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Driving Carbon Capture in Parallel with Industrialization in Developing Countries: Opportunities, Challenges and Strategies

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Abstract

Purpose: This paper reviews the potential of carbon capture and storage (CCS) technologies to help developing nations decrease carbon emissions as they undergo the industrialization required for development. It also identifies the related opportunities, challenges, and strategies for effectively integrating CCS during this process by drawing lessons from the experiences of developed and developing countries that have achieved success.

Materials and Methods: The study employs a thorough literature review, statistical analysis of data, and examination of real-world case studies. Comparing Norway, South Korea, the United States, China, and India's experiences, it focuses on successful models and key factors influencing CCS adoption in different regions, offering insights for other developing nations.

Findings: The review and analysis show that developed countries have made considerable advancements in utilizing CCS technologies to lower emissions, whereas developing nations encounter significant obstacles due to financial constraints, insufficient expertise, and inadequate regulations. Nevertheless, underdeveloped nations can employ CCS technologies for enduring economic expansion with appropriate global cooperation, financial assistance, and technology sharing. Finally, it pinpoints effective tactics and models developing nations can use to improve their CCS capabilities.

Implications to Theory, Practice and Policy: This research has implications for theory, practice, and policy by enhancing understanding of how CCS can help promote sustainable industrial growth in developing nations and providing a template for integrating CCS into national climate plans. It also mentions the importance of detailed and effective regulatory frameworks, financial incentives, and global cooperation required in addressing CCS challenges in developing countries.

Keywords: *Carbon Capture Storage, Industrialization, Developing Countries, Carbon Emissions, Sustainable Development*

JEL Codes: Q54, Q55, O14, L60, O10, O19, Q53, Q58, Q01, Q56

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1.0 INTRODUCTION

As stated by the UNCC (2015) in the Paris Agreement as ratified by both developed and developing nations, the goal of the agreement is to limit the rise in average worldwide temperatures to less than 2°C with a focus on achieving 1.5°C, compared to levels before industrialization.

Before the Industrial Revolution, emissions were low, and progress was sluggish until the mid-20th century. However, by 1990, global CO2 emissions had almost quadrupled from 6 billion tonnes in 1950 to over 20 billion tonnes, and it has continued to grow rapidly, with world emissions of over 35 billion tonnes yearly. Nevertheless, this growth has slowed over the last few years while still less than the expected peak (Ritchie H. et al., 2024). Despite having less historical contribution to global warming, developing nations agreed to this agreement due to their heightened vulnerability to the impacts of climate change. However, these countries encounter distinct obstacles because they depend on fossil fuels for economic development and have limited financial and technical means to adopt advanced climate mitigation technologies. Using an extensive literature review, statistical data, and real-life examples, this article comprehensively analyzes how CCS can contribute to sustainable development while discussing the opportunities, challenges, strategies, and frameworks involved.

With the goal of fast industrial growth, countries such as India and China face significant emissions challenges; for instance, China was responsible for roughly 31% of worldwide emissions in 2022, releasing around 12.7 gigatons (GT) of CO2, while India, as the third-largest emitter globally, emitted 3.4 GT (Friedrich J. Et al (2024), Ritchie H. et al., 2024). These examples underscore the urgent need for effective carbon capture solutions despite the need for both developed and developing countries to pursue greater industrialization required for socioeconomic and political dominance.

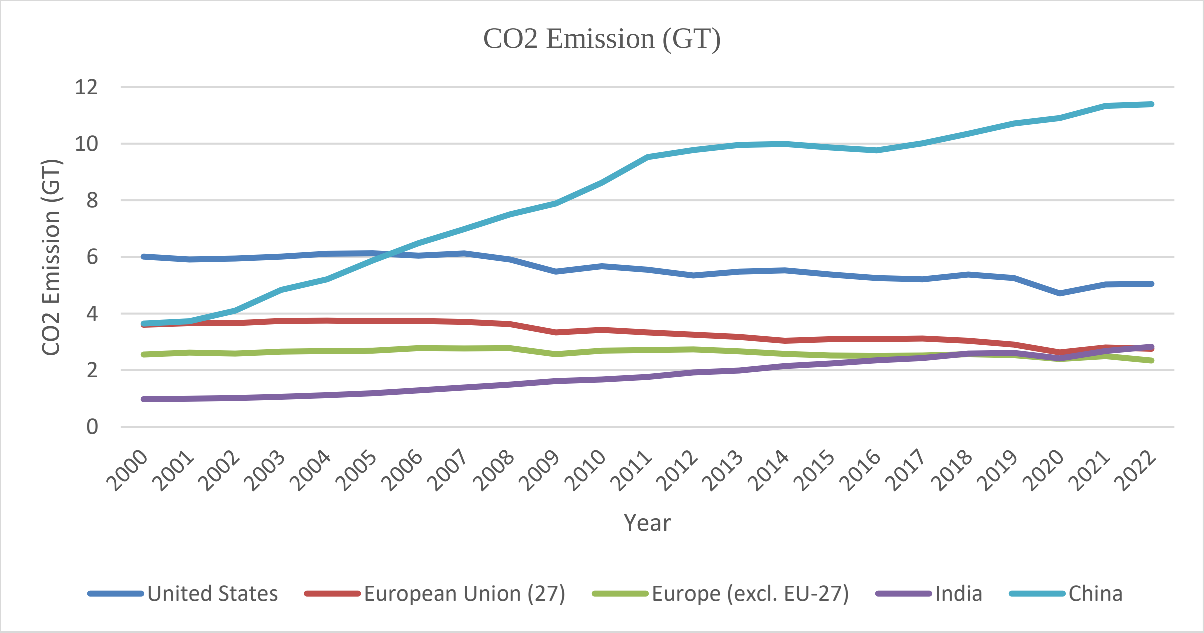

Figure 1: Historic Emission (Ritchie H. et al., 2024)

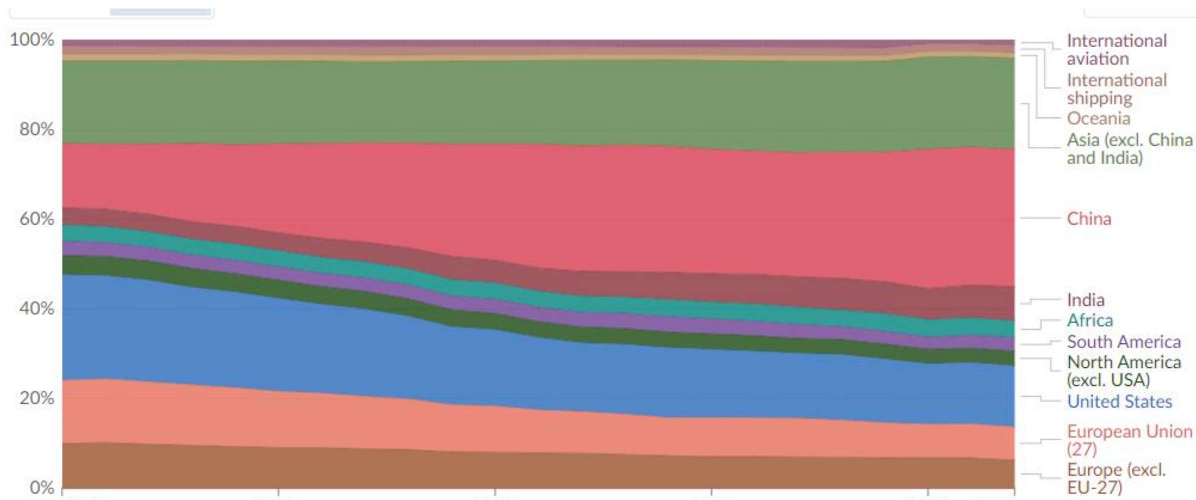

Figure 2: CO2 Emission by World Region (Ritchie H. et al., 2024)

