission reduction at stationary power plants and industry, as coal- and gas-fired plants are significant drivers of CO_2 concentration increase in the atmosphere.

2.3 CO2 Emission Reduction Model Methodology

They key challenge is to successfully limit climate change to the three temperature targets and concurrently generate affordable energy in China and the USA. The decarbonisation has to be cost effective and sustainable. CCS technology is promoted as a potential solution to decarbonise energy generation. These are direct energy generation emissions that take place in China and the USA. The coal and gas consumption data has been acquired from the EIA for the period 2000 to 2019 and emissions are estimated. The future consumption of coal and gas has been forecasted from 2020 to 2100. CO_2ERM builds on BAU CO_2 emission scenarios and assumes that no CO_2 emission reduction technology will be deployed before 2100 in the USA and China.

2.3.1 Equations of CO_2ERM framework

The CO_2ERM methodology is based on five equations that: estimate the CO_2 emissions from coal and gas combustion from 2000 to 2019 for the BAU scenario; forecast consumption of coal and gas between 2020 and 2100 using a linear regression equation; estimate emissions reduced or avoided in the USA and China by installation of CCS for the forecast years of 2020–2100 (i.e. 80 years); and finally estimate the year of breach or overshoot for the respective carbon budgets of 1.5^0C, 1.7^0C and 2^0C temperature targets.

CO_2 emissions $_{\text{coal and gas 2000 to 2100}}$ =
(BAU and forecast energy consumption $_{\text{coal, gas}}$ x CO_2 emission factor $_{\text{coal and gas}}$)
(Gomez et al., 2006) Equation 1

Where:

BAU = emissions from 2000 to 2019, forecast energy consumption = forecasted energy consumption, coal and gas = two fossil fuels, CO_2 emission factor = total carbon content of coal and gas

Forecasted CO_2 emissions $_{\text{coal and gas for 2020 to 2100}}$ =

$$y = a+bx$$ (Microsoft 365, 2021)

Equation 2

Where:

y is the dependent variable and it is the coal and gas CO_2 emissions from 2020 to 2100

x is the forecast year and is the independent variable

a and b are the intercept and slope in the linear regression

CO_2 emissions $_{\text{coal and gas}}$ reduction by CCS in the USA and China $_{\text{2020 to 2100}}$ =

(Total forecasted $_{\text{2020 to 2100}}$ CO_2 emissions $_{\text{coal and gas}}$ in the USA and China – 80% CO_2 emissions $_{\text{coal and gas}}$ reduction by CCS) Equation 3

Cost of CO_2 emission $_{\text{coal and gas}}$ reduction by CCS =

(CO_2 emission reduced in $GtCO_2$ x cost of CO_2 emission reduction per $GtCO_2$) Equation 4

Year of breach of carbon budget for 1.5^0C, 1.7^0C and 2^0C with CCS in the USA and China =

(Total forecasted world emissions between 2020 to 2100) – (total forecasted emission reduction in the USA and China with CCS) Equation 5

2.3.2 Data typology for CO_2ERM framework

The complete dataset is provided in appendix CO_2ERM. The data typology is as follows in the appendix:

- Equation 1 is based on standard IPCC methodology to estimate CO_2 emissions and other GHG emissions from coal and gas stationary combustion. Equation 2 is based on standard linear regression. Equations 3, 4 and 5 are original.
- The data on coal and gas consumption has been acquired from EIA; it is available for the period 2000 to 2019. The forecasting for the period 2020 to 2100 has been carried out using linear regression based on consumption patterns from 2000 to 2019. The EIA coal and gas data is available in terajoules (TJ).
- In the forecasting equation 2, y is the dependent variable and it is the coal and gas CO_2 emissions from 2020 to 2100, and x is the forecast year and is the independent variable.
- In equation 2, for world coal consumption from 2020 to 2100, the intercept a = -895.2070626 and slope b = 0.453402341. For world gas consumption from 2020 to 2100, a = -346 and b = 0.17579. For China's coal consumption from 2020 to 2100, a = -843.055 and b = 0.42344. For China's gas consumption from 2020 to 2100, a = -63.1399 and b = 0.031553. For the USA's coal consumption from 2020 to 2100, a = 122.92 and b = -0.060201157. For the USA's gas consumption from 2020 to 2100, a = -51.437085 and b = 0.02634714. The details are provided in appendix CO_2ERM.
- The CO_2 emission factors for coal and gas are taken from the IPCC for subbituminous coal and natural gas (Gomez et al., 2006), which are 94,600 kg/TJ and 56,100 kg/TJ, respectively. The IPCC methodology provides a default CO_2 emission factor. It is important to note that the CO_2 emission factor takes into account all the carbon in the fuel that is emitted by the process of combustion of coal and gas to generate energy. CO_2 emission factors for all tiers reflect the full carbon content of the fuel less any non-oxidised fraction of carbon retained in the ash, particulates or soot (Gomez et al., 2006). The CO_2 emissions factor for coal is 1.6 times greater than the CO_2 emissions factor for natural gas.

2.3.3 Assumptions of CO_2ERM framework

The CO_2ERM framework is based on the following set of assumptions (the critical analysis of assumptions and data typology is provided in section 2.8):

- China and the USA will continue to use coal and natural gas for energy generation at a rate of consumption as determined from the consumption patterns for the period 2000 to 2019. This is based on linear forecasting, which is based on patterns of energy generation from coal and gas in the USA, China and the world.
- The world BAU consumption and forecasting has been used to calculate the year of overshoot or breach of the climate change-based carbon budgets for 1.5^0C, 1.7^0C and 2^0C temperature changes.
- The data for coal and natural gas consumption data for energy generation has been acquired from the EIA.
- All coal is assumed to be other bituminous and gas is natural gas. Therefore, the CO_2 emission factor used is for other bituminous coal and natural gas.
- BAU scenarios have been estimated from 2000 to 2019 and forecasted from 2020 to 2100. The EIA data on coal and gas consumption is available up to the year 2019.
- The model estimates emission reduction from coal- and gas-fired power plants by 80% of the BAU emissions in the forecast period of 2020 to 2100. It is assumed that CCS plants will be retrofitted to coal- and gas-fired power plants in the USA and China. We assume that there is no emission reduction in the rest of world and CCS is installed in the USA and China only.
- The geological storage for captured CO_2 emissions from power plants is assumed to be located within a participating country.
- Country-specific plausibility for use of CCS in accomplishing emission reduction is determined by carrying out a technology barrier analysis (TBA). The model builds BAU and emission reduction scenarios. In addition, supporting economic, geological and political assessment is provided.

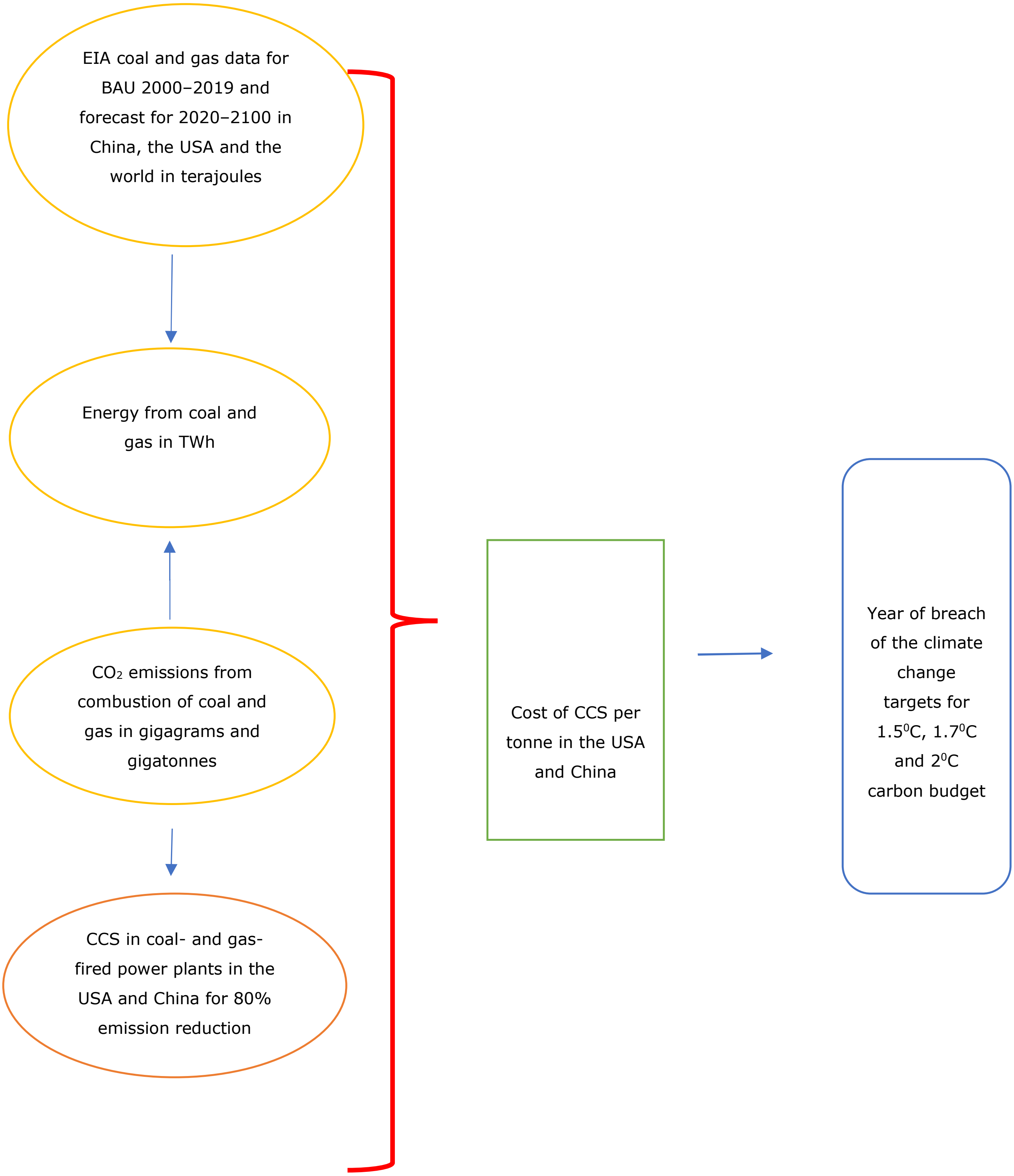

Figure 2.3: CO_2ERM methodology flowchart

A technological barrier analysis is provided in section 2.6.2 and evidence of deployment is shown in section 2.5.

2.4 CO_2ERM Application and Results

The results are based on CO_2ERM equations which are applied to BAU and forecast (FC) scenarios. The complete results are provided in appendix CO_2ERM.

2.4.1 BAU and forecast emission scenarios for China

In the BAU scenario for the year 2000, China combusted coal and natural gas to generate 9,601 TWh and 276 TWh of energy, respectively. The CO_2 emissions from coal and gas in the year 2000 are estimated to be 3.2 $GtCO_2$ and 0.55 $GtCO_2$, respectively. The total emissions were 3.33 $GtCO_2$. In the BAU year 2019, China generated 31,417 TWh of energy from coal and 3,316 TWh from natural gas. The CO_2 emissions are 10.69 $GtCO_2$ and 0.66 $GtCO_2$ from coal and gas, respectively. The total emissions were 11.37 $GtCO_2$.

If the BAU scenario continues, the linear forecast shows that China could generate 116,282 TWh energy from coal in 2100 and generate 17,374 TWh energy from natural gas. The CO_2 emissions from coal could rise to 39.60 $GtCO_2$ and from natural gas to 3.50 $GtCO_2$. The total CO_2 emissions from coal and gas are forecast to be 43.11 $GtCO_2$ in 2100.

The total CO_2 emissions from coal and gas from 2020 to 2100 are forecast to be 2,257 $GtCO_2$. In the CO_2ERM, the CO_2 emission factor for coal is based on other bituminous coal, which is 94,600 kg/TJ. If this emission factor is substituted with the CO_2 emission factor for lignite coal, which has the highest CO_2 emission factor of all coals (101,000 kg/TJ), it will increase the total forecasted emissions (from 2020 to 2100) from 2,257 $GtCO_2$ to 2,398 $GtCO_2$.

If CCS retrofitting was to be successfully carried out on total CO_2 emissions from coal and gas from 2020 to 2100, the total emission reduction could be 1,805.85 $GtCO_2$ for the 80-year period. The forecast shows that China can potentially reduce its total emissions from coal and gas by more than 10 $GtCO_2$ per year. The BAU and forecast scenarios are shown in figure 2.4.

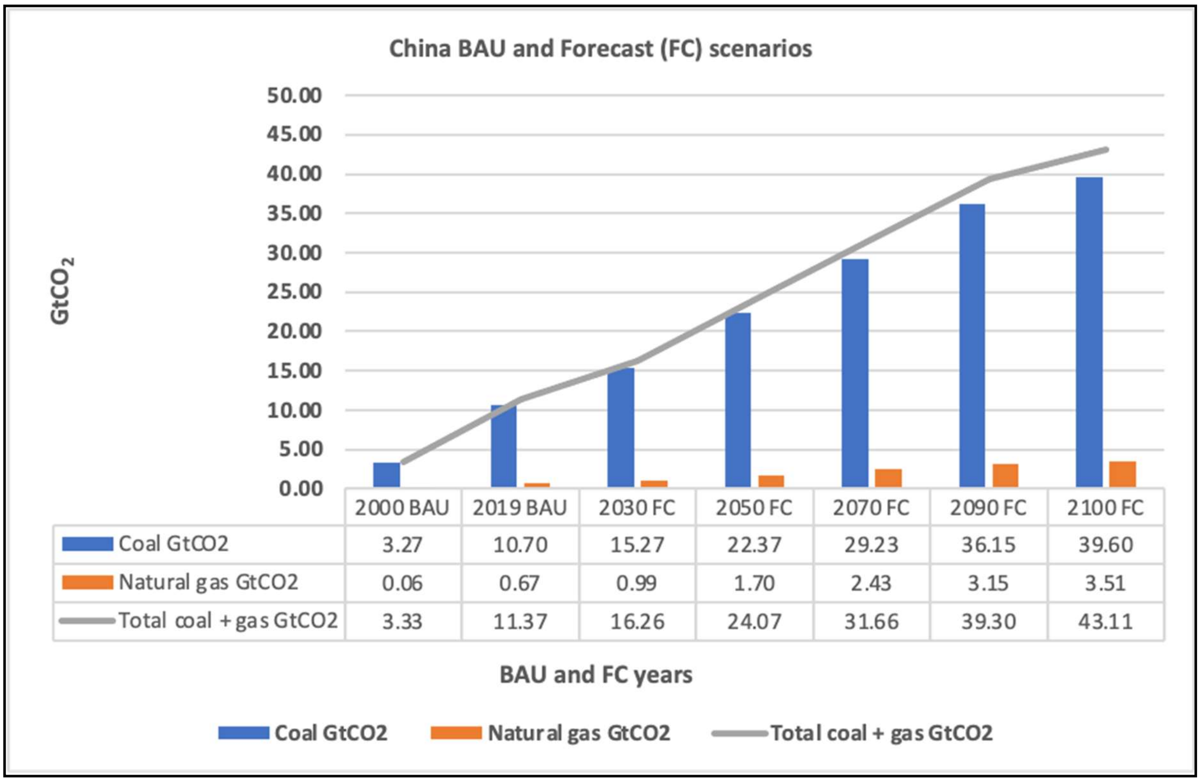

Figure 2.4: BAU and forecast scenarios for China

2.4.2 BAU and forecast scenarios for USA

In the BAU scenario for the year 2000, the USA combusted coal and gas to generate 6,786 TWh and 6,982 TWh of energy, respectively. The CO_2 emissions from coal and gas in the year 2000 are estimated to be 2.31 $GtCO_2$ and 1.41 $GtCO_2$, respectively. The total emissions were 3.72 $GtCO_2$. In the BAU year 2019, the USA generated 3,303 TWh of energy from coal and 9,435 TWh from natural gas. The CO_2 emissions are 1.13 $GtCO_2$ and 1.91 $GtCO_2$ from coal and gas, respectively. The total emissions were 3.03 $GtCO_2$.

If the BAU scenario continues, the linear forecast shows that the USA could end the use of coal by 2037. In 2100, the USA is forecast to generate 22,100 TWh energy from natural gas. The CO_2 emissions from natural gas are forecast to be 4.46 $GtCO_2$.

The total CO_2 emissions from coal and gas from 2020 to 2100 are forecast to be 265 $GtCO_2$. In the CO_2ERM, the CO_2 emission factor for coal is based on other bituminous coal, which is 94,600 kg/TJ. If this emission factor is substituted with the CO_2 emission factor of lignite coal, which has the highest CO_2 emission factor of all coals (101,000 kg/TJ), it will increase the total forecast emissions (from 2020 to 2100) from 265 $GtCO_2$ to 266 $GtCO_2$.

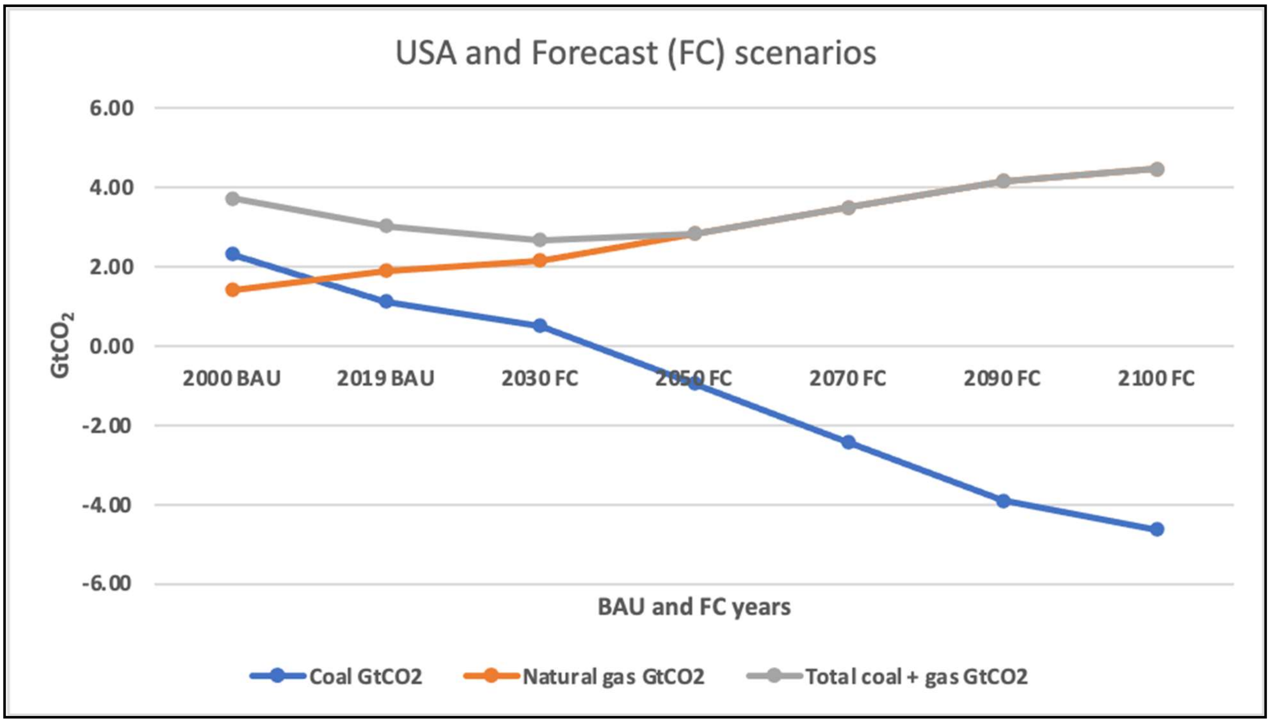

Figure 2.5: BAU and forecast scenarios for the USA

If CCS retrofitting was to be successfully carried out on total CO_2 emissions from coal and gas from 2020 to 2100, the total emission reduction could be 212 $GtCO_2$ for the 80-year period. The forecast shows that the USA can potentially reduce its total emissions from coal and gas by more than 2 $GtCO_2$ per year. The BAU and forecast scenarios are shown in figure 2.5. The forecast shows that the USA could phase out coal from 2037 onwards.

2.4.3 BAU and forecast scenarios for the world

In the BAU scenario for the year 2000, the world (including the USA and China) combusted coal and gas to generate 31,695 TWh and 26,261 TWh of energy, respectively. The CO_2 emissions from coal and gas in the year 2000 are estimated to be 10.79 $GtCO_2$ and 5 $GtCO_2$, respectively. The total emissions were 16.10 $GtCO_2$. In the BAU year 2019, the total emissions from coal and gas are estimated to be 27.20 $GtCO_2$. If the BAU scenario continues, the linear forecast shows that the world could generate 137,525 TWh energy from coal in 2100 and generate 113,661 TWh energy from natural gas. The CO_2 emissions from coal could rise to

46.84 $GtCO_2$ and from natural gas to 23 $GtCO_2$. The total CO_2 emissions from coal and gas is forecast to be 69.79 $GtCO_2$ in 2100. The total CO_2 emissions from coal and gas from 2020 to 2100 is forecast to be 3,997 $GtCO_2$. The BAU and forecast scenarios for the world are shown in figure 2.6.

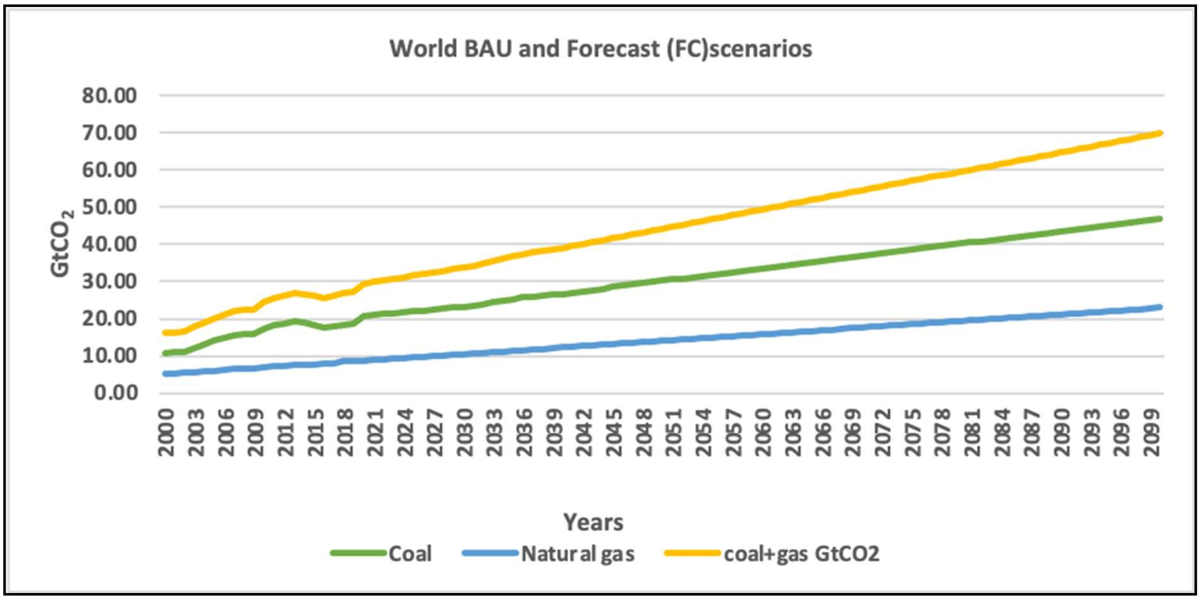

Figure 2.6: BAU and forecast scenarios for the world

These results show if the world's BAU scenario continues, the forecasted total emissions of 3,997 $GtCO_2$ will add 515 ppm of CO_2 to the atmosphere by 2100. The carbon budgets for 2100 temperature targets of 1.5^{0}C, 1.7^{0}C and 2^{0}C are 500 $GtCO_2$, 850 $GtCO_2$ and 1,350 $GtCO_2$, respectively. The above evidence supports the case for deploying CCS as an emission reduction technology at coal- and gas-fired power plants that are used for energy generation. The cost of emission reduction is the cost of managing the negative externality caused by combustion of fossil fuels.

2.4.4 Carbon budget: years of breach before and after CCS

In section 1.6, it was highlighted that the verified total of world fossil fuel emissions in 2019 from energy generation was 33.66 $GtCO_2$. In the CO_2ERM, it is estimated that world emitted 27.20 $GtCO_2$ in the year 2019 from combustion of coal and gas. The linear forecast of the CO_2ERM estimates that the world's coal and gas emissions in the year 2100 will increase to 69.79 $GtCO_2$. The cumulative forecast for the world's CO_2 emissions from coal and gas from the year 2019 to 2100 is 3,997 $GtCO_2$. This is the situation if no emission reduction takes place. The allowed carbon budgets for the 2100 temperature targets of 1.5^{0}C, 1.7^{0}C and 2^{0}C are 500 $GtCO_2$, 850 $GtCO_2$ and 1,350 $GtCO_2$, respectively. Table 2.1 summarises the results and estimates the year of breach or overshoot of allowed CO_2 budgets. The table presents the year of breach or overshoot with and without the use of CCS in China and the USA. As can be seen in the table, the cumulative emissions without any emission reduction or CCS in the top emitters will result in breach of carbon budgets by 2056. If CCS is installed in China and the USA, the breach of carbon budgets is delayed by 10-22 years. A 100% successful CCS in the USA and China will delay the breach of carbon budgets to 2046 or 2078. The complete dataset and results are provided in appendix CO_2ERM.

Table 2.1: Results of CO_2ERM with and without CCS, carbon budgets and years of overshoot

Forecast world emissions: without CCS in the USA and China (2020–2100)	Potential year of breach of carbon budgets: without CCS in China and the USA (2020–2100)	Forecast world emissions: with CCS in the USA and China (2020–2100)	Potential year of breach of carbon budgets: with CCS in China and the USA (2020–2100)
3,997 $GtCO_2$	1.5^{0}C 500 $GtCO_2$ = year 2034–2035 1.7^{0}C 850 $GtCO_2$ = year 2043–2044 2^{0}C 1,350 $GtCO_2$ = year 2055–2056	1,978 $GtCO_2$	1.5^{0}C 500 $GtCO_2$ = year 2045–2046 1.7^{0}C 850 $GtCO_2$ = year 2057–2058 2^{0}C 1,350 $GtCO_2$ = year 2077–2078

2.5 CCS Technology Description

CCS has been actively promoted as a solution to reduce CO_2 emissions from the energy, oil and gas, and cement industries. It has received attention and funding from governments in the USA and has also been assessed as a direct carbon removal technology (CDR). During recent times, CCS has been promoted as a CDR for generation of blue hydrogen from natural gas. For example, the Zero Carbon Humber consortium in the United Kingdom (UK) is working to deliver low carbon hydrogen and CCS to create a zero-carbon industrial cluster in the UK. The project is funded by the UK government (Zero Carbon Humber, 2021) as part of its pledge to meet the targets of the Paris Agreement. The project is run by Equinor (formerly Statoil) at its site in the Humber in the UK. CCS projects have been implemented in a few countries since the 1990s. CCS projects have been set up experimentally at large-scale power plants. Industrial CCS plants have been deployed at pilot scale and enhanced oil recovery (EOR) projects have also been deployed (MIT CCS Project database, 2016).

2.5.1 Process description

According to the IPCC report, CCS captures 85–95% of CO_2 emissions, and a power plant with CCS installed would consume an additional 10–40% more energy (Metz et al., 2005).

