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Decarbonizing India: Harnessing Direct-Air-Capture (DAC) to Combat the Climate Effects of Coal

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The urgent need to address climate change and achieve carbon neutrality has led to the exploration of innovative technologies such as Direct-Air-Capture (DAC). In a country like India, where coal continues to be a significant component of the energy mix, it is essential to evaluate DAC as a potential solution for offsetting carbon emissions. This paper shall provide a qualitative analysis of the applicability and potential benefits of DAC in the Indian context, focusing on its role in achieving net-zero emissions.

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1. Introduction:

The Intergovernmental Panel on Climate Change (IPCC) and the Paris Agreement have emphasised the urgent need for global action to mitigate climate change and limit the rise in global temperatures. As one of the world's largest contributors to greenhouse gas emissions, India plays a crucial role in these global efforts. India's heavy reliance on coal for energy generation presents a significant challenge in achieving its climate goals while ensuring sustainable economic growth.

The IPCC's reports have highlighted the severe consequences of continued high levels of greenhouse gas emissions, including the risks associated with global warming, such as rising sea levels, extreme weather events, and ecosystem disruptions. To address these concerns, the Paris Agreement was adopted in 2015, aiming to limit global warming well below 2 degrees Celsius and pursue efforts to limit the temperature increase to 1.5 degrees Celsius above pre-industrial levels. To achieve this, countries are encouraged to implement mitigation measures, including the deployment of carbon capture, utilization, and storage (CCUS) technologies such as Direct Air Capture (DAC).

Direct Air Capture (DAC) is an emerging technology that involves extracting carbon dioxide (CO_2) directly from the atmosphere. Unlike traditional carbon capture technologies that capture CO_2 from point sources like power plants, DAC offers the potential to remove CO_2 from the atmosphere on a large scale. This technology has gained attention as a potential tool for achieving negative emissions, wherein more CO_2 is removed from the atmosphere than emitted.

In the context of India, where coal consumption is a dominant source of energy generation, the successful implementation of DAC holds immense significance. Coal-based power plants contribute to a significant portion of India's greenhouse gas emissions, exacerbating the challenges posed by climate change. Therefore, exploring and deploying DAC technologies in India can play a crucial role in achieving the country's climate targets while addressing the concerns associated with coal usage.

This paper aims to examine the challenges and opportunities of implementing Direct Air Capture (DAC) in India, considering its heavy reliance on coal and the commitments made under the IPCC and the Paris Agreement. By exploring the potential of DAC as a complementary technology to mitigate CO_2 emissions, this study will contribute to understanding the feasibility, policy implications, and potential pathways for integrating DAC into India's climate change mitigation strategies.

2. The Concept of Net-Zero

The concept of net-zero emissions has emerged as a crucial strategy in addressing the pressing challenge of climate change. As the world grapples with the escalating impacts of global warming, achieving net-zero emissions has gained significant attention as a pathway towards mitigating climate change and preserving a sustainable future. Net-zero emissions refer to the state in which the amount of greenhouse gases (GHGs) emitted into the atmosphere is balanced by the amount removed or offset, resulting in no net addition to atmospheric GHG concentrations. This ambitious goal requires a comprehensive approach that involves reducing emissions from various sectors, such as energy, transportation, industry, and agriculture, while simultaneously deploying technologies and practices that actively remove carbon dioxide (CO_2) from the atmosphere. The importance of striving for net-zero emissions cannot be overstated, as it represents a critical milestone in transitioning towards a low-carbon economy and averting the worst impacts of climate change, including rising temperatures, extreme weather events, sea-level rise, and biodiversity loss. By embracing net-zero emissions, nations can contribute to global climate goals, enhance environmental sustainability, and safeguard the well-being of future generations.

3. The Coal Conundrum in India

Coal has been the backbone of India's energy sector for decades, providing a cheap and abundant source of power. The country's coal reserves, coupled with a growing energy demand to fuel its economic growth and lift millions out of poverty, have made it challenging to abandon coal entirely. Furthermore, India's reliance on coal is deeply embedded in its energy infrastructure, with coal-fired power plants contributing a substantial portion of its electricity generation. Being an affordable source of energy with substantial reserves, coal is going to stay as a major source of energy in the foreseeable future [1]. As coal is the major source of energy in India, the demand will continue with a likely peak between 2030-2035. In 2022-23 (April 2022 to October 2022), the coal consumption in coal-based power plants increased to 447.6 Million Tonnes (MT) as compared to 398.2 MT during the same period of last year with a growth of 12 % [2].

However, the continued reliance on coal poses significant challenges for India's path to achieving net-zero emissions [3-8]. Balancing the need for affordable and reliable energy with the imperative of decarbonization is a complex task that requires careful planning, policy interventions, and the adoption of cleaner energy alternatives.

To address these challenges, India has been increasing its focus on renewable energy expansion, implementing energy efficiency measures, exploring advanced coal technologies such as ultra-supercritical and supercritical plants, and investing in research and development of carbon capture, utilisation, and storage (CCUS) technologies. These efforts aim to reduce the carbon intensity of India's energy sector, diversify its energy mix, and transition towards a more sustainable and climate-resilient energy system.