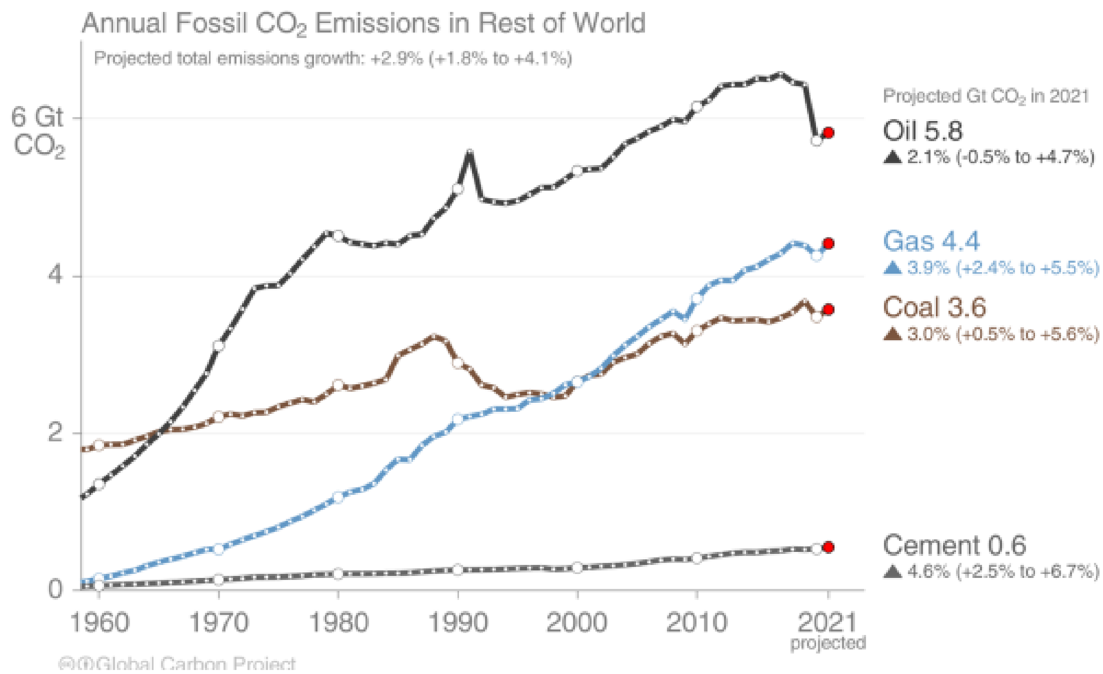

Figure 3: CO2 Emission by Sources (Friedlingstein P et al., 2021)

Problem Statement

Industrialization process in developing nations is crucial for reducing poverty and fueling economic advancement and this depends greatly on fossil fuels, resulting in a notable increase in carbon emissions (IEA, 2023). While aiming to improve their economic and industrial capabilities, these countries are confronted with the double difficulty of decreasing emissions in line with worldwide climate goals and not having the financial resources, technical capacity, and regulatory frameworks adopt advanced carbon mitigation technologies, such as CCS (Global CCS Institute, 2023; Shaw et al., 2022). The reliance on fossil fuels by developing countries is a major obstacle in achieving the ambitious goals of the Paris Agreement, causing a critical gap in global decarbonization efforts (UNCC, 2015). To tackle this problem, it is necessary to fully grasp the possibilities, obstacles, and strategic approaches for implementing CCS amidst the swift expansion of industries in developing nations (Friedlingstein et al., 2021; Liu et al., 2022).

2.0 MATERIAL AND METHODS

This descriptive article addresses historical facts, challenges, opportunities, and potential strategies for optimizing decarbonization using CCS while ensuring the industrial growth of developing nations. Data is collected from literature and industry reports and statistically presented.

Theoretical Review

The Ecological Modernization Theory (EMT) offers a way to comprehend how developing nations can achieve industrial growth while tackling environmental issues, mainly by implementing technologies such as Carbon Capture and Storage (CCS). EMT suggests that sustainable development can be achieved through technological innovations, allowing for both economic growth and environmental protection to progress together. CCS plays a vital role in reducing carbon emissions from industrial processes without impeding economic growth. The idea proposes that environmental issues, like carbon emissions from industrial activities, can be efficiently controlled by utilizing advanced technologies, backed by robust government regulations and global collaboration (Mol A. et al, 2000). EMT is especially important for developing nations, as they frequently do not have the necessary funds or knowledge to implement advanced carbon reduction technologies such as CCS. Nevertheless, the theory highlights the significance of worldwide collaboration, monetary rewards, and strong policy structures to enable the implementation of these technologies. Developing nations can utilize technological innovation to achieve sustainable industrialization and lessen carbon emissions while maintaining economic growth by embracing EMT principles (Mol A., 2002).

Historical Context and Current Trends

Industrialization has been a two-sided coin, resulting in worldwide economic expansion while also playing a major role in increasing carbon emissions, especially in developed countries within the past century with significant carbon emissions. For instance, data shows that the United States has released more than 509 billion tonnes of CO2 since 1850, making up about 20% of historical global emissions (Evans S., 2021, Friedlingstein P et al., 2021). Such extensive industrial activity is characterized by high energy consumption and heavy dependence on fossil fuels. This has laid the foundation for modern economies while creating a precedent for significant environmental consequences. In contrast, the rapid expansion of industries in developing countries such as China increased significantly in 2023, growing by around 565 Mt, the largest global rise, as the country continues its emissions-intensive economic expansion. This surge was partially driven by a historically poor hydro year. Similarly, in the same year, India's emissions grew by around 190 Mt, propelled by strong GDP growth and a weak monsoon, which heightened electricity demand and reduced hydro production (IEA, 2023). Like the USA, the fast-paced industrialization of these developing nations is propelled by the desire to enhance economic status and living standards.

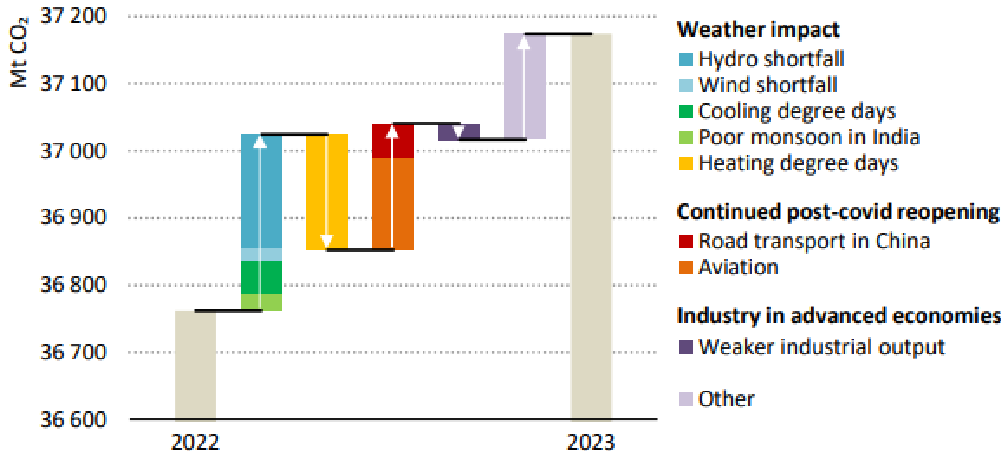

Figure 4: Global CO2 emissions by Driver, 2022-2023 (IEA, 2023)

