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International Collaborative Cluster-Based Carbon Sequestration Plan

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Abstract The status quo climate change forecast was analyzed using the ENROADS software and indicates that the net GHG emissions could reach about 90 gigatons of CO_2 equivalent by 2100, and global temperatures could rise by 3.6°C. This projection will likely be worse even with moderate estimates. The factors used in the reported status quo forecasts are optimistic. From energy mix to population growth and the assumption that gas use could increase while oil declines, this scenario is limited by available gas reservoirs. There needs to be a more aggressive application of CCS to reach Net-Zero by 2050. Carbon Capture and Storage (CCS) has been identified as the leading technology that could help reduce the amount of CO_2 emitted into the atmosphere. At the same time, the search for non-fossil fuel energy sources continues. The amount of CO_2 dilution in the air stream complicates the economics of direct air capture. This research proposes two international collaborative clusters for India. Due to India's growth and use of fossil energy sources, this is necessary to manage CO_2 emissions from coal-fired plants. The results show that cluster-based CCS facilities possess great potential for the world to develop faster carbon capture and sequestration technology and deploy it faster. These cluster CCS systems will create economies of scale and integration necessary to make the CCS technology succeed to help reduce India's and global CO_2 emissions from fossil-fuel-powered electricity generation. If CCS is deployed at the proposed scale, it will reduce atmospheric CO_2 significantly, which would capture more than 250 times more than today's effort.

Keywords: *carbon capture and storage, emission and temperature forecast, ENROAD model, India, cluster model, net zero, collaborative policy, afforestation, fossil power plant, storage in geologic formations*

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1. Introduction

Recent weather events have established the relationship between climate change and bad weather conditions. It has also raised greater public, private, and government concerns about climate change. Some recent severe weather conditions include [1] a record winter storm in Texas, where temperatures dropped to -13°C in February 2021, and disrupted power supply to about 3.5 million homes and businesses. In June of the same year, temperatures reached 34.8°C in Moscow, breaking that month's all-time heat record. Some other severe weather conditions include floods, droughts, and wildfires. In India in October 2021, monsoon floods in a single day killed about 150 people [2] and left thousands of families homeless.

The United Nations and other global climate initiative groups continue to design frameworks and guidelines for mitigating climate change issues. Most countries, including India, have integrated and implemented some of these frameworks into their regulatory instruments and energy policies. According to scientific research and IPCC reports [3], current levels of greenhouse gases (GHG) in the atmosphere are around 400 ppm, and safe levels should be established below 350 ppm. Maintaining GHG levels below 350 ppm is a challenge globally, and this is more so for countries like India, which need the energy to sustain their growing population and economy.

The World Energy Outlook [4] for 2021 presented the State Policies Scenario (STEPS) and temperature path, showing a probability of about 10% for temperature increases above 3.5°C in STEPS by the year 2100. Using ENROADS [5], historical temperatures and emissions were compared based on current progress in climate action. The results indicated a temperature increase of 3.6°C by the year 2100. The model data inputs contain energy supply and demand data specific to the ENROADS model. The Status Quo Forecast (SQF) reflects the current state of climate change policy, projected population, economic growth, and demand efficiency. The energy supply and demand data are similar to that found in the literature [6,7,8]. An analysis of the SQF forecast is presented in the next section.

2. Status Quo Emission and Temperature Forecast

The status quo forecast is a 3.6°C temperature increase by 2100. The various energy mix forecasts for the status quo are presented in Figure 1. In this figure, the global primary energy sources reflect a significant dependence on fossil fuels.

An average SQF forecast of about 0.7% for the consumption of coal energy sources is shown in Figure 2. This growth rate equates to a P15 increase in coal consumption over the past 22 years, from 2000 to 2022. As shown in Figure 3, the P50 growth rate for this period was 1.7%. Most projections use post-COVID-19 baseline figures. The 0.7% is bullish, given the projected population growth from developing countries that cannot afford and rely on natural gas or renewable energy sources.