4. Challenges associated with reducing coal consumption in India

Reducing coal consumption in India poses several challenges due to various factors, including energy demand, economic considerations, and infrastructure limitations. Here are some key challenges:

a. Rising Energy Demand: India's energy demand continues to grow rapidly due to factors such as population growth, urbanisation, and industrial development. Meeting this increasing demand while simultaneously reducing coal consumption requires a significant expansion of

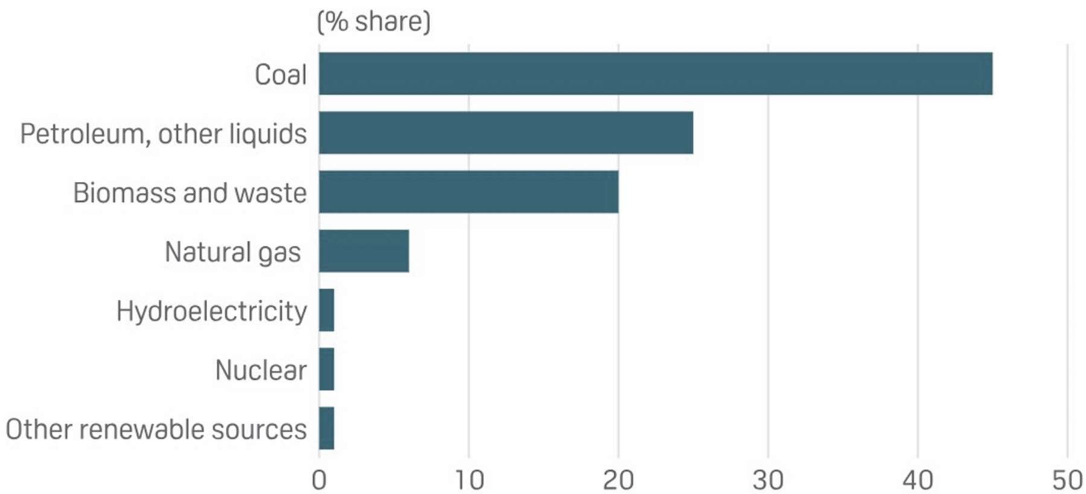

Fig 1: India's total Primary Energy Consumption by Fuel Type
Source: International Energy Agency, World Energy Outlook, 2019

a.

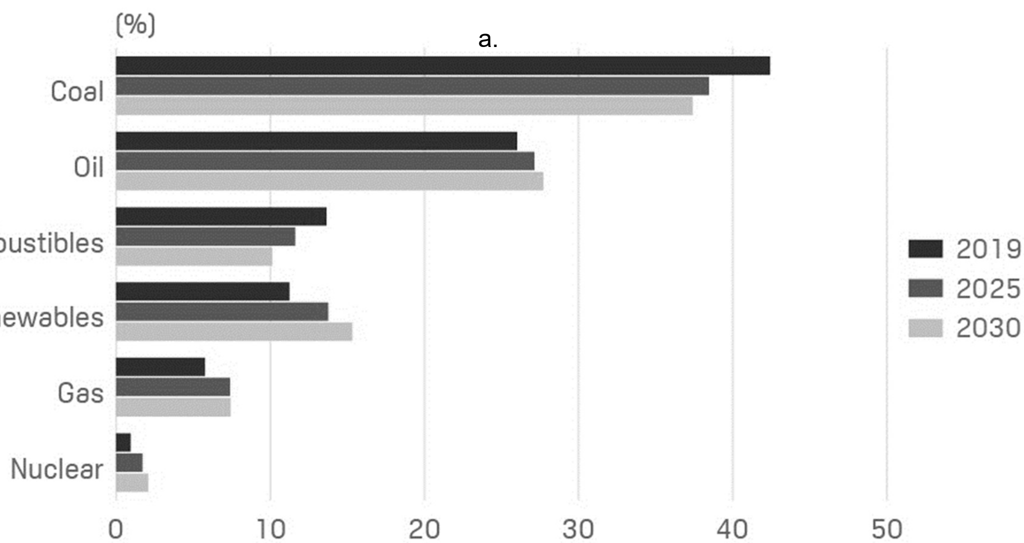

Fig 2: Outlook of Indian Energy Mix.
Source: S&P Global Platts Analytics

b. alternative energy sources, such as renewables and nuclear power. Balancing the need for reliable and affordable energy with the imperative of decarbonization is a complex task that requires careful planning and investments in infrastructure.

c. Economic Considerations: Coal has traditionally been a cost-effective source of energy in India, providing affordable electricity to a large section of the population. Transitioning away from coal may initially lead to increased costs, as renewable energy technologies, such as solar and wind, have higher upfront investment requirements. This economic aspect needs to be carefully managed to ensure a just transition that protects the interests of both consumers and the economy.

d. Infrastructure Limitations: India has a well-established coal-based energy infrastructure, including power plants, mining operations, and transportation networks. Shifting away from coal would require significant investments in alternative infrastructure, such as renewable energy installations, grid upgrades, and storage systems. Upgrading or repurposing existing coal-based infrastructure to accommodate cleaner energy sources can also be challenging due to technical constraints and cost implications.

e. Employment and Social Impacts: The coal sector in India is a significant source of employment, particularly in regions with coal mines and associated industries. Reducing coal consumption would have social and economic implications, including potential job losses and the need for alternative employment opportunities and skill development in renewable energy sectors. Ensuring a just transition for workers and communities affected by coal phase-out is essential to mitigate social impacts.

f. Supply Chain and Logistics: Coal has a well-established supply chain and logistics network in India, with extensive mining operations and transportation infrastructure in place. Shifting to alternative energy sources requires not only developing the necessary infrastructure but also ensuring a smooth transition in the supply chain and logistics for renewable energy technologies, including the availability of raw materials, manufacturing capacities, and efficient distribution networks.

Addressing these challenges requires a multi-faceted approach that combines policy measures, financial incentives, technological advancements, and stakeholder engagement. It is crucial to develop a comprehensive energy transition plan that considers India's unique circumstances and leverages its strengths, such as abundant renewable energy resources, a robust manufacturing sector, and a growing focus on innovation and clean technologies. By navigating these challenges strategically, India can reduce coal consumption, diversify its energy mix, and accelerate the transition to a sustainable and low-carbon economy.