The most famous CCS project was implemented by Statoil (now called Equinor) in Norway; it captured CO_2 emissions using an amine-based capture process. The plant sequesters CO_2 emissions from natural gas (Statoil, Sleipner Vest; 2020). The natural gas at Sleipner contains 9% CO_2. In 1991, the Norwegian authorities introduced a CO_2 offshore tax, with the aim of reducing CO_2 emissions. The tax break, at $50/tonne, generated an incentive for Statoil to remove the CO_2 offshore and inject it into a deep geological layer below the offshore Sleipner platform. This geological layer, known as the Utsira Formation, is based on porous sand rock filled with saltwater, and it stores CO_2 for thousands of years. CO_2 is prevented from seeping into the atmosphere by an 800-metre-thick cap rock. The tax incentive meant a reduction in CO_2 emissions of nearly 1 million tonnes per year, which was roughly 3% of Norwegian CO_2 emissions in the year 1990. The injection of CO_2 costs 17/tCO_2 (Sleipner Fact Sheet, 2016). The field became operative in October

1996. This was the world's first offshore CO_2 capture plant, together with the world's first CO_2 storage project in a geological layer 1,000 metres below the sea floor.

CCS is a chemical and geo-engineering technology that can potentially create large-scale CO_2 emission reduction in power plants that run on coal and natural gas. The technology has been piloted and demonstrated in the USA and Europe. It is being supported by the US Department of Energy, the EU, the World Coal Institute and the IEA. At this stage, CCS is being promoted as an essential technology to secure the future of natural gas.

The technology involves the separation of CO_2 gas from other gases and the transportation of CO_2 gas to secure geological storage. The captured CO_2 emissions are compressed and transported to geological formations. The most critical and expensive step in the CCS process is the capture of CO_2 emissions. The three processes of carbon capture are (Metz et al., 2005; Singh et al., 2011; McKinsey, 2008):

1. Pre-combustion capture.
2. Post-combustion capture.
3. Oxyfuel combustion capture.

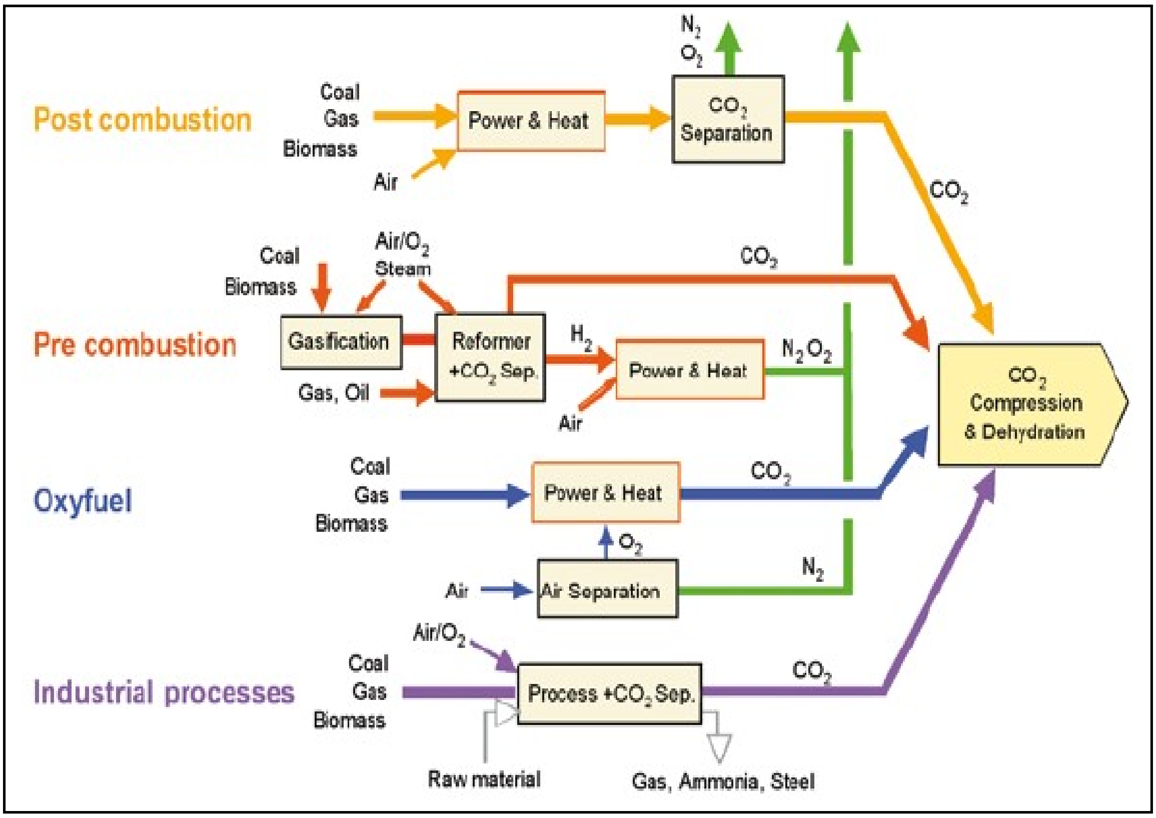

Figure 2.7: CO_2 emission capture process

Source: Metz et al. (2005)

Pre-combustion capture involves a process of fuel and oxygen/air/steam reaction to produce a synthetic gas, which is a mixture of carbon monoxide and hydrogen. The carbon monoxide is passed through a catalytic shift converter to produce CO_2 and Hydrogen (H_2). The CO_2 is removed by physical and chemical separation. The remaining fuel is hydrogen rich and can be used to run boilers and turbines.

The reactions involved are (Metz et al., 2005):

$$C_xH_Y + x\,H_2O \longrightarrow x\,CO + (x+y/2)\,H_2 \quad \Delta H\ +ve$$

$$C_xH_Y + x/2\,O_2 \longrightarrow x\,CO + (y/2)\,H_2 \quad \Delta H\ -ve$$

$$CO + H_2O \longrightarrow CO_2 + H_2$$

The concentration of CO_2 in the CO_2 + H_2 can range from 15% to 65% and the pressure from 2 to 7 MPa. The separated CO_2 is available for storage. Pre-combustion technology produces a carbon-free hydrogen fuel.

Removal of CO_2 takes place in the integrated gasification combined cycle (IGCC) combustion of coal. Both pre-combustion and IGCC are available technologies. The IPCC report indicates that there were only four GW IGCC operational plants at the end of 2007. To use pre-combustion, the turbine needs to function in a hydrogen-rich environment (Metz et al., 2005). The key modern concepts that can allow deployment of pre-combustion CCS are in development. For example, deployment of a carbon molecular sieve, membrane reactor and an adsorption reactor are important in integrating coal-fired power plants with CCS (Compendium of Carbon Capture, 2020; Tsotsis, 2019). This technology is in development and can reduce the energy penalty of cost of CCS projects by 30% and increase the capture of power plant CO_2 by 95%.

In a coal-fired power plant, hydrogen has to be manufactured from coal using the process of gasification. The IPCC reports a base case design, where syngas ($CO + H_2$) is produced. H_2 is removed by a solvent, Selexol, and removal of CO_2 also takes place using Selexol (Metz et al., 2005). The CO_2 is compressed at 150 atmospheres for subsequent transportation and storage. The pre-combustion process can also be used with natural gas. At this stage there appears to be no evidence that a coal-based IGCC plant has been retrofitted with CCS technology. It can be claimed with certainty that the technology is available; for example, coal-based synfuels (Fischer-Tropsch fuels) have been produced on a commercial scale in South Africa (Metz et al., 2005). Synfuel from coal has also been produced in North Dakota, and since 2000, 1.5 $MtCO_2$/year has been transported 300 km to the Weyburn Oil Field in Saskatchewan for enhanced oil recovery (EOR) with CO_2 storage (Metz et al., 2005). Pre-combustion capture incurs an energy penalty to generate physical solvents, such as Selexol (Cuéllar-Franca and Azapagic, 2015).

Post-combustion capture is strategically most relevant to the CO_2ERM model. The post-combustion process can capture CO_2 from any fossil fuel type. The IPCC report on carbon capture and storage quotes the work of Hendriks (1994) and Riemer and Ormerod (1995). According to this work, post-combustion based on absorption processes from solvents is the preferred option. The absorption process has now reached the required commercial scale. In post-combustion absorption, the flue gas is cooled and catalysed by a solvent. The solvent contains flue gas CO_2 and is fed to a stripper. Chemical regeneration is carried out and this creates an energy penalty, further creating desorption heat to remove CO_2 and, consequently, the CO_2 leaves the stripper. CO_2 capture can be in the range 80–95%. Post-combustion capture using absorption is suitable for CO_2 due to its partial pressure of 3–15 kPa. At this pressure, amines are the most suitable absorption solvents. The additional energy is required to regenerate the solvent and to operate liquid pumps and blowers. The three absorption processes that are commercially available for CO_2 capture are: the Kerr-McGee/ABB Lummus Crest process; the Fluor Daniel process; and the Kansai Electric Power process. The relevant absorption for the model appears to be the Kerr-McGee/ABB Lummus Crest Process as it captures CO_2 from coke- and coal-fired boilers and uses mono-ethanolamine (MEA) as a catalyst (Metz et al., 2005). However, MEA absorption is highly energy intensive and not economically viable for all industries (Kuramochi et al., 2012). Mitsubishi Heavy Industries developed a propriety solvent, called KS-1, to be used for carbon capture in coal-fired power plants. In 2008, Mitsubishi demonstrated CO_2 recovery at 1000 MW at Matsushima power station. The project achieved successful test operations of CO_2 at a coal-fired flue gas stream (Kishimoto et al., 2009).

The drawback of post-combustion capture appears to be a high energy requirement to run the solvent regeneration process. A solution to this problem would be to create an additional power unit to retrofit the power plant (Metz et al., 2005). Emerging post-combustion technology involves flue gas CO_2 capture using a molecular sieve or an activated carbon adsorption process. Desorption is carried out using a pressure swing and temperature swing operation (Metz et al., 2005). The IPCC's assessment of post-combustion CO_2 capture is that post-combustion is a proven technology, although the technology does require scaling up to 20 to 50 times for installation in power plants. The IEA considers post-combustion capture to be a current technology (IEA, CO_2 Capture and Storage, 2008).

At the same time, novel concepts on post-combustion are in process of being developed. For example, to reduce the cost of CO_2 capture, Micro-Encapsulated CO_2 Sorbents (MECS) can create a favourable thermodynamic CO_2 capture process (Compendium of Carbon Capture, 2020; Tsotsis, 2019). The key element is the creation of a MECS shell, which has high permeability for CO_2. Two commercial silicones have been identified as promising shell materials (Semicosil 949 and

Tego-Rad 2650). The energy penalty of MECS is low, as they allow a reduction in energy penalty to as low as 11% (Hornbostel et al., 2019).

The oxyfuel process combusts coal with pure oxygen or a mixture of pure oxygen and CO_2-rich flue gas. The flue gas contains 80–98% CO_2 depending on the type of fuel used. The CO_2 is transported during a super critical phase and CO_2 capture efficiency is almost 100%. The IEA considers the oxyfuel process to be at the early stages of development. The IPCC report on sequestration cites the work of Wilkinson (2003), which indicates that the oxyfuel process can be deployed as a retrofit in power plants.

2.5.2 Transport and geological storage

The transport of captured CO_2 is not a new technology and has been taking place since the mid-1980s. The longest CO_2 pipeline is the 502-mile Cortez Pipeline, which delivers 20 metric tonnes of CO_2 to the CO_2 hub at Denver City in Texas. In the USA, there are 3,900 miles of CO_2 pipeline available for EOR (Forbes et al., 2008). The combined length of CO_2 pipelines in the USA is 4,500 miles (Wallace et al., 2015). The location and distribution of CO_2 transport pipelines is determined by the natural geological potential available to store captured CO_2. Captured CO_2 is compressed to a supercritical phase and is transported at temperatures of 55–110 °F and at a pressure of 1,250 psi (Forbes et al., 2008).

Storage of the transported CO_2 is the most important part of the process. The CCS exploits the natural capacity of the Earth's geology to store carbon. Carbon is stored within the Earth's surface naturally in the form of fossil fuels, methane hydrates and soil organic carbon. The unique aspect of anthropogenic storage is that it will require suitable geological formations to securely store captured CO_2. The storage of anthropogenic CO_2 was first proposed in 1970 by several researchers, namely Marchetti in 1977 and Baes et al. in 1980 (Metz et al., 2005).

Storage is schematically represented in the figure below and has been adapted from the IPCC's CCS report. Geological storage of CO_2 takes place at a supercritical state. The geothermal gradient determines the depth at which CO_2 turns supercritical, generally at a depth of 800m or more. Geological storage can take place within a variety of geological formations.

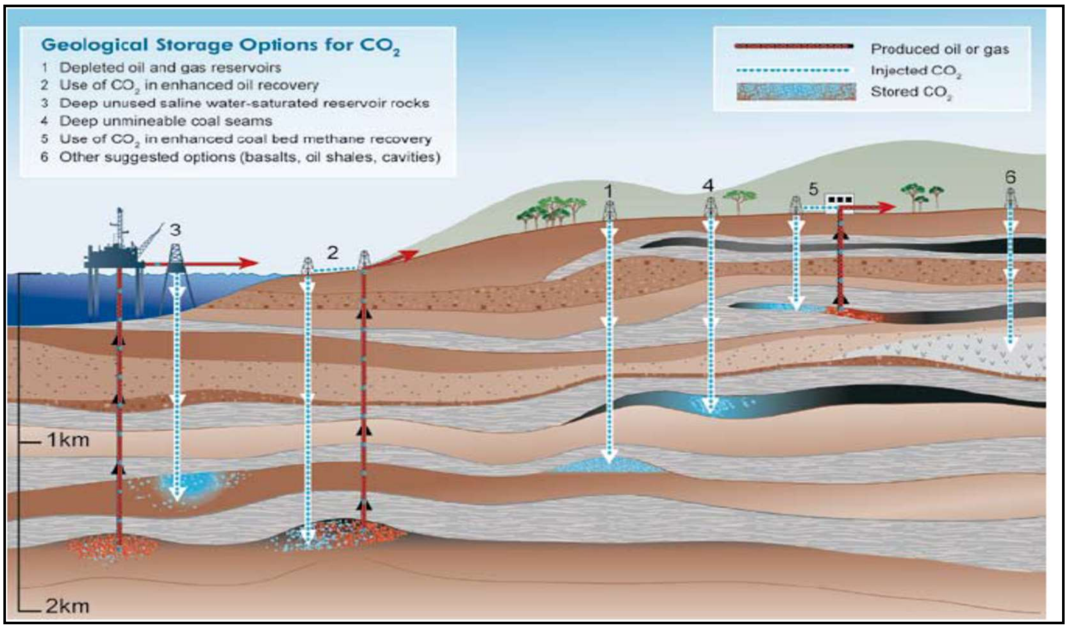

Figure 2.8: Geological storage options

Source: Metz et al. (2005)

The IEA report on CO_2 geological storage indicates that depleted oil and gas fields are the best locations to store anthropogenic CO_2. The second-best choice is within deep saline formations. There are many examples of CO_2 geological storage, for example, the In Salah CO_2 geological storage project in Algeria (Metz et al., 2005). This project is jointly run by BP, Sonatrach and Statoil and involves re-injecting the CO_2 into a sandstone reservoir at a depth of 1,800 m, enabling the storage of 1.2 $MtCO_2$/year. Injection began in April 2004 and the project will eventually store an estimated 17 $MtCO_2$. It is believed that 3.8 $MtCO_2$ has already been sequestered in the subsurface. The CO_2 sequestration performance was monitored using monitoring techniques, such as the time-lapse seismic- micro-seismic methods, wellhead sampling of CO_2, borehole logging, groundwater monitoring, and satellite data. The CO_2 is transported and stored underground in the 1.9 km deep Carboniferous sandstone (Ringrose et al., 2013).

The storage of anthropogenic CO_2 takes place by the injection of CO_2; the increase in pressure allows CO_2 to enter the pore spaces. The primary flow and transport of CO_2 is dependent on: pressure and hydraulic gradients; differences in buoyancy of fluids and CO_2; and mineralisation, dispersion and diffusion (Metz et al., 2005).

In addition, adsorption of CO_2 to organic material influences the process of storage of CO_2. The CO_2 in a gas reservoir creates a single miscible phase of CO_2. When CO_2 is injected into a deep saline formation it forms a liquid supercritical immiscible phase. The CO_2 in the oil bed can be miscible or immiscible depending on the geochemical composition and conditions. If CO_2 is injected into a coal bed, adsorption and desorption of CH_4 takes place and the coal swells or shrinks (Metz et al., 2005). The general criteria that are used to select and characterise a site for geological CO_2 storage are:

- Tectonic activity and associated seismology.
- Storage efficiency, determined by the amount of CO_2 stored per unit volume.
- The temperature of the geological formation; cold sedimentary formations are more suitable, as CO_2 attains higher density at a shallower depth.
- Geothermal and hydrodynamic regimes; the effective porosity is vital, as porosity influences storage capacity and efficiency.
- Basin geology formation and geochemistry.

Sedimentary basins are considered suitable, as they offer stability due to their location on the Earth's continental plates. Such basins are present in the Indian, Atlantic and Arctic Oceans. The storage potential of basins formed by tectonic collision is also considered to be suitable. These basins include: the Appalachian and Andean basins, the Alps, the Carpathians, the western Urals, the Zagros and the Himalayas.

The tectonic basins in the Pacific are not considered suitable due to the potential of CO_2 leakage during seismic activity. Figures 2.8 and 2.9 indicate the location of suitable geological formations for storage of anthropogenic CO_2.

According to the IPCC, depleted oil and gas fields are the ideal locations for CO_2 storage.

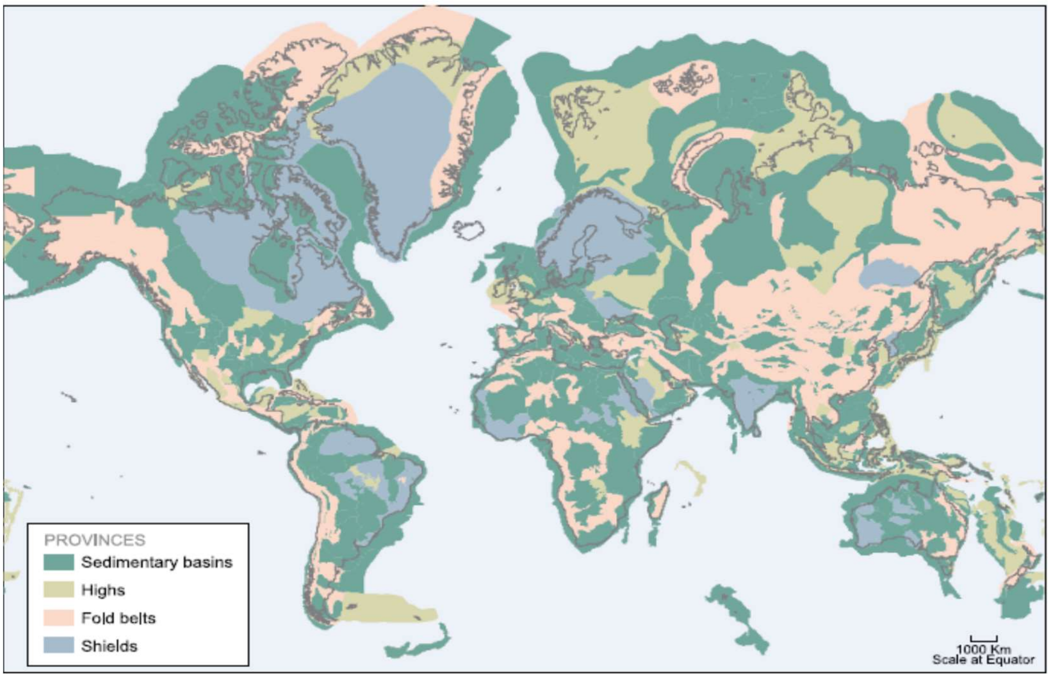

Figure 2.9: Storage location options

Source: Adapted from Metz et al. (2005)

Table 2.2: World geological storage options

Reservoir type	Lower estimate storage capacity ($GtCO_2$)	Upper estimate storage capacity ($GtCO_2$)
Oil and gas fields	675	900
Unmineable coal seams	3–15	200
Deep saline formations	1,000	Uncertain

Source: Adapted from Metz et al. (2005)

The United States Geological Society has carried out research into geological feasibility for CO_2 storage in the USA and has created a geochemical database of 70,000 wells within the USA (Burruss et al., 2009). The database will be valuable in determining the salinities and effective storage capacity of geological formations in the USA. For China, the IEA carried out a study on CCS retrofit in existing coal-fired power plants, the results of which revealed that 385 GW from coal-fired power plants can find storage capacity within a 250-kilometre radius of the plant location (Bennet et al., 2016).

2.5.3 Capture and storage economics

Cost studies detailing the financial aspects of CCS as emission reduction technology are very restricted. The major important work was carried out by the IPCC in 2005. Their research indicated that there was significant uncertainty in determining the cost of CCS due to the diversity and complexity technical processes and the nature of fuel and plant thermodynamic performance. The cost capture and sequestration is dependent on plant performance and plant thermodynamic performance.

The majority of the cost estimations are in reality based on the experience of CO_2 storage in EOR projects and therefore are not accurate for academic research. The cost and financial assessment from pilot studies at coal- and gas-fired power plants and the demonstration of CO_2 capture and storage is not available publicly due to their huge commercial significance. McKinsey & Company published a report called 'Carbon Capture and Storage: Assessing the Economics' in 2008/09, which detailed the cost implications of CO_2 capture. The report was prepared with the help of Alstom, Vattenfall, Shell and Enel. The McKinsey report indicated that the cost of CCS for the first commercial projects would be €35–€50($39–$56)/tCO_2 emission reduction. Capture cost is the most significant cost: €30/tCO_2 captured. The second most expensive aspect of CCS is storage: €10($11)/t$CO_2$ stored. The cost of transport of supercritical CO_2 is €5($6)/t$CO_2$. This cost is based on an injection depth of 1,500 m and transport over a distance of 200–300 km and is also based on capture cost, which includes the cost of investment as well as operating and maintenance costs (McKinsey, 2008).

CCS cost can be measured as 'captured cost' and/or 'avoided cost'. The latter is considered the best measure of the cost of emission reduction.

Avoided cost is a concept: the CCS process consumes additional energy and, as a result, there is increased fuel (coal/gas) consumption. Consequently, the amount of CO_2 emitted by a power plant with CCS is greater than by one without CCS installed. To determine emission reduction, CO_2 emissions from CCS-based coal- and gas-fired power plants need to be compared to those without CCS installed. The difference between them is called 'avoided emissions'. Unless the energy requirements of CCS are zero, the amount of CO_2 avoided is always less than the amount of CO_2 captured. The cost in avoided costs is greater than that of captured cost (Metz et al., 2005). The IPCC prefers to use the avoided cost and also distinguishes between the cost of CO_2 emission reduction through the retrofitting of CCS at existing power plants and the creation of new power plants with a CCS facility installed. The comparative costs are given in Table 2.3 below.

Table 2.3: Costs of CCS

Source	Avoided cost ($/t$CO_2$)
McKinsey capture cost in for new plant	43–61
IPCC capture cost in for pulverised coal fuel plant as retrofit, without cost of storage	31–56
IPCC avoided cost in for pulverised coal fuel plant as retrofit, without cost of storage	45–73
IPCC pulverised coal new plant avoided cost	30–70
IPCC IGCC pulverised coal avoided cost	30–70
Boundary Dam cost	45

Source: McKinsey (2008) and IPCC CCS Report (CCUS, 2020)

The IPCC report for a retrofit scenario on existing power plants indicates that the capture cost of 1tCO_2 in a coal-fired power plant can range from $31 to $56. The avoided cost for the same scenario is $45 to $73. In the case of new plants fired by pulverised coal, the avoided cost ranges between $30 and $70. These are costs in 2008.

In 2018 work carried out by Durmaz (2018) on the economics of CCS, two important factors were identified for a successful price and cost management of CCS. The first is the need for a CO_2 tax, to reduce the emissions from power plants. A tax of $47/t$CO_2$ will be needed to undertake successful CCS-based emission reduction at a commercial scale. The second is learning by doing; for example, the

CCS project by SaskPower at Boundary Dam achieved CO_2 emission reduction at \$38.6/tCO_2. The IEA study on CCS retrofit in China (Bennet et al., 2016) revealed that CCS cost in China can vary significantly. For example, the cost can vary between \$29 and \$129 per MWh of power generated from a coal-fired power plant. Additionally, other research (Lockwood, 2021) shows the future capture cost for next generation coal-fired retrofit plants is \$45/tCO_2. At the same time, the avoided cost of CO_2 for retrofit projects in North America is expected to be \$60–\$80/tCO_2. In the case of China, new retrofit opportunities have been found with an avoided cost of \$30/tCO_2.

2.5.4 Evidence of deployment

There is evidence of CCS deployment across the USA and China. CCS is predominantly being deployed in oil and gas fields as part of EOR or is being deployed if the fossil fuel subsidy and tax supports carbon sequestration. There is also evidence that CCS is being deployed at fossil fuel-fired power plants in the USA and China. Table 2.4 provides examples relating to the evidence of CCS deployment in the USA and China.

The table reveals that power utilities and oil and gas companies in the USA and China are working towards deployment of CCS. CCS is being deployed to reduce CO_2 emissions from coal and natural gas power stations. There are CO_2-only storage projects scattered around the world, run by oil and gas companies such as Statoil and Chevron-Texaco, all of whom are involved in EOR and offshore CO_2 storage. EOR is a technique that enhances the recovery of oil from depleting oil fields. EOR allows for more oil extraction, which eventually produces more CO_2.

The most interesting news about CCS is from the UK, where Equinor (formerly Statoil) has announced the production of natural gas in combination with CCS. The project is called Hydrogen to Humber Saltend (H2H Saltend). It is claimed the project will reduce the amount of CO_2 emitted per year by 900,000 tonnes of CO_2 (H2H Saltend 2020). The hydrogen from natural gas is also called blue hydrogen. The CCS industry is actively promoting CCS as a technology to help the world meet the 1.5^{0}C, 1.7^{0}C, and 2^{0}C temperature targets and stay within their respective carbon budgets. At the same time, new scientific evidence shows that blue hydrogen combustion produces 20% more GHGs compared to natural gas or coal

(Jacobson and Howarth, 2021). The Shenhua Group is one of the biggest coal suppliers in the world and is investing in coal-based CCS in China; the Shenhua Ordos Basin CCS demonstration project was started in 2014 (Xiuzhang, 2014).

Table 2.4: Evidence of CCS deployment in the USA and China

Project name	Location	Feedstock	Size (MW)	Capture process	Start-up date
AEP Alstom Mountaineer	USA	Coal	30	Post-combustion	2008
GreenGen	China	Coal	250/800	Pre-combustion	2009
Williston	USA	Coal	450	Post-combustion	2009–2015
Kimberlina	USA	Coal	50	Oxyfuel	2010
NZEC	China	Coal	Undecided	Undecided	2010
WA Parish	USA	Coal	125	Post-combustion	2012
Appalachian Power	USA	Coal	629	Pre-combustion	2012
Boundary Dam (Canada)	Canada/USA	Coal	139	Post-combustion	2017
Petra Nova	USA	Coal	240	Post-combustion	2018
China Huaneng Shanghai	China	Coal	845	Post-combustion	2008
China Huaneng Tianjin	China	Coal	400	Not known	2011
Shenhua	China	Coal	Not known	Not known	2010
Chongqing Shuanghuai Thermal Power Plant	China	Coal	300	Not known	2010

Source: MIT CCS database 2016, Beck (2020), Boundary Dam factsheet (2014-16), CCS in China (2021)

2.6 CO_2ERM Validation and Barrier Analysis

This section compares the forecasted CO_2 emissions estimated by the CO_2ERM with the emission scenarios in the IPCC SRES (Special Report on Emission Scenarios) and the Representative Concentration Pathway (RCPs) scenarios AR5 report. The IPPC SRES is a group of 40 different emission scenarios. In this section we have used SRES scenarios A1 and A2 to compare the emission forecast of SRES with the emission forecast of CO_2ERM. This section also contains a qualitative geological and technological barrier analysis for CCS deployment in the USA and China.