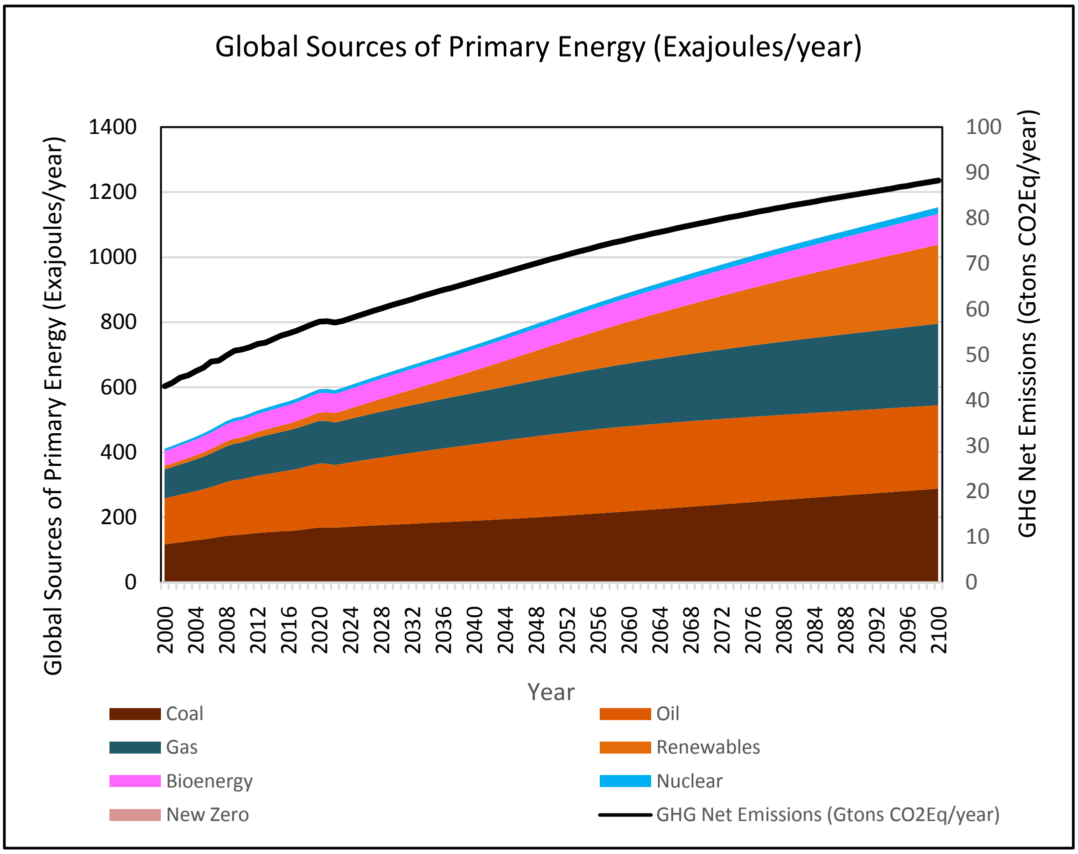

Figure 1. Global Sources of Primary Energy

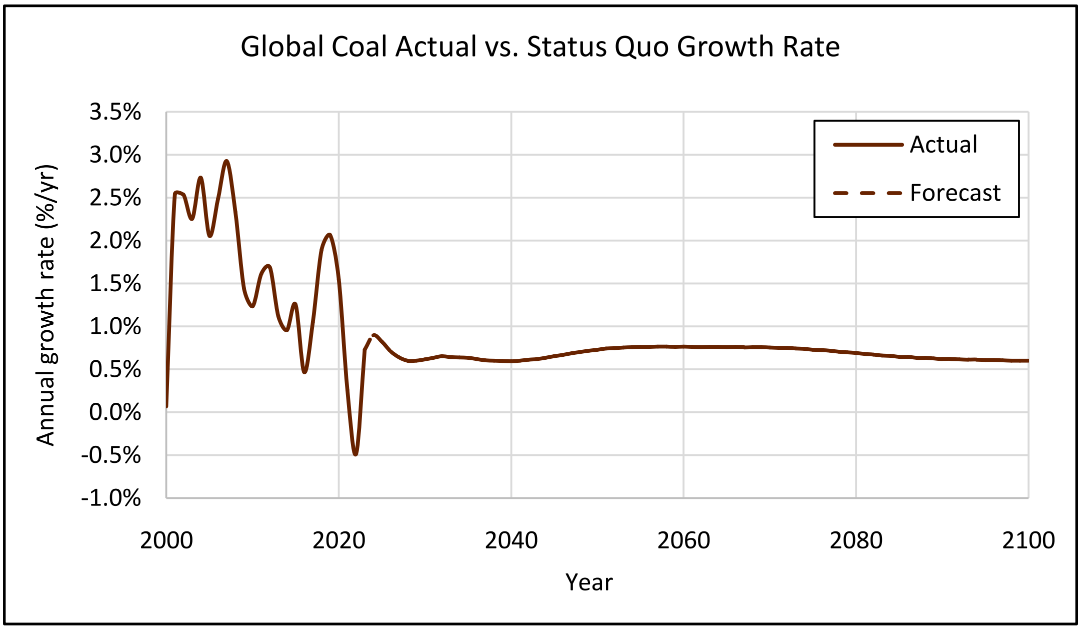

Figure 2. Global Coal Actual and Status Quo Growth Rate

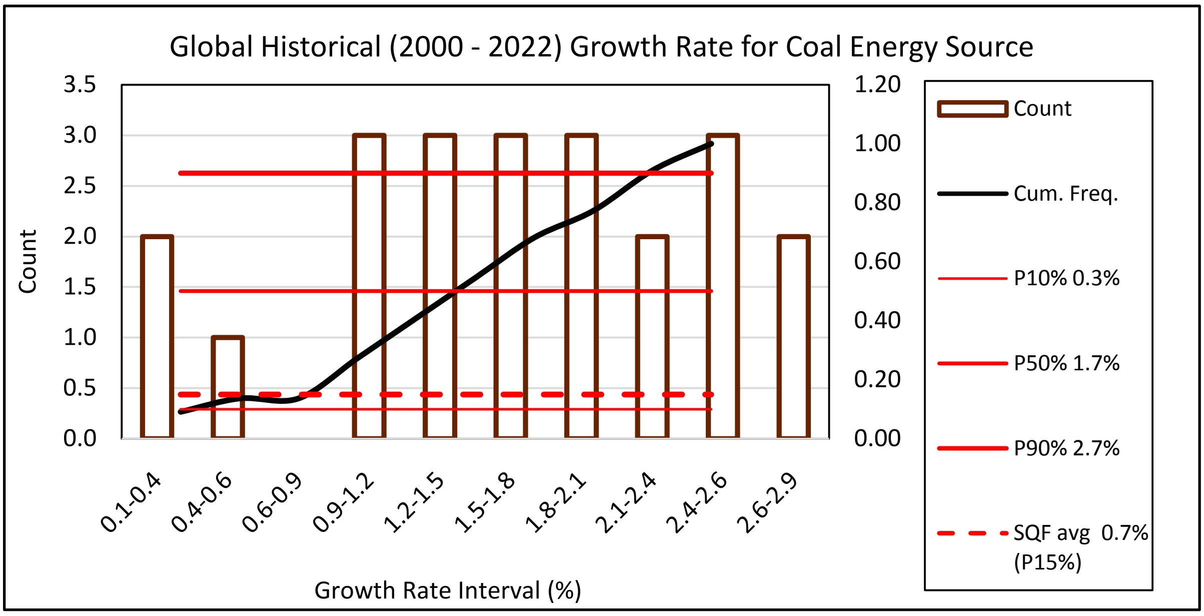

Figure 3. Global (2000 - 2022) Growth Rate for Coal Energy Source

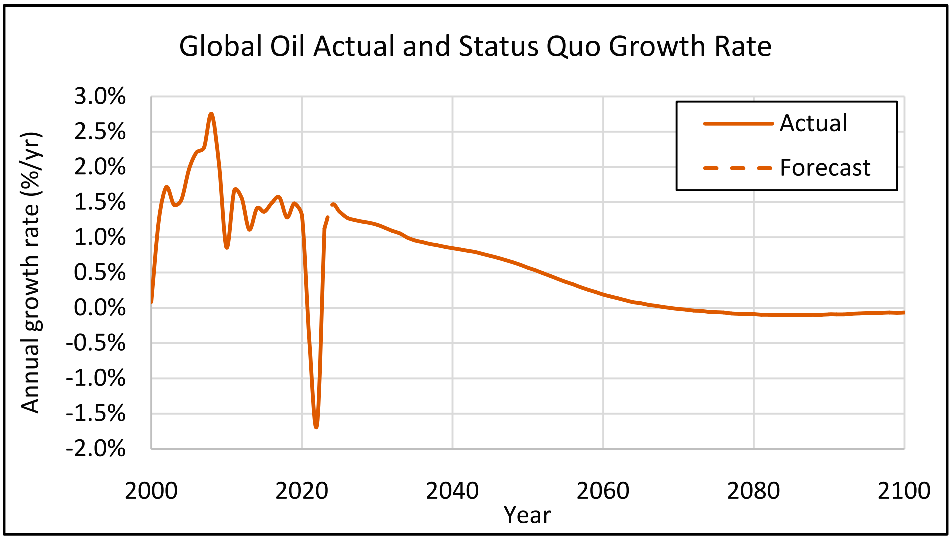

Figure 4. Global Oil Actual and Status Quo Growth Rate

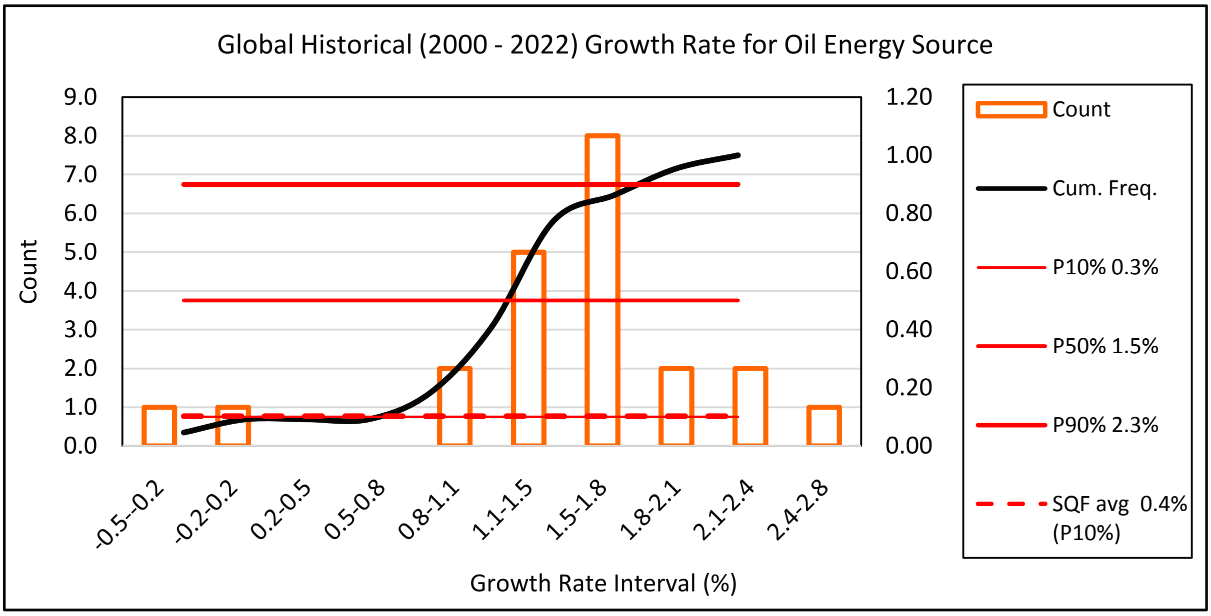

Figure 5. Global Historical (2000 - 2022) Growth Rate for Oil Energy Source

Oil consumption growth SQF started at a rate of 1.5% (see Figure 4), the P50 percentile of oil consumption increase recorded in the last 22 years (see Figure 5). The rate dropped to about 0.1% around 2065, averaging 0.4% over the forecast period. The average corresponds to the 10% percentile (see Figure 5) of oil consumption over the last 22 years. The forecasted SQF oil growth rate decline from 1.5% to 0.1% reflects the expected shift from oil to cleaner energy sources. An average growth rate of 0.4% from 2023 to 2100, compared to 1.5% for P50%, means that other energy sources will absorb 1.1% of oil energy sources' growth. Renewable energy sources have not demonstrated the capacity to meet this amount of energy at the current pace in the last 22 years. In 2022, the oil sources accounted for about 193 EJ of energy, with a 1% growth equivalent to an oil energy increase of about two exajoules shared by renewable energy sources. But in 2022, renewable energy contributed about 29 EJ. Transferring this expected growth from oil sources means that renewable energy needs to increase by 7%, but the highest renewable energy growth rate in the last 22 years is 5.7%.

Like oil, most current forecasts for gas are based on a declining trend in gas consumption growth forecasts. Overall, gas use is decreasing more moderately than oil. Oil consumption peaked at around 263 EJ in 2065, but as shown in Figure 6, as oil consumption declined, gas consumption continued to rise.

As shown in Figure 7, the SQF forecast for gas started at about 1.3% and gradually declined to about 0.5% in 2100. The SQF average growth for gas energy sources was 0.8%, equivalent to 18 percentiles of consumption in the last 22 years, as shown in Figure 8.