5. The Limitations of Source Reduction

As countries and industries strive to reduce greenhouse gas emissions at the source, it is becoming increasingly evident that this effort alone may not be enough. To reach net zero emissions, it is not enough to focus solely on reducing emissions at their source. While reducing emissions is a crucial step in addressing climate change, there are limitations to how much emissions can be reduced in certain sectors, and there are also legacy emissions that continue to contribute to atmospheric carbon dioxide levels. To effectively combat climate change, we must also explore and invest in technologies that remove emissions from the atmosphere directly. While reducing emissions at the source through cleaner energy sources, sustainable practices, and improved efficiency is crucial, it has its limitations. Many sectors, such as aviation, heavy industry, and agriculture, face unique challenges in decarbonizing their operations. Furthermore, historical emissions and existing infrastructure contribute significantly to atmospheric carbon dioxide levels. Therefore, relying solely on source reduction may not be sufficient to meet ambitious emissions reduction targets.

The concept of net zero emissions implies achieving a balance between the amount of greenhouse gases emitted into the atmosphere and the amount removed or offset from the atmosphere. This is important because even if we reduce emissions to zero, the carbon dioxide and other greenhouse gases that have already accumulated in the atmosphere will continue to contribute to global warming.

To address this, the process of removing greenhouse gases from the atmosphere is necessary. This can be done through various methods collectively known as negative emissions technologies (NETs). Some of the commonly discussed NETs include:

a. Afforestation and reforestation: Planting trees or restoring forests helps absorb carbon dioxide through photosynthesis, acting as a natural carbon sink.

b. Carbon capture and storage (CCS): This technology involves capturing carbon dioxide emissions from industrial processes or power generation and storing them underground or utilizing them for other purposes, preventing them from entering the atmosphere.

c. Direct air capture (DAC): DAC involves capturing carbon dioxide directly from the ambient air using specialized technologies and then either storing it or using it for various purposes.

d. Enhanced weathering: This method involves accelerating the natural process of rock weathering, which absorbs carbon dioxide from the atmosphere over long periods of time.

e. Bioenergy with carbon capture and storage (BECCS): BECCS involves using biomass as a source of energy while capturing and storing the resulting carbon dioxide emissions, effectively offsetting those emissions.

These negative emissions technologies can help remove carbon dioxide from the atmosphere, compensating for the emissions that are difficult or impossible to eliminate completely. By combining emission reduction efforts with these removal technologies, it becomes possible to achieve a net balance of zero emissions, ultimately stabilising atmospheric carbon dioxide levels and mitigating the impacts of climate change.

It's important to note that while negative emissions technologies offer potential solutions, they are still under development and face challenges such as scalability, cost-effectiveness, and environmental impacts. Therefore, it's crucial to prioritize emission reductions at their source and simultaneously invest in research and development of effective and sustainable negative emissions technologies to achieve the goal of reaching net zero emissions.

6. Direct-Air-Capture (DAC) and its role in carbon dioxide removal technologies

Direct Air Capture (DAC) [9-20] is an innovative carbon dioxide removal technology that aims to extract CO_2 directly from the ambient air. Unlike traditional carbon capture and storage (CCS) systems that capture CO_2 emissions from point sources like power plants or industrial facilities, DAC systems have the unique capability to capture CO_2 from the atmosphere, regardless of its source. This technology offers a promising pathway for achieving negative emissions, which is essential for mitigating climate change.

DAC systems typically employ a series of chemical reactions or physical processes to capture CO_2 from the air. These processes often involve passing ambient air through adsorbent materials or solvents that selectively bind to CO_2 molecules, allowing for their separation from the rest of the air. Once captured, the CO_2 can be further processed, stored, or utilized in various ways, including enhanced oil recovery, production of synthetic fuels, or even direct sequestration deep underground or in the ocean.

The role of DAC in carbon dioxide removal technologies is crucial for several reasons. First and foremost, it offers a means to directly address the existing and legacy CO_2 emissions that have accumulated in the atmosphere over decades. While efforts to reduce emissions at their source are vital, DAC provides a complementary approach to actively remove CO_2 that has already been emitted, helping to achieve net-negative emissions.

Moreover, DAC technology is not constrained by geographical or sector-specific limitations. It can be deployed in any location and used to capture CO_2 from a wide range of sources, including those that are difficult to decarbonize or are dispersed, such as transportation or agriculture. This versatility makes DAC a promising tool for comprehensive climate mitigation strategies.

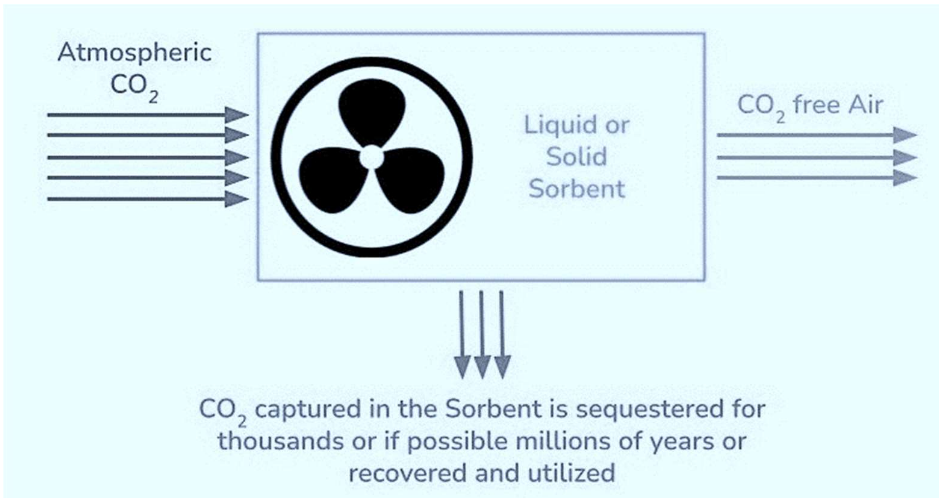

Fig 3: Schematic Representation of the process of Direct Air Capture (DAC)

Furthermore, DAC can potentially provide a reliable and scalable solution for CO_2 removal. As renewable energy sources become more abundant and affordable, DAC systems can be powered by clean energy, minimizing their carbon footprint. With further technological advancements and cost reductions, DAC has the potential to play a significant role in achieving net-zero and even net-negative emissions globally.