According to the information provided by the World Bank Group (2024), infrastructure investments in the developing world have an annual deficit of over $1.5 trillion, covering core sectors such as transport, power, water, and telecommunications required for strategic economic growth. This occurrence of inadequate infrastructure accompanied by obsolete technologies slows economic progress and leads to environmental damage. Similarly, according to the African Development Bank Group's (2023) yearly investment reports, Africa requires $130 billion to $170 billion to close the infrastructural gaps, while Asia will require $1.7 trillion in infrastructure investments to support its growth and address climate change till 2030 (Asian Development Bank, 2017). As a result, numerous developing countries have no choice but to rely on high-emission fossil fuels like coal and diesel generators, resulting in a rise in carbon emissions. With this, it is essential to address these drawbacks by investing in eco-friendly and sustainable technologies like renewable energy initiatives, smart grid systems, and energy-saving practices. For example, despite being the top global polluter, China made substantial investments in solar PV, leading to a growth of over 100 GW of solar capacity in 2022.

Likewise, as per reports from the World Economic Times (2023) and IBEF (2023), India is striving towards ambitious goals through the National Solar Mission to reach 500 GW of renewable energy capacity by 2030. By early 2024, India has effectively implemented around 190 GW, showing significant advancements in decreasing its dependence on coal and reducing carbon emissions. Also, China has made important advancements in carbon capture, utilization, and storage (CCUS) technologies through major projects like the Qilu Petrochemical - Shengli Oilfield CCUS Project, which seizes 1 million tonnes of CO2 yearly, and a future 2 million tonnes per annum (MTpa). Moreover, China has included CCUS in its national policies, with various provincial governments backing its R&D and promotion initiatives (Liu Y. et al 2022, SINOPEC 2023, Norton Rose Fulbright, 2024, Asian Development Bank, 2022). Likewise, India is progressing in CCUS by focusing on incorporating these technologies into its heavy industries and power sectors. It is actively working on various pilot projects and seeking collaborations and partnerships to improve its CCUS capabilities, through policy incentives and funding mechanisms (Shaw R et al., 2022; World Economic Forum, 2024).

These historical and current patterns pave the way for CCS to have a crucial role in developing nations, providing a route to sustainable development without compromising economic advancement, especially for high-polluting industries that are crucial for the economic advancement.

Technology Advancements and Policy Measures

As mentioned, advanced nations have pledged significant amounts of money to renewable energy and energy-efficient technologies to address climate change. For example, the EU has committed to decrease greenhouse gas emissions by at least 55% by 2030 compared to 1990. This ambitious goal is a major part of the EU's wider Green Deal, with the goal of being the first climate-neutral continent by 2050. Implementing carbon pricing, Emission Trading Systems (ETS), and backing renewable energy projects are vital in achieving these reductions. The ETS is the largest carbon market worldwide, responsible for around 40% savings of the EU's greenhouse gas emissions, and it has been crucial in reducing emissions from majorly power plants and industrial facilities by setting limits on emissions and allowing entities to trade permits while promoting cost-effective cuts in emissions (Lang T. et al 2014, Wei W. et al. 2020, European Commission 2021). Besides carbon markets, developments in renewable energy technologies have also been crucial in reducing CO2. For example, solar photovoltaic (PV) and wind energy costs have reduced significantly, allowing them to compete with fossil fuels in energy production. IRENA (2020) reported that from 2010 to 2019, there has been an 82% decrease in procurement and installation of utility-scale solar PV electricity and a 39% reduction in onshore wind costs, and these decreases in costs have caused more people to switch to solar and wind power, which now make up most of the new power capacity installations globally.

Consequently, developing countries are increasingly interested in implementing renewable energy solutions, but they face challenges because of the high costs and limited technical expertise. Despite its plentiful solar resources, Sub-Saharan Africa had a mere 1% share of global solar PV capacity in 2023, as reported by AOW Energy (2024); however, initiatives are underway to enhance this capacity. Countries such as South Africa, Kenya, and Nigeria are experiencing notable advancements in large-scale solar projects and standalone systems needed to supply electricity to underserved areas, mainly rural areas IRENA (2020). By contrast, developed nations are benefiting from far lower costs of renewable energy technologies due to economies of scale and access to financing mechanisms, such as green bonds and government-backed incentives that are typically not available to developing nations on the same scale. This discrepancy underscores the need for greater international financial cooperation to enable developing countries to implement similar energy transitions. Similarly, the Green Climate Fund (GCF) and the World Bank back initiatives are promoting renewable energy and reducing carbon emissions in developing nations. According to the GCF, more than $12 billion will be directed towards climate-related projects like renewable energy and energy efficiency initiatives in 2023. Likewise, the Climate Investment Funds of the World Bank have supported various initiatives to boost the use of renewable energy and enhance energy availability in developing nations (MDB Reform Accelerator, 2023).

Furthermore, the introduction of energy-efficient practices, such as the use of advanced building materials, advanced grid technologies, and energy-efficient devices, has the potential to significantly reduce energy use, just as smart meters and grid control systems can enhance electricity consumption and reduce inefficiencies. For example, China's energy plan focuses on enhancing energy efficiency in industry, buildings, and transportation by integrating these different technologies (Pandiyan et al., 2023; National Development and Reform Commission, 2020).

Apart from renewable energy sources that help reduce CO_2 emissions during production processes, other technological innovations help capture CO_2 emissions, especially for industries that are difficult to decarbonize, such as cement, steel, and chemicals. CCS, for example, seizes CO_2 emissions from industrial activities and power production, then transports and deposits them beneath the ground in geological structures. Petra Nova in Texas, USA, is an excellent example of such a project. It is one of the largest CCS initiatives targeting to capture approximately 1.4 million metric tons of CO_2 each year from a coal plant at the W.A. Parish Generating Station (U.S. Department of Energy, 2023). This is interesting because the technology is important to developing countries with plenty of fossil fuel reserves as it enables them to lower emissions while still using fossil fuels necessary for their development.

Energy Mix and Dependence on Fossil Fuels

Unlike developed countries, developing countries have an energy mix that is highly skewed towards fossil fuels due to their natural abundance and lower cost of production. For instance, as of 2023, coal-fired power plants in China account for about 58% of its electricity generation, while India and South Africa also have approximately 73% and 82% of their electricity generation coming from coal (International Energy Agency, 2023 Business Wire, 2024). In contrast, developed nations have expanded their energy sources by incorporating a greater variety of renewable options. For instance, in 2023, renewable sources constituted 21.3% of the electricity produced in the United States and 44% of the EU's electricity generation, showing a 12.4% rise from the previous year.

Despite the need to move towards a carbon-neutral environment, developing countries often argue that they have the right to develop their economies using fossil fuels, just as developed countries did during their industrialization ages. This argument is supported by the principle of "common but differentiated responsibilities" (CBDR) in international climate agreements, which acknowledges that developed countries bear a more significant historical responsibility for global emissions. The CBDR principle states that all nations have a duty to tackle global environmental degradation, but this duty varies depending on each country's historical role in causing climate change. Nevertheless, this method poses a major hurdle to international climate objectives since the ongoing dependence of developing nations on fossil fuels may exacerbate the effects of climate change.