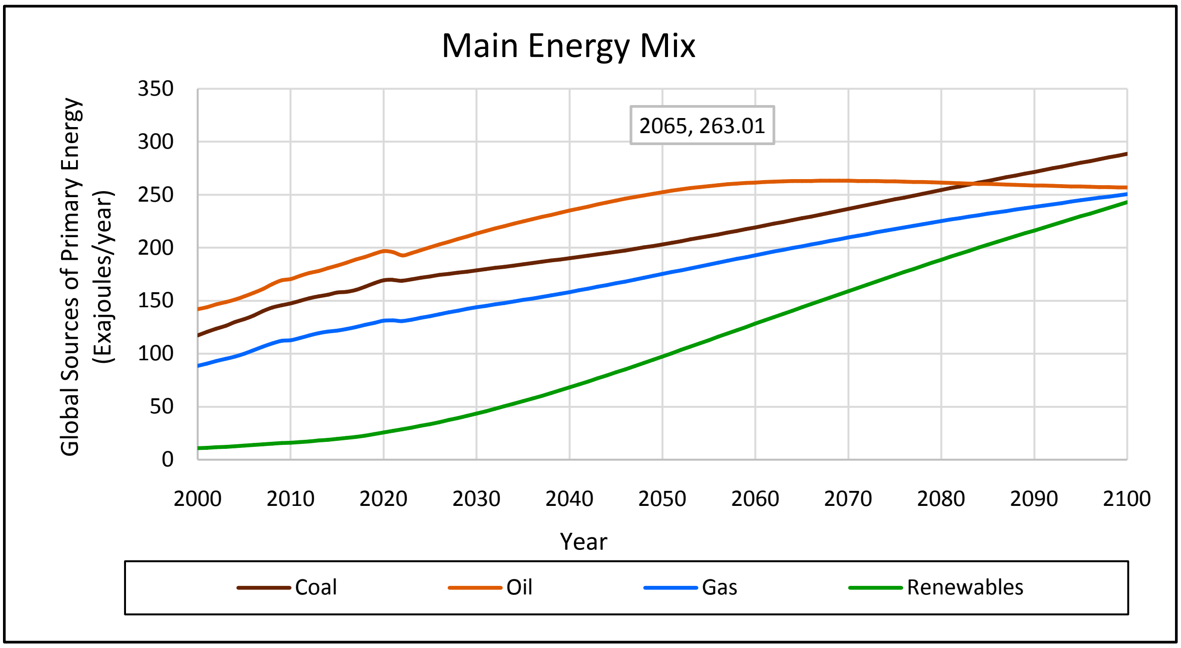

Figure 6. Main Energy Mix is showing declining oil after 2065

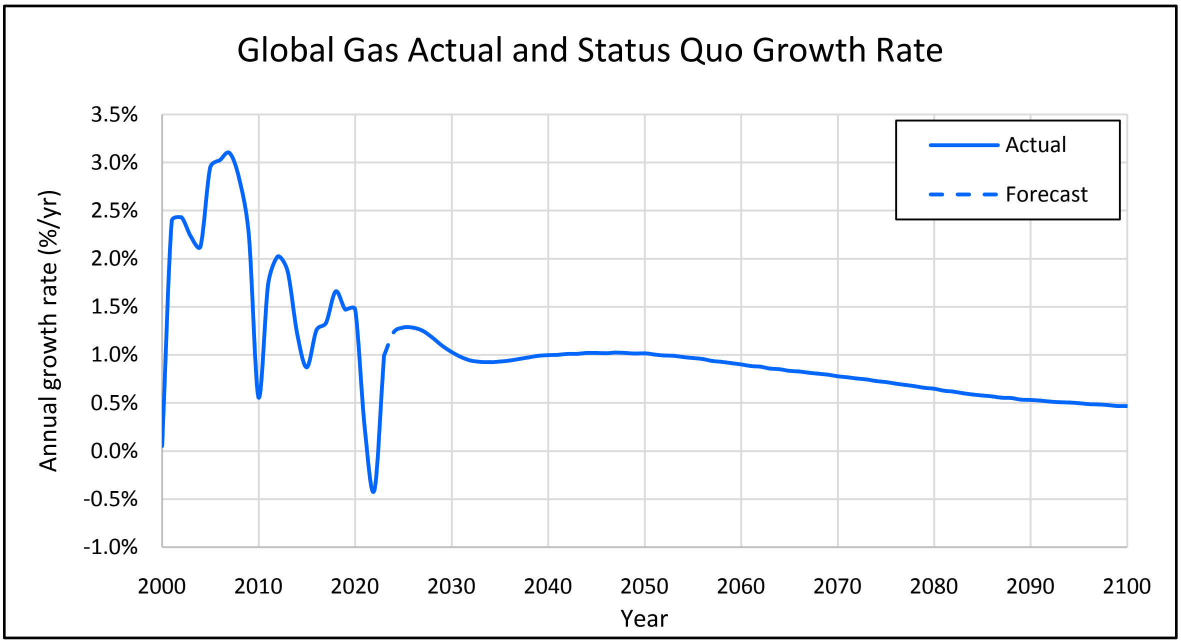

Figure 7. Global Gas Actual and Status Quo Growth Rate

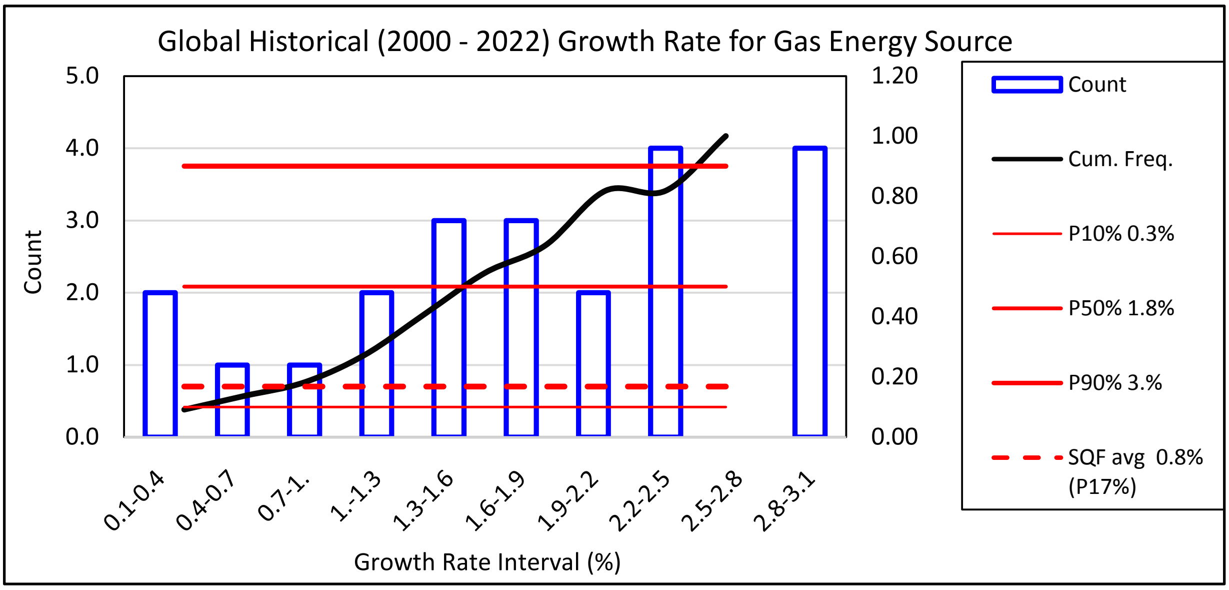

Figure 8. Global Historical (2000 - 2022) Growth Rate for Gas Energy Source

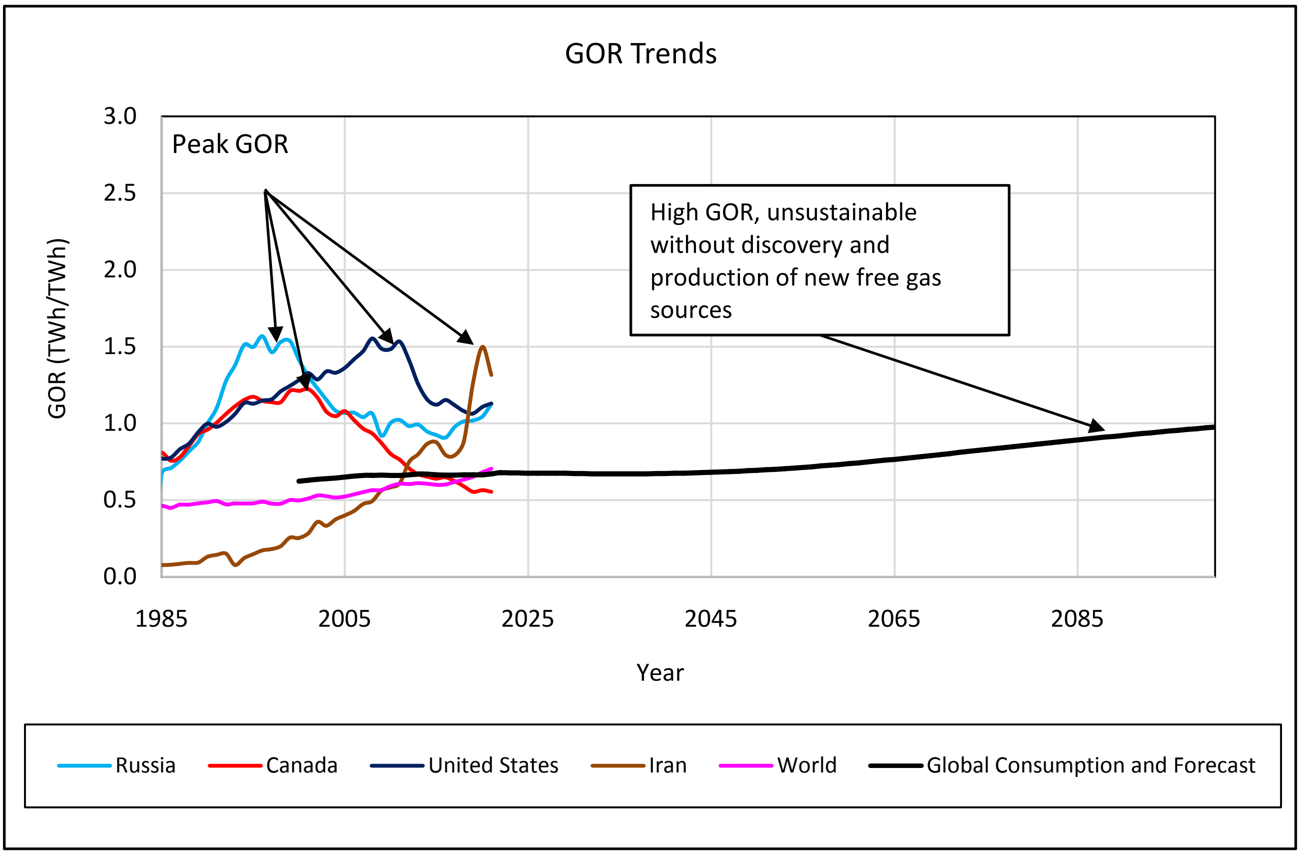

Figure 9. GOR trend for the world and significant gas producers

Since gas production is associated with oil production, it will be challenging to increase gas consumption if oil production declines. The gas-oil ratio (GOR), in the SQF forecast, starts at GOR 0.63 and gradually increases to around 1.0 in 2100. As shown in Figure 8, there are only a limited amount of gas reservoirs worldwide. Global interest in gas has led countries like Russia and the United States to focus on developing gas deposits and shale gas resources, with gas-to-oil production ratios historically peaking at 1.5. Another major gas producer, Iran, reached 1.5 in 2020 and started declining. Production records also show that Canadian GOR peaked at 1.2 around 2001, as shown in Figure 9. Gas-producing countries with LNG supply fleets, like Qatar and Australia, can achieve higher gas-oil ratios, but the market share of these countries in gas supplies is small. At the time of the Russian and American GOR peaks, the global GOR was around 0.6. Barring significant discoveries of gas deposits, the global GOR is expected to fall to about 0.5, the level supported by gas supplies associated with oil production. Therefore, a decline in oil production means a decrease in gas supply. Developing other potential gas sources like gas reservoirs in the Arctic and gas in hydrates could bridge the unassociated gas supply gap. These sources require advanced production techniques that are not yet mature.

The average status quo forecast for renewable energy growth is about 2.7% from 2023 to 2100, as shown in Figure 10. The growth rate is equivalent to the P8 percentile and is modest compared to the historical growth rate of the P50 percentile of 4.2% during the last 22 years. A closer investigation shows that most renewable growth forecasts have higher growth rates at the beginning and lower growth rates in later years, as shown in Figure 11 & Figure 12. A 4.2% - 5.0% forecast from 2023 to 2043 lies between the historical P50 and P90 values. With global inflation, recent increases in interest rates, and the impact of COVID-19 on the worldwide supply chain, it might not be easy to sustain these high growth rates for renewable energy sources in the future.

Bioenergy has an average forecast of 0.6%, equivalent to P16, an area where policymakers could do more to integrate feedstock diversity available in their economy to generate more bioenergy. The current status quo forecast is modest compared to a historical P50 of 1.2%.

Given the recent advances in nuclear technology, especially in modular reactors, it is necessary to introduce this technology into mainstream markets. Based on historical performance, the current projected average growth rate is 0.7% or P27. There is room to accelerate the adoption of this technology.

On the demand side, as shown in Figure 13, future world population growth will be driven by developing countries. Security concerns in these developing countries will favor using cheaper energy mixes instead of renewable energy resources to support growth. They are more likely to choose fossil fuel sources, which will increase CO$_2$ emissions in the atmosphere. It must also be acknowledged that population growth awaits renewable energy development. By 2040, the world's population is expected to reach around 9 billion, an increase of 20% from current levels. This new population cannot depend on renewable resources because renewable energy development needs to increase adoption and development. Thus, from a growth rate of 20%, people would likely use traditional power generation resources over the next 20 years.