Overall, Direct Air Capture is a cutting-edge technology that enables the direct extraction of CO_2 from the atmosphere, offering a critical pathway for carbon dioxide removal. By capturing CO_2 emissions regardless of their source and facilitating negative emissions, DAC plays a vital role in climate change mitigation efforts and supports the transition to a more sustainable and low-carbon future.

7. DAC's potential to capture CO2 emissions directly from the atmosphere

The process of Direct Air Capture (DAC) involves several steps that enable the capture and removal of CO_2 directly from the ambient air. While specific DAC systems may vary in design and implementation, they generally follow a similar overarching process. Here's an overview of the DAC process and its potential for capturing CO_2 emissions:

1. Air Intake: The first step involves the intake of ambient air into the DAC system. Large fans or blowers draw air into the system, usually through filters that remove particulate matter and impurities.

2. CO_2 Capture: Once the air is inside the DAC system, the CO_2 capture process begins. DAC systems employ various techniques to selectively capture CO_2 molecules from the air. These techniques often utilize adsorbents, such as amine-based materials or solid sorbents, which chemically or physically bind to CO_2 while allowing other components of the air to pass through.

3. CO_2 Separation: After the CO_2 molecules are captured, the next step involves separating them from the adsorbent material or solvent. This can be achieved through heating, changes in pressure, or other desorption methods, depending on the specific DAC technology used.

4. CO_2 Purification: The captured CO_2 may contain impurities or other gases that need to be removed for further utilization or storage. Purification processes, such as pressure swing adsorption or membrane separation, are employed to refine the captured CO_2, resulting in a higher purity CO_2 stream.

5. Storage or Utilization: The purified CO_2 can then be stored or utilized for various purposes. It can be compressed and transported for injection into underground geological formations for long-term storage, such as depleted oil and gas reservoirs or deep saline aquifers. Alternatively, the CO_2 can be utilized in industrial processes, such as the production of chemicals, fuels, or building materials, thus creating a market for the captured CO_2 and promoting circular economy approaches.

The potential of DAC for capturing CO_2 emissions directly from the atmosphere is substantial. Unlike other carbon capture technologies that focus on point sources like power plants, DAC has the advantage of being able to capture CO_2 from dispersed sources, making it a versatile and flexible solution. It can capture CO_2 emissions from sectors that are challenging to decarbonize, such as transportation or agriculture, and even remove CO_2 that has already been emitted in the past.

Moreover, DAC has the potential to achieve negative emissions by capturing more CO_2 than is emitted, which is crucial for achieving net-zero emissions. By actively removing CO_2 from the atmosphere, DAC contributes to balancing the carbon budget and mitigating climate change impacts.

8. Intergovernmental Panel on Climate Change (IPCC) on Direct Air Capture (DAC)

The Intergovernmental Panel on Climate Change (IPCC) is a scientific body established by the United Nations to provide policymakers with comprehensive assessments of the scientific, technical, and socio-economic aspects of climate change. The IPCC's reports have emphasized the importance of carbon removal strategies, including Direct Air Capture (DAC), in addressing climate change mitigation goals.

In its landmark report titled "Global Warming of 1.5°C" released in 2018, the IPCC highlighted the urgency of limiting global warming to 1.5 degrees Celsius above pre-industrial levels to avoid the most severe impacts of climate change. The report stressed that achieving this ambitious target would require not only rapid reductions in greenhouse gas emissions but also the deployment of negative emissions technologies, such as DAC, to remove CO_2 from the atmosphere.

The IPCC report stated that carbon removal technologies, including DAC, have the potential to remove CO_2 at a scale necessary to compensate for remaining emissions and achieve net-negative emissions. Net-negative emissions refer to the removal of more CO_2 from the atmosphere than what is emitted, effectively reducing the concentration of CO_2 in the atmosphere.

DAC was recognized as a potential pathway for achieving negative emissions by capturing CO_2 directly from the atmosphere. The IPCC report acknowledged that DAC has the advantage of being able to remove CO_2 from diffuse sources, making it applicable in regions where point-source emissions are limited or dispersed. It highlighted the need for further research, development, and deployment of DAC technologies to improve their efficiency, scalability, and cost-effectiveness.

Furthermore, the IPCC's special report on "Climate Change and Land" released in 2019 emphasised the role of land-based carbon removal strategies, including afforestation, reforestation, and bioenergy with carbon capture and storage (BECCS). While DAC was not explicitly mentioned in this report, it aligns with the broader context of carbon removal technologies discussed by the IPCC.

It is important to note that while DAC technologies are rapidly advancing, they still face challenges in terms of energy requirements, cost-effectiveness, and scalability. Ongoing research and development efforts are focused on improving the efficiency and reducing the environmental footprint of DAC systems. There is also a growing emphasis on exploring synergies between DAC and other carbon capture technologies, such as utilization of CO_2 in industrial processes or storage in geological formations.

The field of DAC is evolving, with numerous pilot projects and demonstration facilities being established globally. These initiatives aim to validate the performance, feasibility, and potential of various DAC techniques in real-world conditions. Continued innovation and collaboration between researchers, industries, and policymakers are vital to drive the development and deployment of effective DAC technologies that can contribute significantly to global climate change mitigation efforts

9. Current worldwide Status of DAC Implementation

There are presently 19 DAC plants operating worldwide, capturing more than 0.01 Mt CO_2/year. DAC active plants capturing in average 10,000 tons of CO_2 annually are still in their infancy and are expensive. DAC technologies still need to improve in three areas: 1) Contactor, 2) Sorbent, and 3) Regeneration to drive down the costs. Technology-based economic development in all three areas is required to achieve <\$100/ton of CO_2 which makes DAC economically viable. Current DAC cost is about 2–6 times higher than the desired cost and depends highly on the source of energy used. As per some estimates, 1250 DAC plants with a capacity of one MtCO_2/year each, would be required to remove 25 GtCO_2 by 2030, assuming a linear growth of carbon capture and storage from the current capacity of 0.0385 Gt per year to a capacity of 20 Gt per year [19-20].