Another concern about CO_2 emission in developing nations is closely tied to their energy mix and industrial activities. Developing nations typically show increased Scope 1 emissions because of the substantial direct burning of fossil fuels in power production and industrial activities, mainly stemming from their heavy use of coal and other fossil fuels for energy and expanding manufacturing industry (Wei W. et al., 2020). Moreover, Scope 2 emissions are increased due to reliance on fossil fuel-generated electricity, whereas quantifying Scope 3 emissions is more difficult. The production of goods influences these emissions, often exported to developed countries, thus raising their overall carbon footprint (Wiedmann T. et al., 2020).

Comparative Analysis of Carbon Emissions

Per Capita Emissions

This helps to determine the level of carbon emission contribution of each person to the country's emission, which is a reflection of the individual's lifestyle. In 2022, the US, China, and India had approximately 14.44 tonnes, 8.85 tonnes, and 1.91 tonnes of CO_2 emissions per person, respectively (IEA, 2023; World Population Review, 2024). This stark difference emphasizes the inequality in energy usage trends and quality of life between developed and developing nations. Developed nations, which built their infrastructure when environmental regulations were less strict, traditionally used fossil fuels, resulting in higher emissions per person. This trend has remained consistent, with developed nations maintaining high per capita emissions despite global efforts to reduce carbon footprints. Despite stringent climate policies implemented by the EU, it averages 7.5 tonnes per capita, with countries such as Germany reaching 9.7 tonnes (Eurostat, 2023). In recent years, developed countries such as the US and Canada have maintained relatively high per capita emissions because of their well-established industrial sectors and high energy consumption rates. In 2023, Canada's per capita emission was approximately 15.2 tonnes, only slightly lower than the 15.5 tonnes recorded in 2018 (World Bank, 2023). In the meantime, India's per capita emissions have increased from 1.6 tonnes in 2010 to 1.92 tonnes in 2022, underscoring its growing energy demands and industrial development (IEA, 2023). Nevertheless, the lower individual emissions in developing nations, like Nigeria's 0.6 tonnes, indicate an opportunity for expansion without raising their carbon footprint to levels observed in developed countries (World Population Review, 2024).

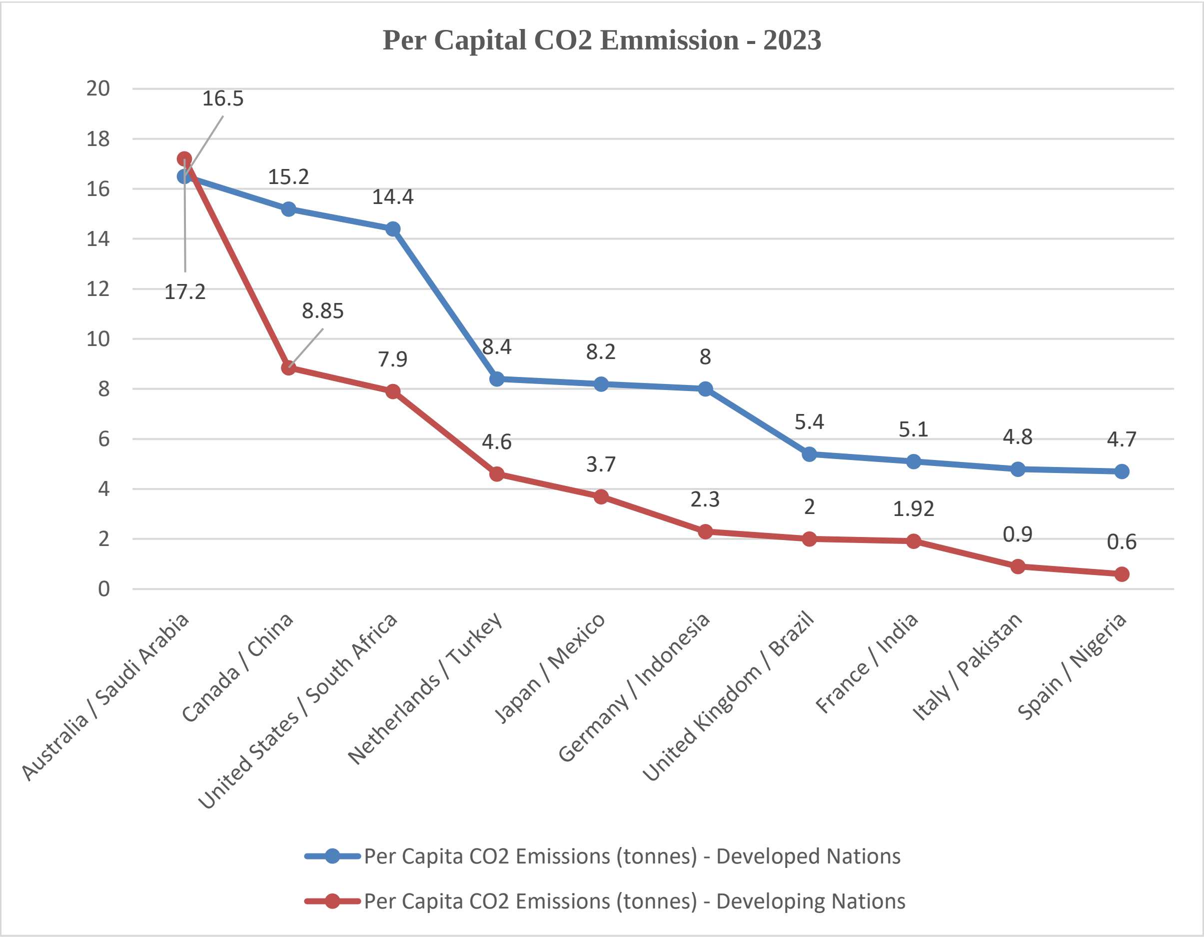

Figure 5: Per Capita Emission for Top 10 Developed and Developing Countries

Emission Intensity

Measuring CO2 emissions per unit of GDP is essential in assessing how efficient a country's economy is in terms of carbon emissions. Developed countries have achieved significant progress in decoupling economic growth from carbon emissions, with a decrease in emission intensity of the European Union by 42% between 1990 and 2019, primarily caused by strict environmental regulations, improved energy efficiency, and increased use of renewable energy sources (European Environment Agency, 2020). In countries like the United States and Germany, emission intensities have declined, indicating improved energy efficiency and reduced reliance on fossil fuels (IEA, 2023). The emission intensity of the United States in 2023 was around 0.30 tonnes of CO2 per $1,000 GDP, slightly higher than Germany's 0.25 tonnes per $1,000 GDP (San Francisco Fed, 2023). Less developed countries face more challenges in reducing their emission intensity due to their heavy reliance on energy-intensive industries and fossil fuels.

Despite advancements in renewable energy utilization, China and India still have relatively high emission intensities of 0.55 and 0.65 tonnes of CO2 per $1,000 GDP, respectively, exceeding those of the US and EU (IEA, 2023). The high energy intensity of GDP in these nations suggests a notable link between economic expansion and energy usage. Another concern is that high emission intensity has become more prominent among countries with rich fossil fuel deposits, a principle called the ‘carbon curse.’ Studies by Chiroleu-Assouline M. et al. (2020) have shown through empirical evidence that there is a U-shaped correlation between resource abundance and CO2 emissions. This indicates that beyond a certain threshold, an increase in natural resources results in higher carbon intensity. Additionally, starting in the early 2000s, countries with abundant resources have seen a rise in CO2 emissions, whereas countries with limited resources have either decreased or kept their CO2 emissions steady. This divergence suggests that resource-rich countries continue to rely heavily on carbon-intensive industries, leading to higher emissions.