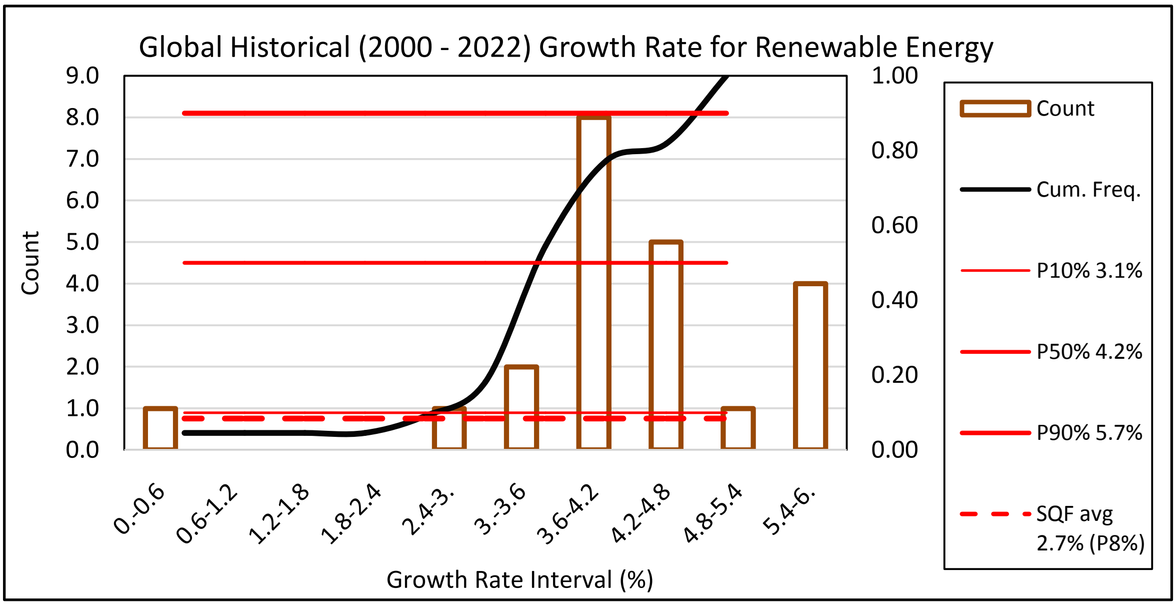

Figure 10. Historical (2000 - 2022) Growth Rate for Renewable Energy Sources

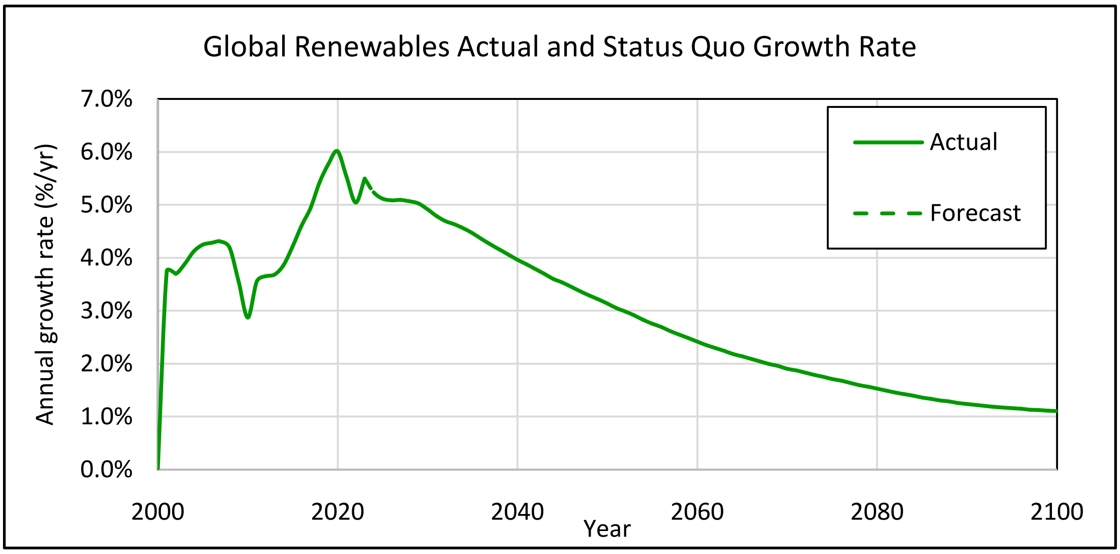

Figure 11. Renewables Actual and Status Quo Growth Rate

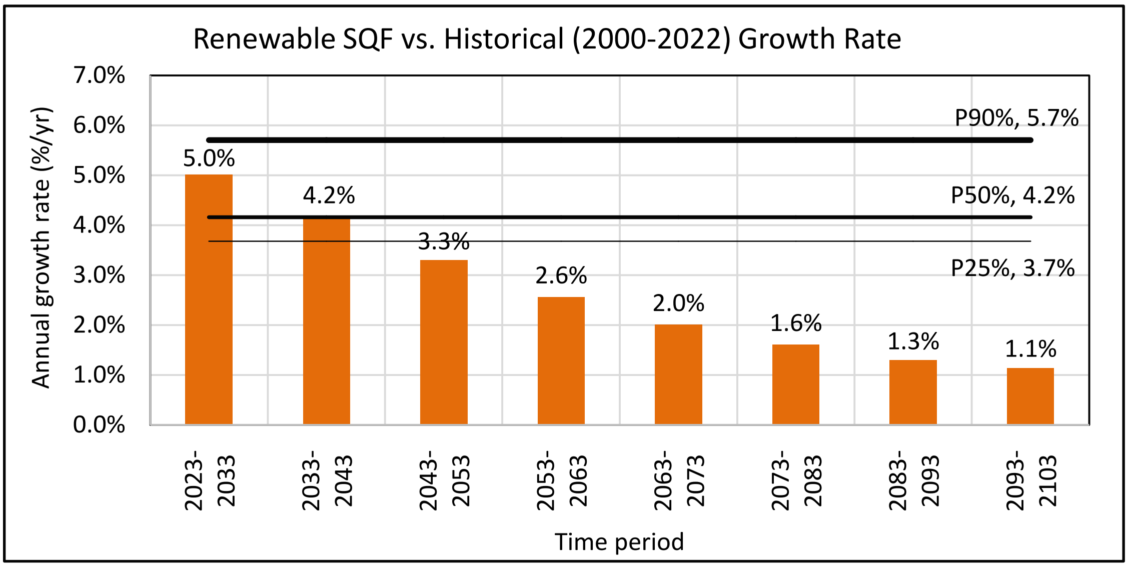

Figure 12. Renewable SQF Growth Rate and Historical (2000-2022) Growth Rate Lines

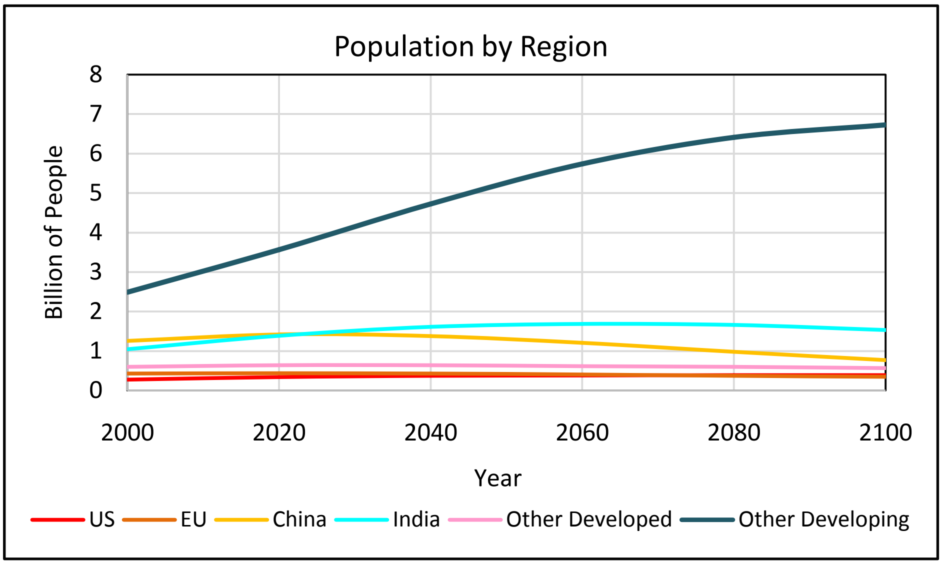

Figure 13. Population by Region

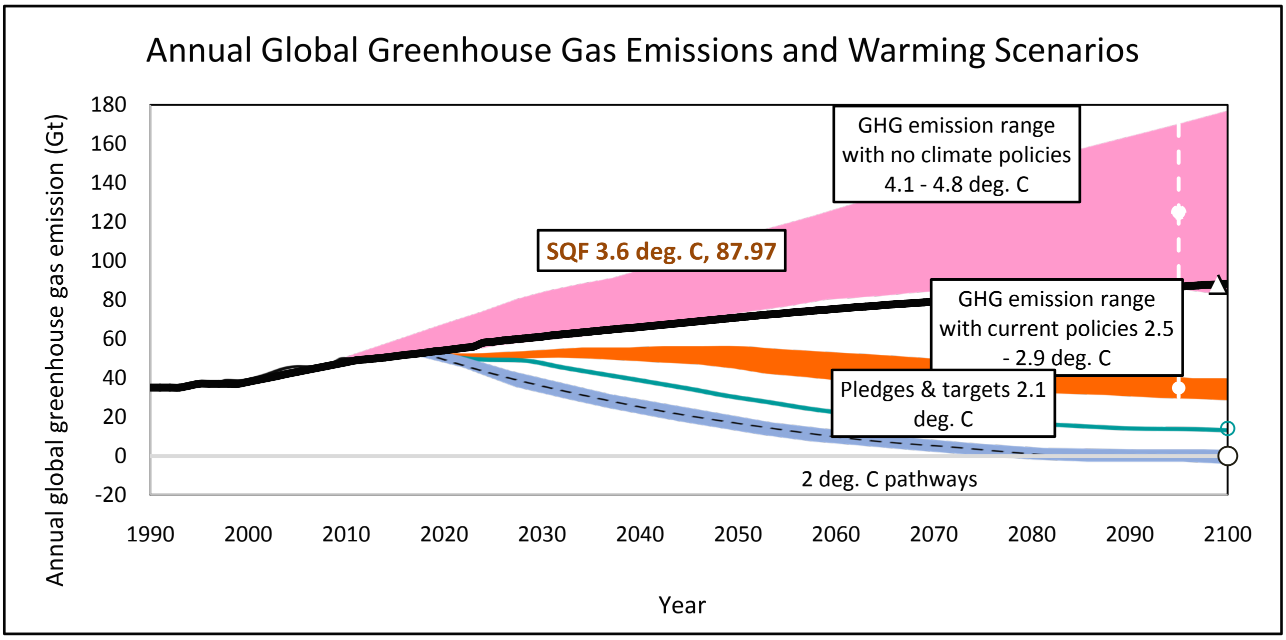

Figure 14. Annual global greenhouse gas emissions and warming scenarios

Business-as-usual projections suggest our net GHG emissions will reach about 90 gigatons of CO_2 equivalent by 2100, and global temperatures will rise by 3.6°C, as shown in Figure 14. Compared with previous projections, the status quo case lies at the border of predictions produced without climate policy. This forecast could mean that climate change policies that have not had a significant impact have been implemented or that climate actions over the past 22 years must be improved.

The data demonstrate that energy consumption for the population growth wave coming from developing countries cannot be managed with renewable sources because 1) growth is imminent, and renewable energy has room for improvement, and 2) developing countries will prioritize social welfare issues over the environment to achieve energy sustainability.

The optimistic assumptions generated a business-as-usual case, which indicated a temperature increase of 3.6°C; therefore, climate action to date is inadequate and calls for aggressive climate action. Another limitation of current projections is that they aim to delay future CO_2 emissions and do not address the removal of already emitted CO_2. Two centuries of industrialization have released CO_2 into the environment that needs to be removed, in addition to the expected emissions from new population growth. Therefore, it is necessary to consider net-negative carbon technologies such as carbon capture and storage.

3. Carbon Capture and Storage Solution

Carbon capture and storage (CCS) is not a new technology; it's extracting carbon dioxide (CO_2) from the air, compressing it, and storing it safely in a geological formation instead of releasing it into the atmosphere. The CCS technology can capture up to 90% of the CO_2 emitted from burning fossil fuels in industrial processes such as power generation and cement production [9]. A report on an overview of CO_2 reduction options [10] highlights various CO_2 reduction options from a technical perspective and divides the possibilities into three categories listed below:

1. Reduced energy intensity
2. Reduced carbon intensity
3. Carbon sequestration

Although sequestration options one and two are less cost-effective per CO_2 reduction unit than other options, they require an appreciable amount of time to be impactful.

This work focuses on direct carbon sequestration, where technical developments in sequestration options are needed, and the potential for carbon sequestration is enormous; thus, sequestering carbon allows time to transition the use of fossil fuels to cleaner forms of energy. As emphasized in the previous section, renewable energy is still under development and needs time before it can fully take advantage of the imminent growth expected of developing countries. It is also likely that developing countries will prioritize social security over environmental security and opt for fossil-based energy sources.

Each sequestration option has advantages and disadvantages in capacity, cost, sequestration time, captured CO_2 stability, and additional environmental impact depending on location, time, and sequestration mechanism. Carbon dioxide can be extracted in various ways, which include post-combustion, pre-combustion, and oxy-fuel [9]. The post-combustion technology removes CO_2 from flue gases produced when fossil fuels are burned, and the concentration of CO_2 in the flue gas has a lot to do with the cost of the sequestration project. Recently, a new generation of CO_2 sequestration technology was introduced. This process, called direct air carbon capture and storage (DACS), is one of the few technologies that can remove carbon dioxide from the atmosphere. Unlike other post-combustion CO_2 removal technologies that capture CO_2 emissions during power generation or heat generation, DACS extracts CO_2 directly from the atmosphere and can be mainly deployed anywhere in the world where electricity is available, subject to the conditions of the location. The Earth's atmosphere comprises 78% nitrogen, 21% oxygen, 0.03% to 0.04% carbon dioxide, about 1% argon, small amounts of other noble gases, and varying amounts of water vapor [11].