10. Role of DAC in India's path to Net Zero

Direct Air Capture (DAC) technology can play a complementary role in India's efforts to achieve net-zero emissions. Here's how DAC can contribute to India's climate goals:

1. Addressing Legacy CO_2 Emissions: India has a substantial carbon dioxide (CO_2) emissions legacy, with significant amounts of CO_2 already present in the atmosphere. DAC provides a unique opportunity to directly capture and remove CO_2 from the ambient air, regardless of its source. By actively addressing legacy emissions, DAC can help offset the accumulated CO_2 that has contributed to climate change over the years.

2. Balancing Hard-to-Decarbonize Sectors: Some sectors in India, such as heavy industries, transportation, and agriculture, present challenges in terms of decarbonization due to the nature of their emissions. DAC can play a crucial role in capturing CO_2 emissions from these sectors, which are dispersed and often difficult to mitigate using conventional methods. By capturing CO_2 directly from the atmosphere, DAC can support these hard-to-decarbonize sectors in reducing their carbon footprint and transitioning towards cleaner alternatives.

3. Enabling Negative Emissions: Achieving net-zero emissions requires not only reducing greenhouse gas emissions but also actively removing CO_2 from the atmosphere to create a net-negative balance. DAC has the potential to achieve negative emissions by capturing more CO_2 than is emitted. By integrating DAC systems with renewable energy sources, India can achieve carbon removal and contribute to the overall goal of balancing emissions with removal, thereby advancing towards net-zero.

4. Flexibility and Versatility: DAC provides flexibility in terms of geographical deployment and scalability. It can be deployed in various locations and does not require proximity to emission sources, making it a versatile solution for capturing CO_2 from dispersed sources. This flexibility allows for the implementation of DAC projects across different regions of India, tailoring the technology to specific local conditions and capturing emissions that are challenging to address through other means.

5. Integration with Carbon Utilization and Storage: DAC can synergistically integrate with carbon utilization and storage technologies, creating a comprehensive carbon management system. The captured CO_2 can be utilized in various industrial processes, such as the production of synthetic fuels, chemicals, or building materials. Additionally, the CO_2 can be stored underground using carbon capture and storage (CCS) techniques, ensuring long-term removal of CO_2 from the atmosphere. This integration enhances the value of DAC by promoting circular economy approaches and enabling the utilization of captured CO_2, thereby creating economic and environmental benefits.

DAC technology offers a valuable tool for India's pursuit of net-zero emissions. By directly capturing CO2 from the atmosphere, DAC can address legacy emissions, complement efforts to decarbonize hard-to-treat sectors, enable negative emissions, provide flexibility in deployment, and integrate with carbon utilization and storage. Incorporating DAC into India's climate strategy can enhance its capacity to achieve ambitious climate targets while advancing towards a sustainable and low-carbon future.

11. Advantages of DAC in addressing the challenges posed by coal dependence in India

Direct Air Capture (DAC) technology offers several advantages in addressing the challenges posed by coal dependence in India. Here are the key advantages of DAC:

1. Carbon Neutrality: Coal-fired power plants are a significant source of carbon dioxide (CO_2) emissions, contributing to climate change. DAC provides a pathway to offset these emissions by capturing an equivalent amount of CO_2 directly from the atmosphere. By integrating DAC with coal-based power generation, India can achieve carbon neutrality, reducing the net emissions associated with coal consumption and moving towards a more sustainable energy system.

2. Flexibility in Location: DAC systems are not dependent on proximity to emission sources, unlike conventional carbon capture technologies that are typically implemented at point sources such as power plants. This flexibility allows DAC installations to be strategically placed in regions where renewable energy resources are abundant or where CO_2 removal is most needed. India's vast geography and diverse climate conditions make it suitable for the deployment of DAC systems in various locations, optimizing the efficiency of CO_2 removal.

3. Capture of Legacy Emissions: India has a significant carbon emissions legacy, with substantial amounts of CO_2 already present in the atmosphere. DAC technology offers the unique ability to capture and remove CO_2 directly from the ambient air, regardless of its source. This capability enables DAC to address legacy emissions, effectively reducing the cumulative impact of past CO_2 emissions and helping India in its journey towards achieving net-zero emissions.

4. Dispersed Emission Sources: In addition to power generation, there are several dispersed emission sources in sectors such as transportation, agriculture, and small-scale industries that are challenging to decarbonize. DAC can play a crucial role in capturing CO_2 emissions from

these sectors by directly extracting CO_2 from the atmosphere. This capability allows DAC to complement other decarbonization efforts in India, enabling the reduction of CO2 emissions from a wide range of sources and supporting the country's transition to a low-carbon economy.

5. Potential for Negative Emissions: DAC technology has the potential to achieve negative emissions by capturing more CO2 than is emitted. This is especially significant in the context of India's efforts to achieve net-zero emissions, as negative emissions can help compensate for sectors that are difficult to decarbonize completely. By actively removing CO_2 from the atmosphere, DAC contributes to balancing the carbon budget and accelerating progress towards the goal of net-zero emissions.

6. Carbon Utilization and Storage: The captured CO_2 from DAC systems can be utilized in various industrial processes, such as the production of synthetic fuels, chemicals, or building materials. Additionally, the CO_2 can be stored underground using carbon capture and storage (CCS) techniques, ensuring long-term removal of CO_2 from the atmosphere. This integration of DAC with carbon utilization and storage technologies promotes circular economy approaches and provides economic incentives for DAC deployment, enhancing its value in addressing the challenges posed by coal dependence.

DAC offers distinct advantages in addressing the challenges associated with coal dependence in India. Its carbon neutrality, flexibility in location, ability to capture legacy emissions, effectiveness in capturing emissions from dispersed sources, potential for negative emissions, and integration with carbon utilization and storage make it a promising technology for complementing India's transition towards a low-carbon future. By leveraging the advantages of DAC, India can reduce the carbon footprint associated with coal consumption and accelerate progress towards its climate goals.