2.6.1 CO_2ERM validation

The A1 world SRES scenario is a rapid economic growth scenario. The cumulative CO_2 emissions (Nakicenovic et al., 2000) in this scenario range from 1,000 GtC to 2,500 GtC. As 1 GtC = 3.66 GtCO_2, the A1 SRES CO_2 emissions would be 3,660–9,150 GtCO_2 towards the year 2100. The CO_2ERM forecast is based on a linear fuel consumption projection for the world, and the forecast scenario is that from 2020 to 2100, the world could emit 3,997 GtCO_2 from consumption of coal and gas. The forecast scenario of CO_2ERM is within the range of the SRES A1 scenario. In the A2 SRES scenario, global cumulative emissions are 1,710–1,860 GtC by the year 2100, emitting 6,258–6,807 GtCO_2. The CO_2ERM forecast scenario is that from 2020 to 2100, the world could emit 3,997 GtCO_2 from consumption of coal and gas. The A2 SRES scenario assumes continued dominance of fossil fuels, and with coal gaining a leading role. The CO_2ERM emission projections are within the range of SRES projections. No policy or technology intervention has been assumed in the CO_2ERM.

The RCPs described in the IPCC Fifth Assessment report (Pachauri and Meyer, 2014) outline four scenarios for the 21^{st} century. The RCP 2.6 is a GHG mitigation scenario, the RCP 4.5 and RCP 6.0 are intermediate scenarios, and the RCP 8.5 is a high GHG emission scenario. The forecast scenario of CO_2ERM is within the range of RCP 4.5 to RCP 6.0. In these RCP scenarios, the annual GHG emissions could be 40–60 GtCO_2e. In the CO_2ERM, the annual world CO_2 emissions from consumption of coal and gas could reach up to 69 GtCO_2 per year.

2.6.2 Technology barrier analysis

The CO_2ERM forecast shows that China's energy consumption from coal and gas will continuously increase. The results mean that China will remain the biggest emitter of CO_2 emissions.

China's eleventh Five Year Plan aimed to create renewable electricity for 3.5 million homes in rural China (IEA, China Power Sector Reforms, 2006). China's fourteenth Five Year Plan, from 2021 to 2025, aims to cut energy consumption per unit of GDP and also cut CO_2 emissions per unit of GDP. China will increase its nuclear power capacity by 40%, to 70 GW. The plan promotes the efficient use of coal (Cooper, 2021). China will not phase out coal. China's State Power Corporation is the dominant energy supplier in the country. Chinese electricity generation and transmission is highly subsidised and is priced below the cost of generation and transmission. The rate of coal subsidisation in China is 9 CNY (Chinese Yuan) to 26.8 CNY per metric tonne of coal in 2013 (Xiang and Kuang, 2020). The low price of electricity has played a significant part in sustaining China, with an average growth rate of 9.5% in the last two decades, and the Chinese electricity industry relies on the supply of a highly subsidised rate of electricity, achieving significant competitive advantage over competitors in other parts of the world. The most recent data on China from the EIA shows that coal supplied 58% of China's total energy consumption in 2019. China's coal consumption grows by 1% each year. China plans to reduce coal use in the domestic residential heating sector and ultimately phase it out. It will be substituted by natural gas (China Analysis EIA, 2020).

To create CO_2 emission reduction, China will need to reform its electricity pricing structure. The additional CNY/kWh needed for CCS could be added to large energy consumers and a competitive power tariff structure could be implemented. In the absence of subsidy reform, Chinese CO_2 emissions will continue to increase, as has been demonstrated in the CO_2ERM forecast scenarios. The Chinese manufacturing industry would need to pay for the cost of CO_2 emission reduction. This cost could be levied as a carbon tax, or the standard power tariff could be increased to pay for the emission reduction. The subsidised power tariffs are not sustainable, as has already been experienced in Europe.

A subsidy reduction in order to adapt energy policy to address climate change is not a priority for China. China's significant manufacturing capacity appears to be critical for world financial stability, and low-cost manufacturing in China has led to a significant increase in living standards for people across the world. In addition, China supplies international money markets with significant funds to maintain the supply of capital, as witnessed during the financial crisis in 2009 and the coronavirus crisis in 2019–2021. It would be difficult for China to remove energy and economic barriers to drastically phase out coal. However, the technology transfer offers a significant opportunity for Chinese industry. China has now emerged as the biggest manufacturer of wind turbines, solar photovoltaic panels and solar thermal panels. CCS technology collaboration could offer China an opportunity to emerge as a market player in the CCS industry, which is currently dominated by European companies. China already has the technological capacity and indigenous market to exploit CCS technology.

The Chinese energy utilities, for example the Huaneng Group and PetroChina, have commercial stakes in CCS. China is working with Japan and Australia in CCS research. In 2021, Huaneng and Glencore signed an agreement to install CCS at the Millmeran coal power station in Australia (Glencore, 2021). The project participants are: Glencore, China Huaneng, Low Emission Technology Australia, Australian National Low Emission Coal Research and Development and the Australian government.

In 1998, China created its first CO_2 storage project – an EOR project in the Liaohe Oil Field in north-east China (Su and Fletcher, 2010). China is also investing in CCS EOR; for example, the Yanchang Oil Field EOR is part of several large-scale projects (Li et al., 2018). Research carried out reveals that the key to creating successful CCS-based CO_2 emission reduction is to build IGCC coal-combustion power plants. These plants are most suited to CCS installation. Ideally, a detailed discussion regarding the condition of power plants would build realistic arguments in support of or against the CO_2ERM. The parameters and the supporting data required are beyond this research and would only be possible with significant collaboration with external institutions.

The geological barrier analysis of China reveals that the country has significant CO_2 storage capacity. China has 28 onshore sedimentary basins and 10 large offshore basins. Many of these basins are not near point sources of CO_2 emissions. An estimate of geological storage reveals potential capacity of 12 $GtCO_2$ in 68 unmineable coalfields and 1,000–2000 $GtCO_2$ in 24 deep saline formations (IEA, CO_2 Capture and Storage, 2008). Consequently, there does not appear to be a geological barrier to the CO_2 abatement model. According to the IEA, 310 gigawatts (GW) of existing coal-fired power capacity could be fitted with a CCS retrofit (Bennett et al., 2016).

The CO_2ERM model would encounter a significant political barrier: a reduction in subsidy and a rise in the cost of electricity would have political implications. The Chinese manufacturing industry is run by the state and the Chinese Communist Party (CPC). The political barrier is difficult, especially as the human development index value of China is 0.761, which places China 85th in the global list (UN Development Programme, China Human Development Indicators, 2020). By comparison, the human development index value of the USA is 0.926, and the human development ranking of the USA is 17. These numbers have significant importance in climate change negotiations (UN Development Programme, USA Human Development Indicators, 2020). The energy and economic barriers are significant, due to the role played by state subsidies provided to industry, but the technology barrier is not significant, as China has significant technological and geological capacity. The political barrier is complicated due to China's climate alliance with India. China and India oppose the immediate phasing out of coal from energy generation.

The results of the model and the above evidence reveal that the model and its aspects are of relevance to China and that CCS-based emission reduction is plausible or potentially viable for China.

The EIA analysis shows that coal now provides 19% of electricity and natural gas 40% of electricity in the USA (EIA, 2020). US energy strategy is based on energy dominance, which involves fuel diversification, finding new low-cost fossil fuels, energy efficiency, renewable energy installation and the expansion of strategic petroleum reserves. The US maintains a balance between these factors to maintain energy dominance. Coal is the third largest fuel in the total primary energy supply (TPES). The growth in solar and wind power has led to a decline in the use of coal (US Energy Review, 2019). Market factors – for example, the shale gas revolution, flat power demand growth, environmental regulations and an expansion in renewables – have led to a decline in coal use. Coal supplied 50% of US electricity generation in 2008, and in 2018, this had reduced to just below 30%. In the Bipartisan Budget Act of 2018, Congress increased tax credits for CCS. The Department of Energy and the political administration expects that progress in CCS can be applied to both new and existing coal-fired power plants (US Energy Review, 2019).

The country's major energy generators are American Electric Power, NRG Energy, Luminant Energy, Duke Energy and Southern Company. These companies are currently participating in various federal CCS demonstration projects and accept that CO_2 emission reduction is critically important for the future of their businesses. Southern Company runs a demonstration plant at its Plant Barry and is carrying out CO_2 injection in Tuscaloosa. It also manages the National Carbon Sequestration and Storage Centre for the Department of Energy (Southern Company, 2021) and, in conjunction with American Electric Power, is running CO_2 emission reduction based on CCS at its power plants. American Electric Power is using Alstom's ammonia-chilled post-combustion separation process, and technology validation is taking place at its 20 MWe Mountaineer Power Plant. The capture benchmark is 90% (Cerimele, 2012). In 2019, there were 80 active CCS projects and 52 completed projects (Compendium of CCS technology, 2020).

The USA also has a CCS management structure in place, with research and development being led by the Department of Energy. The transport of CO_2 is regulated by the Department of Transport, and storage is regulated by the US EPA. The National Energy Technology Laboratory (NETL) manages the US CCS programme, and its objective is to create 90% capture capability and 99% storage permanence, but with less than 10% increase in the cost of electricity.

The above arguments and evidence indicate that US electricity generators appear to have accepted CCS as a technological solution; this solution would secure major coal contracts for this century. Economic impact does not appear to deter the USA;

for example, a 'showcase project' of $1.7 billion, under the FutureGen Initiative, aims to create a 'zero emissions' power plant at Mattoon, Illinois. The project is both an IGCC and CCS project and was funded through the American Recovery Act 2009 (FutureGen Initiative, 2009). However, the US government later pulled out of this project due to costs (Tollefson, 2015).

The geological barrier analysis indicates that the USA has significant sequestration capacity. Its saline formations can support 919–3,378 $GtCO_2$ storage; unmineable coal seams can store 156–183 $GtCO_2$; and oil and gas fields can store 90 $GtCO_2$ (IEA, CO_2 Capture and Storage, 2008). Therefore, there are no geological barriers to the model. The USA maintains a strong research capacity in CCS through various programmes and collaborations. There is collaboration between Los Alamos, Lawrence Livermore, Pacific Northwest and Lawrence Berkeley National Laboratories.

The above evidence collected and analysed indicates that there are no technological barriers to the proposed model.

Political management of the climate change phenomenon is a significant factor in policy making for the US government. During the 2009 financial crisis, the American Recovery and Reinvestment Act of 2009 was passed, and this law was used as a financial bulwark to support CCS installations. In the USA, the Waxman-Markey Bill provided an estimated $75 billion in incentives for coal use with CCS towards the year 2030 and approximately $177 billion towards the year 2050 (Pew Centre, Waxman and Markey, 2010).

Despite the USA not ratifying the Kyoto Protocol and withdrawing from the Paris Agreement, the country has a significant capacity to reduce CO_2. The USA has been constant in supporting CCS; for example, in 2021, it announced $20 million of funding to accelerate the deployment of regional CCS (Department of Energy, 2021). In 2021, the Council on Environmental Quality delivered a report to US Congress on the deployment of CCS. The report identified CCS as a key carbon removal technology and delineated a framework for scaling of CCS in a timely manner. This report outlines the supply chain components of CCS in the energy market: for example, in the cosmetics, petrochemical, cement, transportation and pharmaceutical industries (Council on Environmental Quality, 2021). The above evidence therefore supports the CO_2ERM concept and principles. Energy and economic barriers are not significant for the USA. The cost of abatement is already being met by federal legislation and state-based energy efficiency programmes. The political barrier comes into play on the international stage. However, on the national stage, the policymakers and political establishment have already created federal and state climate change programmes.

The above analysis suggests that it is plausible to deploy the CCS model in the USA. The results of the CO_2ERM show that a successful CCS programme could reduce emissions by 2–4 GtCO_2 per year and help stay within the allowed carbon budgets. The CCS-based emission reduction model is plausible if the national fuel mix is dominated by coal and gas, there is technological capacity present and significant financial support is provided. Both the USA and China have these resources available.

2.7 Critical Analysis of the CO_2ERM

This section supports the CO_2ERM model framework by carrying out critical analysis of the CO_2ERM. The objective of the critical analysis is to assess the realistic applicability of the assumptions. The analysis develops insight into the deliverability of the CO_2ERM. The critical analysis is based on evidence of deployment, results of the CO_2ERM, and historical and most recent evidence.

2.7.1 Critical analysis of the CO_2ERM assumptions

The CO_2ERM is based on the concept that CCS can create rapid emission reductions of CO_2 from coal and gas in the USA and China to allow the world to stay within the carbon budgets. The CO_2ERM model framework has been proposed to examine the claim of the IEA and the IPCC that carbon capture and sequestration is a credible technology. CCS technology is being advertised as a viable technology by the gas industry and is considered essential to reducing CO_2 emissions from energy generation activities.

The results of the CO_2ERM reveal that emission reductions of 12 GtCO_2 per year can be achieved from coal- and gas-fired power stations and installations in the

USA and China. This figure is the maximum CO_2 emission reduction limit that could be accomplished in the USA and China. The forecast period for the model is 2020 to 2100. During this 80-year period, the CO_2ERM in the USA and China could potentially deliver emission reductions of 2,018 $GtCO_2$. In absence of the CO_2ERM, the forecast emissions could be 3,997 $GtCO_2$, which will breach the allowed carbon budgets before 2100.

In section 1.6.2, it was shown that CO_2 emissions from energy generation have constantly increased (Olivier and Peters, 2020). The cause behind this is the absence of relevant market forces to drive emission reduction in the USA, China and other countries. The absence of appropriate market forces and legal commitments has led these countries to continuously increase their CO_2 emissions. They are heavily dependent on coal and gas to accomplish their national development objectives.

The CO_2ERM identifies the top emitters and proposes emission reduction in the USA and China, the underlying rationale being that high CO_2 BAU and forecast scenarios are suitable for carrying out CO_2 emission reduction. This premise is not wrong; however, a CO_2ERM based on CCS would encounter significant political, financial, legal, technological and geological constraints. These constraints are serious and very challenging for the USA and China.

The above argument demonstrates that investment in climate change prevention should focus on renewable energy generation, and the CCS should form a small component of climate change policy. The results in section 2.4 reveal that even if CCS is installed in China and the USA, the breach of carbon budgets is delayed by a mere 10 years to 22 years. A 100% successful CCS would delay the breach of carbon budgets from 2046 to 2078. CCS could not achieve the significant emission reduction to prevent climate change that is being claimed.

Focus on deploying renewable energy sources will help greatly to create low carbon energy generation systems. Significant advances are being made in the creation of renewable energy technologies and in the installation of renewable energy projects. These projects deploy conventional renewable energy technologies and also innovatively harness solar energy. There is significant renewable energy activity taking place in the USA and China. It is likely that future renewable energy sources will significantly displace coal and gas as the predominant energy generation fuel. The above statements can be supported by a relevant example as follows. The Global Energy Review carried out by the IEA in 2021 (Global Energy Review IEA, 2021) highlights key points about world energy demand. For example, the world's overall energy demand is set to rise by 4%, and the demand for coal is set to increase by 4.5%, which is 60% more than all renewables. The natural gas demand is set to increase by 3.2%. The electricity demand is also set to increase by 4.5%; half of this increase will take place in China. Renewables are forecast to provide half of the increase in world electricity supply. China is going to account for half of this increase, followed by the USA.

The above evidence reveals that linear extrapolation carried out by the CO_2ERM in order to estimate fossil fuel consumption in post-2030 BAU scenarios may or may not be correct. Coal, gas and renewables are being deployed, but the rate of energy demand is also increasing significantly. The CO_2ERM estimates that coal and gas will be continuously used towards the year 2100. It estimates that use of coal will end in the USA towards the year 2037. The CO_2ERM transfers the burden of emission reduction on to China and the USA. It does not consider or acknowledge the role played by coal-, gas- and oil-producing countries in increasing the atmospheric CO_2 concentration. The forecast shows that China could potentially lower its total emissions from coal and gas by more than 10 $GtCO_2$ per year. The forecast shows that the USA could potentially lower its total emissions from coal and gas by more than 2 $GtCO_2$ per year. If we assume the cost of carrying out CCS to be \$45/tCO_2, the cost of reducing emissions by 1 $GtCO_2$ per year would be \$45 billion.

The CO_2ERM does not include the EU as a high CO_2 emitter. The logic behind the exclusion of the EU is that EU member states are already sharing the burden of emission reduction through the implementation of EU climate change policy directives. In addition, the EU has agreed to legally binding GHG emission cuts for the Kyoto commitment period. The EU has also supported the Kyoto Protocol by linking its domestic carbon emission trading scheme, the EU ETS, with the CDM.

The CO_2ERM does not include the cost of CCS equipment installation, capture, transportation and sequestration. All available research literature indicates generic costs for CCS activities. Further the CO_2ERM does not recognise national and regional constraints in delivering CCS. The cost criteria employed to calculate cost of abatement are too generic and should be country specific and specific to the plant where CCS is to be retrofitted. Moreover, the CO_2ERM does not assume any increase in power tariffs. The IPPC estimates a likely increase of 65% in power tariffs; there would be national and regional differences in the USA and China, which would affect the affordability of the model. In addition, transmission and distribution losses would be significant and these losses would entail additional infrastructural investment to optimise CCS emission reduction at power plants.

The CO_2ERM assumes that all coal- and gas-fired power plants in the USA and China would be equipped with CCS equipment. At this stage, all CCS projects appear to be pilot and technology demonstration projects. The commercial viability of the technology and its ability to withstand investment risk analysis and legal risk analysis are not proven. This creates market uncertainty and affects investor confidence, which means that CCS technology would require significant tax-payer securities in participating countries.

The CO_2ERM implementation could have the following implications for participating countries.

The increase in power tariffs would need to be absorbed by industrial and residential consumers. This would increase inflation and consequently increase central bank interest rates. This could create political furore in the USA. The increase would affect China's industrial competitiveness, and the investment in CCS would divert funds from renewable energy projects: for example, China built the Three Gorges Dam at a cost of $30 billion, and an investment of billions in CCS would not be a prudent policy decision. The CO_2ERM has a negative return on investment.

The CO_2ERM would remove CO_2, but polluting gases, i.e. SO_2 and N_2O, would require a separate catalytic decomposition. Therefore, each CCS-operated plant would have two-tiered environmental protection technologies installed. The

CO_2ERM would not have any effect on minimising transmission and distribution losses. SF_6, a powerful GHG, would continue to be leaked and emitted into the atmosphere at transmission and distribution transformers.

2.7.2 Critical analysis of the CO_2ERM technology framework

The important infrastructural components of a CCS-based CO_2ERM are:

- Power plant sites.
- Capture equipment.
- Transport pipelines.
- Storage and sequestration sites.

CCS capture takes place using pre-, post- and oxyfuel combustion processes. Pre-combustion capture of CO_2 takes place using fuel and oxygen reactions. CO_2 is captured by chemical processes, due to the creation of synthetic gas (carbon monoxide and hydrogen). The process of gasification is vital for a successful capture process to take place. This process is a characteristic of IGCC power plants. The CO_2ERM assumes that CCS would be deployed at coal-fired power plants in China and the USA. The majority of Chinese power plants are also conventional pulverised coal plants (Yunhan, 2007). A study carried out in 2020 (Xia et al., 2020) on the potential for IGCC power plant to achieve near-zero emissions found that the levelised cost of electricity without CO_2 capture was \$103/MWh, which increased to \$131/MWh with pre-combustion CO_2 capture. This study concluded that an IGCC plant with integrated CO_2 capture remains too expensive to be widely used in China.

Both the USA and China are vital to the implementation and philosophy of the CO_2ERM. Pre-combustion CO_2 capture at pulverised coal plants is expensive; research reveals that pre-combustion works best with IGCC plants. The dominance of pulverised coal plants within the power generation sector would impede the implementation of the CO_2ERM and would add to the cost of CO_2 emission reduction. The most suitable process for CO_2 capture at pulverised coal plants is post-combustion-based CCS. Post-combustion capture is highly energy intensive: an additional energy penalty is created to run the solvent regeneration process and to operate liquid pumps. The additional energy penalty would increase the cost of emission reduction and consequently increase the rates of power tariffs. In addition, post-combustion technology requires scaling up at this stage.

The above arguments, statements and facts demonstrate that pre- and post-combustion CO_2 capture processes are not the most suitable capture techniques for China. However, oxyfuel combustion capture appears to be the more suitable capture process for China. However, the evidence of deployment reveals that oxyfuel capture plants are at a demonstration stage and, due to project requirements, the majority of these demonstration projects are located within the EU.

The WRI briefing note on IGCC in the USA reveals that IGCC is not yet considered commercially viable there; although there are several operational IGCC power plants in the USA, they are not predominant in the US energy generation sector (IGCC with CCS, WRI). The above evidence reveals that CCS CO_2 capture could be carried out efficiently in IGCC power plants. However, IGCC power generation technology is not the predominant power generation technology in either the USA or China. This creates a significant constraint for the implementation of the CO_2ERM.

The evidence available from the IEA reveals that, at this stage, CCS is being used to capture CO_2 for the EOR process. The cost of CO_2 storage and transport appears to be too high. Whilst the USA has the experience and pipeline capacity to carry out CCS operations, such flexibility is absent in China. This lack of flexibility would also add to the cost of CO_2 abatement and would create a constraint for CCS deliverability.

In 2006, the UNFCCC rejected a CCS project at White Tiger Oil Field (WTOF) in Vietnam as the project methodology did not fully characterise the geological risk associated with the proposed project activity. The absence of elaborate geological risk assessment data would trigger stringent regulatory benchmarks for CCS-based projects. These benchmarks would: encapsulate potential risks emanating from the leakage of sequestered CO_2 and trans-boundary migration of sequestrated CO_2 plumes; increase the cost of project insurance; and create an additional legal and cost constraint for CO_2 emission reduction projects. An increase in insurance premiums could also occur due to the high operational risk potential of CCS, as this is a new technology. The CO_2ERM would also encounter project-specific monitoring, reporting and verification (MRV) constraints. If CCS were used in conjunction with the CDM, the UNFCCC would demand rigorous and detailed MRV plans. These plans would entail negotiations with regulatory authorities in China; with these authorities having no experience of managing this type of process, potentially stringent benchmarks could be imposed on CCS projects, resulting in potential investment uncertainties for project developers and power companies. Tsouris et al. (2010) compared CCS with alternative energy technologies and found that CCS could be cost effective at \$12–\$26/tCO_2 but that CCS is less effective than renewable energy in combating climate change.

At the same time, advances have been made in critical areas of CCS technology. For example, the cost of electricity in post-combustion capture would increase by 70%. To address this barrier for post-combustion capture, sorbent-based capture projects are being developed. For example, compared to MEA, the Hitachi H3-1 solvent (National Carbon Capture Center, 2019) can achieve 90% capture and the regeneration energy is at least 34% lower.

To some extent, the above arguments challenge the claim that CCS is an essential technology to help avoid dangerous anthropogenic climate change. At this stage, the CCS-based CO_2ERM appears to have very limited deliverability in the USA and China.

2.7.3 Critical analysis of the CO_2ERM political framework

The CO_2ERM proposed a single gas abatement model to stabilise the atmospheric concentration of CO_2 and prevent a breach of the available carbon budget.

Analysis of the Kyoto Protocol, Paris Agreement, Glasgow Pact and COP negotiations reveals that the USA, China and other countries are in profound disagreement about the modus operandi of the political structures required in order to achieve CO_2 and other GHG emission reduction and to prevent climate change. Protracted and tortuous negotiations have not yet been able to propose a political agreement. The US position is that China and India should also agree to binding cuts before the USA agrees and ratifies a Kyoto-type agreement. The USA considers that a legally binding GHG emission reduction treaty would jeopardise its economic productivity and industrial competitiveness.

The USA withdrew from the Paris Agreement, thus setting a precedent; this created a political uncertainty and increased the cost of emission reduction (Zhang et al., 2017). In 2019, China and the USA emitted 8 tCO_2/capita and 15 tCO_2/capita, respectively (Figure 1.5). The USA does not recognise that its per capita CO_2 emissions should be constrained. The US philosophy is that if markets and economic productivity encourage CO_2 emissions, then markets should provide appropriate solutions to reduce these emissions. Climate change negotiations between big powers and emitters is a complex and difficult process and is transactional in nature. For example, during the early 1990s, the US administration exerted political pressure on Russia to forestall the Kyoto Protocol's entry into force. The Russians were cajoled and coerced by the EU and eventually succumbed, facilitating the Kyoto Protocol's entry into force. Russian brinkmanship forced the EU into allowing Russian entry to the World Trade Organization (WTO). The US Senate then passed the Byrd-Hagel Resolution, which states that the USA should not be a signatory to the Kyoto Protocol or any other agreements unless developing countries also agree to a GHG emission reduction treaty (The National Carbon Capture Centre, 1997). The current Biden administration did signal its willingness to negotiate and allowed the Glasgow Pact in 2021 to be signed, but the constant change in political composition of US legislature and its partisanship would make the passage of purposeful climate change legislation very difficult.

The USA climate strategy is to undertake domestic research and investment in CCS, smart grid technology and energy efficiency programmes. The American Recovery and Reinvestment Act of 2009 invested \$36 billion in energy management projects related to climate change; CCS technology received \$3.4 billion. In 2021, the Bipartisan Infrastructure Deal (White House, 2021) aimed to reduce US emissions by 50–52% in 2030. The deal invests \$65 billion in clean energy transmission and grid technology. The US position on climate change policy has an umbilical relationship with two geostrategic pivots of American power: the predominance of US economic power (emanating from its economic productivity) and its military power (it will not compromise its geostrategic position, especially when China and Iran are emerging as geostrategic players in the South China Sea, the Arabian Sea and the Indian Ocean).

In the light of the above statements, the assumption that the USA could be part of a CO_2ERM political framework appears to be optimistic, but this assumption is not naive and can be labelled 'prescient'. To support this claim, a suitable example is provided as follows. The American Clean Energy and Security Act 2009 proposed the creation of the biggest carbon emission trading mechanism, known as the Waxman-Markey cap and trade system. The US strategic aim is to create an emission reduction and trading system, which offers a glimmer of hope and opportunity for the CO_2ERM. The USA wants to exploit, harness and manipulate its domestic market and mature financial sector in order to accomplish CO_2 emission reduction. The emission trading system would be a variant of the EU ETS but it has encountered political opposition.

The creation of the CO_2 emission cap and trade system in the USA could challenge the dominance of the CDM and the EU ETS in the international carbon emissions market. The US system would need to reduce its emissions by almost 1–2 $GtCO_2$ per year to comply with its annual cap. The number of credits or offsets required to support the system is not readily available domestically. These credits can be supplied by China and other countries. This system could support a range of technologies, including CCS, and could allow diffusion of technology from the USA to China.

The CO_2 emission cap and trade system should create additional emission reductions, supported by the US fiscal stimulus packages. The potential implementation of the CO_2ERM in the CDM could allow prospective emission reductions to be consumed by the EU ETS and the CO_2 emission cap and trade system. These arrangements would reduce the cost of CCS and help achieve greater market acceptance of CCS.

The above scenario is difficult to realise, as political barriers are formidable. Lack of economic purpose and financial incentive is a major barrier in CCS technology development. Financial business models are not viable for CCS-based emission reduction. The cost of emission reduction is high and not sustainable. This position is supported by researchers and policymakers; for example, it has been demonstrated that CCS projects are not sensitive to current market conditions (Kapetaki and Scowcroft, 2017). The commercial barriers have been there for some time, and this situation has not changed. In the most recent paper on CCS (Wang et al., 2021), it was highlighted that CCS projects do not produce any direct economic benefit, in the absence of carbon prices. It was concluded that if the capture capacity of a CCS project increases by 1 $MtCO_2$ per year, the rate of failure increases by 50%.