The amount of CO_2 dilution in the airstream complicates the economics of DACS. This technology uses a series of fans to force air through contactors that collect CO_2. Because CO_2 concentration in the air is minimal, the process requires many contactors and land resources. In addition to the land area needed to house the contactors, the process involves a lot of energy to extract CO_2 from the air due to its lean state. As CO_2 is absorbed or adsorbed, more energy demand is needed to release CO_2 for the next stage in the process.

For this reason, most carbon engineering companies add renewable energy to their projects to improve the net negative carbon produced. According to the literature [12], fossil fuel power plants with CO_2 capture and storage units consume approximately 25% of the energy produced by the power plant to operate its CCS system. In DACS, that number is well over 25%. Other factors, such as humidity and air flow speed, affect the system's design and performance. For these reasons, it isn't easy to scale the DACS projects. They are costly as they require additional resources and processes to capture and concentrate large amounts of CO_2 before disposal. However, various locations have special conditions that benefit the economy of a particular site. Ultimately, the profitability of a project is affected by its site conditions.

For example, in Iceland, the Orca DACS project was operational in 2021, extracting CO_2 directly from the air. The Orca facility can process 4,000 tons of CO_2 annually (equivalent to the CO_2 emissions from about 870 vehicles). The system uses a fan to draw air into a collector containing filter material to capture carbon dioxide. Once the filter media is filled with CO_2, the collector is closed, and the temperature is increased to release the CO_2 from the filter media. A high concentration of gas can then be collected [13]. All captured CO_2 is injected in special injection wells located in nearby basalt formations, where it is permanently converted to stone. The plant uses power generated from a nearby geothermal power station, which helped the overall economics of the plant since electricity is relatively cheap because of geothermal energy in Iceland. According to Bloomberg UK, the capital cost for the Orca facility was between US$10M-$15M to build [14].

It has long been known that reducing the cost of renewable energy requires scale and integration. Recent work [15] on the renewable energy source used a geographically explicit cost optimization model to determine the impacts of cost reduction strategies and interrelationships of economies of scale. The model showed that upscaling and integration showed the highest cost reductions. Other forms of renewable energy sources, such as wind, have also been identified to have benefited from economies of scale. The global growth of offshore wind technology should be accompanied by reducing the cost of building wind farms through economies of scale and learning [16]. When it comes to CO_2 capture and sequestration, size is also required. Assessing high CO_2 streams will significantly improve the economics of CCS. The cluster concept provides an environment to access high concentrations of CO_2 gas streams, enabling economies of scale and integration.

4. Collaborative Cluster-Base CCS for India

The concept of clusters is well known in economics; according to Michael Porter [17], clusters, or geographical concentrations of interconnected firms, are a prominent feature of virtually all national, regional, state, and even regional economies urban areas, especially in the most developed countries. The prevalence of clusters provides essential insights into the microeconomics of competition and the role of location in competitive advantage. Although the old incentives for clustering have become less critical with globalization, the new competitive effects of clustering are becoming increasingly important in an increasingly complex, knowledge-based, and dynamic economy. Clusters represent a new way of thinking about the national, state, and local economies as they demand new roles for businesses, government, and other organizations in improving competitiveness. Theoretically, the cluster concept, frameworks, recent empirical findings, and discussion of the main pillars of cluster-based economic policy can be found in the literature [18,19,20]. The following section shows how clusters can be leveraged for energy policy development, especially for CCS in countries like India.

India's GDP has multiplied recently and is expected to grow for decades [21]. It is necessary to account for the corresponding growth in primary energy demand with GDP growth and to assess the impact of CO_2 emissions, considering all issues related to sustainability, particularly climate change. The energy supply types and technologies, supply security, and self-sufficiency. Recent data shows that coal-fired power plants meet most new energy needs [22]. The choice of coal as the default energy source is expected, as many coal mines exist in India.

In India, the investments in renewable energy, such as wind, solar and geothermal sources, have yet to grow to the level of replacing conventional energy sources; therefore, the energy demand forecast for India has shown that the combustion of fossil fuels will continue to increase shortly. As shown in Table 1 and Figure 15, India projected coal consumption for power generation would increase by 67% from 1,029 million tons (mt) in 2022 to about 1515 mt in 2030. Accordingly, CO_2 emissions have also increased at an average rate of 5% per year, as shown in Table 2 and Figure 16; therefore, there is a need to look for alternative ways of reducing CO_2 emissions.

As part of its CO_2 sequestration efforts, India enacted the Forest Conservation Act of 1980 [23]. Natural CO_2 removal methods such as planting trees are indirect, require a lot of planning, and take a long time to become effective. The indirect component of a CO_2 sequestration plan involves a program to increase tree planting and revitalize depleted forests with additional trees. India ranks 10th in the world regarding deforestation [24]. According to Global Forest Watch, in 2010, India had seventy-seven million hectares of natural forest covering 24% of its land area. By 2021, 127 thousand hectares of natural forest have been lost. This equates to 64.4 million tons of CO_2 emissions. In 2022, tree coverage was estimated to be about 81 million ha (see Table 3). Forests play an essential role in removing and storing carbon from the atmosphere; through photosynthesis, in this process, CO_2 is taken from the air, converted into organic compounds, and stored as wood. In India, more than 70% of people living in rural areas rely primarily on forests for their basic biomass needs, such as firewood, food, and shelter [25]; this need has become India's primary source of deforestation.

Despite the deforestation challenge, India has grown its forest area by about 0.34% per year for 42 years since it passed the Forest Conservation Act of 1980 [23]. The forest growth rate has stabilized at around 0.4% per year in the last ten years. Nevertheless, there is more room for growth in forestation since the current forest area is only about 24% of the total land mass of India as compared to 35% of the land mass in 1880 (see Figure 16).

The CO_2 emission level has grown exponentially because of the economic growth in the country. It will be challenging for India to restore its forest area to 1880 levels in terms of the land mass because such land is needed for development and urbanization. Given the limitations to carbon sequestration by reforestation, it is essential to take CCS seriously. Carbon Capture and Storage (CCS) has been identified as the leading technology that could help reduce the amount of CO_2 emitted into the atmosphere as the search for non-fossil energy sources continues. The technology is costly and subjected to economic viability challenges. According to the IEA *Net-Zero-by-2050* forecast [28], carbon capture, use, and storage (CCUS) contribute to the transition to net zero in many ways. These include addressing emissions from existing energy assets, providing solutions in some of the most challenging areas to reduce emissions, such as cement, helping to scale up hydrogen production with low emissions rapidly, and allowing partial removal of CO_2 from the atmosphere. The IEA forecast includes three main CCUS classifications: CCUS from fossil fuels and processes (power, industry, merchant hydrogen production, and non-biofuels), CCUS from bioenergy (power, industry, biofuels production), and CCUS from direct air capture. By 2050 it was forecasted that 7,600 mt CO_2 would be captured, and 5,245 mt CO_2 (70%) would be due to CO_2 from fossil fuels and processes.

Table 1. India Demand and Projection for Coal in Power (mt)a Government of India, Ministry of Coal [35]

Year	2022	2023	2024	2025	2026	2027	2028	2029	2030
Coal Amount (MTs)	1029	1081.5	1134	1186.5	1249.75	1313	1380.5	1448	1515.5
% Of 2020 Coal	14%	19%	25%	31%	38%	45%	52%	60%	67%

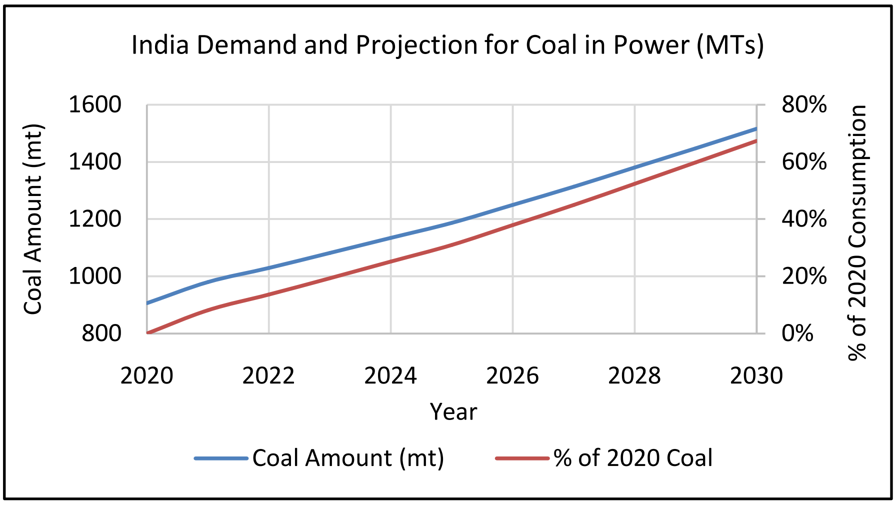

Figure 15. India's demand and projection for coal in power [35]

Table 2. India's Annual CO_2 Emissions (million tons) from Coal Plants [36]

Year	2010	2012	2014	2016	2018	2020	2021
CO_2 emissions	1,016	1,245	1,447	1,530	1,678	1,588	1,802
Growth (per year)	0%	14%	10%	3%	7%	-5%	13%
Change (%)	0%	23%	42%	51%	65%	56%	77%

Table 3. Tree Sequestration Analysis

Tree coverage in the year 2022	81	Million hectare
Target sequestration area	0.2%	Set target
Target sequestration area	162,457	hectare
Average tree density per hectare	2500	tree per hectare [37]
Number of trees	406,141,344	trees
Carbon absorption per tree	21	kg/year [38]
Total Carbon absorption per tree	8,528,968	million tons of CO_2
Cost of forestation	568,597,881	$

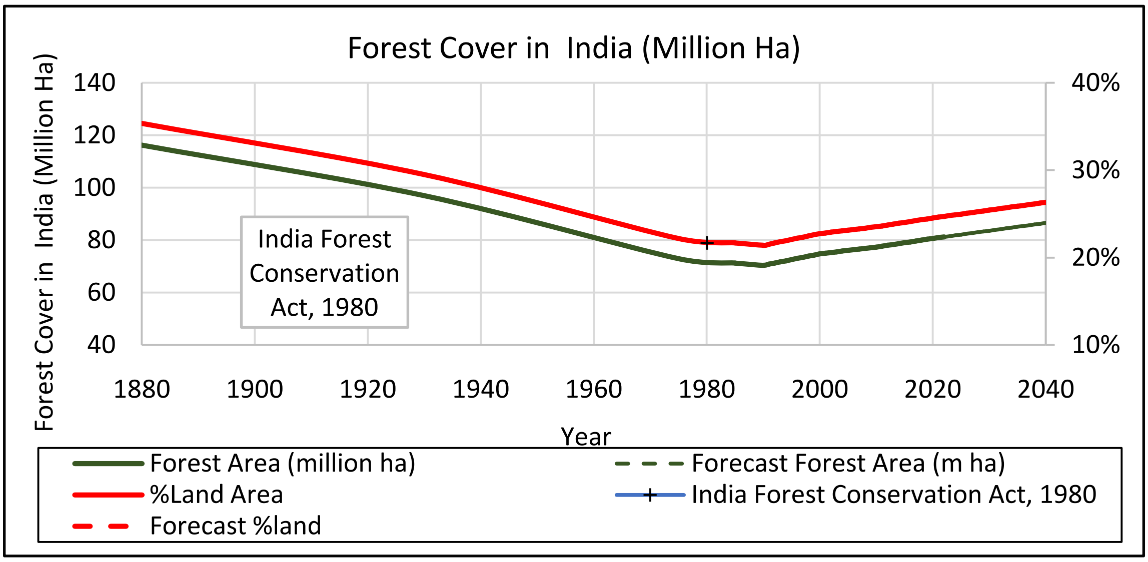

Figure 16. Forest Cover in India (Mha) [26,27]