12. Challenges and Limitations of Implementing DAC in India: Technological and Regulatory barriers

While Direct Air Capture (DAC) technology holds promise for carbon dioxide removal, its implementation faces several challenges and limitations. It is important to consider these factors when assessing the feasibility and effectiveness of DAC projects. Here are key challenges associated with DAC implementation:

1. Financing and Investment: The financing and investment landscape for DAC projects need to be addressed to attract sufficient capital for widespread adoption. DAC projects often require substantial upfront investments, and securing funding can be challenging. Creating financial mechanisms such as dedicated funds, subsidies, or incentives specifically for DAC projects can attract private sector investment. Exploring innovative financing models, such as blended finance, impact investing, or public-private partnerships, can also help overcome financial barriers and unlock investment opportunities for DAC projects.

2. Scale and Deployment Challenges: Scaling up DAC technology to achieve meaningful carbon dioxide removal on a large scale presents logistical and deployment challenges. DAC systems need to be designed, manufactured, and deployed at a size and capacity that can effectively address significant CO_2 emissions. Developing the necessary infrastructure, including carbon capture and storage facilities, CO_2 transportation networks, and storage sites, requires substantial planning and investment. Ensuring the timely and coordinated deployment of DAC projects at the necessary scale is a complex task that requires collaboration among various stakeholders.

3. Infrastructure Development: The implementation of DAC projects requires the development of supporting infrastructure, including carbon capture, transportation, and storage facilities. The establishment of a comprehensive carbon capture and storage (CCS) infrastructure is essential for the effective deployment of DAC technology. This involves identifying suitable storage sites, ensuring the safe transportation of captured CO_2, and addressing technical and regulatory challenges associated with CCS. Investment in infrastructure development and regulatory frameworks specific to CCS and DAC can facilitate their widespread adoption.

4. Regulatory Framework: The regulatory framework plays a crucial role in enabling the adoption of DAC technology. There is a need to establish clear and supportive regulations that govern DAC operations, CO_2 transportation, and storage. The regulatory framework should address issues such as liability, permitting processes, monitoring, reporting, and verification of CO_2 removal. Collaborative efforts involving government agencies, environmental authorities, and experts in the field can help develop comprehensive regulations that balance environmental protection and facilitate the growth of DAC projects.

5. Skilled Workforce and Capacity Building: The successful adoption of DAC technology requires a skilled workforce with expertise in areas such as engineering, chemistry, materials science, and environmental management. Building capacity through targeted training programs, academic collaborations, and knowledge-sharing initiatives can address the shortage of skilled professionals in the DAC field. Investing in research and educational institutions to develop specialized programs and courses on carbon capture and DAC can help build a competent workforce capable of driving DAC adoption.

6. Research & Development Need:

   a. DAC technology is still in the early stages of development and deployment. There is a need for further research and development to enhance its efficiency, lower costs, and improve scalability. Technological advancements are required to optimize the capture materials, develop more efficient sorbents or solvents, and increase the carbon capture capacity of DAC systems. Collaborative research efforts between academia, industry, and research institutions can accelerate technological advancements and bridge the existing knowledge gaps.

   b. To make DAC economically viable, cost reduction through research, development, and technological innovations is necessary. Additionally, supportive policies and financial mechanisms, such as carbon pricing or incentives for carbon removal, can help incentivize investment and drive down costs

   c. The captured CO_2 needs to be safely stored or utilized to prevent its re-release into the atmosphere. Establishing reliable and long-term storage sites for CO_2 presents technical and regulatory challenges. Similarly, developing commercial pathways for carbon utilization, such as converting CO_2 into useful products, requires further research, development, and market demand. The availability of viable storage options and carbon utilization pathways is crucial for the success of DAC implementation.

7. International Collaboration: DAC deployment can benefit from international collaboration and knowledge sharing. Engaging with global initiatives, research consortia, and international partnerships can help address technological and regulatory barriers. Collaboration with countries that have advanced DAC projects and regulatory frameworks can provide valuable insights and facilitate the transfer of knowledge and best practices.

International cooperation can also support capacity building, research collaborations, and the development of common standards and protocols

By addressing technological barriers through research and development, investing in infrastructure development, establishing a supportive regulatory framework, facilitating financing and investment, promoting capacity building, and fostering international collaboration, India can overcome the barriers that may hinder the widespread adoption of DAC technology. Proactive measures and a collaborative approach among government agencies, industry stakeholders, research institutions, and international partners can accelerate the adoption of DAC and contribute to India's net-zero emissions goals.

13. Policy framework required to support DAC deployment in India

The deployment of Direct Air Capture (DAC) technology in India requires a robust policy framework that supports its implementation, incentivizes investment, and facilitates the scaling-up of this emerging technology. Here are key considerations for the policy framework:

1. Carbon Pricing and Market Mechanisms: Implementing a carbon pricing mechanism, such as a carbon tax or cap-and-trade system, can create economic incentives for DAC deployment. A carbon price would assign a financial value to CO_2 emissions, providing a market signal that encourages industries to reduce emissions and invest in carbon capture technologies like DAC. Additionally, establishing a market for carbon credits or offsets can enable the monetization of CO_2 removal, creating revenue streams for DAC project developers and stimulating private sector participation.

2. Research and Development Support: To drive innovation and cost reduction in DAC technology, the policy framework should prioritize research and development support. This includes funding research institutions, incentivizing private sector investment in R&D, and fostering collaboration between industry and academia. By investing in research and development, policymakers can accelerate the technological advancements needed to make DAC more efficient, scalable, and economically viable.

3. Establishing a clear regulatory framework: This includes defining guidelines for CO_2 storage and transportation, ensuring environmental safety, and addressing legal and liability considerations associated with CO_2 capture and utilization. A supportive regulatory environment would provide clarity and certainty for DAC project developers, investors, and stakeholders, facilitating the implementation and operation of DAC systems.