There is some domestic, political and technological incentive to create indigenous CO_2 abatement plans; both the USA and China are investing in renewable energy projects to support their domestic energy and technology sectors. However, the CO_2ERM has estimated that both countries would continue to depend heavily on coal and gas to feed their industrial and energy generation activities. The cost of CCS emission reduction at $45/$tCO_2$ is very expensive. For China to create an emission reduction of 1$GtCO_2$ per year it would cost the country $45 billion per year. This potential cost can be compared with the cost of constructing the Three Gorges Dam, the world's biggest hydroelectric power station, which was constructed at a cost of $30 billion and generates 18,200 MW of renewable hydroelectricity and also prevents flooding of the Yangtze Basin (Three Gorges Dam, International Rivers). Therefore, the potential cost of creating emission reduction using CCS in China is significant.

The history of climate change negotiations (Table 1.1) from COP 1 to COP 26 can be used to forecast the future of climate change negotiations. These negotiations have been stumbling along for almost 30 years. Major accomplishments have been the Kyoto Protocol, Paris Agreement and acceptance of allowed carbon budgets. The prevailing pace of emission reductions taking place is not adequate to prevent climate change, but the countries involved have been able to main a steady momentum, thus enhancing the chance that the USA and China could come to a reasonable agreement on the issue.

The technology barrier and critical analysis of the CO_2ERM proposals and assumptions reveals that the model has an acceptable degree of plausibility and deliverability for the USA. The model proposals for China appear to be optimistic.

The claim that CCS is an essential technology does not appear to be entirely correct as there are important technological constraints that limit its applicability within the energy markets.

Chapter 3 CDM Assessment Methodology and Emission Trading

3.1 CDM and Emission Trading

The CDM is vital for an effective system of GHG emission reduction and international carbon trading. Carbon emission trading is important for the creation of new technologies, developing carbon finance markets. Big GHG emitter companies and countries use international carbon trading to accomplish their net-zero pledges. This chapter proposes a CDM AM. The objective of the CDM AM is to strengthen, modernise and reform the CDM and emission trading to meet climate change targets. The CDM was introduced as a carbon offset or credit generation vehicle for international carbon emission trading, within articles 12 and 6 of the Kyoto Protocol (Yamin and Depledge, 2004) and article 6 of the Paris Agreement (Leva and Vaughan, 2021). The size of the international carbon market is projected to be $1 trillion by 2050 (Yu et al., 2021). Carbon markets will play an important role in accomplishing the 1.5^{0}C, 1.7^{0}C and 2^{0}C climate targets. The primary objective of the CDM has been to deliver low-cost GHG emission reduction in developing countries and allow developed countries or big corporations to purchase these emission reductions as Certified Emission Reductions (CERs). The CERs are traded between different market players in the international carbon market. The concept of emission trading was introduced by Prof. J. H. Dales in his famous essay, 'Pollution, Property and Prices' (1968) (Peeters, 2005). For the last 20 years, the CDM has been an important part of emission trading. However, the CDM has been criticised for lacking credibility and for creating an incentive to continue the emission of GHGs (Gollier and Tirole, 2015). The CDM market and project activity is regulated by the UNFCCC, and it determines if a CDM project is additional. The most recent report on the CDM issued by the UNFCCC (UNFCCC CDM Achievements, 2018) shows that 7,803 CDM projects were registered; these projects reduced GHG emissions by 2 GtCO_2e, making it possible to invest $304 billion. Research evidence shows that carbon emission trading can have a significant constraining effect on carbon emissions in the coal-fired power sector, leading to phase-out of coal- and gas-fired power stations (Luo, Wang and Zhao, 2022). Recent published evidence also highlights that carbon emission trading that has taken place through the EU ETS reduced CO_2 emissions in regulated firms by 8–12%, this happened due to investments made in reducing the emission intensity of production (Colmer et al., 2022).

World carbon emission market activity started with the creation of the World Bank's PCF in 2000. The fund started with the capitalisation of $135 million and increased to $2.3 billion (World Bank, 2010). The 2021 World Bank State and Trends of Carbon Pricing report shows that demand for CERs and voluntary emission reductions is growing (World Bank, 2021). The major participants in the PCF are the Netherlands, Canada, Norway, Finland, Sweden and the Japan Bank for International Cooperation. In addition, companies such as BP Amoco, Rabobank, Chubu Electric Power, Norsk Hydro, Mitsubishi Corporation and Gaz de France are involved. The carbon emission trade can be broadly categorised into compliance and voluntary trade markets. The compliance trade market is driven by trade in carbon assets emerging from the CDM, the EU ETS and the voluntary trade markets. CERs and voluntary emission reductions (VERs) are used as offsets by companies and countries.

This chapter is based on case study data from the UNFCCC CDM project documents. A case study of a published paper on emission reduction in EU road transport is provided in section 3.10. It is necessary to examine whether CDM-based CERs and emission trading can contribute to the 1.5^0C, 1.7^0C and 2^0C targets.

Every CDM project, irrespective of its size, geographical location or technological profile, follows a tiered process from project origination to CER issuance. Project regulation by the UNFCCC maintains the market credibility of the CDM process. The 7-step process to carry out a CDM project activity is as follows:

1. Project developers who want to create CERs initiate the project activity in a host country (a developing or non-Annex 1 country only) and develop a project design document (PDD).
2. Project developers obtain written approval from the host country's authorising body, called the designated national authority (DNA).

3. The PDD is sent for validation of potential emission reductions using a project-specific baseline methodology.
4. Project activity is monitored for a specific period. Monitoring the methodology is important to ensure the reproducibility and repeatability of emission reduction activity.
5. The results of the project activity in the PDD are submitted to a designated operational entity (DOE) for verification of emission reductions; the DOE verifies emission reductions and certifies the reductions accordingly.
6. Verification is communicated to the UNFCCC, and CERs are issued by the UNFCCC.
7. The CERs are distributed among project participants.

Each CDM project uses a specific baseline methodology to describe project activity, to verify the emission baseline and to quantify the emission reductions. The baseline methodology used is either an approved methodology and/or a new methodology. The UNFCCC has allowed for small-scale project activity, as such projects can be developed at remote locations and can exploit local hydel and wind resources effectively. Such projects are integrated with the sustainable development needs of communities located in remote and inaccessible areas.

A baseline methodology is used to quantify the emission baseline and to calculate the emission reductions accrued to the project activity. For example, the baseline methodology, ACM0001 is used to calculate the emission reductions from conversion of landfill gas to electricity and the AM0001 methodology is used to measure the decomposition of HFC-23 (UNFCCC, Approved Baseline and Monitoring Methodologies, 2022). Each methodology has a set of rules that is an essential part of the project activity. These rules aim to integrate the project activity with international and national carbon markets and to achieve effective emission reduction through diversified marginal abatement. The rules maximise the opportunities created by CDM activity within the host country; for example, when calculating baseline emissions for CDM activity in the cement sector, a CDM project uses ACM0005. This methodology takes into account regional and national cement production volumes. The methodology defines a 'region' where CDM activity can take place. A region is defined as a geographic area where at least 75% of the CDM recipient's output is sold and where at least five other cement plants exist and where the regional production of cement is at least four times compared to the annual output of a CDM recipient (UNFCCC, CDM Methodology Booklet, 2020). This methodology monitors ratio of clinker, additives and electricity demand.

The CDM project activity is carried out in different sectors. For example, in energy generation, energy distribution, chemical industry, mining, waste management and solvent manufacture. The CDM project activity analysis has been carried out by using datasets from the UNFCCC CDM database and the CDM dataset available from the Institute of Global Environmental Strategies (Louhisuo and Takahashi v8.7, 2021). The IGES database has 10,510 project entries and is very detailed. The total number of CERs issued to the international carbon market by UNFCCC is 2,115,519,437 tCO_2e or 2.11 $GtCO_2e$. To present an accurate analysis of CDM project activity and CER volumes, the author has used two different criteria:

- Sector-/project-specific CDM analysis of registered projects.
- Country-specific CDM analysis of registered projects.

The largest number of projects has been registered for renewable energy generation: hydroelectricity generation (2,631 projects), wind power (2,578 projects), biogas energy generation (890 projects) and biomass energy generation (832 projects). The renewable energy projects comprise 76% of the CDM project activity.

Industrial CDM project activity is small compared to renewable energy projects. For example, the HFC-23 decomposition, SF_6 replacement and N_20 decomposition and CH_4 recover projects, created non-CO_2 emission reduction equal to 1.14 $GtCO_2e$. Non-CO_2 emission reduction in CDM projects accounts for approximately 54% of total CDM GHG abatement. The sum of the CO_2 abatement and non-CO_2 abatement results are shown in table 3.1.

Table 3.1: CDM data analysis results

Major CDM categories (CO_2 emission reduction)	Number of projects	Emission reduction (tCO_2e)
Hydroelectricity	2,631	324,006,072
Wind power	2,578	283,683,526
Biomass	832	52,396,041
CO_2 emission reduction from renewable energy projects ($GtCO_2$)	0.66	
CDM categories (non-CO_2 reduction)		
HFC reduction/avoidance (non-CO_2 reduction)	468	539,941,798
N_2O decomposition (non-CO_2 reduction)	618	361,728,480
PFC reduction (non-CO_2 reduction)	2	104,966
SF_6 replacement (non-CO_2 reduction)	40	8,941,075
Biogas (non-CO_2 reduction)	841	35,777,395
CH_4 recovery and utilisation (non-CO_2 reduction)	890	189,520,508
Total non-CO_2 emission reduction ($GtCO_2e$)	1.14	
Total CDM emission reduction from UNFCCC up to 2021 ($GtCO_2e$)	2.11	

Source: Author and data from IGES CDM Project Database (2021)

Renewable energy CDM projects create 0.66 $GtCO_2$, emission reduction from the total of 2.11 $GtCO_2e$. At the same time, the effect of renewable energy projects on the carbon intensity of coal-dependent electric power grids appears to be negligible, as China and India have very high grid carbon emission factors. Chemical industry CDM abatement projects dominate the carbon emission markets due to the low cost of abatement for high global warming, long-lived GHGs.

The country-specific CDM project activity analysis reveals that China is the most dominant CDM player. It has a total of 5,094 CDM projects and India has 2,640.

The available evidence shows that experience in international trade, host county energy demand and the cost of carbon emission reduction play important parts in determining the success of a country in the CDM market (Li and Lin, 2021). China is very effective in terms of CDM registration as it takes project developers shorter time to register CDM projects in China as compared to other countries (Liu, Stephane and Zhang, 2018).

3.2 Emission Reduction with CDM and Emission Trading

The CDM and emission trading have been active for 20 years. This section highlights the net emission reduction achieved by the CDM and emission trading. The methodology adopted is as follows and the results are shown in table 3.2.

- The CDM emission reduction data used was acquired from the IGES database (Louhisuo and Takahashi v8.7, 2021).
- VER emission reductions were taken from the Verra Registry (Verra, 2022) and the EU ETS analysis was taken from the paper by Bayer and Aklin (2020).

Table 3.2: Results of emission trading

Total projected CDM abatement = 2.11 GtCO_2e Total CDM CO_2 abatement = 0.66 GtCO_2e Total CDM non-CO_2 abatement = 1.14 GtCO_2e
Voluntary Emission Reduction (VER) projects (1,772 projects) = 0.85 GtCO_2e
Emission reduction in EU ETS = 1.2 GtCO_2e
Net emission reduction from CDM abatement + VER abatement + EU ETS reduction = 4.16 GtCO_2e

Source: Author

3.3 Why the CDM AM is needed

CDM project activity has achieved significant emission reductions within the chemical industry in China and India. These emission reductions have been used by EU ETS and the carbon market. Emission reduction has taken place within the adipic acid, fertiliser and refrigerant manufacturing industries in India, China, Pakistan, South Africa, Chile, Mexico, Uzbekistan, Israel, Thailand, Colombia, Indonesia, South Korea and Brazil. These projects have been able to accomplish the emission reductions of long-lived GHGs using CDM project activities, which would not have happened in the absence of the CDM. In a BAU scenario (i.e. without CDM) there is no incentive for manufacturers to abate the long-lived GHGs.

The emission reduction achieved is additional, credible and verifiable. In the majority of chemical industry projects, there is evidence of technology transfer, involving advanced SCR, which is used to decompose HFC-23 and N_2O. The dominance of CERs in the carbon emissions market is due to these chemical industry projects. The CDM has also spurred VER project activity in North America. The strongest criticism levelled at CDM project activity and the UNFCCC is due to its failure to deliver significant CO_2 emission reduction and non-stringent application of the additionality criteria. There are issues of carbon leakage within CDM projects.

The strategic role of the CDM is to deliver credible CERs to the carbon market and to create a sustainable development framework in the host countries. It is difficult to analyse the role played by each CDM project. This research has critically analysed 100 CDM projects, and the CDM AM has been used on 13 CDM projects in order to justify the criticism directed at the CDM. These projects have been selected randomly from a set of case studies with appropriate project location, gas-specific abatement and date of registration.

The emission reduction of CO_2 is difficult to achieve, as the cost of technology, fuels and national policies do not support CDM-related CO_2 emission reduction. CER revenue or price alone cannot achieve CO_2 emission reduction as the price is determined by the interplay of Kyoto emission reduction targets, Paris targets and national installation caps in the EU ETS. For example, the Onsan CDM project in

Korea is an N_2O emission abatement project, and the financial value of its CERs is determined by the global warming potential of N_2O gas, which is 310 times greater than the global warming potential of CO_2. The reduction of N_2O waste gas is more lucrative than generation of electricity using low carbon emission coefficient fuels. The CER is a commodity, engineered to facilitate trade in emission reductions. The CER is transformed into a financial derivative and trade in CERs takes place due to value imparted to CERs by relevant articles of the Kyoto Protocol, the Paris Agreement and the EU ETS.

The process of CER creation is complicated and the project cycle could extend from 10 to 21 years. There is no legal definition of carbon (i.e., for CERs and other carbon-based commodities), and during the research it has been difficult to investigate the methods used to determine the price of carbon commodities (e.g., CER, ERU, VER and others). The International Accounting Standards Board has been working since 2005 to determine how carbon should be accounted for (Reyes, 2011).

CERs are packaged and traded as a carbon collateralised debt obligation (CDO) (Prada, 2010). This CDO is traded as a structured product by financial institutions in the stock market and as an over-the-counter (OTC) commodity. The traded value or price of 1 CER (e.g., $16 per CER) is the cost of carbon as a commodity; this is the value of a CER, as a carbon CDO. This value does not reflect the cost of creating the CER. The CER revenue of a CDM project is determined by the market and is critical to project implementation. Critics could argue that CER revenue is hypothetical; however, this argument is not valid. Each CDM project generates CERs and has some kind of emission reduction purchase agreement (ERPA) secured against its potential CERs. Therefore, the point that CER revenue is hypothetical is not plausible. CER revenue is real. However, it does not represent the technical and social cost of emission reduction. Emission trading is a very effective policy tool for emission reduction. For example, integrating emission trading systems between the EU and China can reduce total emissions by 5%, without any impact on economic welfare (Li, Weng and Duan, 2019).

The analysis reveals that CERs are arranged in stacks of CDOs; these stacks or tranches are assigned risk ratings. The risk rating determines the value of CER CDOs. The financial value per CER (e.g. $16 per CER) is not the value of a single unit of CER, it is the value of risk assigned to the commodity by financial engineering techniques. The CERs are packaged and re-packaged into CDO tranches. The financial value of CER cannot be used to determine the cost of emission reduction using CDM. The non-CO_2 CERs are at a reduced market risk as they are created in significant volumes and the technology risk and deployment lag time associated with non-CO_2 CER delivery is minimal.

The biggest barrier to accomplishing the goals of climate change prevention regimes is the market. The market creates the emission reduction caps and has a manipulative leverage on the type of greenhouse gas abatement carried out by CDM projects, as well as non-CDM GHG reduction and emission trading projects.

The Stern report on climate change (Stern Review, 2008) emphasises the critical role emission trading could play in combating climate change. The risks of climate change are real and cannot be countered by manipulating emission trading and financial engineering techniques. Emission trading, the Kyoto Protocol, the Paris Agreement, the Glasgow Pact and the EU ETS appear to have formed a confluence of emission reductions that have provided liquidity to the carbon-based financial markets.

The second major criticism of the CDM is the non-stringent application of additionality. Additionality imparts credibility to the CERs and creates confidence in the carbon emission market. There are projects where CERs have been called 'subprime carbon', due to the non-additional nature of emission reductions that are flooding the carbon market.

The demonstration of additionality is an important barrier for a CDM project, and project developers use innovative techniques to prove this. Most of the developing countries pursue a national renewable energy plan. In such a scenario the inclusion of wind and hydroelectric projects would be 'non-additional', as they have no significant technological, financial, policy or common practice barriers. For these projects, CER revenue is an additional profit stream.

However, if wind and hydroelectric renewable energy CDM projects (in China, India and Brazil only) were considered non-additional, it would stifle the market and would be counterproductive. To categorise these projects as non-additional would affect market confidence. CDM projects may appear to be non-additional, but these projects are able to generate a unique momentum in the renewable energy market worldwide. For example, India and China have been creating wind farms and local hydroelectric power plants because both countries have strong national targets to achieve rural electrification using renewables. The CDM should be recognised for generating a policy momentum and creating an additional CER revenue stream for project developers.

The researchers Wara and Victor, of Stanford University, applied Gresham's Law of Business Ethics to the concept of CDM additionality (Wara and Victor, 2008). They claim that it is inconceivable that renewable CDM projects are additional and, applying Gresham's Law, state that non-additional false credits will drive additional credible credits out of the market. This criticism is justified to a degree. However, CDM plays an important role in the sustainable development of local communities and neither the theory of negative externality nor Gresham's Law are applicable, as the benefits are not quantifiable and CDM generates a political willingness to pay.

If Gresham's Law is applied to CDM additionality, wind farm CDM projects and hydroelectric projects would be non-additional. CDM and its relationship with international emission trading are illustrated in figure 3.1.

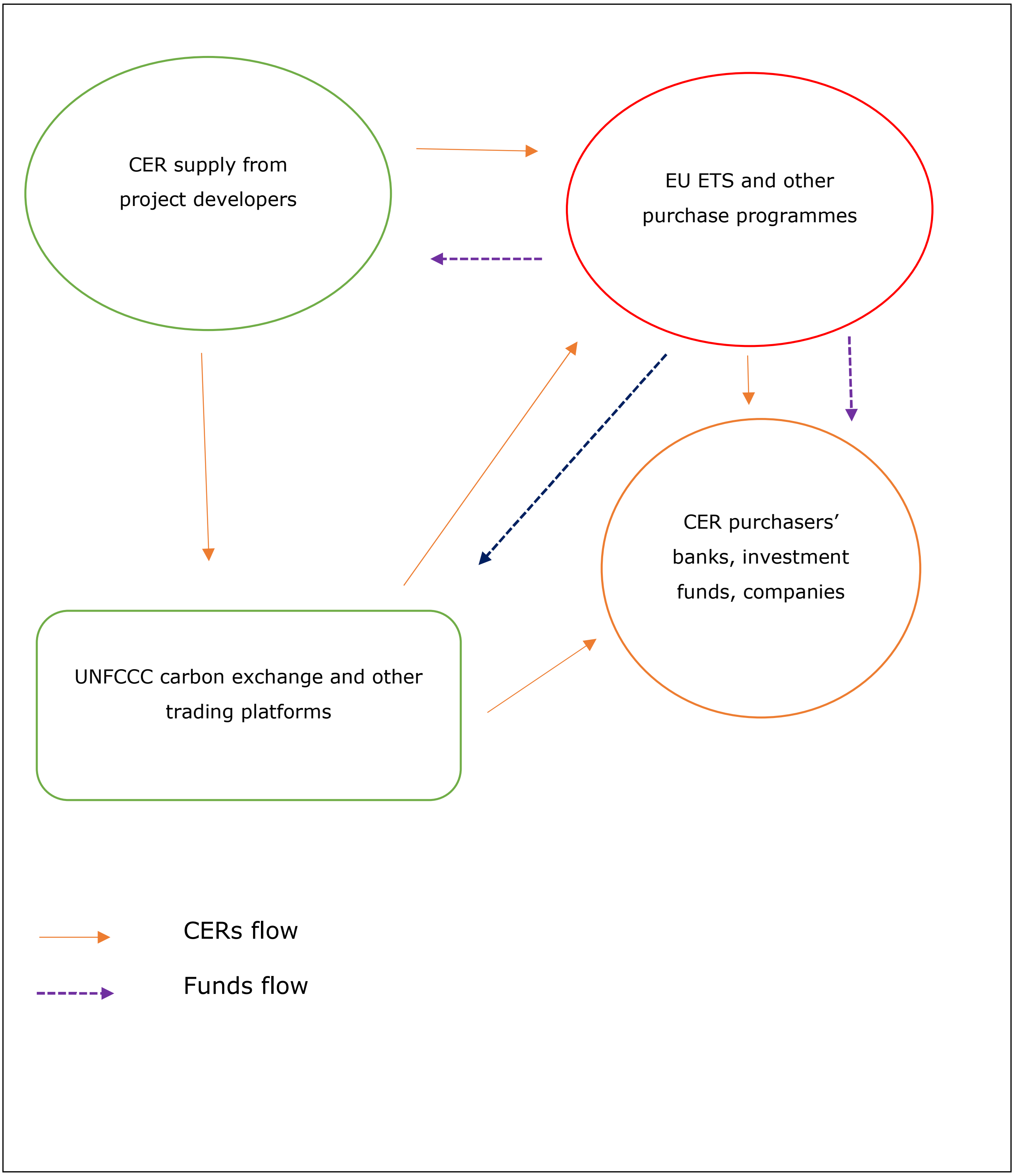

Figure 3.1: CDM and carbon emission trading

The objective of the CDM AM and emission trading is to strengthen, modernise and reform CDM-based projects, emission trading and the carbon markets.

The CDM has provided carbon markets (e.g., the EU ETS and VER markets) with the political legitimacy, operational flexibility and asset liquidity required to create a cost-effective international emission trading system. Kyoto compliance buyers (e.g., the EU) have driven CDM project activity in developing countries. CERs originating from CDM project activities are supplementing the EU's emission reduction efforts and are protecting European manufacturing. The reliance on non-CO_2 emission reduction has led to inadequate CO_2 emission reduction, with the CDM not being able to create large-scale CO_2 emission reduction.

CDM project activity in the renewable energy generation category appears to be 'weakly additional' and 'non-additional'. Wind farms, hydroelectric and biogas projects are not strictly additional because these projects would happen in the absence of the CDM. There are no financial, technological or common practice barriers that impede the development of renewable projects in China, India and Brazil. These countries have a majority share in hydroelectric and wind farm projects and have indigenous national programmes that promote and install various forms of renewable energy projects.

The CDM project registration process is not effectively able to screen out non-additional projects. For CERs to be credible, the emission reduction must be additional to BAU scenarios. The following example supports this argument.

The Sichuan Muli River Dashawan Hydropower CDM project (UNFCCC project 2850, 2022) is one of the largest hydroelectric CDM projects in China, creating a 240 MW power capacity and feeding the Central China Grid. The project claims additionality as there is no oil and gas available on the project site and the cost of these fuels is expensive. In addition, the project claims that there are not enough renewable energy resources (i.e. wind and tidal resources) available. The project demonstrates that the creation of the hydroelectric power plant is, therefore, additional.

The CDM scenario created for the above project is not credible as there is no effect on the grid emission coefficient, and China is developing hydroelectricity as a national priority. The project creates an inconceivable and purely hypothetical alternative scenario analysis to demonstrate additionality. Similar projects could be carried out many times in China, Brazil and India. The hydroelectric power projects in China, India and Brazil appear to be non-additional as they do not alter the BAU scenario: there is no net abatement of any GHG. The CDM projects feed the grid without displacing CO_2 and non-CO_2 gases and create a revenue stream for project developers and stakeholders. The inadequacies of the CDM can be characterised as follows:

- The CDM project mechanism and the emission trading principles do not recognise the differentiation between additionality and non-additionality. The additionality of a CDM or emission trading project is directly related to global GHG emission reduction and is therefore related to the stabilisation of atmospheric GHGs and accomplishing 1.5^0C, 17^0C and 2^0C climate goals.
- Additionality is not a generic concept, as it is applied by the UNFCCC in registering CDM projects. A hydroelectric project in China, India or Brazil is most likely non-additional, due to the absence of relevant barriers. However, a similar project is additional in Bhutan or Nepal. The CDM must create a net reduction of CO_2, which would not happen in a BAU scenario. The CDM must create net emission reduction that contributes to the efforts to stabilise GHG concentrations in the atmosphere.
- CDM additionality does not differentiate and recognise the principles of atmospheric GHG stabilisation. CDM additionality also fails to recognise the importance of CO_2-only reduction.
- Technological barriers should determine CDM additionality. At present, additionality is determined by the cost of emission reduction: low-cost industrial GHG reduction has been achieved at the expense of CO_2 abatement.

- From the years 2004 to 2021, the CDM accomplished abatement of 2.11 $GtCO_2e$. The CDM data analysis (table 3.2) reveals that 1.14 $GtCO_2e$ was non-CO_2 based.
- The CDM has not been able to create large-scale afforestation and land use projects; only 20 CDM projects are registered under the land use category. Due to the lack of these projects, offset buyers are buying offsets from VER projects. Lack of supply and consequent market demand has led to the creation and acceptance of low-quality offsets from VER (non-CDM assets) projects.
- The CDM does not recognise the technological and economic gap between developing and less developed countries.
- The CDM has created 2,631 hydroelectric and 2,578 wind farm projects (Louhisuo and Takahashi, 2021), with only 140 solar PV projects registered. The CDM is unable to create grid parity in solar energy projects. Consequently, there is asymmetry in renewable energy project origination.
- The CDM has a strong regional bias: the total number of projects created in Africa is 293; the total number of projects registered in India and China is 2,604 and 5,094, respectively (Louhisuo and Takahashi, 2021).

The above arguments and evidence necessitate a reform of the CDM project mechanism. This reform should strengthen the CDM and make it readily accessible to the relevant challenges of climate change policy. The CDM AM will address these challenges. This methodology addresses the inadequacies of project registration and project monitoring.

The objectives of the CDM AM are:

- To define additionality in order to create credible GHG emission reduction.
- To create a quantitative framework that measures the contribution of each CDM project towards GHG emission reduction.

- To create a qualitative framework that measures the contribution of each CDM project towards source-based and process-based GHG emission reduction.
- To measure the contribution of CDM to GHG emission reduction within the industrial, energy, agricultural and transportation sectors.

The methodology has been applied to a sample of 13 CDM projects that are registered with the UNFCCC.

3.4 CDM Assessment Methodology: Pre- and Post-Registration Reform

The critical analysis of the CDM carried out identifies three major aspects that determine the success or failure of the CDM as an emission reduction policy lever: cost effectiveness, strength of additionality and technology transfer. The diversity and flexible interplay of these aspects is vital for the future of CDM emission reduction and for it to achieve its potential and to exploit the market forces that would deliver cost-effective GHG emission reduction solutions. Although, each aspect has challenges associated with it, the CDM and emission trading can play a vital role in accomplishing climate targets and the allowed carbon budget.

The CDM AM measures the contribution of a CDM project towards GHG emission reduction. The proposed CDM AM encapsulates the aspects and strategic impact of the CDM on climate change policy. It measures the performance of the CDM to achieve cost-effective abatement, technology transfer and the building of a renewable energy industry.

The proposed CDM AM is divided into two parts: the qualitative pre-registration assessment and the quantitative post-registration assessment of CDM projects. The methodology considers GHGs as a negative externality, which is responsible for causing climate change. The methodology has been applied to 13 case studies in the industrial manufacturing, energy generation, agricultural and transportation sectors. These case studies are registered CDM projects where the CERs have been issued by the UNFCCC. A total of 100 CDM projects were reviewed, but not all have been included as they are repetitive.

3.4.1 Qualitative assessment: pre-registration

The proposed qualitative assessment measures the CDM contribution to the abatement of GHGs in the IEAT sectors through technology transfer, technology creation/innovation and the diversification of renewable energy generation sources. The GHG emissions are generated through direct and indirect combustion of fossil fuels and fossil fuel derivatives.