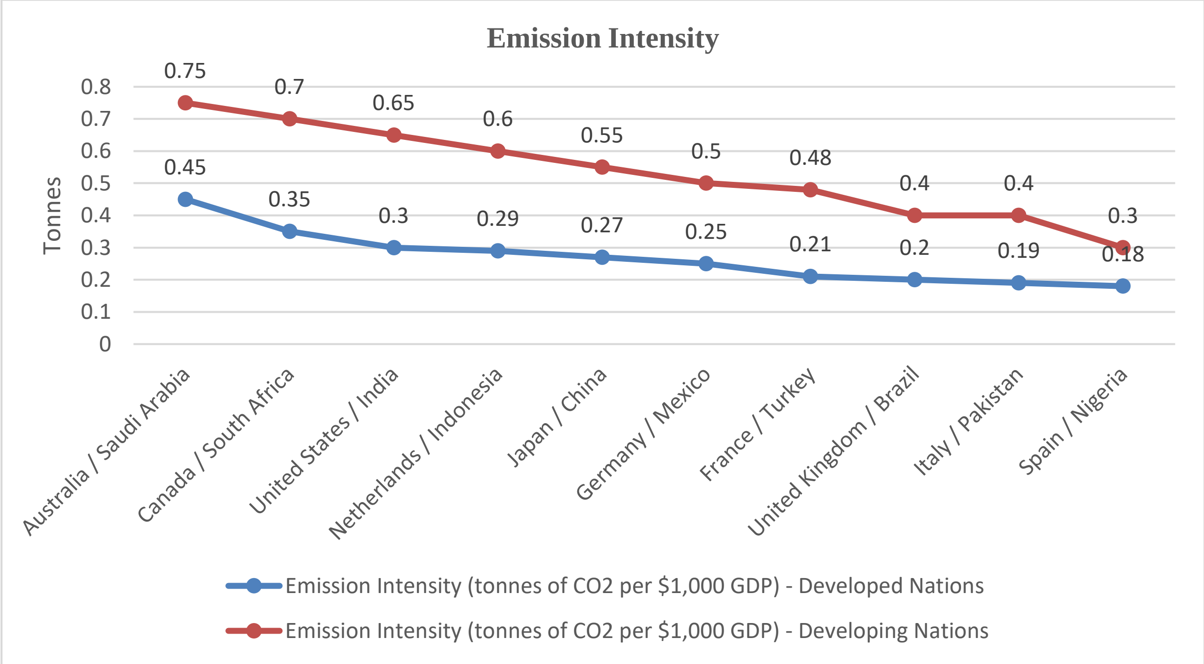

Figure 6: Emission Intensity for Top 10 Developed and Developing Countries

Analyzing per capita emissions and emission intensity provides a detailed understanding of a nation's carbon footprint and economic productivity. This measurement is crucial because it highlights the difficulties these nations face in reconciling economic advancement with sustainable methods. In the end, even though developed countries are successful in decreasing emission intensity through innovation and regulation, developing nations face challenges with higher per capita emissions because of speedy industrialization and lack of access to clean technology, which highlights the need for international assistance in shifting towards sustainable energy sources (IEA, 2023; European Environment Agency, 2020).

Emerging Technologies

Improvements in CCS technologies are dependent on enhancing the efficiency and affordability of carbon capture, which will contribute to the crucial decrease in worldwide carbon emissions. Some key areas of interest include emerging technologies like advanced CO2 absorption materials such as solid sorbent-based capture technologies, direct air capture (DAC), and integration with renewable energy sources such as the integration of bioenergy with carbon capture and storage (BECCS).

Solid Sorbent-Based Capture Technologies

This method uses materials that can absorb CO2 selectively from gas mixtures. These substances provide higher selectivity and capacity for absorbing CO2 than conventional amine-based solvents, which could result in reduced operational expenses and energy needs. The procedure includes sending the gas through a solid sorbent bed to trap CO2, and the sorbent can be regenerated for reuse by heating or reducing pressure to release the CO2. Carbon Clean Solutions and similar companies have created advanced solid sorbent-based capture technologies and have effectively used them in different industrial settings, achieving a CO2 capture efficiency of up to 90%. The cost of this technology is relatively low, approximately $40-50 per tonne of CO2 captured, making it a viable option for industrial sectors in India and the United Kingdom due to its high efficiency and affordability (Al-Mamoori et al., 2017; Carbon Clean Solutions, 2023). Over the past five years, the United States has experienced substantial growth in adopting this technology, with an annual increase of more than 15%, and it currently contributes approximately 12% of the total CO2 captured in the U.S., with the country leading global deployment. The U.S. is followed by the United Kingdom, which has also seen rapid adoption due to government incentives and industrial demand (Carbon Clean Solutions, 2023).

Direct Air Capture (DAC)

Using a solid or liquid sorbent, CO2 is captured chemically from the atmosphere and can be released through heating or chemical reactions for storage after collection. This technology provides flexibility in placement, especially in areas where it is difficult to contain point-source emissions. Companies like Climeworks and Carbon Engineering are at the forefront of advancing DAC technology, demonstrating its potential for widespread success. For example, the Orca plant in Iceland by Climeworks captures 4,000 tons of CO2 each year and is powered by renewable sources. Nevertheless, DAC is presently the most costly CCS technique, estimated at $600 per metric ton of captured CO2, far from the average of $45 for Solid Sorbent-Based Capture Technologies. Despite high expected capital expenditure, the technology's scalability and potential for significant CO2 removal make it a crucial focus for development (Climeworks, 2023; Carbon Engineering, 2023).

Bioenergy with Carbon Capture and Storage (BECCS)

This integrates biomass energy generation with CO2 capture by burning biomass like wood or agricultural waste, and the CO2 emitted is then captured and stored in the ground. The Drax Power Station in the UK employs BECCS, which captures CO2 from burning biomass and stores it underground. By 2030, when fully operating, this technique can potentially remove more CO2 from the atmosphere than is emitted during energy production, capturing approximately 8 million tons of CO2 annually. BECCS provides energy generation and carbon sequestration advantages, with anticipated expenses ranging from $100 to $150 per metric ton of captured CO2. The United Kingdom is leading the way in deploying BECCS, demonstrating its potential for broader adoption (IEA, 2024).

Comparative Analysis

Solid sorbent-based capture appears to be the most economical among these new technologies, costing approximately $40-50 per tonne of CO2 captured and achieving up to 90% efficiency. Even though DAC provides high scalability and flexibility, it still holds the title of being the most expensive option for $600 per tonne of CO2 captured. BECCS offers the advantage of removing emissions and reasonably costs $100-150 per tonne of CO2 stored. Different methods vary in efficiency and cost-effectiveness, with solid sorbent-based capture being the most established and economical, DAC showing potential for widespread implementation, and BECCS combining energy generation with carbon removal. The developments in CCS technologies offer a way to make different industrial sectors more environmentally friendly by reducing their carbon emissions, thus helping to meet global emission reduction targets (Progress in Energy and Combustion Science, 2023; IEA, 2024).

Successful CCS Models and Strategies

Carbon Capture and Storage (CCS) technologies are being more widely acknowledged for their ability to decrease significantly worldwide carbon emissions, making up about 14% of the required cuts to reach net-zero emissions by 2050, as stated by the International Energy Agency (IEA, 2023). CCS deployment has consistently increased in the last ten years, with worldwide storage capacity rising from 40 million tonnes of CO2 annually in 2010 to more than 130 million tonnes in 2023 (Global CCS Institute, 2023). It is estimated that CCS could contribute to around 25% of global CO2 decreases by 2040, with nations pledging to more challenging climate goals, increasing the importance of CCS in worldwide carbon reduction (IEA, 2023). This trend highlights how crucial CCS is in the worldwide effort to reduce climate change, especially in industries with the most challenging emissions to remove.