4. Financial Mechanisms: DAC deployment requires substantial upfront investments. The policy framework should include financial mechanisms, such as grants, subsidies, low-interest loans, or tax incentives, to incentivize private sector investment in DAC projects. Creating dedicated funding schemes or setting up a DAC-specific fund can attract capital and stimulate innovation in the sector. Public-private partnerships can also be fostered to leverage both public and private sector resources for DAC deployment.

5. Long-Term Planning and Targets: The policy framework should include long-term planning and establish clear targets for DAC deployment aligned with India's climate goals. Setting specific targets for DAC capacity and carbon removal can provide a roadmap for industry and investors, creating a sense of direction and certainty. Long-term planning should consider factors such as technology development, infrastructure requirements, and the integration of DAC with other climate mitigation strategies.

6. International Cooperation: DAC deployment can benefit from international cooperation, collaboration, and knowledge sharing. India should engage in international initiatives, such as the Mission Innovation Carbon Capture, Utilization, and Storage (CCUS) Innovation Challenge, to access global expertise, share best practices, and collaborate on research and development efforts. International partnerships can facilitate technology transfer, enhance policy learning, and create opportunities for joint projects, supporting the growth of DAC deployment in India.

7. Stakeholder Engagement and Public Awareness: Engaging stakeholders, including industry, civil society organisations, and local communities, is vital for the successful deployment of DAC. The policy framework should encourage stakeholder consultations, public awareness campaigns, and information dissemination to ensure a transparent and inclusive process. Engaging with stakeholders can help address concerns, build public acceptance, and promote the understanding of DAC's role in achieving climate goals.

By designing a comprehensive policy framework that incorporates carbon pricing, research and development support, a clear regulatory environment, financial mechanisms, long-term planning, international cooperation, and stakeholder engagement, India can create an enabling environment for DAC deployment. This policy support will encourage investment, drive innovation, and accelerate the adoption of DAC technology, contributing to India's efforts to achieve its climate targets and transition to a sustainable, low-carbon future.

14. Potential economic incentives and investment opportunities for DAC projects in India

The deployment of Direct Air Capture (DAC) projects in India presents significant economic incentives and investment opportunities. Here are key factors to consider:

1. Carbon Offsetting and Trading: DAC projects can generate carbon offsets by capturing and removing CO_2 from the atmosphere. These offsets can be traded in voluntary or compliance carbon markets, providing a potential revenue stream for DAC project developers. India's commitment to reducing greenhouse gas emissions and its participation in international climate agreements create a favourable market environment for carbon offset trading. DAC projects can benefit from this market mechanism, enabling them to monetize the CO_2 removal and attract investments.

2. Government Grants and Subsidies: The Indian government, through its various Ministries and departments, offers grants and subsidies for projects aligned with its climate and environmental objectives. DAC projects that contribute to carbon reduction and have the potential for technological innovation can access funding programs aimed at promoting clean technologies. For example, initiatives such as the National Clean Energy Fund or the Sustainable and Accelerated Adoption of Efficient Textile Technologies (SAEET) Fund can provide financial support for DAC projects in India.

3. Green Finance and Impact Investing: The growing interest in sustainable investments and green finance presents opportunities for DAC projects. Impact investors and green funds seek environmentally beneficial projects with the potential for climate change mitigation. DAC, as a technology that directly addresses carbon removal, aligns well with the objectives of these investors. By positioning DAC projects as sustainable and impactful, project developers can attract private investments from individuals, institutions, and funds dedicated to supporting climate solutions.

4. Collaborative Partnerships: Collaboration between public and private entities can unlock investment opportunities for DAC projects. Public-private partnerships can leverage the expertise, resources, and networks of both sectors to accelerate project implementation. The Indian government can facilitate such partnerships by providing policy support, regulatory clarity, and incentives to attract private investment in DAC projects. Collaborations between research institutions, technology providers, and project developers can also foster innovation and ensure the commercial viability of DAC technologies.

5. Circular Economy and Carbon Utilization: DAC projects can integrate with carbon utilization technologies, such as the production of synthetic fuels, chemicals, or building materials using captured CO_2. These circular economy approaches create additional economic value by utilizing CO_2 as a feedstock for various industries. DAC projects that incorporate carbon utilization pathways can attract investment from industries looking to reduce their carbon footprint while exploring sustainable production methods.

By capitalizing on carbon offset trading, corporate social responsibility initiatives, government grants and subsidies, green finance and impact investing, technology and infrastructure development, collaborative partnerships, and circular economy opportunities, DAC projects in India can unlock significant economic incentives and attract the necessary investments. This not only drives the growth of DAC technology but also contributes to India's sustainable development goals, climate targets, and transition to a low-carbon economy.

15. Proposed Approach for the implementation of Direct-Air-Capture in India: Public – Private Partnership (PPP) Model

The urgent need to combat climate change and reduce greenhouse gas emissions has presented a formidable challenge that requires collective action and collaboration from both public and private sectors. This fragmented approach might result in suboptimal utilization of resources, limited investment opportunities, and slower progress towards achieving global carbon reduction targets. There is a pressing need to establish a Public Private Partnership (PPP) model for the implementation of DAC in India, that brings together public and private sector companies, fostering collaboration, pooling of resources, and joint efforts to accelerate the development and deployment of DAC facilities.

A PPP Model approach can support the implementation of DAC in India in the following ways:

1. Financial Resources: DAC facilities require substantial upfront investment. By forming a consortium, multiple companies can pool their financial resources, making it easier to secure the necessary funding. Public sector entities can contribute public funds, grants, or subsidies, while private sector companies can provide capital investment. The collective financial strength of the consortium members increases the chances of securing the required capital, making the implementation of a DAC facility more feasible.

2. Risk Sharing: DAC projects involve inherent risks, including technological uncertainties, market fluctuations, and regulatory changes. When private and public companies come together in a consortium, these risks can be shared among the members. Risk sharing allows for a more balanced distribution of project risks and reduces the burden on individual companies. It enables better risk mitigation strategies and increases the overall resilience of the DAC facility implementation.