The amount and rate of GHG emissions created is dependent on: the amount of fuel combusted for IEAT activities; the type of fossil fuel combusted; and the efficiency of the combustion technology used. The relationship between the amount of GHGs emitted and the amount of fossil fuel combusted is a direct linear relationship, as no single quantity can be zero at a particular time.

The energy input into the IEAT sectors is transformed into economic value in the form of goods and services, and the unusable energy is emitted as GHGs. The unusable energy is emitted as CO_2, CH_4, F-gases and N_2O. There is a direct proportional relationship between fossil fuel combustion and GHG emissions:

Energy Input + Combustion Technologies = Energy Goods and Services + Greenhouse Gases

No quantity in the relationship can be zero and according to the law of conservation of energy and the first law of thermodynamics. The greater the energy input, the greater the gas emitted and the greater the negative externality created. The limiting variable is the efficiency of the combustion technology. Fossil fuels and the technology used in industry emit CO_2, CH_4 and N_2O and F-gases. The agricultural sector produces CH_4 and N_2O, and the transportation sector emits CO_2 and N_2O.

The CDM exploits the direct linear cause-and-effect relationship in the IEAT sectors, creating emission reductions in these sectors.

The proposed qualitative assessment uses a linear policy model to measure the performance of the CDM. The proposed model is schematically represented in figure 3.2.

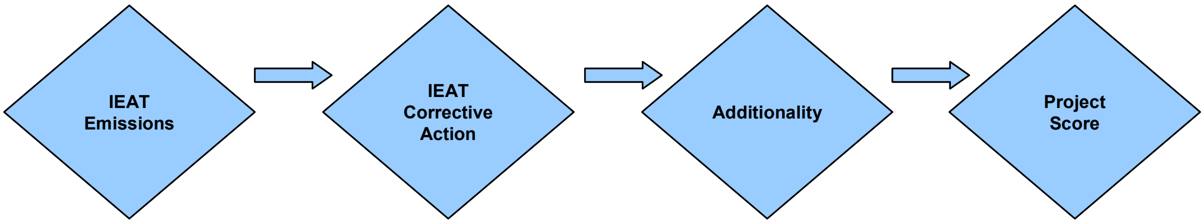

Figure 3.2: Linear qualitative assessment model schematic

The resulting qualitative assessment model is shown in Table 3.3.

The proposed qualitative assessment categorises the emission sources and applicable CDM corrective actions. Each project in the relevant category is measured with respect to CDM corrective action required to reduce emissions in the relevant category. The CDM corrective action indicator assesses the success of CDM projects in reducing GHG emissions from a relevant emission category. The CDM project in the relevant category must use one corrective action from the applicable category. For each applicable CDM corrective action indicator achieved, the proposed qualitative assessment assigns a score of unity. For each applicable CDM corrective action indicator not achieved, the proposed qualitative assessment assigns a score of zero. A negative score cannot be assigned to a corrective action as some corrective actions are not applicable to the entire CDM project category and each CDM project has some benefit that cannot always be quantified.

Table 3.3: New CDM assessment methodology – qualitative

Emission category	Emission sources (negative externality)	Impact indicator six gases	CDM corrective action indicator (positive externality)		Weightage	Additionality
			Emission avoidance	Emission reduction		
Industrial activity	Fossil fuel; coal, gas and oil industrial process waste; landfill	CO_2, CH_4, N_2O, HFC, PFC and SF_6 -positive RF	Renewable energy capacity building	Fuel substitution technology transfer for energy efficiency, waste management	1,0	1,0
Energy generation	Fossil fuel; coal, gas and oil waste; landfill transport; supply chain	CO_2, CH_4, N_2O, PFC and SF_6 -positive RF	Renewable energy capacity building	Fuel substitution through technology transfer and waste management	1,0	1,0
Agriculture	Enteric fermentation; fertiliser production and use; waste management and land use	CO_2, CH_4, N_2O -positive RF	Renewable energy capacity and sink capacity addition	Feedstock change, afforestation and waste management	1,0	1,0
Transport	Road, air and sea transport	CO_2, CH_4, N_2O -positive RF	Public transport	Energy efficient transport	1,0	1,0

Source: Author

The most important component of the proposed qualitative assessment is the applied concept of additionality, since it imparts legitimacy to the CDM emission reduction. Emission reduction that takes place in a continued BAU scenario is not credible, as it does not contribute to accomplishing climate change targets. The financial value and the legal status of CERs is a manifestation of additionality. Additionality is important for carbon emission trading to make international emission trading effective and legitimate for meeting the climate targets. For the qualitative assessment of the CDM AM, additionality has been applied to registered CDM projects as follows:

- For industrial CDM projects, a project is additional if there is no financial incentive to abate HFC-23, N_2O, PFC and SF_6. The reduction of these gases is not possible in a BAU scenario, as there is no economic incentive to abate them.

- For renewable energy CDM projects, CDM additionality should displace CO_2 by overcoming technology, financial and common practice barriers. A renewable energy CDM project could be solar, hydroelectric, wind, tidal or a biomass CDM project. The definition and application of additionality in renewable CDM projects is the most challenging aspect of the CDM. Strictly hydroelectric or hydropower projects would be non-additional, as they do not alter the BAU scenario. However, there is strong evidence that renewable energy technologies, including hydroelectricity, are penetrating the markets in Asia and Latin America; this penetration has been facilitated by the CDM. Whilst a renewable energy CDM project does not alter the BAU scenario, it enables technology penetration and dissemination. Renewable energy CDM projects have introduced and mobilised private investment, effective project management, innovative financial instruments and venture capital in developing countries. These aspects of the CDM cannot be encapsulated by determining project-specific additionality. A CDM project has a limited opportunity to alter the BAU scenario, with the BAU scenario being determined by the grid and national policy; however, a CDM project alters the BAU scenario at a micro level, where change to low carbon technology is not detectable. CDM project activity in renewables should always be considered as additional because it integrates micro-generation with technology penetration. A CDM project is installed at a local level and net emission reduction cannot be achieved at this level.

- Agricultural CDM additionality should be able to create an economic incentive to avoid/reduce enteric fermentation and to create a CDM project to reduce N_2O, CO_2 and CH_4 gases through waste and land management.
- For the transportation sector, a CDM project should be able to create a low CO_2 emission transport system by fuel substitution, by renewable based electrification and/or by introducing fuel-efficient transportation. A transportation sector CDM project is additional if the project imports a technology hitherto absent in a project host country.
- A credible CDM project should be able to apply the above criteria of CDM-based GHG emission reduction. Additionality makes CDM and emission trading long term and irreversible.
- If the project fulfils the relevant criteria of additionality, the additionality is unity. If the project does not fulfil the relevant criteria, the additionality is zero.
- The result is presented as a project score, which is the sum of the applicable corrective action indicators and the product of the additionality score. If the project is non-additional, the abatement is not credible.

The qualitative assessment equation devised to measure a qualitative result is:

Qualitative Assessment = ((∑ CDM Corrective Action Indicators) x Additionality Score))

3.4.2 Quantitative assessment: post-registration

Emission reductions created by the CDM in the form of CERs are the result of independent validation and periodic verification. The CERs are sold in the market as primary CERs and are bought by countries and companies as secondary CERs.

The objective of the quantitative assessment is to measure the performance of a CDM project in creating accurate GHG emission reduction. The quantitative assessment measures the efficiency of a CDM project, the quotient of CDM performance and the market commodity value (MCV).

The quantitative component of the CDM AM measures:

- The magnitude of project level emission reduction created by a CDM project.
- The rate of CER delivery with respect to the crediting period. This is measured by the quotient of performance (QOP).
- The financial value of abatement in the carbon market. Currently, CER is valued at $0.4–$5 (Muller, 2017) and is measured by the MCV.
- The magnitude of CO_2 and non-CO_2 abatement in relevant projects.
- A set of equations has been devised to carry out the quantitative assessment component of the assessment methodology.
- The CDM efficiency is the quotient of emission reduction achieved (number of CERs issued by the UNFCCC) and the emission reduction potential of the project. The result, which is a unitless quantity, indicates the magnitude of effective emission reduction created by a CDM project.

CDM Efficiency = Emission Reduction Achieved/Total Emission Reduction Potential

The QOP gives the performance of the CDM project, taking into account the time taken to create GHG emission reduction and the emission reduction potential of a CDM project in the crediting period. The time taken to achieve the abatement is called the measuring period.

$$QOP = \frac{\text{Emission Reduction Achieved } (tCO_2e)/\text{Measuring Period}}{\text{Emission Reduction Potential } (tCO_2e)/\text{Crediting Period}}$$

The QOP is a unitless measure. The measuring period is the time taken by a project to earn CERs. The crediting period is the period during which the CDM can claim emission reductions (CERs). The crediting period can be 10 years or 21 years with 7-year intervals. The crediting period in CDM projects can be any number of years as long as it does not exceed a 10-year period in any one interval.

The financial value of the CERs is measured by:

*Market Commodity Value (MCV) = k*Emission Reduction Achieved*

where k is constant at $0.4–$5, based on the market value of CERs. The MCV measures the financial value that the project-based CDM abatement achieves.

The evidence of analysis of CDM projects also indicates that there is asymmetry in CO_2 and non-CO_2 abatement. This approach measures the amount of CO_2 emission reduction between sectors. At present, the UNFCCC does not differentiate between the two types of emission reduction.

3.4.3 Case study selection criteria and data collection

The CDM case studies used to study and implement the CDM AM were selected using the following criteria:

- Projects were reviewed from CDM host countries: India, South Africa, China, Brazil, Honduras, Argentina, Malaysia and Colombia. China and India are large CDM host nations. A diverse selection was adopted to capture the geographical diversity of CDM projects in developing countries.
- Each CDM project selected is a UNFCCC registered project and CERs have been issued.
- The industrial sector case studies belong to projects that are implemented in an industrial installation involved in the emission of N_2O, HFC, PFC and SF_6.
- The energy sector case studies belong to a cluster of CDM projects that create CERs through CO_2 abatement using renewable technologies.
- The agricultural CDM project case studies belong to a cluster that converts agricultural waste to energy and/or creates CERs through GHG abatement of these agricultural operations.
- The transportation CDM projects belong to a cluster that creates CERs through building public transport systems or through improving the energy efficiency of a transport system.

The data for the case studies reviewed was acquired from the UNFCCC CDM project database.

3.4.4 Contribution of CDM assessment methodology

The present CDM registration and validation process is not adequate for creating credible GHG emission reduction. The CDM AM identifies those inadequacies in CDM and emission trading is due to:

- Non-differentiation by market forces between the reduction of CO_2 and non-CO_2 GHGs. The present methodology is not able to differentiate between authentic emission reduction and unauthentic emission reduction.
- The application of additionality in renewable energy generation is inadequate. BAU scenarios created to support CDM projects do not appear to exist, especially in India, China and Brazil. The weakly additional and/or non-additional hydroelectric and wind farm CDM projects could drive credible and additional abatement out of the market, as barriers to CO_2 abatement remain and continue to strengthen. A renewable energy CDM project is implemented at a local level and is generally a micro-generation project. A strict implementation of additionality is difficult to achieve at a local level; however, a CDM facilitates technology penetration and private investment, adding to the renewable energy capacity in developing countries.

The qualitative component of the CDM assessment methodology addresses the issue of weak and/or non-additionality in renewable energy generation.

If the renewable energy additionality criteria of the CDM AM are applied strictly, the majority of hydroelectric and wind-based projects would be determined as non-additional. There are no identifiable barriers to CDM project origination. In the case of China, there are no technological, policy, financial or common practice barriers to project implementation. The hydroelectric and wind projects in China use the CDM baseline methodologies, ACM0002 and AMS.I.D. China is the world's leading producer of wind turbines. Similarly, China is creating the world's biggest hydroelectric power projects.

There appears to be no linkage between additionality and technology import/innovation in hydroelectric projects and wind power farms in China. Whilst these CDM projects are not creating net CO_2 abatement and are feeding the rebound demand of the grid, they are adding to the renewable energy capacity of the grid. They are also feeding the BAU demand, which is subsidised by low tariff, coal-based power generation. The low power tariff contributes to the creation of non-additional hydropower and wind farm CDM projects.

The CDM AM decouples the low tariff and non-additionality linkage. The qualitative component corrects the anomaly, and non-additional projects are not be registered. A search of the CDM database in the renewable category for India and China does not reveal any significant solar-based CDM project. This is due to the fact that solar energy technology suffers from negative grid parity and these projects are not commercially viable. The lack of application of additionality has pushed solar CDM projects out of the market.

In the case of India, the government utility, the National Hydroelectric Power Corporation (NHPC), has a monopoly within the Indian hydroelectric market. It is constructing major hydroelectric stations, for example, Teesta, Parbati, Chutak and Subansiri hydroelectric power projects. As there are no domestic barriers to these projects, it is extraordinary that a CDM hydroelectric project can demonstrate additionality in India. There are no barriers to overcome, as the relevant alternative renewable energy scenarios created to demonstrate additionality are fictitious. The emission reductions of such projects are weakly additional.

The CDM AM addresses these issues and reforms the CDM pre-registration and post-registration process.

The CDM AM improves the current methodology by differentiating between CO_2 and non-CO_2 abatement. The present CDM process does not carry such differentiation, and as a consequence, the CDM has emerged as a high-volume non-CO_2 abatement vehicle. The QOP will determine the magnitude of real abatement achieved. At present, once the CDM project is registered, there is no legal requirement to achieve projected abatement.

The CDM AM unlocks the potential of CO_2 abatement through a new concept of additionality. The present CDM has locked the CDM in strongly additional industrial GHG abatement and weakly additional renewable energy generation.

The CDM AM strengthens the emission trading links with the CDM, as CERs are used by companies in different countries. The CDM AM reduces the need for validation of projects; this process is unnecessary and delays CER issuance by the UNFCCC. In the absence of validation, strong additionality would adequately demonstrate the BAU and applicable CDM scenarios.

3.5 Energy Case Studies

3.5.1 La Esperanza Hydroelectric Project (UNFCCC CDM project ref: 009)

The project activity involves building a hydroelectric power plant in Honduras. The project will create renewable energy of 13.822 MW (UNFCCC, La Esperanza Hydroelectric Project, 2018) and will displace CO_2 emissions from a diesel- and fuel oil-dependent grid; Honduras' electricity power generation is dominated by diesel.

3.5.1.1 Qualitative assessment

Both the qualitative and quantitative assessments are provided in Appendix 3.

The project creates renewable capacity and avoids CO_2 and N_2O emissions from the grid by the positive displacement of these two gases. The project also creates renewable capacity, enhances natural sink capacity by afforestation and creates waste management in the catchment area. Therefore, the CDM corrective action score of the project is 3.

However, a detailed study of the project reveals that Honduras has significant domestic capacity and knowledge in hydroelectric power generation. There are no policy, financial or technological barriers to the project. This would categorise the project as weakly additional. The qualitative score is 3.

La Esperanza is weakly additional. It is not a non-additional project. As stated in previous sections, renewable CDM projects integrate micro-generation with technology penetration. La Esperanza integrates micro-generation and waste management in a single project. The project has taken place due to financial backing from EU companies. The project participant is atmosfair gGmbh, based in Germany.

3.5.1.2 Quantitative assessment

The project's emission reduction potential is 36,272 tCO_2e/year and the abatement achieved in 48 months is 51,803 t-CO_2e (UNFCCC, La Esperanza Hydroelectric Project, 2018). The crediting period is 21 years; the emission reduction potential is 761,712 tCO_2e.

The CDM efficiency of the project is 0.62 and the QOP is 0.81. The MCV (market commodity value) of CERs generated is assumed to be $2,342,980–$187,438.

The La Esperanza CO_2 abatement is weakly additional and the project appears to create a carbon revenue stream for the project developers.

3.5.2 Zhangbei Manjing Wind Farm (UNFCCC CDM project ref: 233)

This CDM project in China is a renewable energy CDM project that harnesses wind power. The renewable energy generated is transferred to the North China Grid to enhance its renewable energy portfolio. The total installed capacity is 45 MW (Zhangbei Manjing Windfarm Project, 2015). The project produces 45 MW of wind power and emission reduction is estimated to be 96,746 tCO_2e per year. The project life span is 20 years.

3.5.2.1 Qualitative assessment

Both the qualitative and quantitative assessments are provided in Appendix 3.

The North China Grid is a coal-based power grid, with coal generating 86% of its power. The CDM for the project does not affect the emission build and operating margin of the grid. There is no technology transfer and there are no policy, technical or common practice barriers to overcome. The project's carbon revenue increases the internal rate of return.

The project is weakly additional. It is not non-additional as it adds to the renewable energy capacity of the grid, which is dominated by coal-fired power generation. The project stakeholder is Vitol SA, a Swiss energy trading company and an important market player in the EU carbon market.

The qualitative score is 1.

3.5.2.2 Quantitative assessment

The emission reduction potential of the project is 1,934,920 tCO_2e and the reduction achieved is 1,210,138 tCO_2e (Zhangbei Manjing Windfarm Project, Project Design Document. 2015). The measuring period is 13 years, with a crediting period of 20 years.

The CDM efficiency of the project is 0.63 and the QOP is 0.96. The MCV is $484,055–$6,050,690.

3.5.3 Rithwik Biomass Project (UNFCCC CDM project ref: 253)

The Rithwik CDM project in India uses waste and cultivated biomass to generate power, which is transmitted to the grid. The project uses Prosopis juliflora, mango and eucalyptus as wood biomass. It also uses agricultural biomass (rice husk, maize and coconut shells) to generate electricity of 6 MW (UNFCCC, Rithwik Biomass Project, 2005). The project created a Prosopis juliflora farm to secure the biomass supply chain.

3.5.3.1 Qualitative assessment

Both the qualitative and quantitative assessments are provided in Appendix 3.

The project creates renewable energy and also converts waste to energy; in a BAU scenario, the waste would be landfilled, generating CH_4. There is no technological innovation or transfer involved in the project. The CDM corrective action score is 2.

The project is additional, as a major technological barrier to overcome is fuel supply sustainability. Carbon revenue hedges the power tariff risks and also secures the fuel supply. The project overcomes policy, financial, technological and common practice barriers and is therefore additional.

The qualitative score is 2.

3.5.3.2 Quantitative assessment

The emission reduction potential of the project is 186,298 tCO_2e and the emission reduction achieved so far is 143,733 tCO_2e (Rithwik Biomass, 2010) in 6 years. The crediting period is 7 years.

The CDM efficiency is 0.77 and the QOP is 0.60. The MCV is $57,493–$718,665.

3.6 Industrial Case Studies

The industrial cluster CDM assessment carried out involves the assessment of reduction of HFC-23, SF_6, PFC and N_2O. The industrial cluster case studies below are based on HFC-23 and N_2O CDM projects.

3.6.1 Changshu HFC-23 Decomposition Project (UNFCCC CDM project ref: 0306)

The Changshu HFC-23 decomposition project achieves emission reduction of HFC-23 gas in China’s chemical manufacturing sector (UNFCCC, Changshu Project Design Document, 2006 and 2012). This project is the biggest CDM project in terms of volume of emission reductions achieved and volume of CERs generated. Total emission reduction potential is 219,182,229 tCO_2e, reducing 0.2191 $GtCO_2e$ over a crediting period of 21 years. HFC-23 reduction is important as HFC-23 emission reduction is not part of the Montreal Protocol on substances that deplete Ozone. The CDM is the only mechanism available to create HFC-23 emission reduction.

3.6.1.1 Qualitative assessment

Both the qualitative and quantitative assessments are provided in Appendix 3.

The Changshu plant produces industrial HFC-23 as a waste gas from the manufacture of HCFC-22 and HFC-32. HFC-23 is produced from the liquefaction of chloroform with hydrogen fluoride (UNFCCC, Changshu Project Design Document, 2006 and 2012).

CDM abatement is limited to HFC-23; the warming potential of HFC-23 is 11,700 of CO_2. The project activity involves thermal decomposition of HFC-23 using advanced oxidation. The technology was licensed from VICHEM and the project deploys the CDM corrective action for technology transfer. The project receives a CDM corrective action score of 2 for technology transfer and waste management.

The project is additional, as there is no national or international requirement to abate HFC-23 gas from the Changshu manufacturing facility. The carbon revenue from the project is used to fund the project and also to fund the Chinese sustainable development fund. The project overcomes technology, policy and financial barriers to create CERs, so the additionality is unity. The project qualitative score is 2. The project is strongly additional.

3.6.1.2 Quantitative assessment

The emission reduction potential of the Changshu CDM project is 219,182,229 tCO_2e and the real emission reduction achieved is 58,922,499 tCO2e (UNFCCC, Changshu Project Design Document, 2006 and 2012).

The time taken to achieve the reduction is 6 years. The crediting period of the project is 21 years. The CDM efficiency is 0.27 and the QOP is 0.94. The MCV achieved due to emission reduction is $23,569,00–$294,612,495.

3.6.2 Indo-Gulf Fertilizer CO_2 Removal Project (UNFCCC CDM project ref: 123)

This project removes CO_2 from ammonia manufacture. The removal of CO_2 takes place by shifting a high-pressure regenerator to a low-pressure regenerator (UNFCCC, Indo-Gulf CO_2 Removal Project Design Document, 2005 and 2015). Consequently, the process saves 18.5 tonnes of steam and saves energy (natural gas) consumption from the plant, thereby reducing emissions of CO_2 and N_2O. The process creates emission reduction in urea manufacture and is the first of its kind in the world. The project involves technology transfer from Italy to India.

3.6.2.1 Qualitative assessment

Both the qualitative and quantitative assessments are provided in Appendix 3.

The CDM is created through technological transfer from the Italian Company M/S GV Italy. The technology modifies the process of ammonia and urea manufacture. The CDM corrective action score of the project is 1. The project is additional, as carbon revenue is used to support the project’s research and development. The CDM revenue helps overcome the financial barrier. The project also overcomes policy barrier and common practice barriers and is unique in installing technology to remove CO_2 from ammonia and urea manufacture. The qualitative score of the project is 1.

The project is strongly additional. The project makes an energy saving of 96 GWh/year.

3.6.2.2 Quantitative assessment

The emission reduction potential of the project is 244,490 tCO_2e. The reduction achieved by the project is 160,928 tCO_2e (Indo-Gulf CO_2 Removal, 2005 and 2015). The measuring period is 9 years and the crediting period is 10 years.

The CDM efficiency is 0.66 and the QOP is 0.73. The MCV is $64,371–$804,640.

3.6.3 Ugar Sugar Bagasse Cogeneration Project (UNFCCC CDM project ref: 189)

The Ugar Sugar Plant is a bagasse cogeneration CDM project in India. The project creates a renewable energy source of 16 MW, with an installation of bagasse dryers, ThyssenKrupp boilers and high-pressure turbines (UNFCCC, Ugar Sugar Bagasse Cogeneration Project Design Document, 2005 and 2007). The project displaces the South India grid's coal-based CO_2, N_2O and CH_4 emissions. It is one of the first cogeneration CDM projects developed in the world.

3.6.3.1 Qualitative assessment

Both the qualitative and quantitative assessments are provided in Appendix 3.

The project uses bagasse as an energy source, displacing grid emissions. The project does not displace sugar plant emissions. Grid emissions are reduced through technological innovation and there is no evidence of significant waste management. Therefore, the CDM corrective action score assigned is 1.

The carbon revenue generated finances the project. It overcomes financial, policy and technological barriers. Bagasse cogeneration is new to India and bagasse availability is a significant technological barrier. The project is additional and the total qualitative score is 1.

3.6.3.2 Quantitative assessment

The emission reduction potential of the project is 639,348 tCO_2e and the emission reduction achieved is 94,783 tCO_2e (Ugar Sugar Project Design Document, 2005 and 2007) in the measuring period of 2 years. The crediting period is 10 years. The CDM efficiency of the project is 0.15 and the QOP is 0.74. The MCV created by the project is $37,913–$473,915.

3.6.4 Jinan Iron and Steel Project (UNFCCC CDM project ref: 812)

The project activity involves capture of heat from blast of furnace gas (BOG) and coke oven gas (COG) to fuel a combined cycle power plant (CCPP). The project installs 544 MW from the CCPP and displaces CO_2 emissions from the Shangdong power grid (UNFCCC, Jinan Iron and Steel Works BOG and COG Utilisation CDM Project Design Document, 2006 and 2013).

In a BAU scenario, the BOG and COG are emitted as waste gases. The project is a CO_2 emission reduction project.

3.6.4.1 Qualitative assessment

Both the qualitative and quantitative assessments are provided in Appendix 3.

CCPP BOG-COG technology was deployed for the first time in China in an iron and steel plant. The project is a technology transfer project and carbon revenue is part of the project's implementation finance. The project overcomes technological, policy, financial and common practice barriers and is therefore additional.

The project scores for technology transfer and the total score is 1.

3.6.4.2 Quantitative assessment

The total emission reduction potential is 11,135,894 tCO_2e and the reduction achieved is 8,110,370 tCO_2e (Jinan Iron and Steel, 2006 and 2013). The measuring period of the project is 7 years and the crediting period is 7 years.

The CDM efficiency is 0.73 and the QOP of the project is 0.73. The MCV is $3,244,148–$40,551,850.

3.6.5 Taishan Cement Waste Recovery Project (UNFCCC CDM project ref: 366)

The Taishan CDM project in China is a waste heat recovery project that captures waste heat from rotating kilns in two clinker production lines (UNFCCC, Taishan Cement Works Waste Heat Recovery and Utilisation for Power Generation Project Design Document, 2005 and 2013). The energy created totals 13.2 MW and avoids combustion of 52,000 tonnes of coal. The project displaces CO_2, N_2O and CH_4 emissions.

3.6.5.1 Qualitative assessment

Both the qualitative and quantitative assessments are provided in Appendix 3.

The project installs heat recovery boilers that carry a high design risk; this is a technological innovation project. The project uses waste heat and reduces emissions by recovering waste heat. The carbon revenue improves the project’s revenue. The project overcomes policy, technological, financial and common practice barriers. The project is additional and the qualitative score is 1.

3.6.5.2 Quantitative assessment

The emission reduction potential of the project is 741,260 tCO_2e (Taishan Cement, 2005 and 2013) and the abatement achieved is 383,987 tCO_2e. The measuring period is 6 years and the applicable crediting period is 7 years.

The CDM efficiency of the project is 0.52 and the QOP is 0.60. The MCV is $153,595–$1,919,935.

3.6.6 N_2O Decomposition at Liaoyang Petrochemical Company (UNFCCC CDM project ref: 1238)

The Liaoyang Petrochemical Company's N_2O decomposition project in China at the Petrochemical China installation is the second biggest CDM project in terms of potential for emission reduction. The project activity involves catalytic decomposition of N_2O emitted during adipic acid production. The N_2O is decomposed to N_2 and O_2. There is no legislative requirement to reduce N_2O emissions in China, and there is no international requirement to reduce N_2O emissions from adipic acid production. The N_2O has a global warming potential of 310; its abatement is only possible through the CDM project mechanism.

The plant produces 17,4105 tonnes of adipic acid annually. The acid is manufactured from cyclohexane oxidation to produce cyclohexanone and cyclohexanol. The mixture of ketone and alcohol is oxidised by nitric acid, and N_2O is produced by the oxidation of the ketone-alcohol mixture by nitric acid. N_2O is a waste gas in this process and there is no economic incentive to reduce its emission (UNFCCC, Liaoyang Petrochemical Company Project Design Document, 2007 and 2014). The project activity decomposes N_2O through a catalytic process that does not consume gas, and 95% decomposition is achieved. The patented technology for selective catalytic decomposition is transferred from a German company, BASF. The N_2O-rich gas is fed to a droplet separator and gas is diluted by air from a compressor. The reaction is highly exothermic and N_2O flow is controlled to avoid depletion of the catalyst. The diluted mixture is preheated at 180°C and then at 480°C. The gas is fed to a DEN_2O reactor, which destroys N_2O. The reactor gas is then fed to a DENOX reactor and N_2O is converted to N_2 and H_2O.

3.6.6.1 Qualitative assessment

Both the qualitative and quantitative assessments are provided in Appendix 3.