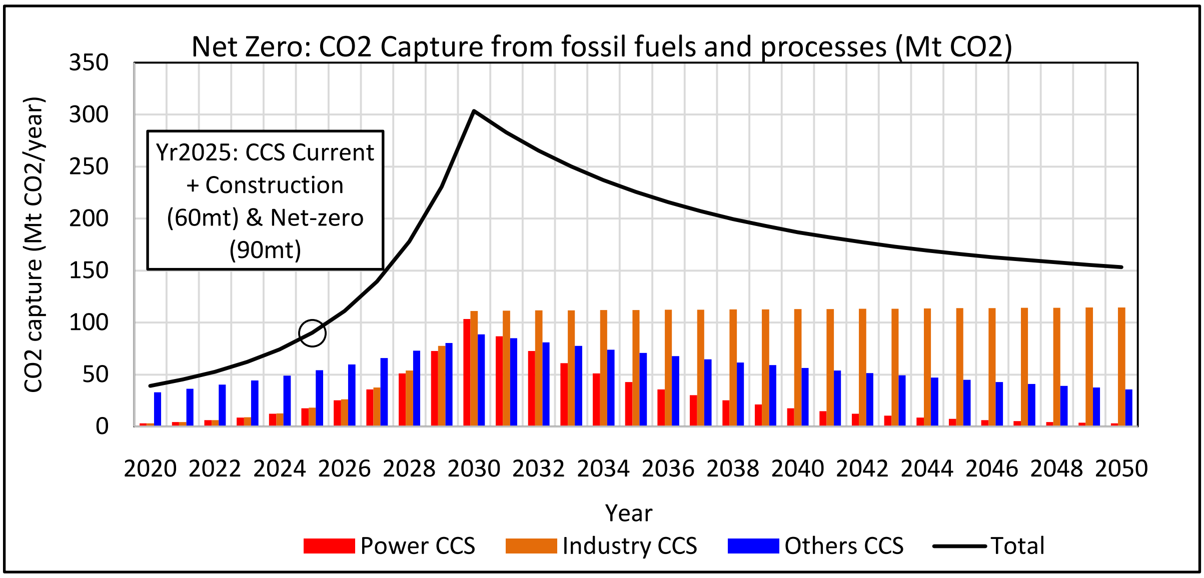

Figure 17. Net Zero: CO_2 capture from fossil fuels and processes (Mt CO2)

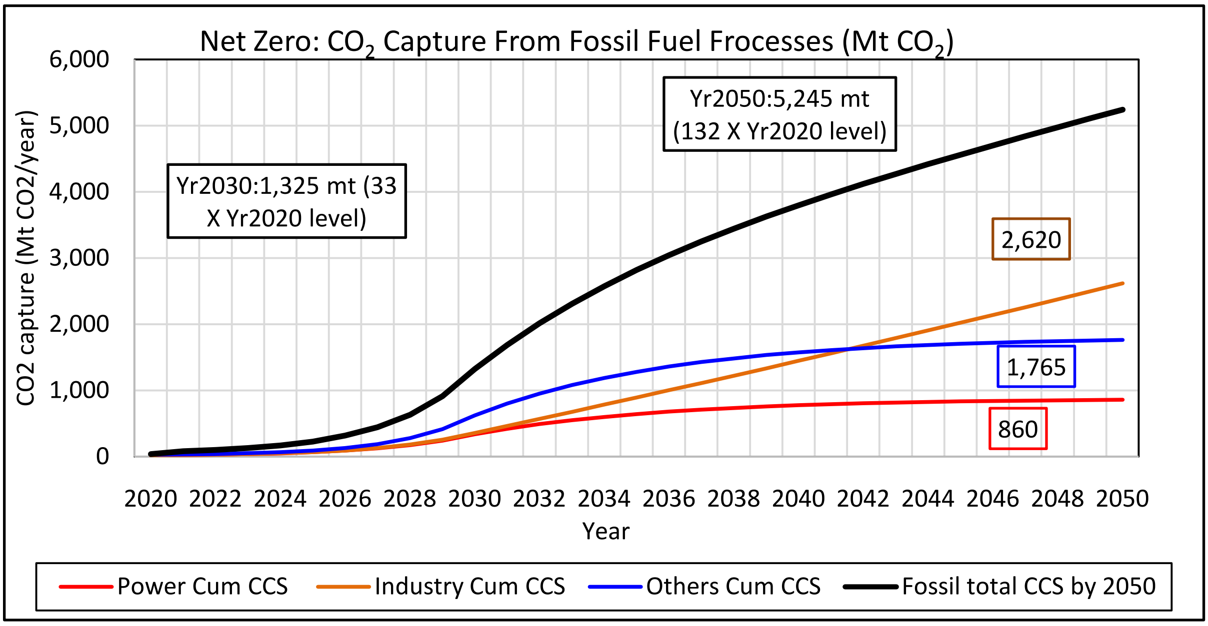

Figure 18. Net Zero: CO_2 capture from fossil fuels and processes (Mt CO2)

The IEA *Net-Zero-by-2050* forecast [28] also shows that much reliance is placed on CCS technology, but the status quo needs to reflect the dependency on carbon capture and sequestration. As shown in Figure 17, peak sequestration will happen in 2030, less than ten years from this SQF forecast year of 2023. The size of the amount of CO_2 that is required to be captured from the air to reach net zero is staggering. By 2030, the required volume will be about 33 times our current removal capacity, and by 2050 it will be about 132 times (see Figure 18).

The engineering design and planning timeline suggests that some CCS projects delivering 2030 CO_2 capture and sequestration should be at the permit stage. According to the Global CCS Institute CCS facility database [29], we have about 16 CCS projects under construction, most of which will be ready by 2025. These projects will capture about 19.1 million tons per year of CO_2. The largest CCS project is a low-carbon hydrogen and low-carbon ammonia production facility in Ascension County, Louisiana, USA, expected to capture about 5 million tons of CO2 annually.

Total CCS capacity will grow to about 60 million tons per year, including existing CCS projects and 16 identified projects under construction scheduled for completion by 2025. Figure 17 shows a gap of about 30 million tons per year compared with 2025 net zero forecasts of 90 million tons of CO_2 per year. The world anticipates there are other CCS projects worldwide that are in the planning stage that will bridge the gap that has been identified.

India was chosen for cluster-based CCS facilities because of the great potential it offers the world to develop faster carbon capture and sequestration technology and deploy it faster. It will become a global laboratory for learning more about CCS if successful. We propose creating two clusters: one in the Western part of India and the other in the East-central region. Starting with the first cluster (see Figure 19 and Figure 20), in the Western part of the country, some of the giant coal-fired power plants in the Gujarat state produce 3,000 – 4,000 MW of electricity in this area. A plant-by-plant assessment of CO_2 emissions in the area surrounding the site of the first cluster identified 86 power and industrial plants [30]. These include coal and gas-fired power plants, oil refineries, cement plants, and steel mills. The study estimates around 335 million tons of CO_2 based on the plants' production. It was also found that the states of Gujarat and Maharashtra emit 334 million tons per year of anthropogenic CO_2 emissions [31], and CO_2 emissions from power generation were 221 mt per year in 2020, of which coal-fired power plants account for nearly 80 % of these emissions.

In addition to the existing coal-fired power plants, many industries in the cluster area will benefit from the project. India is fast developing; while the energy transition in India is yet to shake up the traditional coal-dependent industry [32], new power addition will likely come from coal-fired plants. This cluster will also act as a world laboratory site to explore ways to reduce CCS project costs. The idea of an international collaboration facility is not new; for example, the International Space Station (ISS) is a research laboratory located about 250 miles from the Earth that allows scientists worldwide to send experiments that give them unprecedented data. The ISS has many stakeholders, including researchers and program managers between agencies. Everyone has expectations about the program and plays a vital role in developing the technology [33]. CERN, the European Council for Nuclear Research, also demonstrates another example of multi-stakeholder scientific cooperation.

Previous research [34] on the success of CERN has described it as an effective mechanism for global cooperation in resolving deadlocks and cross-border political challenges; it solves both the bottlenecks of existing institutions and the difficulty for countries to enter into new agreements when problems arise. CERN has shown that global science megaprojects and their communities have successfully developed complex processes and mechanisms that enable collaboration. The success of CERN employs researchers to explore whether the applicability of the new way out of the financial burden of innovation applies to other fields of carbon capture and sequestration. CERN also uses equitable funding mechanisms carefully to calculate annual capital contributions from members and innovative in-kind donations from non-member countries to fill the funding gap. CERN leadership's day-to-day operations use a gentle approach to its international partners and employees. Multidisciplinary teams are managed by implementing inclusive and consensus-based decision-making. The funding and management of the proposed cluster will be like that of CERN.

These cluster CCS systems will create economies of scale and integration necessary to make the CCS technology succeed and help reduce India's and, thus, global CO_2 emissions from fossil-fuel-powered electricity generation. As shown in Figure 21, in 2012, CO_2 emission from coal-fired power plants in India grew by 13% per annum. Without the CO_2 sequestration program, emissions will grow to about 3,000 million tons of CO_2 in the next ten years. This is twice the CO_2 emissions level that was recorded in the year 2020. The proposed plan is to arrest the growth of CO_2 emissions and sustain them at 2022 levels, which is 1,892 million tons per year. As shown in Figure 22, in the next ten years, this proposed sequestration plan would have reduced emissions from 3,000 to 1,892 million per year, equivalent to a 60% reduction in emissions from fossil-fuel power plants.