Norway's CCS Leadership

Norway has emerged as a global leader in CCS technology, demonstrating significant advancements and successful implementations. The country's government has actively backed CCS with significant funding, advantageous regulations, and global partnerships. A prominent CCS project in Norway, the Northern Lights project is part of the extensive Longship initiative, which aims to capture and store CO2 from industrial sources underground in geological formations under the North Sea. By 2023, the first stage of the Northern Lights project plans to capture and store 1.5 million tons of CO2 annually, with goals to raise this to 5 million tons in future phases (Equinor, 2023). The technology involves capturing CO2 from industrial sources such as cement plants and waste-to-energy facilities, then transporting it via pipelines to offshore storage sites, where the carbon dioxide is injected into the subsurface geological formations beneath the ocean floor. Northern Lights, 2023, states that this technology is highly successful because of the thorough geological surveys and advanced injection methods used to guarantee the stability and safety of the storage locations. Norway's effective implementation of CCS can be credited to its thorough policy structure, mainly the Norwegian CCS Strategy and the government's commitment to reaching carbon neutrality by 2050. For example, the government has allocated over $2.7 billion to the Longship project (Ministry of Petroleum and Energy 2022), which supports current CCS projects, with additional aims to develop new technologies and enhance existing ones.

Developing countries with significant industrial activities and comparable geological conditions for CO2 storage, such as Malaysia and Egypt, could benefit from adopting similar CCS technologies. For example, Malaysia, renowned for its robust petrochemical industry, and Egypt, with major cement and petrochemical sectors, could utilize CCS to decrease emissions from these industries. Both countries have geological structures suitable for storing CO2, such as deep saline aquifers and exhausted oil and gas reservoirs. Malaysia's National Energy Policy and Egypt's Integrated Sustainable Energy Strategy, with the help of international financial and technical assistance, could emulate Norway's successes in CCS. The specific CCS technology used in Norway can be adapted by conducting geological surveys to identify suitable storage sites and establishing the necessary infrastructure for CO2 transport and injection. Furthermore, the Northern Lights project showcases the potential of using geological formations beneath the seabed for CO2 storage, which is particularly relevant for countries with extensive coastlines and dependence on fossil fuel or heavy industries

United States' CCS Deployment

The U.S. government's backing and significant investments from private companies have created many effective CCS initiatives, making it a front-runner in deploying CCS technologies. One of the most remarkable projects is the Petra Nova project in Texas, where CO2 is captured from a coal-fired power plant and utilized for enhanced oil recovery. During its active time before shutting down, Petra Nova trapped about 1.6 million tons of CO2 annually (NRG Energy, 2020) through post-combustion CO2 capture, extracting CO2 from the smokestacks of the power plant, compressing it, and sending it through pipelines to oil fields for injection. The Global CCS Institute (2023) states that this process has a dual benefit: decreasing CO2 emissions and increasing oil production, which are wins on both sides. The U.S. government has backed CCS with different policies and incentives, like the 45Q tax credit, which offers financial incentives for captured and stored CO2. Notably, the Carbon Capture Program of the U.S. Department of Energy funds research and development to advance CCS technologies, while, the Infrastructure Investment and Jobs Act of 2021 allocated significant funding for CCS infrastructure, highlighting the U.S.'s commitment to expanding CCS capabilities (U.S. Department of Energy, 2023).

Likewise, countries like Nigeria, which have high industrial CO2 emissions and oil fields, could see advantages in implementing this model to decrease their carbon footprint and enhance their oil production. Nigeria has a large deposit of coal, which is used for energy generation, and CCS could be utilized to mitigate emissions. Similar countries can also leverage international funding and technical assistance to establish CCS infrastructure, supported by policies similar to the U.S.'s 45Q tax credit and investment in R&D. Since integrating CCS with enhanced oil recovery is particularly applicable for countries with established oil industries, this approach will also be instrumental in the Middle East, it will not only decrease CO2 emissions there but also offer a financial benefit by boosting oil production.

South Korea's Industrial Growth and Carbon Capture

South Korea has made substantial investments in CCS technologies, playing a significant role in its endeavors to decrease carbon emissions. The government's strategies, such as offering financial rewards and strong backing for research and development (R&D), have created a favorable atmosphere for technological advancements and industrial expansion. In 2023, South Korea's leading steel manufacturer, POSCO, implemented advanced CCS methods to capture and store around 2 million tons of CO2 from its steel plant emissions yearly, critical in reducing its carbon footprint (POSCO, 2023). Similarly, the government unveiled a proposal in 2022 to raise its funding for research and development of green technology to $2.5 billion by 2030, with a notable amount dedicated to CCS advancement (Ministry of Trade, Industry and Energy, 2022). These actions aim to enhance the industrial incorporation of CCS and other technologies that reduce emissions, aligning with South Korea's ultimate goal of achieving carbon neutrality by 2050.

Developing countries with growing steel industries, like India and Brazil, can implement similar strategies to reduce their carbon footprints. By providing government incentives and fostering public-private partnerships, these countries can facilitate the adoption of CCS technologies in their industrial sectors. For instance, India's National Institute of Advanced Studies (NIAS) could partner with South Korea's Green Technology Center to exchange knowledge and technology in CCS implementation tailored to address specific regional challenges. Furthermore, South Korea's emphasis on R&D can be replicated by establishing dedicated research institutions focusing on CCS and other green technologies. Collaboration with international bodies can accelerate the development of region-specific solutions, enhancing the effectiveness of these technologies in reducing emissions. According to statistical trends, CCS technologies are expected to become more efficient and increase in capacity with ongoing investment and supportive policies. This trend is important because it shows the possibility of significant decreases in carbon emissions from industrial sources. With this, developing countries can make significant strides in balancing industrial growth with environmental sustainability by emulating South Korea's successful example.

China's CCS Deployment

China has shown notable advancements in CCS deployment among developing countries, as multiple pilot projects have highlighted the possibility of widespread implementation. The strong government support, international collaboration, and significant investment in research and development have been the main factors driving this advancement. The Yanchang CCS project, which receives backing from the Asian Development Bank, is a prime instance of trapping CO2 emissions from coal gasification and sequestering them in deep saline aquifers. By 2023, this initiative has effectively trapped over 410,000 tons of CO2 each year, demonstrating the effective incorporation of CCS in petrochemical operations (Asian Development Bank, 2023). Various important policies in China support CCS initiatives, such as the National Development and Reform Commission's (NDRC) 14th Five-Year Plan for Greenhouse Gas Control and the Ministry of Science and Technology's CCS Technology Development Plan. These guidelines outline the support for funding, research, and the application of CCS technologies to help decrease carbon emissions and achieve the nation's carbon neutrality target by 2060. As stated earlier, South Africa and Indonesia, which have significant coal and petrochemical sectors, may gain advantages by implementing comparable CCS technologies.

Furthermore, China's approach to integrating CCS with renewable energy sources offers a valuable model. For instance, Qinghai Province is currently investigating the integration of CCS with solar energy to achieve a consistent energy supply and decrease overall emissions. This combination of solar and CCS systems could be especially advantageous in areas with ample solar resources, like North Africa and the Middle East, where it could guarantee energy security and promote environmental sustainability.