The project creates significant emission abatement through technology transfer. The CDM corrective action score is 1. The project is additional as carbon revenue funds the project and there is no economic incentive to abate N_2O. The project overcomes financial, policy and common practice barriers. The total qualitative score for the project is 1.

3.6.6.2 Quantitative assessment

The abatement potential of the project is 83,035,519 tCO_2e and the abatement achieved is 64,078,279 tCO_2e. The measuring period is 7 years and the crediting period is 13 years. The CDM efficiency of the project is 0.77 and the QOP is 1.43. The MCV is $25,631,312–$320,391,395.

3.6.7 Palm Kernel and Cement Project (UNFCCC CDM project ref: 247)

This CDM project in Malaysia replaces coal fuel with palm kernel fuel to manufacture Portland cement. The agricultural waste is used as a fuel, replacing coal. The high availability of palm kernel makes the project feasible and diverts waste from landfill disposal. In a BAU scenario, palm kernels are left to rot and emit CH_4 (UNFCCC, Palm Kernel and Cement Production Project Design Document, 2005 and 2010).

3.6.7.1 Qualitative assessment

Both the qualitative and quantitative assessments are provided in Appendix 3.

The project is based on European technology and converts waste to industrial energy. The CDM corrective action score is 2. The project is additional, as it overcomes technological, policy and financial barriers. The qualitative assessment score is 2.

3.6.7.2 Quantitative assessment

The emission reduction potential is 619,460 tCO_2e (Palm Kernel and Cement Production, 2005 and 2010) and the reduction achieved is 607,273 tCO_2e. The measuring period is 10 years and the crediting period is 10 years.

The CDM efficiency is 0.98 and the QOP is 0.98. The MCV is $242,909–$3,036,365.

3.7 Agricultural Case Studies

The agricultural case studies are based on CH_4 emission reduction.

3.7.1 Granja Becker AWMS Project (UNFCCC CDM project ref: 108)

The Granja Becker CDM project in Honduras is an agricultural CDM project that creates emission reductions from the manipulation and improvisation of livestock operations. The project is an agricultural waste management system (AWMS) project (UNFCCC, Granja Becker Greenhouse Gas Mitigation Project Design Document, 2004 and 2006).

Animal waste is subjected to anaerobic digestion; the biogas from this is then captured and combusted. In a BAU scenario, animal waste is stored in open-air lagoons and CH_4 is emitted into the atmosphere, creating a negative externality due to the livestock-based operations. Therefore, the Granja Becker CDM abates CH_4, CO_2 and N_2O.

3.7.1.1 Qualitative assessment

Both the qualitative and quantitative assessments are provided in Appendix 3.

The open-air lagoon is converted to an anaerobic digester. The project creates emission reduction using the technological innovation of baseline agricultural operations and also creates energy from waste. The CDM corrective action score is 2. The energy created is sold to the grid and creates renewable energy.

The project overcomes a significant financial barrier as well as common practice barriers and the technological barriers. The significance of the financial barrier implies that the project is additional. The total qualitative score is 2.

3.7.1.2 Quantitative assessment

The emission reduction potential of the project is 5,086 tCO_2e (Granja Becker, 2004). The abatement achieved is 3,339 tCO_2e in 2 years. The CDM efficiency is 0.66, the QOP is 3.28 and the MCV is $1,336–$16,695.

The crediting period is 10 years. The financial value of positive externality as a commodity indicates market willingness to pay in order to reduce negative externality. The financial value of the project is not significant.

3.7.2 Bagepalli Biogas Project (UNFCCC CDM project ref: 121)

The project activity proposes to set up 5,500 biogas plants for households (UNFCCC, Bagepalli Biogas Programme Project Design Document, 2005 and 2018). The project will generate energy for cooking and heating water. The project replaces the BAU scenario of cooking and heating with firewood. The project creates 6 MW of energy for 5,500 households.

3.7.2.1 Qualitative assessment

Both the qualitative and quantitative assessments are provided in Appendix 3.

The project abates CO_2, CH_4 and N_2O, converting agricultural waste to energy. The project scores a CDM corrective action score of 1. There are no policy or technological barriers to the project. There are thousands of such projects in India that use biogas for cooking and these are not CDM projects.

The project should be considered as non-additional and emission reduction is not credible. India launched the National Biogas and Manure Management Programme in 1980 and therefore projects of this type are not credible.

3.7.2.2 Quantitative assessment

The emission reduction potential of the project is 283,899 tCO_2e; the reduction achieved in 14 years is 194,133 tCO_2e (UNFCCC, Bagepalli Biogas Programme Project Design Document, 2005 and 2018*)*. The CDM efficiency of the project is 0.68, the QOP is 1.03 and the MCV is $77,653–$970,665.

3.8 Transport Case Studies

3.8.1 BRT Bogotá Trans Mileno Project (UNFCCC CDM project ref: 672)

This project creates a sustainable mass public transport system by deploying fuel-efficient buses in Bogotá, Colombia. The project creates a bus rapid transit (BRT) system by deploying dedicated lanes, feeder lanes, an integrated fare system and terminals (UNFCCC, BRT Bogotá Colombia TransMilenio Phase II–IV Project Design Document, 2006 and 2012). The project transports 1.8 million passengers every day and 9,000 conventional buses will be scrapped. The GHGs abated are CO_2, N_2O and CH_4.

3.8.1.1 Qualitative assessment

Both the qualitative and quantitative assessments are provided in Appendix 3.

The project introduces technology based on Euro II and Euro III, replacing the BAU technology, Euro I. The project also builds a sustainable transport system and the CDM corrective action score is 2. The project uses carbon revenue to fill the funding gap of $125 million, overcomes policy, technological and financial barriers, and is additional. The qualitative score is 2.

3.8.1.2 Quantitative assessment

The emission reduction potential is 4,052,426 tCO_2e. The reduction achieved is 511,423 tCO_2e (UNFCCC, BRT Bogotá Colombia TransMilenio Phase II–IV Project Design Document, 2006 and 2012) in 12 years. The CDM efficiency is 0.13 and the QOP is 0.07 with respect to the crediting period of 13 years. The MCV is $204,569–$2,557,115.

3.9 CDM Assessment Methodology Results

This section discusses the results of the CDM AM carried out on CDM case studies. The qualitative score determines the verifiability of emission reduction and the CDM efficiency and QOP measures the performance of a CDM project. The results are provided in table 3.4.

Projects with a qualitative score of 2 or more and a QOP ≥ 1 are creating significant emission reduction and are reducing negative externality in energy generation and industrial/agricultural/transportation activities. There is no relationship between the qualitative score and the QOP. The results reveal that the speed, quality and efficiency of emission reduction are determined by:

- Technological innovation or transfer, in order to exploit the law of mass action and the laws of thermodynamics.
- Exploitation of the available technology and local fuel supply in order to create abatement.
- The strength of additionality applied and implemented by the CDM project.
- Efficient project management.

If we assume that the qualitative score is the measure of efficiency, La Esperanza project is most strongly additional and has delivered efficient abatement. If we assume AE is the measure of efficiency, the Rithwik biomass project has the highest AE and has a qualitative score of 2. These projects are strongly additional.

Table 3.4: Results of CDM assessment methodology

Project name	CDM project category	Additionality	CDM efficiency	QOP	Qualitative score	Efficiency
Changshu HFC 23	Industrial	Additional	0.27	0.94	2	Efficient CDM
Indo Gulf	Industrial	Additional	0.66	0.73	1	Efficient CDM
Ugar Sugar	Industrial	Additional	0.15	0.74	1	Efficient CDM
Jinan Iron & Steel	Industrial	Additional	0.73	0.73	1	Efficient CDM
Taishan Cement	Industrial	Additional	0.52	0.60	1	Efficient CDM

N_2O LYPC	Industrial	Additional	0.77	1.43	1	Efficient CDM
Palm Kernel	Agricultural	Additional	0.98	0.98	2	Efficient CDM
La Esperanza	Energy	Weakly additional	0.62	0.81	3	Efficient CDM
Zhangbei Manjing	Energy	Weakly additional	0.63	0.96	1	Efficient CDM
Rithwik Biomass	Energy	Additional	0.77	0.60	2	Efficient CDM
Granja Becker	Agricultural	Additional	0.66	3.28	2	Efficient CDM
Bagepalli Biogas	Agricultural	Non-additional	0.68	1.03	1	Efficient CDM
BRT Bogotá	Transport	Additional	0.14	0.07	2	Non-efficient CDM

Source: Author

The CDM AM also points out and highlights difference between CO_2 and non-CO_2 emission reduction. As can be seen from the results in table 3.4, the non-CO_2 emission reduction is significant compared to the CO_2 emission reduction projects. These results confirm the findings of analysis provided in tables 3.1 and 3.2. The evidence is based on a small sample of 13 projects from different countries and reflects the underlying success and failures of the CDM project mechanism. The sample is small but captures the underlying trend and market forces that are shaping the emission trading market.

Emission reduction and emission trading works for the industrial, energy and agricultural sectors. It does not really work for the transportation sector. This can be seen in the fact that from 2006 to 2021, only 33 CDM projects have been registered.

In the sample of projects selected for the CDM AM, total emission reduction potential is 322,822,541 tCO_2e. The emission reduction delivered is 134,889,481 tCO_2e, which means that for the cohort of case studies, the CDM efficiency is 0.42. From within the sample of 13 projects, a total of 134,889,481 tCO_2e of emissions were reduced, of which total non-CO_2 emission reduction is 123,000,778 tCO_2e.

The results lead to a conclusion that emission trading and the CDM work well for emission reduction of non-CO_2 GHGs.

3.10 Emission Reduction in European Road Transport from 2000 to 2018

Decarbonisation of road transport in response to the climate change threat is a complex political, economic and technological challenge for all stakeholders in the EU. Road transport GHG emissions are formed of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) gas emissions. CO_2 is the most predominant GHG, and the International Energy Agency's (IEA) report on CO_2 emissions from fuel combustion (Dataset IEA, 2017a) revealed that road transport accounted for 24% (= 7.75 $GtCO_2$) of the world's CO_2 emissions in 2015. Similarly, the European Environment Agency's (EEA) report (European Union Greenhouse Gas Inventory 1990–2015 and 2017) stated that road transportation accounts for 24% of Europe's CO_2 emissions. The methodology used in the paper estimates or measures GHG emissions in all EU member states and reveals the sustainability implications of the EU's road transport policy. Vital points relevant to long-term sustainability implications are taxes for fuel, technology transfer, and fiscal and regulatory areas. The paper looks at the energy input from diesel and gasoline, the emissions output of EU road transport and the new sustainability requirements. The sustainability approach identifies the prevailing political and domestic economic opportunities and the future trajectories in EU road transport. Future road transport policy goals within and outside the EU will eventually integrate road transport sustainability with the TCRE and carbon budget requirements for the EU's carbon budget and identify opportunities that could limit global warming to 1.5^0C or 2^0C. This approach will be unique to the EU.

The IPCC mobile source methodology is widely used to estimate GHG emissions caused by the consumption of diesel and motor gasoline by automobiles, light trucks, heavy duty vehicles, buses and motorcycles. It is the best choice for estimating GHG emissions based on the amount of fuel consumed and/or sold (Waldron et al., 2006) and has been used in similar studies (e.g. Guo et al., 2016, and Liu et al., 2015). The method is based on Equations 1 and 2 below, which are based on the IPCC Tier 1 approach.

$$\text{Energy consumption (TJ)}_{\text{gasoline, diesel,}} = \{(\text{Amount of fuel [kt]}) * (\text{NCV of fossil fuel [TJ/kt]})\} \quad (1)$$

$$CO_2, N_20 \text{ and } CH_4 \text{ emissions}_{\text{gasoline, diesel}} = \{(\text{Energy consumption [TJ]}) * (CO_2\ N_20 \text{ and } CH_4 \text{ emission factor [kg/TJ]})\} \quad (2)$$

$$\text{Emission change}_{\text{year 2018/year 2000}} = (CO_2, N_20 \text{ and } CH_4 \text{ emissions}_{\text{gasoline, diesel}})_{\text{year 2018}} - (CO_2, N_20 \text{ and } CH_4 \text{ emissions}_{\text{gasoline, diesel}})_{\text{year 2000}} \quad (3)$$

$$\text{Emitted carbon}_{\text{year 2000/year 2018}} = (CO_2 * \text{GWP of } CO_2 + N_20 * \text{GWP of } N_20 * + CH_4 * \text{GWP of } CH_4) \quad (4)$$

Where CO_2, N_2O and CH_4 emissions$_{\text{gasoline, diesel}}$ is the GHG emissions from diesel and gasoline; NCV is the net calorific value of fuel for carbon in diesel and gasoline (TJ/Gg); emission factor is the carbon emission factor for CO_2, N_2O and CH_4 emissions (kg/TJ) from diesel and gasoline; and GWP is the global warming potential of a specific GHG. The results are provided in table 3.5 and figure 3.3 below. The complete dataset is contained in Appendix 3A. The IPCC methodology provides a default CO_2 emission factor (Waldron et al., 2006) and net calorific value (NCV) (Garg et al., 2006) of diesel and motor gasoline. It is important to note that the CO_2 emission factor takes into account all the carbon in the fuel that is emitted by the process of combustion. This approach was used by Moro and Lonza (2015). The data for motor gasoline and diesel consumption was acquired from the IEA data services for 2000 and 2018. The data for 2018 is the most recent dataset available from the IEA.

Table 3.5: Diesel and gasoline carbon emissions for the EU28 (2000 and 2018)

Diesel CO_2eGg 2000	**Gasoline CO_2eGg 2000**	**Diesel CO_2eGg 2018**	**Gasoline CO_2eGg 2018**
130,957	106,829	180,133	63,429
Total CO_2eGg in 2000 and 2018	237,786	243,562	
Net addition of carbon to atmosphere in GtC	0.237	0.243	

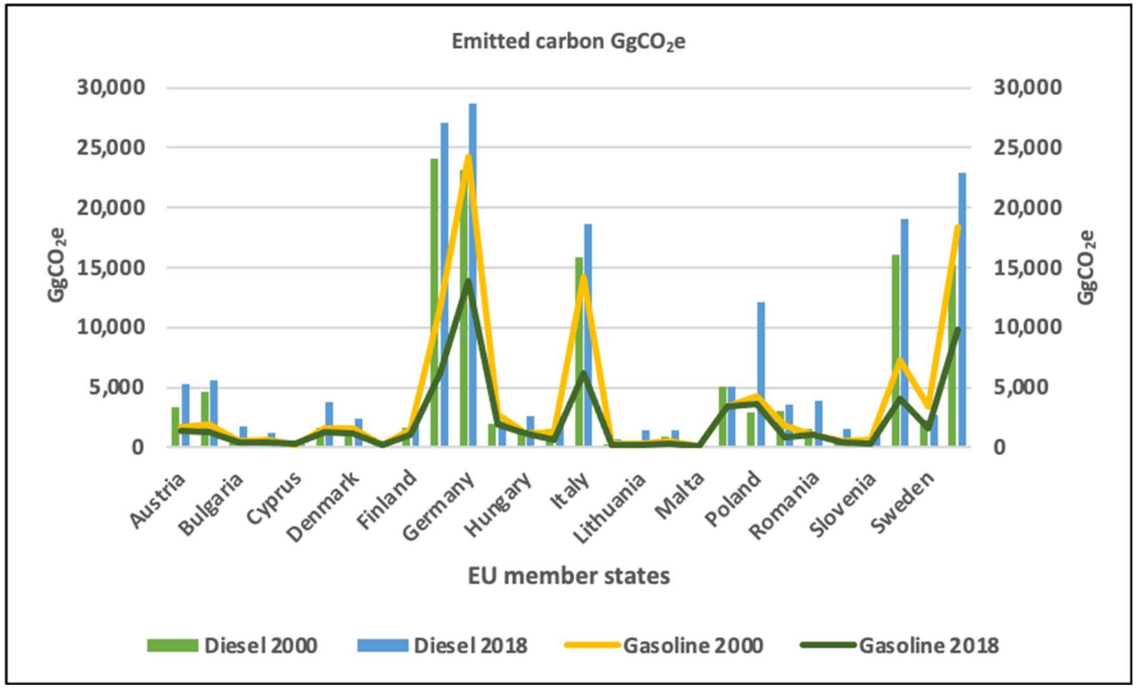

Figure 3.3: Emitted carbon from diesel and gasoline use by EU member states in 2000 and 2018

The majority of member states exhibited a consistent pattern of diesel GHG emissions increasing and gasoline GHG emissions decreasing between 2000 and 2018. The total GHG emissions from diesel were highest in Poland, the United Kingdom, Germany, Spain and France and lowest in Cyprus, the Netherlands, Malta, Estonia and Greece. The GHG emissions from gasoline were highest in Germany, the United Kingdom, Italy, France and Spain and lowest in Malta, Hungary, Estonia, Romania and the Slovak Republic. The Netherlands was an exceptional case as its diesel and gasoline road transport emissions remained constant between 2000 and 2018.

Overall, transport carbon emissions increased between 2000 and 2018, with the EU's road transport sector adding 0.23–0.24 Gt of carbon to the atmosphere each year. The net amount of diesel- and gasoline-based energy consumed by the EU's road transport sector was 3,335 TWh in 2000 and 3,377 TWh in 2018. It is profoundly challenging to permanently substitute these energy requirements with low carbon options, and these results suggest that the total EV charging capacity for Europe needs to exceed 3,000 TWh per year if a net zero in road transport is to be accomplished.

The underlying cause of the constant increase in diesel consumption is the nature of the fuel market and the fuel taxation system in the EU. As we have seen, gasoline consumption decreased in all member states (expect one) and diesel emissions increased. High duty on gasoline and lower duty on diesel has contributed to a market-based shift in favour of diesel road transport vehicles. Customers choose diesel vehicles as they are considered better value for money in the long term. This belief in the economy of diesel has led to an increase in diesel emissions. The EU's fuel duty policy is influenced by the long-term goal of getting more mileage from diesel fuel and thereby maximising the purchasers' advantage in the oil import market. The fuel excise policy is skewed, even though diesel has a higher CO_2 emissions factor than gasoline: 74,100 $KgCO_2$/TJ for diesel and 69,300 $KgCO_2$/TJ for gasoline. The carbon content of diesel is also higher than that of gasoline, while the net calorific values of diesel and gasoline are similar. The EU does not gain any substantial advantage by consuming more diesel, nor does it have any particular incentive to do so.

At present, there is a real risk that road transport GHG emissions will consume the majority of the EU's carbon budget (Buysse and Miller, 2021). One study calculated the EU's carbon budget for 2010 to 2100 as being 83 Gt and 116 Gt for the 1.5^0C and 2^0C scenarios, respectively (Meyer-Ohlendorf, 2018). Another study calculated the EU's carbon transport budget as being between 10.2 and 12.1 $GtCO_2e$, which included aviation, rail and navigation emissions (Plotz et al., 2021).

The BAU trajectory of road transport carbon emissions in the EU is outlined in table 3.5. There are limitations to the BAU scenario, however, as it assumes that long-term carbon emissions will remain at 0.23 or 0.24 $GtCO_2e$ per year. The results and the critical analysis shows EU transport carbon budget in a BAU scenario of 0.23 or 0.24 $GtCO_2e$ per year could be completely consumed in 2060s. Road transport emissions could consume 16%–22% of the EU's total carbon budget in 2100.

Table 3.6: BAU road transport emissions and EU carbon budget for 1.5^{0}C and 2^{0}C scenarios

EU total carbon budget (2010–2100) in *Ecologic study*	EU transport carbon budget (2010–2100) in Fraunhofer study [29], including aviation, shipping and navigation	EU diesel and gasoline road transport carbon emissions in 2000 and 2018, respectively
83–116 $GtCO_2e$	10.2–12.1 $GtCO_2e$	0.23 and 0.24 $GtCO_2e$
Carbon emissions in BAU trajectory: excluding aviation, shipping and navigation		
0.23 $GtCO_2e$ and 0.24 $GtCO_2e$ per year if diesel and gasoline BAU emissions continue for 11 years, 31 years and 81 years from 2019 to 2100		
2019–2030	**2019–2050**	**2019–2100**
2.53–2.64 $GtCO_2e$	7.13–7.44 $GtCO_2e$	18.63–19.44 $GtCO_2e$
EU transport carbon budget in a BAU scenario of 0.23 or 0.24 $GtCO_2e$ per year could be completely consumed in the 2060s. Road transport emissions could consume 16–22% of EU total carbon budget in 2100		

3.11 Critical Analysis of the CDM AM

The CDM AM re-characterises additionality and applies sectoral additionality to reform and modernise the CDM. This makes emission trading more effective, which contributes to climate targets. The key area of reform is the speedy delivery of CERs. Theoretically, additionality should lead to net emission reduction of GHGs; for example, a renewable energy CDM project in a developing country adds to the renewable capacity of the grid but is not able to reduce the carbon intensity of the grid. The grid in a BAU scenario is run by fossil fuels.

Renewable energy CDM projects, particularly hydroelectric and wind farm projects, have been subject to criticism. Critics argue that these types of projects in China and India are non-additional. The application of the CDM AM on renewable energy demonstrates that, whilst a project may appear non-additional, it is integrated with local conditions and accomplishes micro-generation at a local level. In the absence of a CDM, this type of micro-generation would not be possible, e.g. La Esperanza hydroelectric and Zhangbei Manjing wind farm projects would not take place. These projects do not create net emission reduction of grid-based GHG emissions but contribute to the net renewable energy generation capacity of the grid. The Zhangbei Manjing wind farm project feeds renewable energy to the North China Grid, which is powered by coal-fired power stations. A CDM project that feeds renewable energy to such a grid would be additional. The CDM AM uses the carbon intensity of the grid to characterise additionality.

The CDM AM uses corrective actions to create credible emission reductions in the industrial, agricultural and transportation sectors. This net emission reduction of GHGs is accomplished through technology transfer, e.g. the Changshu HFC-23 decomposition CDM project. The additionality in this project is created by technology transfer. GHG emissions in the industrial, agricultural and transportation sectors are generally point source emissions, for example from a cement manufacturing plant. These point source emissions can be reduced by technological intervention.

The CDM AM uses a qualitative component to determine the effectiveness of CDM emission reduction. The qualitative component is based on a set of corrective action indicators. These indicators, if applied, lead to strong additionality. Each CDM project category employs a set of specific corrective actions; for example, an agricultural CDM project can create credible GHG emission reduction by deploying technology to reduce emissions from enteric fermentation, fertiliser production and use, land use management and waste management. Whilst the corrective actions identify the BAU processes that emit GHG emissions, the corrective actions are generic and it is not possible for CDM project developers to manipulate all potential emission reduction pathways. The choice of an emission reduction pathway selected for a project activity is determined by the cost of technology and the cost of project activity. The corrective action indicators lead to strong additionality and can alter the BAU scenario in order to create a sectoral transformation for a sustainable future.

The quantitative component improves CER delivery for the project developer. At present, there is no mechanism that accelerates CER delivery; efficient CER delivery is vital to convert emission reductions into CERs, but currently the UNFCCC takes many months to issue CERs. This delay affects the liquidity of CERs in the market, affects their price for buyers and also increases the cost of loans required to carry out project activity. The significant time taken by UNFCCC to issue CERs creates a financial risk for the project developer and affects market confidence. CER issuance should be carried out in batches, and these batches could be spaced over the project's lifespan. This can be achieved by abolishing the project validation step in the CDM project cycle. The verification of project activity and demonstration of strong additionality proposed by the CDM AM adequately ensures the integrity of the CDM project cycle.

GHG emission reduction in a project-based CDM model should be efficient; CDM projects appear to get burdened and slowed down by excessive regulatory pressures.

The MCV parameter indicates the financial value accrued to CDM emission reductions. It is not accurate and it does not capture the market fluctuations that affect the price of CERs. The CDM project does not operate in isolation from the markets: it is affected by market forces at every step and the CDM AM embeds these forces into the assessment process.

The CDM AM strengthens the CDM by differentiating between weak and strong additionality. The CDM AM implements additionality at a local level in renewable energy CDM projects and demonstrates that the CDM projects that might appear to be non-additional are infact additional due to the BAU conditions of the local area and the connecting grid.

The CDM AM does not characterise the linkage between additionality and the financial viability of CDM project implementation. A renewable energy CDM project may be weakly additional or non-additional; at the same time, the CDM process does allow initiation of micro-generation in remote and inaccessible parts of developing countries. CER revenue allows micro-generation to take place. In the absence of a CDM, micro-generation project activity would not take place. CER revenue makes a micro-generation project financially viable for a project developer and increases the renewable energy capacity of the grid.

The complexity in the application of additionality does not fully resolve the dilemma of how to determine additionality. The CDM AM's approach to additionality is heterogeneous and sector specific. This approach adds to the complexity and also allows non-stringent application of additionality. The CDM AM has not been able to develop a balance between net emission reduction, micro-generation and technology transfer. These three aspects are essential to achieve strong additionality. In addition, the CDM AM applies additionality at the project level, but this can be difficult to accomplish as the BAU scenario is often determined by factors that are outside the project system boundaries, especially in energy efficiency and transportation sector projects.

The CDM AM does not offer solutions to accelerate the process of technology transfer between countries. The USA and EU member countries have made huge progress in technologies, for example CCS at coal-fired power plants, smart metering to reduce energy demand and concentrated solar power technology. These technologies would initiate the process of the transformation required to create low carbon economies. The CDM AM does not offer any suggestions on how to accelerate the process of technological change, nor does it de-couple the linkage between emissions and economic growth.

The CDM AM aims to reform the CDM to ensure its continuity and progress. At the same time, the complex application of additionality and the QOP would create project management and project administration problems. The CDM AM could also lead to problems with the project consultation process: protracted consultations with the community, stakeholders and regulators could add to the cost of project implementation and slow project activity. The CDM AM does not fully resolve the issues of project administration and does not significantly shorten the project cycle. However, it does offer an opportunity to abolish the need to carry out project validation; this is a small change and would not have a strategic impact on improving the rate of project registration.

The CDM AM does not fully characterise the impact of the financial markets on the CDM. The price of CERs fluctuates in these markets; the EU ETS linkage with the CDM determines the price of CERs. The linkage between the CDM and the EU ETS is not characterised by the CDM AM. In addition, the CDM AM does not characterise the sustainable development component of a CDM project. The criterion of sustainable development is considered an important aspect of the CDM. The BAU scenarios that the CDM strives to transform are often determined by complex interrelationships between fuel poverty, deforestation, sanitation, illiteracy and unemployment. The CDM AM does not characterise the role that these human factors could play in reforming the CDM process.

Chapter 4 Discussions, Conclusions and Future Research

This chapter carries out critical analysis and discussion of research outputs, the CO_2ERM and the CDM AM. The chapter also provides conclusions and suggestions for the direction of future research. The initial analysis presented the biggest direct contributors of CO_2 into the atmosphere from fossil fuel combustion as being the USA, China, the EU27, Russia, Japan, India, Germany, and the United Kingdom. The current situation means that 33.66 $GtCO_2$ is being emitted per year from fossil fuel combustion. At the same time, the projected total carbon budget to control climate change at 1.5^0C, 1.7^0C and 2^0C targets is 500 $GtCO_2$, 850 $GtCO_2$ and 1,350 $GtCO_2$, respectively.

4.1 Critical Discussion of CO_2ERM and CCS

The CO_2ERM assumes that the rest of the world continues to emit CO_2 from coal and gas combustion and that if CCS is installed in China and the USA, the breach of carbon budgets is delayed by 10 years to 22 years. This is in a BAU scenario, where 33.66 $GtCO_2$ is being emitted per year from coal- and gas-fired power plants and industry.

The potential year of breach of carbon budgets without CCS in China and the USA (from 2020–2100) is year 2034–2035, year 2043–2044 and year 2055–2056 for 1.5^0C, 1.7^0C and 2^0C climate targets, respectively.

The potential year of breach of carbon budgets with CCS in China and the USA (from 2020–2100) is year 2045–2046, year 2057–2058 and year 2077–2078 for 1.5^0C, 1.7^0C and 2^0C climate targets, respectively.