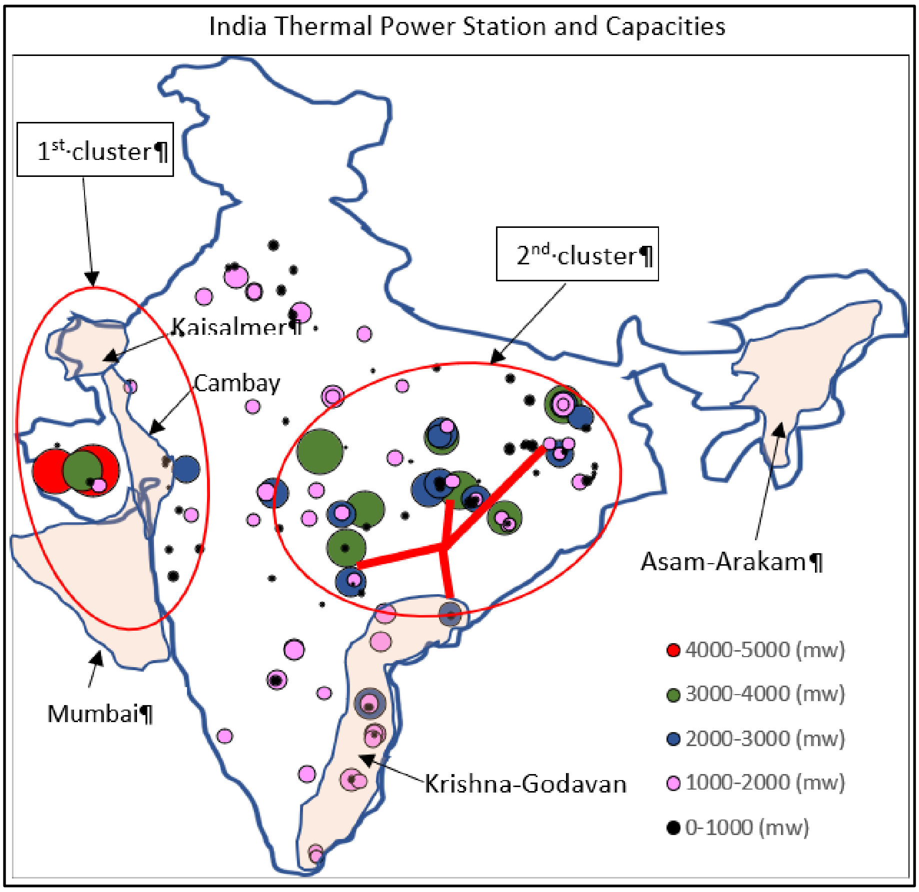

Figure 19. India Thermal Power plants and capacities [44]

Figure 20. Crude Oil and LPG Pipelines of India [45]

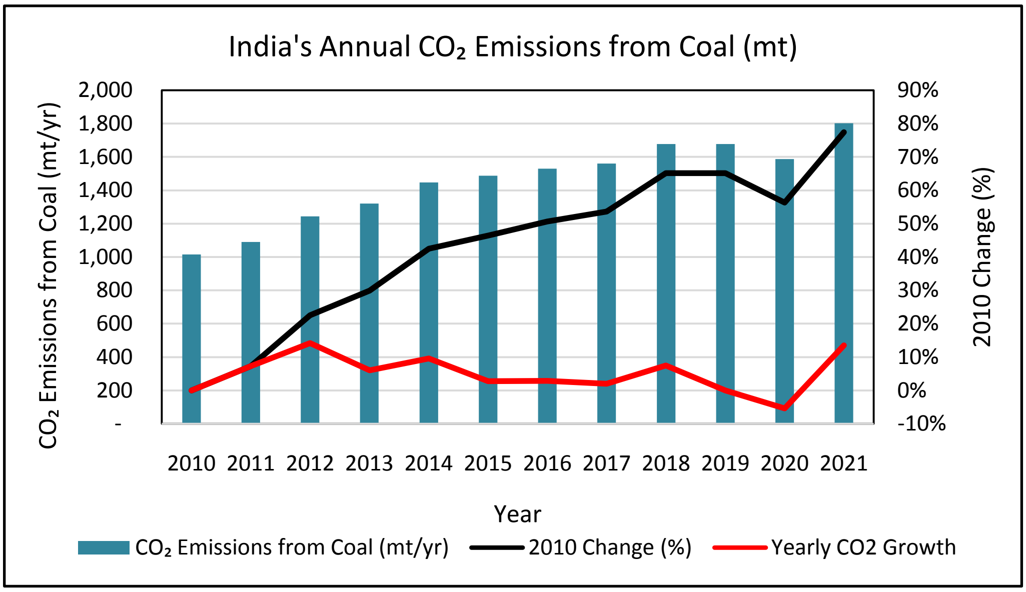

Figure 21. India's Annual CO_2 Emissions from Coal [36]

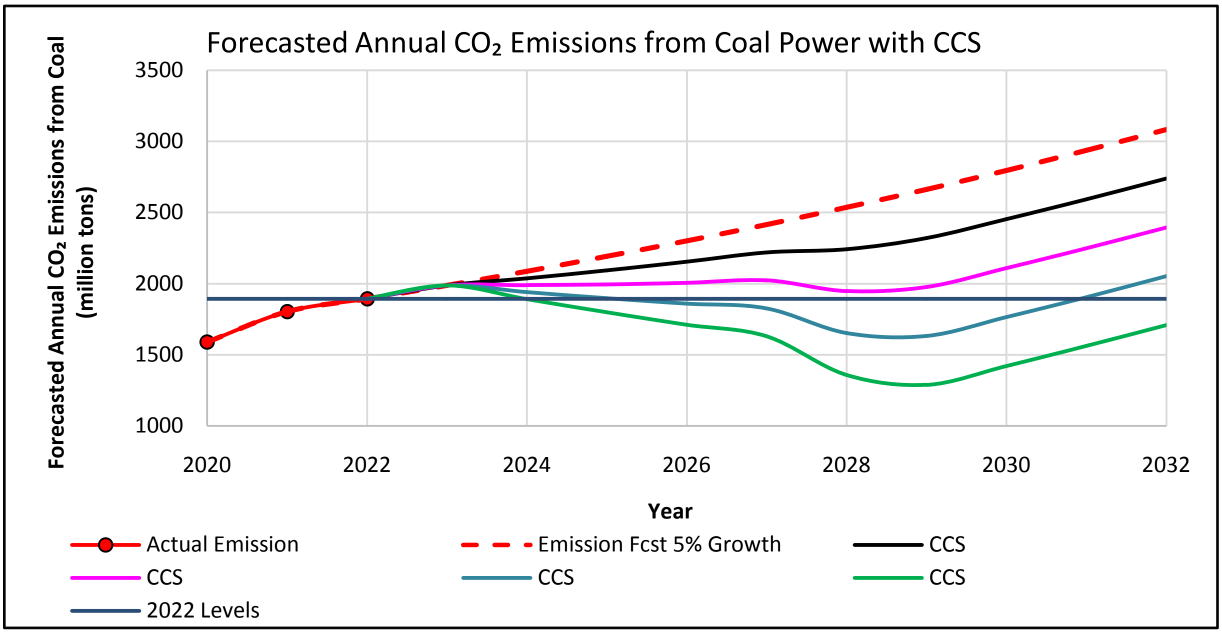

Figure 22. Indian Forecasted Annual CO_2 Emissions from Coal Power with CCS Capex as %GDP

The sequestration plan will entail directly capturing CO_2 from several power plants in India and storing the captured CO_2 in depleted oil and gas reservoirs and deep formations.

A simple analysis of existing CCS project costs and capacities shows that the average capital required to capture one million tons of CO_2 annually is about $300 million (see Table 4). This estimate is not rigorous because most reported costs did not specify whether expenses like pipelines are included in their calculations. To reduce CO_2 emissions to 2022 levels in the next ten years, India and its research partners would contribute and spend about $60 billion annually for ten years, as shown in Figure 23 and Figure 24. These costs are not trivial, but when shared among research countries, the cost becomes manageable. The projected cost ranges from 0.2% of India's 2023 GDP of USD 3.5 trillion [39] to 2% of India's 2026 GDP of USD 3.7 trillion, assuming a 2% GDP growth annually. CCS expenditure below this level will be inadequate and will not achieve the sequestration planned objectives of reducing future emissions to 2022 levels, as shown in Figure 23.

Table 4. Cost and capacity of CCS projects [40]

Project	Location	Cost Billion $	Capacity (mt)
Century Plant	West Texas, US	1.1	8.4
Great Plains Synfuels Plant	Beulah, North Dakota	2.1	3
Petra Nova Carbon Capture	Houston, Texas	1	1.6
Average		1.4	4
CCS costs one million tons of CO_2		0.3	1.0

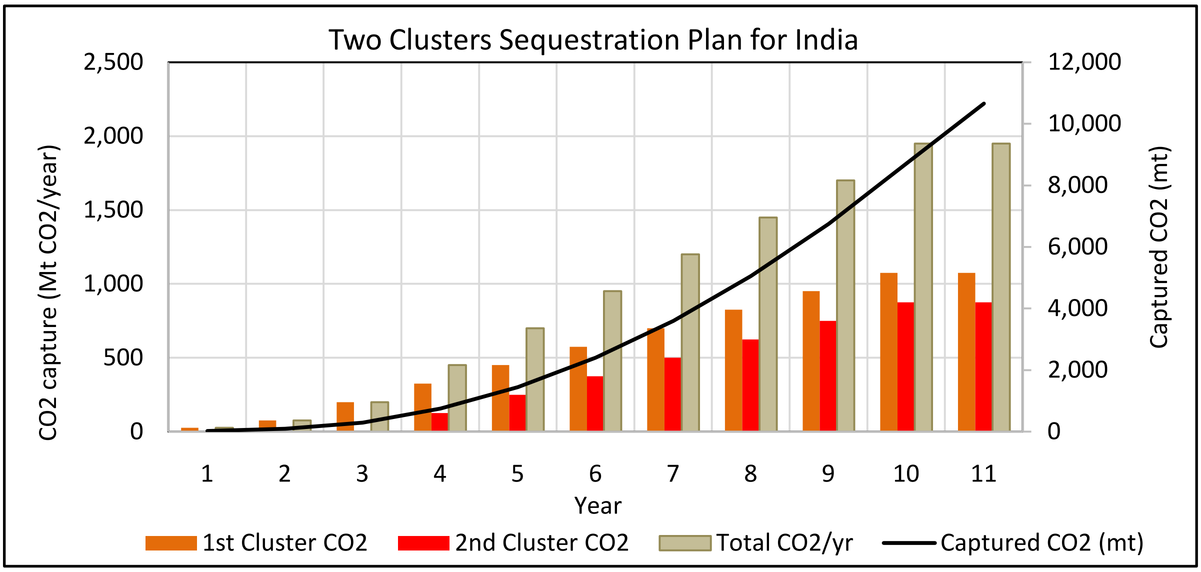

Figure 23. CO_2 Volumes for a Two Clusters Sequestration Plan for India

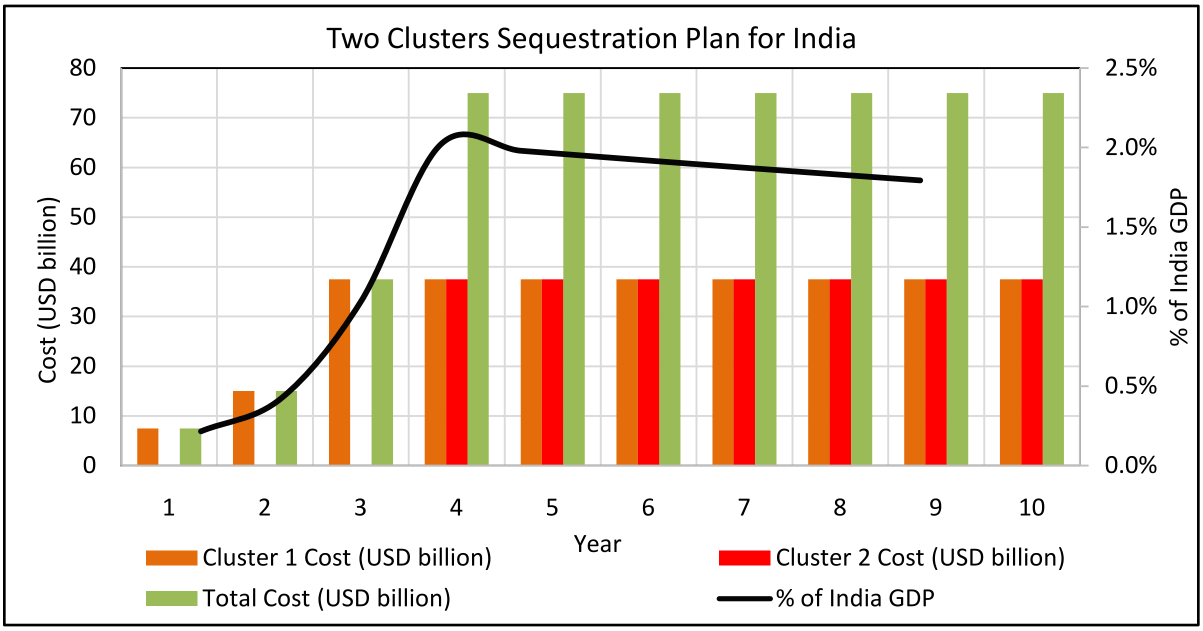

Figure 24. Cost Estimates for a Two Clusters Sequestration Plan for India

Various geologic structures in the sedimentary basin could store the sequestered CO_2. The research has identified some potential storage sites; these areas have existing oil and gas operations and have several depleted oil and gas reservoirs, which include the Mumbai and Cambay sedimentary basins in the Western part of the country. Other sedimentary basins include the Kaisalmer basin in Rajasthan, the Krishna-Godavan basin in the West, and the Asam-Arakam sedimentary basin in the Northeast part of the country, as indicated in Figure 19. A recent CCS study for India identified these areas as potential storage sites and other structures in saline aquifers, coal seams, and basalt formations [42].