Challenges and Opportunities

As mentioned earlier, developing countries face challenges in implementing CCS technologies, such as high upfront costs, lack of technical expertise, inadequate regulatory frameworks, lack of public support, and the extensive infrastructure needed for CO2 transport and storage. Despite these challenges, developing nations can gain advantages from CCS technologies. Introducing CCS can decrease carbon emissions, boost energy security, and generate economic opportunities by promoting job growth in the green technology industry. Developing nations can drive carbon capture alongside industrialization by adopting strategies and lessons from successful models, thus aiding global climate goals and promoting sustainable economic growth.

Industrialization Growth Trends vs. Carbon Emission Reduction Trends

Developed nations have made substantial advancements in decreasing carbon emissions while maintaining economic growth. Between 1990 and 2019, the European Union decreased its greenhouse gas emissions by 24%, despite a 60% increase in GDP (European Environment Agency, 2020), while the U.S. has experienced a disconnect between economic growth and carbon emissions, with emissions decreasing by 12% from 2005 to 2019 despite a 25% growth in the economy (U.S. Environmental Protection Agency, 2020). Contrarily, many developing nations see a rise in industrial activity and carbon output simultaneously. Between 2000 and 2020, China saw its GDP grow by almost 900%, while its carbon emissions increased by about 290% to reach around 11.2 gigatonnes (GT) of CO2 in 2022, accounting for roughly 31% of global emissions. Even with its large CO2 output, it has made substantial investments in clean energy and carbon capture technologies, such as the Qilu Petrochemical - Shengli Oilfield CCUS project, which sequesters 1 million tons of CO2 per year (International Energy Agency, 2023). Similarly, India has experienced significant economic growth as carbon emissions have increased, with 400% growth in its GDP, and a corresponding 250% rise in carbon emissions between 2000 to 2020, hitting 2.9 GT of CO2 in 2022. India is enhancing its CCS abilities by concentrating on incorporating these technologies into its heavy industries and power sectors with the help of various pilot projects and international partnerships (World Economic Forum, 2024). In view of these developments, governments in developing nations can use the carrot and stick (incentives and penalties) model to promote CCS while encouraging industrial growth. This two-pronged method guarantees that businesses are motivated and must incorporate CCS into their practices.

Key Strategies and Frameworks for Developing Countries

Policies and Frameworks

Creating comprehensive legal and regulatory frameworks is essential for effectively implementing CCS technologies, and these frameworks should address critical issues such as permitting, long-term liability, and safety standards for CO2 storage. For guidance, nations looking to build strong regulatory systems can look to countries such as Norway and the United States. The IEA's CCUS Legal and Regulatory Database is useful for policymakers, presenting top practices and legal strategies from various countries (IEA, 2022; OECD, 2022). For instance, Norway's regulations for CCS involve strict monitoring and verification demands to maintain the safety and integrity of CO2 storage (Global CCS Institute, 2023). Implementing comparable structures in emerging nations can aid in constructing a trustworthy and protected CCS system.

Incentives

Financial rewards are crucial in prompting the acceptance of CCS technologies. Governments of developing nations can implement tax credits, subsidies, and grants to lower the financial burden on industries investing in CCS just as seen in the U.S. 45Q tax credit, which provides significant financial support for CO2 capture and storage projects, offering up to $50 per tonne of CO2 captured and stored (IEA, 2024). This encouragement has sparked multiple CCS initiatives in the United States, including the Petra Nova project, which annually traps 1.6 million tons of CO2 in operation (Global CCS Institute, 2023). Developing nations can implement comparable incentive systems to promote investment in CCS. For instance, Indonesia might introduce tax benefits for firms that invest in CCS to reduce emissions from its coal-fired power stations which currently produce approximately 2.3 million tonnes of CO2 annually (International Energy Agency, 2023)

Public Awareness and Acceptance

Increasing public awareness and acceptance of CCS technologies is essential for their effective adoption. Educational campaigns and stakeholder engagement can increase public confidence and backing for CCS projects by openly sharing CCS's benefits and safety measures, thereby boosting public trust. In Canada, the Alberta Carbon Trunk Line project has successfully engaged local communities through transparent communication and public consultations, enhancing public support for the project (Pembina Institute, 2023). This would be highly helpful to developing countries due to the low social trust of most citizens in their government and blue-chip firms.

Technology Transfer

Technology transfer is vital for developing nations to acquire advanced CCS technologies and expertise through international collaboration. Collaborations with advanced nations and global organizations can help simplify knowledge and technology exchange. For instance, a partnership between China and Norway, where Norway's DNV GL provided technical expertise to enhance China's CCS capabilities, led to the Yanchang CCS project, which captures over 400,000 tonnes of CO2 annually (DNV GL, 2020). Similarly, South Korea has transferred its CCS technology to Indonesia, aiding in the reduction of 1 million tonnes of CO2 emissions annually from its coal-fired power plants (IEA, 2021). As developing nations follow suit, the transfer of technology could help to reduce the dangers of delayed progress, unsuccessful attempts, and the need for trial and error, which could be devasting and frustrating.

Financial Aid

Obtaining financial aid from international sources can support implementing CCS projects in developing countries. According to the Green Climate Fund (2023), as of 2023, it has committed over $12 billion to various climate-related projects, demonstrating the potential for substantial financial support. Likewise, the Climate Investment Funds from the World Bank have supported numerous initiatives to expand renewable energy and enhance energy availability in developing nations (World Bank, 2023). Nevertheless, despite these initiatives, there remains a significant financial shortfall for the global expansion of CCS technologies, requiring an estimated $655 billion in investments by 2050 to develop essential CCS infrastructure worldwide. This investment is essential for capturing and storing 7.6 gigatonnes of CO2 annually by 2050, a goal in line with the climate objectives of the Paris Agreement (IEA, 2021). Currently, the available funding falls short of the amount needed, underscoring the need for more financial assistance to bridge this gap and fully unleash the potential of CCS in reducing global carbon emissions. Likewise, given the financial need of developing countries for more pressing socioeconomic needs, there would be high dependency on the developed world to provide the resources for transition.

Infrastructure Development

Establishing the necessary infrastructure for capturing, transporting, and storing CO2 is essential. This includes building pipelines to transport CO2 to storage sites and establishing storage sites such as depleted oil and gas fields or deep saline aquifers. An example of this is the HyNet North West project in the UK, which establishes a CO2 transport and storage system that can be emulated by developing countries (HyNet North West, 2023). This is important because it touches on fundamental mistakes countries make when many start major infrastructural projects without planning and executing supporting infrastructure and systems to make them work. For instance, Cape Wind was planned to be the first offshore wind farm in the U.S.; however, the project faced numerous challenges, and one of the key issues was the lack of adequate transmission infrastructure to deliver the generated electricity to the mainland grid. Despite obtaining initial approvals and funding, the project failed to progress and was ultimately terminated in 2017 after facing years of challenges (Offshore Wind, 2017).

Implementation and Monitoring

Successful implementation of CCS technologies requires a structured and phased approach, as seen in Figure 6.1. The first stage involves assessment and planning, crucial for identifying suitable geological formations for CO2 storage and evaluating CCS projects' technical and economic feasibility. This first stage includes comprehensive geological surveys and feasibility studies to ensure the viability and safety of storage sites. Likewise, it entails assessments to help determine the best locations for CO2 storage, considering factors such as geological stability, capacity, and nearness to CO2 sources (Global CCS Institute, 2021). Following the assessment and planning phase, legal and regulatory frameworks must be developed, including permitting processes, liability rules, and safety standards, to ensure that CCS operations comply with international best practices. Policies should be designed to address long-term liability and environmental impacts to guarantee the integrity and safety of CO2 storage (International Energy Agency, 2022). Countries like Norway and the United States have set precedents with their robust regulatory systems, which can serve as models for developing nations (Global CCS Institute, 2023).