The critical points about CO_2ERM and CCS are based around capture technology and capture economics. The capture economics relies on prices of natural fuel; for example, Petra Nova CCS operations stopped due to low gas prices.

There will be major differences in the cost of CO_2 reduction between the USA and China, which CO_2ERM does not take into account. These cost differences can be substantial and long term. The USA has invested in CCS and has the expertise to deliver the CCS projects. In the case of China, the focus is on renewable energy and hydroelectricity. CCS-based emission reduction is plausible or potentially viable for China. The results and evidence indicate that there are no technological barriers to the proposed model in the USA or China. The above analysis suggests that it is plausible to deploy the CCS model in the USA. The cost of CCS is effective when CCS is combined with EOR but that leads to more oil production and more CO_2 emissions. Standalone CSS retrofitted to power plants is unlikely to be cost effective. The cost of CCS has to be heavily subsidised by the sale of oil using EOR. In reality, the cost is significant.

In the case of the USA, the dominant fuel is gas, and in China it is coal. This is a vital difference that needs to be taken into account in terms of cost and technology.

CO_2 pipelines in the USA are for EOR to service the oil and gas industry. There are differences in energy penalties in China and the USA. Each CCS project has an energy penalty dependant on the nature of the capture process, and CO_2ERM does not take into account the emissions and cost of the energy penalty.

The CO_2ERM forecast of coal and gas consumption in the USA and China is based on linear projection and it has drawbacks. It is likely that the USA and China will make significant progress in deployment of renewable energy. The Institute for New Economic Thinking at University of Oxford in their working paper on energy transition (Way et al., 2021) concluded that CCS is a low-growth sector that has not produced any cost improvements in 50 years, and the cost of fossil fuels provides a lower hard boundary. The electricity provided by CCS will be uneconomical, even if CCS is given away as a free technology.

In terms of sustainability, the implications of CO_2ERM mean CCS will produce more carbon emissions when used in conjunction with EOR, adding to the problem of air pollution and emission of particulates associated with coal and gas.

4.2 Critical Discussion of the CDM AM and Emission Trading

A critical analysis of the CDM led to the creation of the CDM AM. This methodology was then applied to 13 case studies. The objective of the CDM AM was to speed up the creation of CERs for the carbon market and reform and strengthen the CDM. To improve pre-registration of CDM projects, the methodology applies relevant corrective action indicators and additionality. The application of additionality is important, as it determines a project's net contribution to GHG emission reduction. Post-registration assessment is quantitative and reveals the performance efficiency of a CDM project. The results of the CDM AM indicate that industrial abatement projects based on fuel substitution and waste gas decomposition are strongly additional and are efficient in CER delivery.

The CDM AM uses the BAU carbon intensity of the grid to re-characterise additionality in renewable energy CDM projects. These projects may appear to be non-additional as they do not create net abatement; in reality, renewable energy CDM projects accomplish micro-generation at a local level. This micro-generation contributes to sustainable development and would not take place in the absence of the CDM.

The results of the CDM AM and review of available evidence show that the CDM and emission trading are very successful in reducing emissions of GHGs in chemical and other types of industry. The main point that the CDM and emission trading cannot address is that the emission reductions created by the CDM and emission trading are not of the scale that would help accomplish climate targets for 1.5^0C, 1.7^0C and 2^0C. For example, in section 3.2, the available evidence is that for nearly 20 years, the total emission reduction accomplished is 4.16 $GtCO_2e$. To achieve climate targets, we know that net emission reduction per year has to be substantially more. However, the CDM and emission trading do play a vital role in creating market space for renewable energy, energy efficiency and reducing the cost of technology. They also play an important role in the trading of carbon assets.

The CDM AM focuses on creating credible emission reductions and giving the CDM market legitimacy. The results show that the CDM and emission trading are unlikely to play a substantial role in meeting climate targets. The CDM and emission trading processes are too slow to generate the volume of emission reductions needed to achieve climate targets. The key issue that has not been resolved by the CDM and emission trading is that the price of carbon emission reductions, as CERs or VERs, has not been strong enough to create an incentive for decarbonisation. The structure of international and national markets is such that it is very challenging to reduce 1 $GtCO_2$ of emissions per year using the CDM and emission trading.

The key role the CDM and emission trading play is that they help industry to buy carbon offsets for different types of corporate programmes.

4.3 Results and Conclusions

The results show that the allowed carbon budget per year for 1.5^0C, 1.7^0C and 2^0C targets is 6.25 $GtCO_2$, 10.62 $GtCO_2$ and 16.87 $GtCO_2$, respectively, in a BAU scenario, where 33.66 $GtCO_2$ is being emitted per year from coal- and gas-fired power plants and industry. Therefore, to meet these targets, emission reduction targets per year should be 27.38 $GtCO_2$, 23.04 $GtCO_2$ and 16.76 $GtCO_2$, respectively.

The top emitters are China and the USA, which emit more than 10 $GtCO_2$ and 5 $GtCO_2$, respectively, from combustion of coal and gas in their energy generation services. It is likely that they will remain the top emitters for the rest of this century. The CO_2ERM, which hypothesises the installation of CCS at coal- and gas-fired plants, would reduce BAU emissions by 80% and could potentially reduce annual emissions in the USA and China by more than 2 $GtCO_2$ and 10 $GtCO_2$, respectively. The linear forecast shows that total world BAU emissions will be 3,997 $GtCO_2$ from the year 2020 to 2100, and if CCS were successfully installed in China and the USA during this period. The total world BAU emissions would be reduced to 1,978 $GtCO_2$, which is a 50% reduction from the world BAU scenario.

However, the installation of CCS in China and the USA would not be adequate to meet the 1.5^0C, 1.7^0C and 2^0C carbon budget targets or delay the breach of carbon targets. The following conclusions can be drawn from the results and barrier analysis carried out of CO_2ERM:

- The CO_2ERM would not offset the annual increase in CO_2 emissions. The CO_2ERM would not have a significant impact on reducing the annual increase in the concentration of atmospheric CO_2.

- The barrier analysis reveals that CO_2ERM is plausible for the USA. It also has plausibility for China.

- The time of installation and potential cost associated with CCS makes it unfeasible on grounds of sustainability, climate target acquisition and technology effectiveness.

- There is an energy penalty associated with CCS, which means to keep CCS running, more coal and gas will need to be burned.

- The cost of gas and coal would make the process of CCS ineffective and exorbitant. In addition, the cost of gas capture and transport would make it unfeasible.

The results show that none of the objectives of the CO_2ERM could be achieved completely. The evidence available, the results of the CO_2ERM and the barrier analysis of CCS indicates that CCS is a viable technology at a concept stage. However, it cannot create significant CO_2 emission reduction to prevent dangerous climate change.

The results of the CDM and emission trading show that it is possible to reduce GHG emissions, both CO_2 and non-CO_2, by using a CDM project methodology and emission trading. The results show that the CDM and emission trading have reduced emissions by 4.16 $GtCO_2e$. The CDM AM methodology used to review the registered CDM projects shows that the CDM is very effective in reducing the emission of powerful GHGs. However, the CDM is not effective in generating emission reductions within the transport sector. The case study published in Applied Sciences shows that electrification of the EU's transport sector could reduce carbon emissions by 0.23 Gt carbon per year. The underlying cause of the increase in transport-based emissions within the EU is the system of fuel taxation used.

The CO_2ERM model has contributed to the understanding of CCS in a global context. The viability of CCS is limited due to cost, technology maturity and fuel mix requirements. The model also identifies economic, political and technological barriers that CCS deployment could encounter. The major inadequacy of CCS is that the cost of emission reduction does not support renewable energy installation programmes in the USA and China. There is little leverage to avoid this, as CO_2 emissions are predominant GHG emissions generated from the combustion of coal and gas. The main conclusions of the research are:

- For climate change targets to be met successfully, China and the USA must reduce coal- and gas-based emissions and move their energy generation services to renewables.
- CCS is a potential technology, but its installation and execution are not adequate to meet the climate change targets and expectations.
- There are barriers to CCS delivery due to the cost of fuel and technology maturity.
- The CDM and emission trading can reduce GHG emissions, and these reductions would need to be greater than 10 $GtCO_2e$ per year to help achieve climate change targets.

- The EU can make a big contribution through electrification of its transportation sector to remove dependency on diesel and gasoline fossil fuels.

4.4 Future Research

The direction of future research is based on three key areas of climate change policy, as outlined below.

The use of CCS to capture and sequester carbon emissions from industrial clusters in Europe that run on natural gas and CCS is being proposed to be used in conjunction with the generation of blue hydrogen. This area of research is important to guide the policymakers. However, CCS and blue hydrogen generation can make for a good or bad national policy. Already research shows that blue hydrogen produces the same amount of GHG emissions as coal.

The second area of future research is the use of emission trading and creation of carbon emission reduction for the emission trading system. This is a vital policy area that will receive investment and political attention. Emission trading has clear advantages in delivering technological change in reducing GHG emissions from industry and energy generation services.

The third area of future research is the research and policy analysis of the EU’s road transport policy. The EU’s dependence on diesel and gasoline is a challenge, and several member states of the EU have made progress with electrification. Future research should focus on the relationship between fuel taxation and the road to electrification.

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Appendix CO_2ERM: worksheets for CO_2ERM in Chapter 2

BAU and forecast coal/gas consumption and cumulative emissions in the WORLD from EIA data							
BAU source data: International - U.S. Energy Information Administration (EIA)							
1 TJ to TWh=	2.78E-04	1 Gg=	0.000001	Gt			
bituminous coal CO_2 emission factor kg/TJ=		94,600	natural gas CO_2 emission factor kg/TJ=		56,100		
bituminous coal CH_4 emission factor kg/TJ=		1	natural gas CH_4 emission factor kg/TJ=		1		
bituminous coal N_2O emission factor kg/TJ=		1.5	natural gas N_2O emission factor kg/TJ=		0.1		
		BAU 2000-2019 $GtCO_2$	**Projected 2020-2100 $GtCO_2$**	**World emissions with CCS in China and USA $GtCO_2$**			
emissions from coal+gas		455.74	3,997.26	1,978.79			
Years	**World coal energy consumption**	**World gas energy consumption**	**Energy from coal**	**Energy from gas**	**CO_2 emissions from coal**	**CO_2 emissions from gas**	**emissions from coal+gas**
	terajoules TJ	**terajoules TJ**	**tera watt hour TWh**	**tera watt hour TWh**	**Gigatonne Gt**	**Gigatonne Gt**	**Gigatonnes of carbon dixoxide $GtCO_2$**
Years	**BAU/projected EIA data**	**BAU/projected EIA data**	**B14*B4**	**C14*B4**	**(B14*C5)/(1.E+06)*D4**	**(C14*F5)/(1.E+06)*D4**	**(F14+G14)**

2000	114,103,565	94,538,122	31,695	26,261	10.79	5	16.10
2001	115,341,374	94,882,602	32,039	26,356	10.91	5	16.23
2002	118,117,392	99,238,767	32,810	27,566	11.17	6	16.74
2003	127,947,623	102,115,885	35,541	28,366	12.10	6	17.83
2004	138,873,635	105,289,098	38,576	29,247	13.14	6	19.04
2005	149,006,253	108,256,016	41,391	30,071	14.10	6	20.17
2006	157,572,909	112,165,227	43,770	31,157	14.91	6	21.20
2007	165,249,468	115,761,720	45,903	32,156	15.63	6	22.13
2008	167,910,887	119,087,071	46,642	33,080	15.88	7	22.57
2009	168,781,926	115,158,622	46,884	31,989	15.97	6	22.43
2010	182,934,795	125,998,863	50,815	35,000	17.31	7	24.37
2011	193,325,352	129,763,942	53,701	36,046	18.29	7	25.57
2012	198,905,755	132,728,820	55,252	36,869	18.82	7	26.26
2013	202,823,113	134,682,813	56,340	37,412	19.19	8	26.74
2014	202,031,232	135,200,264	56,120	37,556	19.11	8	26.70
2015	195,062,462	137,211,800	54,184	38,114	18.45	8	26.15
2016	185,528,800	140,005,098	51,536	38,890	17.55	8	25.41
2017	189,666,328	144,596,450	52,685	40,166	17.94	8	26.05
2018	193,788,779	151,813,947	53,830	42,171	18.33	9	26.85

2019	195,595,481	154,954,226	54,332	43,043	18.50	9	27.20
2020	218,453,141	155,574,899	60,681	43,215	20.67	9	29.39
2021	222,262,595	158,897,724	61,740	44,138	21.03	9	29.94
2022	225,329,641	161,961,263	62,592	44,989	21.32	9	30.40
2023	227,643,300	165,131,142	63,234	45,870	21.54	9	30.80
2024	229,865,103	168,277,782	63,851	46,744	21.75	9	31.19
2025	232,222,242	171,426,197	64,506	47,618	21.97	10	31.59
2026	234,787,352	174,553,275	65,219	48,487	22.21	10	32.00
2027	237,543,475	177,760,990	65,984	49,378	22.47	10	32.44
2028	240,520,512	181,041,609	66,811	50,289	22.75	10	32.91
2029	243,259,637	184,384,458	67,572	51,218	23.01	10	33.36
2030	245,500,976	186,962,773	68,195	51,934	23.22	10	33.71
2031	248,653,372	190,218,898	69,070	52,839	23.52	11	34.19
2032	252,651,478	193,599,615	70,181	53,778	23.90	11	34.76
2033	257,221,756	197,045,227	71,450	54,735	24.33	11	35.39
2034	262,311,062	200,445,094	72,864	55,679	24.81	11	36.06
2035	267,467,612	203,600,181	74,297	56,556	25.30	11	36.72
2036	271,896,775	206,589,018	75,527	57,386	25.72	12	37.31
2037	274,964,633	209,450,820	76,379	58,181	26.01	12	37.76

2038	277,761,441	212,365,287	77,156	58,990	26.28	12	38.19
2039	280,248,131	215,674,342	77,847	59,910	26.51	12	38.61
2040	282,115,472	219,052,744	78,365	60,848	26.69	12	38.98
2041	285,666,337	222,219,956	79,352	61,728	27.02	12	39.49
2042	289,363,275	225,403,077	80,379	62,612	27.37	13	40.02
2043	293,153,620	228,577,723	81,432	63,494	27.73	13	40.56
2044	296,958,875	231,752,623	82,489	64,376	28.09	13	41.09
2045	300,748,068	234,925,064	83,541	65,257	28.45	13	41.63
2046	304,508,657	238,094,311	84,586	66,137	28.81	13	42.16
2047	308,236,389	241,256,878	85,621	67,016	29.16	14	42.69
2048	311,927,935	244,420,097	86,647	67,894	29.51	14	43.22
2049	315,586,296	247,593,255	87,663	68,776	29.85	14	43.74
2050	319,166,005	250,787,398	88,657	69,663	30.19	14	44.26
2051	322,579,180	253,920,878	89,605	70,534	30.52	14	44.76
2052	325,876,871	257,050,321	90,521	71,403	30.83	14	45.25
2053	329,129,790	260,191,284	91,425	72,275	31.14	15	45.73
2054	332,406,293	263,357,552	92,335	73,155	31.45	15	46.22
2055	335,791,994	266,553,700	93,276	74,043	31.77	15	46.72
2056	339,345,143	269,761,048	94,263	74,934	32.10	15	47.24

2057	343,042,966	272,961,939	95,290	75,823	32.45	15	47.77
2058	346,770,605	276,136,921	96,325	76,705	32.80	15	48.30
2059	350,492,692	279,281,557	97,359	77,578	33.16	16	48.82
2060	354,157,510	282,431,354	98,377	78,453	33.50	16	49.35
2061	357,662,386	285,597,969	99,351	79,333	33.83	16	49.86
2062	361,141,884	288,763,922	100,317	80,212	34.16	16	50.36
2063	364,608,568	291,930,932	101,280	81,092	34.49	16	50.87
2064	368,074,124	295,098,500	102,243	81,972	34.82	17	51.37
2065	371,545,165	298,266,888	103,207	82,852	35.15	17	51.88
2066	375,026,289	301,436,090	104,174	83,732	35.48	17	52.39
2067	378,521,227	304,605,965	105,145	84,613	35.81	17	52.90
2068	382,033,347	307,775,873	106,120	85,493	36.14	17	53.41
2069	385,565,574	310,945,781	107,102	86,374	36.47	17	53.92
2070	389,120,917	314,116,735	108,089	87,255	36.81	18	54.43
2071	392,696,886	317,291,425	109,082	88,137	37.15	18	54.95
2072	396,278,708	320,463,940	110,077	89,018	37.49	18	55.47
2073	399,851,609	323,632,727	111,070	89,898	37.83	18	55.98
2074	403,404,138	326,797,694	112,057	90,777	38.16	18	56.50
2075	406,929,895	329,960,568	113,036	91,656	38.50	19	57.01

2076	410,431,815	333,124,410	114,009	92,535	38.83	19	57.52
2077	413,922,306	336,291,237	114,978	93,414	39.16	19	58.02
2078	417,416,642	339,461,585	115,949	94,295	39.49	19	58.53
2079	420,922,320	342,633,696	116,923	95,176	39.82	19	59.04
2080	424,444,648	345,804,482	117,901	96,057	40.15	19	59.55
2081	427,983,742	348,973,841	118,884	96,937	40.49	20	60.06
2082	431,526,686	352,143,104	119,869	97,818	40.82	20	60.58
2083	435,070,771	355,312,133	120,853	98,698	41.16	20	61.09
2084	438,613,739	358,480,949	121,837	99,578	41.49	20	61.60
2085	442,154,015	361,649,544	122,821	100,458	41.83	20	62.12
2086	445,690,473	364,817,948	123,803	101,338	42.16	20	62.63
2087	449,222,423	367,986,215	124,784	102,218	42.50	21	63.14
2088	452,749,689	371,154,407	125,764	103,098	42.83	21	63.65
2089	456,272,741	374,322,539	126,742	103,978	43.16	21	64.16
2090	459,792,825	377,490,625	127,720	104,859	43.50	21	64.67
2091	463,312,167	380,658,806	128,698	105,739	43.83	21	65.18
2092	466,833,565	383,827,579	129,676	106,619	44.16	22	65.70
2093	470,359,001	386,996,912	130,655	107,499	44.50	22	66.21
2094	473,889,206	390,166,546	131,636	108,380	44.83	22	66.72

2095	477,423,522	393,336,088	132,618	109,260	45.16	22	67.23
2096	480,960,025	396,505,207	133,600	110,140	45.50	22	67.74
2097	484,496,256	399,673,822	134,582	111,021	45.83	22	68.26
2098	488,030,293	402,842,097	135,564	111,901	46.17	23	68.77
2099	491,561,418	406,010,341	136,545	112,781	46.50	23	69.28
2100	495,089,737	409,178,787	137,525	113,661	46.84	23	69.79

Cumulative world forecast emissions			Cumulative world emissions 2020-2100	Year of overshoot after CCS in USA and China
without CCS GtCO2 2020-2100	ER CCS in USA	ER CCS in China	with CCS in USA and China GtCO2	Cumulative world emissions GtCO2
29.39	2.48	10.31	16.60	16.60
59.33	2.45	10.68	16.81	33.41
89.74	2.42	11.00	16.98	50.39
120.53	2.38	11.28	17.14	67.52
151.72	2.34	11.52	17.32	84.85
183.31	2.30	11.75	17.54	102.38
215.31	2.26	11.99	17.76	120.14
247.75	2.22	12.24	17.98	138.12
280.66	2.18	12.50	18.22	156.34
314.02	2.16	12.77	18.43	174.77
347.73	2.13	13.01	18.57	193.34

381.93	2.09	13.26	18.85	212.19
416.69	2.06	13.54	19.16	231.35
452.08	2.03	13.88	19.47	250.81
488.13	2.00	14.27	19.80	270.61
524.86	1.97	14.68	20.08	290.69
562.17	1.95	15.08	20.28	310.97
599.93	1.92	15.44	20.41	331.38
638.12	1.93	15.71	20.55	351.93
676.73	1.95	15.96	20.70	372.64
715.71	1.98	16.19	20.80	393.44
755.20	2.02	16.42	21.06	414.50
795.22	2.04	16.72	21.26	435.76
835.77	2.07	17.02	21.46	457.23
876.87	2.09	17.34	21.66	478.89
918.50	2.12	17.66	21.85	500.74
960.66	2.14	17.98	22.04	522.78
1,003.36	2.17	18.30	22.22	545.00
1,046.58	2.19	18.62	22.40	567.40
1,090.32	2.22	18.94	22.59	589.99
1,134.58	2.25	19.25	22.76	612.75

1,179.34	2.27	19.57	22.92	635.67
1,224.59	2.30	19.87	23.08	658.75
1,270.32	2.33	20.17	23.24	681.99
1,316.54	2.35	20.46	23.41	705.40
1,363.26	2.38	20.74	23.60	729.00
1,410.50	2.41	21.03	23.79	752.79
1,458.26	2.43	21.33	24.00	776.79
1,506.56	2.46	21.64	24.20	800.99
1,555.38	2.49	21.96	24.38	825.37
1,604.73	2.51	22.27	24.56	849.93
1,654.59	2.54	22.59	24.73	874.66
1,704.95	2.56	22.90	24.90	899.55
1,755.82	2.59	23.21	25.07	924.62
1,807.20	2.62	23.51	25.25	949.87
1,859.08	2.64	23.81	25.42	975.29
1,911.47	2.67	24.11	25.60	1,000.89
1,964.36	2.70	24.42	25.78	1,026.68
2,017.77	2.72	24.72	25.96	1,052.64
2,071.69	2.75	25.02	26.15	1,078.79
2,126.12	2.78	25.32	26.33	1,105.12

2,181.07	2.80	25.63	26.52	1,131.64
2,236.54	2.83	25.94	26.70	1,158.34
2,292.52	2.86	26.24	26.88	1,185.22
2,349.01	2.88	26.55	27.06	1,212.28
2,406.02	2.91	26.86	27.24	1,239.52
2,463.53	2.94	27.17	27.41	1,266.93
2,521.56	2.96	27.47	27.59	1,294.52
2,580.09	2.99	27.78	27.77	1,322.29
2,639.13	3.01	28.08	27.94	1,350.23
2,698.68	3.04	28.38	28.13	1,378.36
2,758.75	3.07	28.69	28.31	1,406.67
2,819.32	3.09	28.99	28.49	1,435.16
2,880.42	3.12	29.30	28.67	1,463.83
2,942.02	3.15	29.60	28.85	1,492.69
3,004.14	3.17	29.91	29.03	1,521.72
3,066.76	3.20	30.21	29.21	1,550.94
3,129.90	3.23	30.52	29.39	1,580.33
3,193.56	3.25	30.83	29.57	1,609.90
3,257.72	3.28	31.13	29.75	1,639.65
3,322.39	3.31	31.44	29.93	1,669.58

3,387.58	3.33	31.74	30.11	1,699.69
3,453.27	3.36	32.05	30.29	1,729.98
3,519.48	3.39	32.35	30.47	1,760.45
3,586.20	3.41	32.66	30.65	1,791.10
3,653.43	3.44	32.96	30.83	1,821.93
3,721.17	3.46	33.27	31.01	1,852.94
3,789.42	3.49	33.57	31.19	1,884.14
3,858.19	3.52	33.88	31.37	1,915.51
3,927.47	3.54	34.18	31.55	1,947.06
3,997.26	3.57	34.49	31.73	1,978.79

BAU and forecast coal/gas consumption and cumulative emissions in China from EIA data								
BAU source data: [International - U.S. Energy Information Administration (EIA)]								
1 TJ to TWh=	2.78E-04	1 Gg=	0.000001	Gt		**$cost of CCS 1 tCO2**	45	
bituminous coal CO2 emission factor kg/TJ=		94,600	natural gas CO2 emission factor kg/TJ=		56,100	**$cost of CCS 1 GtCO2**	45,000,000,000.0	
bituminous coal CH4 emission factor kg/TJ=		1	natural gas CH4 emission factor kg/TJ=		1			
bituminous coal N2O emission factor kg/TJ=		1.5	natural gas N2O emission factor kg/TJ=		0.1			
		Total BAU 2000-2019	**Total projected 2020-2100**	**total emission reduction CCS scenario 80%**				
GtCO2 emissions from coal+gas		69.15	265.78	212.62				
Years	**USA coal energy consumption**	**USA gas energy consumption**	**Energy from coal**	**Energy from gas**	**CO2 emissions from coal**	**CO2 emissions from gas**	**emissions from coal+gas**	
	terajoules TJ	**terajoules TJ**	**tera watt hour TWh**	**tera watt hour TWh**	**Gigatonne Gt**	**Gigatonne Gt**	**Gigatonnes of carbon dixoxide GtCO2**	
	BAU/projected EIA data	BAU/projected EIA data	B14*B4	C14*B4	(B14*C5)/(1.E+06)*D4	(C14*F5)/(1.E+06)*D4	(F14+G14)	
2000	24,430,814	25,135,626	6,786	6,982	2.31	1.41	3.72	

2001	23,677,320	24,026,320	6,577	6,674	2.24	1.35	3.59	
2002	23,622,837	24,804,448	6,562	6,890	2.23	1.39	3.63	
2003	24,058,382	24,087,603	6,683	6,691	2.28	1.35	3.63	
2004	24,291,601	24,185,110	6,748	6,718	2.30	1.36	3.65	
2005	24,528,837	23,807,719	6,814	6,613	2.32	1.34	3.66	
2006	24,174,498	23,463,110	6,715	6,518	2.29	1.32	3.60	
2007	24,453,827	24,965,532	6,793	6,935	2.31	1.40	3.71	
2008	24,064,951	25,155,647	6,685	6,988	2.28	1.41	3.69	
2009	21,045,418	24,705,125	5,846	6,863	1.99	1.39	3.38	
2010	22,369,466	25,927,738	6,214	7,202	2.12	1.45	3.57	
2011	21,154,119	26,328,432	5,876	7,313	2.00	1.48	3.48	
2012	18,739,807	27,524,911	5,206	7,646	1.77	1.54	3.32	
2013	19,407,883	28,280,914	5,391	7,856	1.84	1.59	3.42	
2014	19,364,778	28,890,418	5,379	8,025	1.83	1.62	3.45	
2015	16,747,837	29,743,180	4,652	8,262	1.58	1.67	3.25	
2016	15,302,785	29,963,957	4,251	8,323	1.45	1.68	3.13	
2017	14,917,051	29,599,690	4,144	8,222	1.41	1.66	3.07	
2018	13,973,017	32,868,600	3,881	9,130	1.32	1.84	3.17	
2019	11,894,267	33,969,506	3,304	9,436	1.13	1.91	3.03	**Emissions reduced by 80% CCS**

2020	13,929,028	31,802,963	3,869	8,834	1.32	1.78	3.10	2.48
2021	13,292,652	32,272,609	3,692	8,965	1.26	1.81	3.07	2.45
2022	12,412,506	33,040,771	3,448	9,178	1.17	1.85	3.03	2.42
2023	11,441,304	33,731,798	3,178	9,370	1.08	1.89	2.97	2.38
2024	10,440,069	34,510,895	2,900	9,586	0.99	1.94	2.92	2.34
2025	9,469,848	35,232,346	2,631	9,787	0.90	1.98	2.87	2.30
2026	8,534,912	35,952,991	2,371	9,987	0.81	2.02	2.82	2.26
2027	7,659,617	36,611,751	2,128	10,170	0.72	2.05	2.78	2.22
2028	6,807,274	37,184,742	1,891	10,329	0.64	2.09	2.73	2.18
2029	6,059,101	37,843,588	1,683	10,512	0.57	2.12	2.70	2.16
2030	5,377,920	38,474,190	1,494	10,687	0.51	2.16	2.67	2.13
2031	4,493,507	38,994,307	1,248	10,832	0.43	2.19	2.61	2.09
2032	3,809,471	39,550,699	1,058	10,986	0.36	2.22	2.58	2.06
2033	3,117,403	40,070,291	866	11,131	0.29	2.25	2.54	2.03
2034	2,276,868	40,631,005	632	11,286	0.22	2.28	2.49	2.00
2035	1,572,579	41,202,104	437	11,445	0.15	2.31	2.46	1.97
2036	974,148	41,772,308	271	11,603	0.09	2.34	2.44	1.95
2037	229,287	42,368,639	64	11,769	0.02	2.38	2.40	1.92
2038	-590,382	42,930,892	-164	11,925	-0.06	2.41	2.41	1.93
2039	-1,393,090	43,383,136	-387	12,051	-0.13	2.43	2.43	1.95