The priority sought for India in the next few years is to develop CCS infrastructure in the 1st cluster (see Figure 19). This area also has a promising pipeline network (see Figure 20) that could be upgraded to gather and transport CO_2 from various coal power plants in the area for sequestration and injection in single or multiple locations. The sedimentary formation in the Cambay and Mumbai basins have deep sandstones and basalt reservoirs (see Figure 25 & Figure 26) that could hold CO_2 with minimal risk of atmospheric leakage. The average geophysical properties of these sandstones indicate porosity of about 18% and permeability of 10 to 50 mD [43], which is adequate to inject the captured CO_2. The thick shale caprock overlying these sandstone and basalt formations will also help as a seal to secure the CO_2 in place.

The next phase in the proposed sequestration plan is to take the lessons learned from the development of the 1st cluster and apply them to the development of the 2nd cluster located in the Central/NE areas of the country in three years. This area has the country's highest amount of coal-fired power plants; as illustrated in Figure 19, most of the plants in this area generate about 2,000 – 3,000 MW of electricity, resulting in substantial CO_2 emissions. The plan is to develop these areas and connect some of these plants with a pipeline network that will eventually gather the CO_2 and deliver it to dedicated facilities in the Eastern part of the country, where it would be compressed and injected underground in the Krishna-Godavan and Cauvery formations. The Krishna-Godavari Basin's lithostratigraphy has thick sandstone of the Tirupati and Razole formations overlayed by the Palakollu shale, which could serve as a storage reservoir for the captured CO_2.

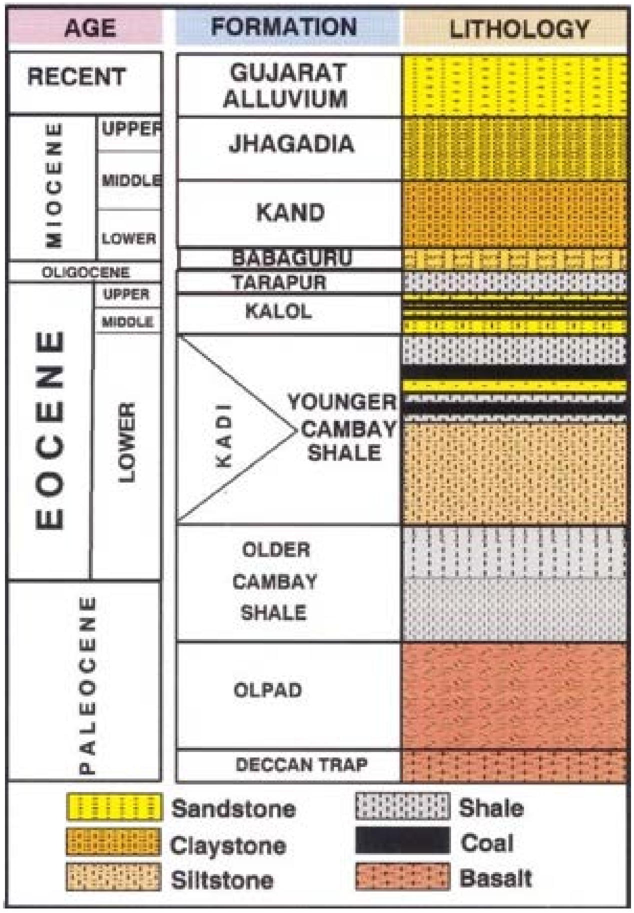

Figure 25. Generalized stratigraphy of study Cambay and Mumbai [43]

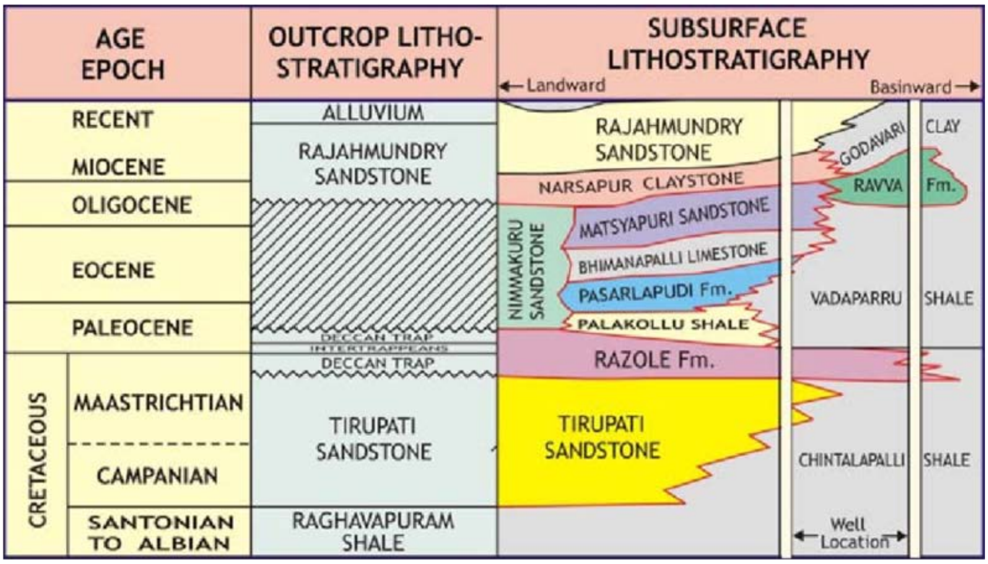

Figure 26. Generalized lithostratigraphy of the Krishna-Godavari Basin [47]

The Gollapalli sandstone formation, at a depth of about 6,450 ft, has 14 – 15% effective porosity. The geo-mechanical properties show an average bulk modulus of about 15Gpa; these properties support the potential suitability of this formation for CO_2 storage [46]. The plan for direct sequestration using CCS would remove nearly 150 million tons of CO_2 in the second year of the program; the sequestered volume of CO_2 will grow to one million tons of CO_2 per year when developments in the 1st and 2nd clusters are completed, and fully operational in the next ten years.

If CCS is deployed at the scale that has been proposed, it will reduce atmospheric CO_2 significantly, and it would also capture more than one billion tonnes each year, which is 250 times more than today's effort in 2023. Injecting such amounts of CO_2 requires a geological understanding of the formation and assessing the long-term conditions of subsurface CO_2 containers. Some of the skills needed to evaluate these storage units exist in the oil and gas industry. The CCS storage formation selection process is like the characterization process of an oil and gas reservoir. A consortium of stakeholders will find ways to optimize performance, reduce costs and ensure safe operations. Monitoring techniques and regulatory compliance would be required to be part of the project.

5. Conclusion

The World Energy Outlook for 2021 presented the State Policies Scenario (STEPS) and temperature path, which showed a probability of about 10% for temperature increases above 3.5°C in STEPS in 2100. Using the ENROADS status quo forecast, the research demonstrated that business-as-usual projections suggest that the net GHG emissions will reach about 90 gigatons of CO_2 equivalent by 2100, and global temperatures will rise by 3.6°C. Compared with previous predictions, the status quo case shows that we are not making much progress, and efforts of the last 22 years are similar to projections of implementation of no climate policies.

The results also indicated that energy consumption for the population growth wave coming from developing countries could not be managed with renewable sources alone, renewable energy also needs further development, and developing countries will prioritize social welfare issues over the environment to achieve energy sustainability. Various factors show that most status quo forecasts are optimistic for multiple reasons. For example, the 0.7% growth rate of the consumption of coal energy sources is bullish since the addition of the global population will be coming from developing countries where social security, as compared to environmental protection, is given more priority in selecting an energy mix. Most status quo forecasts assume peak oil and increasing gas consumption. This assumption is challenging given that gas production is mainly oil-related; it will be difficult to increase gas consumption if oil production declines. If we discover new sources of gas reservoirs, we can increase gas production with oil production. Whereas most renewable forecasts have higher growth rates at the beginning and lower growth rates in later years, with global inflation, recent increases in interest rates, and the impact of COVID-19 on the worldwide supply chain, it might not be easy to sustain these high growth rates for renewable energy sources in the near term.

The optimistic assumptions generated a business-as-usual case, which indicated a temperature increase of 3.6ºC, so climate action to date is expected to be inadequate and calls for aggressive climate action. Another limitation of current projections is that they aim to delay future CO_2 emissions and do not address the removal of already emitted CO_2. Two centuries of industrialization have released CO_2 into the environment that needs to be removed. In addition, we must remove the expected emissions from new population growth. Therefore, it is necessary to consider negative carbon technologies such as carbon capture and storage. Carbon Capture and Storage (CCS) has been identified as the leading technology that could help reduce the amount of CO_2 emitted into the atmosphere, but the technology is costly and subjected to economic viability challenges. The amount of CO_2 dilution in the airstream complicates the economics of DACS; the process requires many contactors, land resources, and a large amount of energy to extract CO_2 from the air due to its lean state, and net negative carbon production needs to be improved. Accessing high concentrations of CO_2 streams is necessary to improve the economics of CCS. We have proposed and analyzed the cluster concept providing an environment of high concentration of CO_2 gas streams, enabling economies of scale and integration.

The research proposes two clusters for India, with growth, which is necessary to manage CO_2 emissions from coal-fired power plants. The natural CO_2 sequestration efforts need to be improved in India. The IEA *Net-Zero-by-2050* forecast [28] for carbon capture, use, and storage (CCUS) contributes to the transition to net zero in many ways. The size of the amount of CO_2 that is required to be captured from the air to reach net zero is staggering. By 2030, the required volume will be about 33 times our current removal capacity, and by 2050 it will be about 132 times.

India was selected for cluster-based CCS facilities because of the great potential it offers the world to develop faster carbon capture and sequestration technology and deploy it faster. An international research collaboration model similar to CERN is proposed to manage the required financial commitment. These cluster CCS systems will create economies of scale and integration necessary to make the CCS technology succeed and help reduce India's and, thus, global CO_2 emissions from fossil-fuel-powered electricity generation. This could cost India and its research partners up to $60 billion annually for ten years, but it becomes manageable when shared among research countries. If a CCS were deployed at the scale that we have proposed, it would reduce atmospheric CO_2 significantly, capturing more than one billion tonnes each year, 250 times more than today's effort. The captured CO_2 will be stored in the sedimentary formation in the Cambay and Mumbai basins in the West and the Godavan and Cauvery formations in the East which are safe and in depths of 6,500 feet.

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