3. Scaling Up and Cost Reduction: DAC facilities need to be scaled up to have a significant impact on CO_2 removal. By pooling resources and knowledge within members in the PPP, members can collectively invest in research and development efforts aimed at scaling up DAC technology and reducing its costs. Collaboration can facilitate sharing of best practices, lessons learned, and technological advancements, leading to economies of scale and more cost-effective solutions.

4. Expertise and Resources: A consortium allows for the pooling of diverse expertise and resources from private and public sector companies. Private sector companies bring their technical know-how, engineering capabilities, and project management expertise to the consortium. Public sector entities contribute regulatory knowledge, policy support, and access to research institutions. By leveraging the combined expertise and resources of consortium members, implementation challenges related to technical aspects, regulatory compliance, and operational efficiency can be effectively addressed.

5. Access to Research and Development: DAC technology requires ongoing research and development to improve efficiency, reduce energy consumption, and develop new capture and utilization techniques. Through a consortium, members can collaborate on research initiatives, share data, and jointly invest in R&D activities. This collective approach allows for a broader knowledge base, increased research capacity, and faster technological advancements in DAC.

6. Collaborative Decision-making: DAC facilities require strategic decision-making involving considerations such as facility location, carbon utilization options, and project timelines. A consortium allows for collaborative decision-making processes, where all stakeholders have a voice in shaping the project. By involving both private and public sector companies, diverse perspectives and insights can be brought to the table, resulting in more informed and balanced decisions. This collaborative approach helps streamline the decision-making process and ensures that the DAC facility implementation aligns with the interests and goals of all consortium members.

7. Regulatory and Policy Support: Public sector entities within the consortium can provide valuable regulatory and policy support. They can help navigate the regulatory landscape, identify potential challenges, and facilitate a smoother regulatory approval process. Public sector involvement can also help influence policy frameworks, creating an enabling environment for DAC implementation. This support can significantly streamline the permitting process, address regulatory hurdles, and expedite the implementation of the DAC facility.

8. Efficient Resource Allocation: Implementing a DAC facility involves various resources such as land, energy, water, and CO_2 transportation infrastructure. A consortium approach allows for optimised resource allocation and utilization. By leveraging the expertise and networks of consortium members, resources can be efficiently allocated based on the strengths and capabilities of each member. This collaborative approach maximizes resource efficiency and reduces redundancy, resulting in a more streamlined and cost-effective implementation process.

9. Infrastructure and Supply Chain Development: DAC facilities require a robust infrastructure and supply chain to support their construction, operation, and maintenance. A consortium can facilitate coordination among members to identify common infrastructure needs, such as access to renewable energy sources, CO_2 storage sites, or transportation networks. Pooling resources and expertise can expedite the development of necessary infrastructure, making DAC projects more viable and efficient.

10. Market Development and Carbon Offsetting: DAC facilities generate Carbon Removal Credits, which can be monetized and traded on carbon markets. However, the market for carbon removal is still in its early stages, and mechanisms for valuing and trading these credits need further development. Through a consortium, members can collaborate on market development initiatives, engage with policymakers and industry stakeholders, and collectively drive the creation of a robust and transparent market for Carbon Removal Credits.

Overall, a consortium of private and public sector companies, in the form of a PPP Model can bring together financial resources, expertise, regulatory support, and community engagement capabilities. This collaborative approach enhances project feasibility, risk mitigation, decision-making, and resource allocation, making the implementation of a DAC facility easier and more effective.

16. Conclusion

In conclusion, the article highlights that Direct Air Capture (DAC) holds great promise for India to achieve its Net-Zero emissions goal, even in the face of continued reliance on coal as a major energy source for the foreseeable future. By employing a consortium approach, India can effectively implement DAC technology and mitigate the environmental impact of coal-based energy generation.

The article acknowledges that coal is a significant contributor to India's energy mix and acknowledges the challenges associated with transitioning away from it. However, it emphasizes that DAC provides a viable solution by capturing carbon dioxide directly from the atmosphere, regardless of the source of emissions. This approach allows India to address its carbon footprint while continuing to utilize its coal resources to meet growing energy demands.

The key to successful DAC implementation lies in adopting a PPP Model approach. A collaboration between Private and Public Sector companies will provide India with the necessary expertise, technology, and funding required for large-scale DAC deployment. By pooling resources and knowledge, the consortium can optimize DAC operations, increase efficiency, and drive down costs, making it a more feasible and attractive option for India's net-zero ambitions.

Furthermore, the article emphasises the importance of policy support and favourable regulatory frameworks to incentivize the adoption of DAC technologies. By implementing measures such as carbon pricing, tax incentives, and research grants, the Indian government can encourage private sector participation and investment in DAC infrastructure. This collaborative effort will not only help India reduce its carbon footprint but also stimulate innovation and create new economic opportunities in the green technology sector.

The article asserts that DAC, combined with a PPP Model approach, can enable India to reach its net-zero emissions target while continuing to rely on coal for energy generation. By leveraging international partnerships, fostering technological advancements, and implementing supportive policies, India can embrace DAC as a crucial tool in its journey towards a sustainable and environmentally conscious future.

However, suggestions for any other suitable route for successful implementation of the Technology are open for discussion.

About Novonanmek Material Sciences Private Limited

Novonanmek Material Sciences Private Limited is a Climate Technology Startup based in Delhi, India. Novonanmek has already developed and is currently in the process of implementing a State-of-the-art Direct-Air-Capture (DAC) technology that combines both technology and nature that can be easily scaled to Gigatons, thereby bringing the cost to a level where it becomes commercially viable to businesses. Novonanmek also develops engineered materials for carbon capture and other purposes.

Recently Novonanmek has been recognized by United Kingdom Research and Innovation (UKRI) as one of the innovative and high-tech carbon capture startups in India.

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