2040	-2,230,554	44,089,099	-620	12,247	-0.21	2.47	2.47	1.98
2041	-3,235,691	44,899,899	-899	12,472	-0.31	2.52	2.52	2.02
2042	-4,007,646	45,483,284	-1,113	12,634	-0.38	2.55	2.55	2.04
2043	-4,751,127	46,042,127	-1,320	12,789	-0.45	2.58	2.58	2.07
2044	-5,485,473	46,602,826	-1,524	12,945	-0.52	2.61	2.61	2.09
2045	-6,220,871	47,160,274	-1,728	13,100	-0.59	2.65	2.65	2.12
2046	-6,964,191	47,725,360	-1,934	13,257	-0.66	2.68	2.68	2.14
2047	-7,717,346	48,296,393	-2,144	13,416	-0.73	2.71	2.71	2.17
2048	-8,481,584	48,876,650	-2,356	13,577	-0.80	2.74	2.74	2.19
2049	-9,255,082	49,463,248	-2,571	13,740	-0.88	2.77	2.77	2.22
2050	-10,038,677	50,049,122	-2,789	13,903	-0.95	2.81	2.81	2.25
2051	-10,824,007	50,643,343	-3,007	14,068	-1.02	2.84	2.84	2.27
2052	-11,603,562	51,245,450	-3,223	14,235	-1.10	2.87	2.87	2.30
2053	-12,397,012	51,845,365	-3,444	14,401	-1.17	2.91	2.91	2.33
2054	-13,186,555	52,445,471	-3,663	14,568	-1.25	2.94	2.94	2.35
2055	-13,970,764	53,041,152	-3,881	14,734	-1.32	2.98	2.98	2.38
2056	-14,763,492	53,634,920	-4,101	14,899	-1.40	3.01	3.01	2.41
2057	-15,552,242	54,227,047	-4,320	15,063	-1.47	3.04	3.04	2.43
2058	-16,323,400	54,816,800	-4,534	15,227	-1.54	3.08	3.08	2.46
2059	-17,086,934	55,406,275	-4,746	15,391	-1.62	3.11	3.11	2.49

2060	-17,849,210	55,991,779	-4,958	15,553	-1.69	3.14	3.14	2.51
2061	-18,608,932	56,560,120	-5,169	15,711	-1.76	3.17	3.17	2.54
2062	-19,369,998	57,133,912	-5,381	15,871	-1.83	3.21	3.21	2.56
2063	-20,152,138	57,727,643	-5,598	16,035	-1.91	3.24	3.24	2.59
2064	-20,937,314	58,323,588	-5,816	16,201	-1.98	3.27	3.27	2.62
2065	-21,722,841	58,919,334	-6,034	16,366	-2.05	3.31	3.31	2.64
2066	-22,507,189	59,514,515	-6,252	16,532	-2.13	3.34	3.34	2.67
2067	-23,289,519	60,108,169	-6,469	16,697	-2.20	3.37	3.37	2.70
2068	-24,069,613	60,700,300	-6,686	16,861	-2.28	3.41	3.41	2.72
2069	-24,847,565	61,290,862	-6,902	17,025	-2.35	3.44	3.44	2.75
2070	-25,623,798	61,880,266	-7,118	17,189	-2.42	3.47	3.47	2.78
2071	-26,398,801	62,468,838	-7,333	17,352	-2.50	3.50	3.50	2.80
2072	-27,173,408	63,056,301	-7,548	17,516	-2.57	3.54	3.54	2.83
2073	-27,947,854	63,643,317	-7,763	17,679	-2.64	3.57	3.57	2.86
2074	-28,721,632	64,230,763	-7,978	17,842	-2.72	3.60	3.60	2.88
2075	-29,496,207	64,818,697	-8,193	18,005	-2.79	3.64	3.64	2.91
2076	-30,271,585	65,407,409	-8,409	18,169	-2.86	3.67	3.67	2.94
2077	-31,047,549	65,996,738	-8,624	18,332	-2.94	3.70	3.70	2.96
2078	-31,825,269	66,586,691	-8,840	18,496	-3.01	3.74	3.74	2.99
2079	-32,604,884	67,177,270	-9,057	18,660	-3.08	3.77	3.77	3.01

2080	-33,384,986	67,768,367	-9,274	18,825	-3.16	3.80	3.80	3.04
2081	-34,164,711	68,360,036	-9,490	18,989	-3.23	3.83	3.83	3.07
2082	-34,943,612	68,951,930	-9,707	19,153	-3.31	3.87	3.87	3.09
2083	-35,721,006	69,542,123	-9,923	19,317	-3.38	3.90	3.90	3.12
2084	-36,496,476	70,130,552	-10,138	19,481	-3.45	3.93	3.93	3.15
2085	-37,271,732	70,718,830	-10,353	19,644	-3.53	3.97	3.97	3.17
2086	-38,047,161	71,307,247	-10,569	19,808	-3.60	4.00	4.00	3.20
2087	-38,822,975	71,895,917	-10,784	19,971	-3.67	4.03	4.03	3.23
2088	-39,599,264	72,484,930	-11,000	20,135	-3.75	4.07	4.07	3.25
2089	-40,376,019	73,074,279	-11,216	20,298	-3.82	4.10	4.10	3.28
2090	-41,153,169	73,663,926	-11,431	20,462	-3.89	4.13	4.13	3.31
2091	-41,930,604	74,253,797	-11,647	20,626	-3.97	4.17	4.17	3.33
2092	-42,708,200	74,843,819	-11,863	20,790	-4.04	4.20	4.20	3.36
2093	-43,485,837	75,433,925	-12,079	20,954	-4.11	4.23	4.23	3.39
2094	-44,263,441	76,023,987	-12,295	21,118	-4.19	4.26	4.26	3.41
2095	-45,040,947	76,613,911	-12,511	21,282	-4.26	4.30	4.30	3.44
2096	-45,818,215	77,203,675	-12,727	21,445	-4.33	4.33	4.33	3.46
2097	-46,595,237	77,793,265	-12,943	21,609	-4.41	4.36	4.36	3.49
2098	-47,372,013	78,382,707	-13,159	21,773	-4.48	4.40	4.40	3.52
2099	-48,148,538	78,972,029	-13,375	21,937	-4.55	4.43	4.43	3.54

2100	-48,924,945	79,561,274	-13,590	22,100	-4.63	4.46	4.46	3.57

BAU and forecast coal/gas consumption and cumulative emissions in China from EIA data								
BAU source data: International - U.S. Energy Information Administration (EIA)								
1 TJ to TWh=	2.78E-04	1 Gg=	0.000001	Gt		**$cost of CCS 1 tCO_2**	45	
bituminous coal CO_2 emission factor kg/TJ=		94,600	natural gas CO_2 emission factor kg/TJ=		56,100	**$cost of CCS 1 $GtCO_2$**	##########	
bituminous coal CH_4 emission factor kg/TJ=		1	natural gas CH_4 emission factor kg/TJ=		1			
bituminous coal N_2O emission factor kg/TJ=		1.5	natural gas N_2O emission factor kg/TJ=		0.1			
		Total BAU 2000-2019	**Total projected 2020-2100**	**total emission reduction CCS scenario 80%**				
$GtCO_2$ emissions from coal+gas		162.28	2,257.31	1,805.85				
Years	**China coal energy consumption**	**China gas energy consumption**	**Energy from coal**	**Energy from gas**	**CO_2 emissions from coal**	**CO_2 emissions from gas**	**emissions from coal+gas**	
	terajoules TJ	**terajoules TJ**	**tera watt hour TWh**	**tera watt hour TWh**	**Gigatonne Gt**	**Gigatonne Gt**	**Gigatonnes of carbon dixoxide $GtCO_2$**	

	BAU/projected EIA data	BAU/projected EIA data	B14*B4	C14*B4	(B14*C5)/(1.E+06)*D4	(C14*F5)/(1.E+06)*D4	(F14+G14)	
2000	34,563,024	994,892	9,601	276	3.27	0.06	3.33	
2001	36,084,342	1,074,126	10,023	298	3.41	0.06	3.47	
2002	38,432,987	1,170,104	10,676	325	3.64	0.07	3.70	
2003	45,785,618	1,260,669	12,718	350	4.33	0.07	4.40	
2004	55,305,391	1,488,756	15,363	414	5.23	0.08	5.32	
2005	64,625,708	1,824,150	17,952	507	6.11	0.10	6.22	
2006	71,829,206	2,197,857	19,953	611	6.80	0.12	6.92	
2007	76,910,799	2,745,375	21,364	763	7.28	0.15	7.43	
2008	79,502,110	3,005,039	22,084	835	7.52	0.17	7.69	
2009	85,939,043	3,445,716	23,872	957	8.13	0.19	8.32	
2010	95,081,592	4,154,857	26,412	1,154	8.99	0.23	9.23	
2011	105,100,928	5,097,613	29,195	1,416	9.94	0.29	10.23	
2012	110,797,926	5,594,164	30,777	1,554	10.48	0.31	10.80	
2013	114,323,367	6,350,729	31,756	1,764	10.81	0.36	11.17	
2014	112,736,207	7,053,172	31,316	1,959	10.66	0.40	11.06	
2015	107,628,225	7,429,037	29,897	2,064	10.18	0.42	10.60	
2016	100,147,606	8,063,167	27,819	2,240	9.47	0.45	9.93	

2017	103,531,668	9,289,849	28,759	2,581	9.79	0.52	10.32	
2018	107,638,441	10,911,120	29,900	3,031	10.18	0.61	10.79	
2019	113,102,001	11,936,765	31,417	3,316	10.70	0.67	11.37	**Emissions reduced by 80% CCS**
2020	129,952,460	10,660,082	36,098	2,961	12.29	0.60	12.89	10.31
2021	134,428,569	11,222,531	37,341	3,117	12.72	0.63	13.35	10.68
2022	138,262,076	11,958,446	38,406	3,322	13.08	0.67	13.75	11.00
2023	141,565,744	12,697,104	39,324	3,527	13.39	0.71	14.10	11.28
2024	144,296,233	13,431,480	40,082	3,731	13.65	0.75	14.40	11.52
2025	146,878,779	14,150,984	40,800	3,931	13.89	0.79	14.69	11.75
2026	149,588,584	14,858,650	41,552	4,127	14.15	0.83	14.98	11.99
2027	152,527,149	15,556,953	42,369	4,321	14.43	0.87	15.30	12.24
2028	155,600,640	16,242,989	43,222	4,512	14.72	0.91	15.63	12.50
2029	158,663,285	16,928,821	44,073	4,702	15.01	0.95	15.96	12.77
2030	161,468,960	17,580,904	44,852	4,884	15.27	0.99	16.26	13.01
2031	164,383,174	18,206,547	45,662	5,057	15.55	1.02	16.57	13.26
2032	167,774,803	18,827,096	46,604	5,230	15.87	1.06	16.93	13.54
2033	171,919,791	19,468,361	47,755	5,408	16.26	1.09	17.36	13.88
2034	176,582,916	20,090,020	49,051	5,581	16.70	1.13	17.83	14.27

2035	181,647,205	20,714,750	50,458	5,754	17.18	1.16	18.35	14.68
2036	186,612,867	21,339,134	51,837	5,928	17.65	1.20	18.85	15.08
2037	190,980,482	21,928,449	53,050	6,091	18.07	1.23	19.30	15.44
2038	194,232,364	22,500,752	53,953	6,250	18.37	1.26	19.64	15.71
2039	197,176,676	23,118,340	54,771	6,422	18.65	1.30	19.95	15.96
2040	199,835,874	23,842,405	55,510	6,623	18.90	1.34	20.24	16.19
2041	202,320,858	24,642,330	56,200	6,845	19.14	1.38	20.52	16.42
2042	205,885,644	25,284,714	57,190	7,024	19.48	1.42	20.90	16.72
2043	209,585,843	25,911,312	58,218	7,198	19.83	1.45	21.28	17.02
2044	213,389,886	26,536,975	59,275	7,371	20.19	1.49	21.68	17.34
2045	217,261,429	27,163,385	60,350	7,545	20.55	1.52	22.08	17.66
2046	221,143,403	27,791,830	61,429	7,720	20.92	1.56	22.48	17.98
2047	225,005,290	28,422,612	62,501	7,895	21.29	1.59	22.88	18.30
2048	228,838,641	29,056,180	63,566	8,071	21.65	1.63	23.28	18.62
2049	232,646,614	29,693,138	64,624	8,248	22.01	1.67	23.67	18.94
2050	236,426,372	30,333,712	65,674	8,426	22.37	1.70	24.07	19.25
2051	240,160,860	30,979,270	66,711	8,605	22.72	1.74	24.46	19.57
2052	243,803,066	31,627,711	67,723	8,785	23.06	1.77	24.84	19.87
2053	247,334,031	32,276,783	68,704	8,966	23.40	1.81	25.21	20.17

2054	250,774,455	32,925,722	69,660	9,146	23.72	1.85	25.57	20.46
2055	254,187,612	33,576,363	70,608	9,327	24.05	1.88	25.93	20.74
2056	257,635,123	34,226,775	71,565	9,507	24.37	1.92	26.29	21.03
2057	261,185,324	34,876,835	72,551	9,688	24.71	1.96	26.66	21.33
2058	264,870,070	35,526,072	73,575	9,868	25.06	1.99	27.05	21.64
2059	268,669,710	36,170,122	74,630	10,047	25.42	2.03	27.45	21.96
2060	272,493,684	36,805,277	75,693	10,224	25.78	2.06	27.84	22.27
2061	276,305,115	37,433,777	76,751	10,398	26.14	2.10	28.24	22.59
2062	280,057,821	38,065,767	77,794	10,574	26.49	2.14	28.63	22.90
2063	283,705,076	38,711,584	78,807	10,753	26.84	2.17	29.01	23.21
2064	287,326,946	39,359,007	79,813	10,933	27.18	2.21	29.39	23.51
2065	290,932,251	40,006,563	80,815	11,113	27.52	2.24	29.77	23.81
2066	294,530,327	40,653,879	81,814	11,293	27.86	2.28	30.14	24.11
2067	298,130,028	41,300,677	82,814	11,472	28.20	2.32	30.52	24.42
2068	301,736,713	41,946,782	83,816	11,652	28.54	2.35	30.90	24.72
2069	305,353,547	42,592,058	84,820	11,831	28.89	2.39	31.28	25.02
2070	308,982,980	43,236,432	85,829	12,010	29.23	2.43	31.66	25.32
2071	312,627,729	43,879,936	86,841	12,189	29.57	2.46	32.04	25.63
2072	316,290,168	44,522,694	87,858	12,367	29.92	2.50	32.42	25.94

2073	319,970,640	45,165,070	88,881	12,546	30.27	2.53	32.80	26.24
2074	323,663,501	45,807,344	89,907	12,724	30.62	2.57	33.19	26.55
2075	327,358,381	46,449,655	90,933	12,903	30.97	2.61	33.57	26.86
2076	331,043,435	47,092,091	91,957	13,081	31.32	2.64	33.96	27.17
2077	334,710,169	47,734,958	92,975	13,260	31.66	2.68	34.34	27.47
2078	338,354,973	48,378,429	93,987	13,438	32.01	2.71	34.72	27.78
2079	341,981,785	49,022,689	94,995	13,617	32.35	2.75	35.10	28.08
2080	345,600,563	49,667,893	96,000	13,797	32.69	2.79	35.48	28.38
2081	349,223,186	50,313,722	97,006	13,976	33.04	2.82	35.86	28.69
2082	352,855,637	50,959,305	98,015	14,155	33.38	2.86	36.24	28.99
2083	356,501,290	51,603,715	99,028	14,334	33.73	2.89	36.62	29.30
2084	360,158,784	52,246,866	100,044	14,513	34.07	2.93	37.00	29.60
2085	363,820,356	52,889,855	101,061	14,692	34.42	2.97	37.38	29.91
2086	367,483,856	53,532,865	102,079	14,870	34.76	3.00	37.77	30.21
2087	371,147,269	54,175,977	103,096	15,049	35.11	3.04	38.15	30.52
2088	374,808,955	54,819,251	104,114	15,228	35.46	3.08	38.53	30.83
2089	378,467,831	55,462,721	105,130	15,406	35.80	3.11	38.91	31.13
2090	382,123,240	56,106,397	106,145	15,585	36.15	3.15	39.30	31.44
2091	385,774,887	56,750,267	107,160	15,764	36.49	3.18	39.68	31.74

2092	389,422,887	57,394,291	108,173	15,943	36.84	3.22	40.06	32.05
2093	393,067,903	58,038,410	109,186	16,122	37.18	3.26	40.44	32.35
2094	396,711,258	58,682,554	110,198	16,301	37.53	3.29	40.82	32.66
2095	400,354,860	59,326,666	111,210	16,480	37.87	3.33	41.20	32.96
2096	404,000,643	59,970,703	112,222	16,659	38.22	3.36	41.58	33.27
2097	407,649,948	60,614,629	113,236	16,837	38.56	3.40	41.96	33.57
2098	411,303,070	61,258,412	114,251	17,016	38.91	3.44	42.35	33.88
2099	414,959,241	61,902,050	115,266	17,195	39.26	3.47	42.73	34.18
2100	418,616,833	62,545,569	116,282	17,374	39.60	3.51	43.11	34.49

Appendix 3: worksheets for CDM Assessment Methodology in Chapter 3

CDM AM case studies				
DATA:	http://cdm.unfccc.int/Issuance/cers_iss.html			
CDM ref	**Project Name**	**CDM IEAT**	**Host country**	**Gas Abated**
306	Changshu HFC 23 decomposition	Industrial	China	HFC-23
123	Indo Gulf Fertilisers Ltd	Industrial	India	CO_2
189	Ugar sugar works cogeneration	Industrial	India	CO_2
812	Jinan Iron and Steel	Industrial	China	CO_2
366	Taishan Cement Waste heat	Industrial	China	CO2
1238	N20 decomposition LPC	Industrial	China	N_20
247	Palm Kernel and Cement Production	Agriculture	Malaysia	$CO_2/CH_4/N_20$
9	La Esperanza Hydroelectric	Energy	Honduras	CO_2
233	Zhangbei Manjing Wind Farm	Energy	China	CO_2
253	Rithwik Biomass	Energy	India	CO_2
108	Granja Becker GHG mitigation	Agriculture	Brazil	$CO_2/CH_4/N_20$
121	Bagepalli Biogas	Agriculture	India	CH_4
672	BRT Bogota	Transport	Colombia	$CO_2/CH_4/N_20$

Qualitative Assessment for CDM Assessment Framework												
CDM Category	**BAU Emission Source/s**	**Climate Indicators**	**CDM Corrective Actions in project**		**Weightage**	**Corrective Action Score**	**Additionality**					**Total Project Score**
ENERGY SECTOR		GHG emissions reduced	**Project emission avoidance methods**	**Project emission reductions pathway**	Maximum	Assigned	**Carbon**	**Financial**	**Technology**	**Policy**	**Additionality**	
					score	score	Revenue	Barrier	Barrier	Barrier	Score	
La Esperanza Hydroelectric	CO_2, N_2O, CH_4 from diesel grid	CO_2,$N_2$0,CH_4	Hydel electric capacity(13.822 MW)	no technology transfer	1	1	yes	no	no	no	1	3
				sink creation or sequestration	1	1						
				waste management	1	1						
				score		3						
Zhangbei Manjing Wind Farm	CO_2,CH_4,N_2O from coal/diesel	CO_2,$N_2$0,CH_4	Wind Capacity (45MW)	no technology transfer	1	1	yes	no	no	no	1	1
				no sink creation	1	0						
				no waste management	1	0						
				score		1						
Rithwik Biomass	CO_2,CH_4,N_2O from coal/diesel	CO_2,$N_2$0,CH_4	Biomass capacity (6MW)	no technology transfer	1	1	yes	yes	yes	yes	1	2
				no sink creation	1	0						
				no waste management	1	1						
				score		2						

				score		2						
INDUSTRIAL SECTOR												
Changshu HFC23 decomposition	Fossil fuels	CO_2,$N_2$0,CH_4	grid fuel substitution	no plant/grid fuel substitution	1	0	Yes	Yes	Yes	Yes	1	2
	coal, gas, oil											
	Industrial Process	HFC23	not applicable	Technology Transfer	1	1						
	waste: landfilling	CH_4,$CaCl_2$	Waste Management	Reuse and Recycling	1	1						
				score		2						
Indo-Gulf CO2 removal	Fossil fuels natural gas	CO_2,$N_2$0,CH_4	grid fuel substitution	no plant/grid fuel substitution	1	0	Yes	Yes	Yes	Yes	1	1
	Industrial Process	CO_2	not applicable	Technology Transfer/innovation	1	1						
	waste: landfilling	$N_2$0,CH_4,CO_2	Waste Management	no waste management	1	0						
				score		1						
Ugar Sugar Cogeneration	Fossil fuels	CO_2,$N_2$0,CH_4	grid fuel substitution	no grid/plant fuel substitution	1	0	Yes	Yes	Yes	Yes	1	1
	coal, gas, oil											
	Industrial Process	CO_2,$N_2$0,CH_4	not applicable	technology/transfer innovation	1	1						
	waste: Landfilling	CH_4	Waste Management	no waste management	1	0						
				score		1						
Jinan Iron & Steel	Fossil fuels	CO_2,$N_2$0,CH_4	grid fuel substitution	plant/grid fuel substitution	1	0	Yes	Yes	Yes	Yes	1	1
	coal, gas, oil											
	Industrial	CO_2,$N_2$0,C	not applicable	Technology	1	1						

	Process	H_4		Transfer/innovation								
	waste: landfilling	CH_4	Waste Management	waste management	1	0						
				score		1						
Taishan Cement Waste heat	Fossil fuels	CO_2,$N_2$0,CH_4	grid fuel subsitution	plant/grid fuel substitution	1	0	Yes	Yes	Yes	Yes	1	1
	coal, gas, oil											
	Industrial Process	CO_2,$N_2$0,CH_4	not applicable	Technology Transfer/innovation	1	1						
	waste: landfilling	CH4	Waste Management	waste management	1	0						
				score		1						
N20 decomposition LYPC	Fossil fuels	CO_2,$N_2$0,CH_4	grid fuel subsitution	plant/grid fuel substitution	1	0	Yes	Yes	Yes	Yes	1	1
	coal, gas, oil											
	Industrial Process	CO_2,$N_2$0,CH_4	not applicable	Technology Transfer	1	1						
	waste: landfilling	CH4	Waste Management	waste management	1	0						
				score		1						
Palm Kernel and Cement Production	CH_4, N_2O, CO_2 from coal and waste	CO_2,$N_2$0,CH_4	not applicable	Technology Transfer	1	1	Yes	Yes	Yes	Yes	1	2
				sink creation	1	0						
				enteric fermentation	1	0						
				waste to energy	1	1						
				score		2						

AGRICULTURE SECTOR												
Granja Becker	CH_4,N_2O,CO_2 from animal waste	CH_4,N_2O, CO_2	not applicable	technology innovation	1	1	no data	yes	yes	yes	1	2
				sink creation	1	0						
				enteric fermentation	1	0						
				waste to energy	1	1						
				score		2						
Bagepalli Biogas	CH_4,N_2O,CO_2 from animal waste	CH_4,N_2O, CO_2	not applicable	Technology Transfer	1	0	yes	no	no	no	0	0
				sink creation	1	0						
				enteric fermentation	1	0						
				waste to energy	1	1						
				score		1						
TRANSPORT SECTOR												
BRT Bogota	CO_2, N_20 from diesel combustion	$C0_2$,N_20	not applicable	Technology Transfer	1	1	yes	yes	yes	yes	1	2
				Fuel substitution	1	0						
				waste to energy	1	0						
				sustrans	1	1						
				score		2						

Quantitative Assessment for CDM Assessment Framework										
QOP	quotient of performance									
MCV	market commodity value $									
k : CER price $	0.4	5								
Project Name	**CDM category**	**Host**	**Measuring period in years**	**Emission reduction potential tCO_2e**	**emissions reduced tCO_2e**	**CDM efficiency**	**Crediting period/years**	**QOP**	**MCV $ 0.4/CER**	**MCV $5/CER**
Changshu HFC23	Industrial	China	6	219,182,229	58,922,499	0.27	21	0.94	23,569,000	294,612,495
Indo Gulf Fertilisers Ltd	Industrial	India	9	244,490	160,928	0.66	10	0.73	64,371	804,640
Ugar Sugar Cogeneration	Industrial	India	2	639,348	94,783	0.15	10	0.74	37,913	473,915
Jinan Iron and Steel	Industrial	China	7	11,135,894	8,110,370	0.73	7	0.73	3,244,148	40,551,850
Taishan Cement Waste heat	Industrial	China	6	741,260	383,987	0.52	7	0.60	153,595	1,919,935
N20 decomposition LYPC	Industrial	China	7	83,035,519	64,078,279	0.77	13	1.43	64,078,279	320,391,395
Palm Kernel and Cement Production	Industrial	Malaysia	10	619,460	607,273	0.98	10	0.98	242,909	3,036,365
La Esperanza Hydroelectric	Energy	Honduras	16	761,712	468,596	0.62	21	0.81	187,438	2,342,980
Zhangbei Manjing Wind Farm	Energy	China	13	1,934,920	1,210,138	0.63	20	0.96	484,055	6,050,690
Rithwik Biomass	Energy	India	9	186,298	143,733	0.77	7	0.60	57,493	718,665
Granja Becker GHG mitigation	Agriculture	Brazil	2	5,086	3,339	0.66	10	3.28	1,336	16,695
Bagepalli Biogas	Agriculture	India	14	283,899	194,133	0.68	21	1.03	77,653	970,665
BRT Bogota	Transport	Colombia	12	4,052,426	511,423	0.13	13	0.14	204,569	2,557,115
Total				322,822,541	134,889,481	0.42				

Appendix 3A: result worksheet for published paper

Diesel and Gasoline carbon emissions in EU 28 (2000 and 2018)					
CO_2e emission in Gg 2000		**CO_2e emission in Gg 2018**			
Diesel	**Gasoline**	**Diesel**	**Gasoline**		
130,957	106,829	180,133	63,429		
total CO_2e in Gg 2000 and 2018	237,786	243,562			
Net carbon GtC	0.237	0.243			
Table 2: BAU road transport emissions and EU carbon budget for 1.5^0Cand 2^0C scenario					
EU total carbon budget from 2010-2100 in Ecologic study [23]	**EU transport carbon budget 2010-2100 in Fraunhofer study [24], includes aviation, shipping and navigation**	**EU diesel and gasoline road transport carbon emissions in 2000 and 2018 respectively, [table1]**			
83 – 116 GtCO_2e	10.2 – 12.1 GtCO_2e	0.23 and 0.24 GtCO_2e			
Carbon emissions in BAU trajectory: excluding aviation, shipping and navigation					
0.23 GtCO_2e or 0.24 GtCO_2e per year if diesel and gasoline BAU emissions continue for 11 years, 31 years and 81 years from 2019 to 2100					

2019-2030	**2019-2050**	**2019-2100**			
2.53 - 2.64 $GtCO_2e$	7.13 – 7.44 $GtCO_2e$	18.63 – 19.44 $GtCO_2e$			
EU transport carbon budget in a BAU scenario of 0.23 or 0.24 $GtCO_2e$ per year could be completely consumed in early 2060s. Road transport emissions could consume 16% - 22% of EU total carbon budget in 2100					