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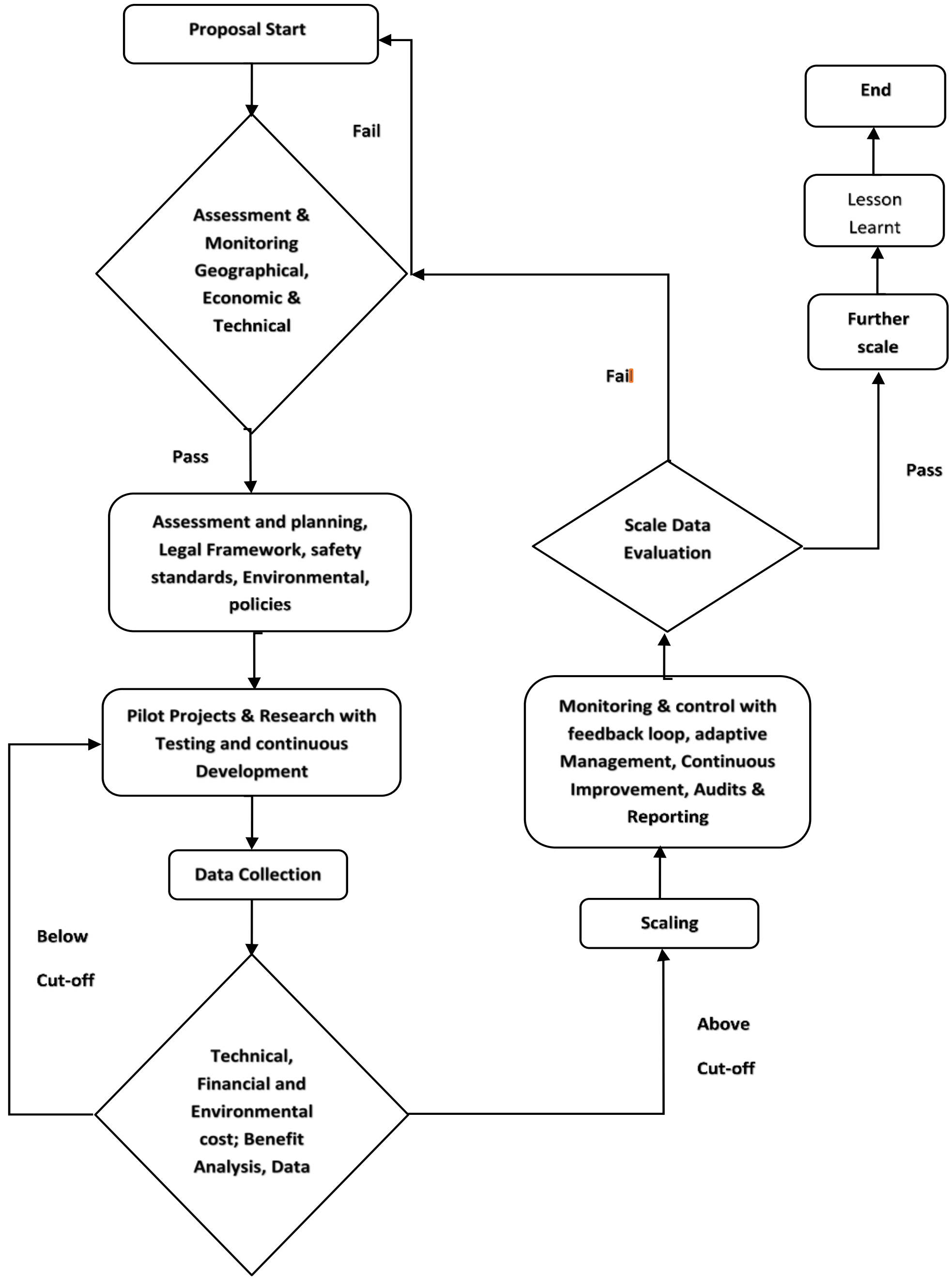

Figure 7: CCU Strategic Framework for Implementation

The next phase involves implementing pilot projects to demonstrate the effectiveness of CCS technologies and build local expertise. Pilot projects are critical for refining CCS technologies and operational procedures, allowing stakeholders to understand the practical challenges and benefits. These projects provide valuable data and insights, which can be used to optimize CCS operations and build confidence among investors and the public. Scaling up successful pilot projects into full-scale operations is the final stage. This expansion requires comprehensive monitoring and verification systems to ensure safety and integrity. Continuous monitoring systems for CO2 storage sites use advanced technologies such as seismic monitoring, satellite imaging, and ground-based sensors to detect potential leaks or anomalies, providing real-time data to manage risks effectively (Northern Lights, 2023). Regular audits and periodic reporting from CCS projects ensure compliance with regulatory standards and transparency in operations (IEA, 2022). Similarly, adaptive management strategies are essential to address issues that arise during the implementation and operation of CCS projects via ongoing evaluation and adjustment of practices to improve performance and mitigate risks. Lastly, it is critical to maintain the effectiveness and safety of CCS technologies over the long term by incorporating feedback and new information, adaptive management ensures continuous improvement and resilience in CCS operations (Global CCS Institute, 2023).

3.0 CONCLUSION AND RECOMMENDATIONS

This article highlights CCS's crucial importance in tackling economic growth and reducing carbon emissions, especially in developing nations. With the global effort to reach the ambitious goals of the Paris Agreement, CCS is identified as a vital tool in reducing the environmental consequences of industrialization. A thorough analysis of literature and real-world data shows that developed nations have successfully incorporated CCS technologies and lowered emissions. However, developing countries struggle with financial limitations, limited technical knowledge, and insufficient regulatory systems.

Lessons valuable for developing nations can be learned from the experiences of countries such as Norway, South Korea, and the United States. Efficient strategies for CCS deployment are showcased through Norway's robust policy framework and successful CCS projects, South Korea's significant investments in R&D and industrial applications, and the U.S.'s financial incentives and pilot projects. Developing nations can utilize these templates, with assistance from global collaboration, economic support, and technology sharing, to enhance their CCS capacities and realize sustainable industrial growth. Future research must prioritize conducting empirical studies to evaluate CCS projects' impacts and influence across different economic and geographic settings. By comparing various CCS technologies, their cost-effectiveness, and environmental impact, we can better understand the best options for different areas. Furthermore, investigating the combination of CCS with renewable energy sources, like hybrid systems merging solar power with CCS, may provide new solutions for consistent energy supply and lowering emissions. Research studies could also explore how CCS technologies are viewed and embraced by the public in developing nations, assessing the impact of educational initiatives and methods for involving key stakeholders. Recognizing the social interactions and possible opposition to CCS projects is essential to creating effective policies and communication approaches that enhance public backing and confidence.

In summary, despite the remaining significant challenges, the potential gains of CCS technologies for developing nations are considerable. Through international support, utilizing successful models from developed countries, and investing in technological innovation, developing nations can significantly reduce their carbon emissions and attain sustainable economic development. This in-depth research is designed to assist policymakers, researchers, and industry stakeholders in implementing CCS projects and supporting the global battle against climate change.

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