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Evaluation of Direct Air Capture Methodologies Based on Clean Energy and Sequestration Potential from Indian Perspective

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Abstract

Climate change is one of the major challenges faced by the world in the 21st century. The recent IPCC (Intergovernmental Panel on Climate Change) report highlights that even with the rapid decarburization, the existing greenhouse gases in the atmosphere have severe irreversible impacts on the climate. Therefore, negative emissions technologies like direct air capture (DAC), bio-energy with carbon capture and storage, afforestation and reforestation, etc. are expected to play an important role in climate change strategies. Researchers are working on scaling up the technologies to get significant benefits. However, the different direct air capture methodologies are energy-intensive. While researchers are working on identifying ways to improve process efficiency, this research is focused on identifying the areas of application where DAC is more effective. This study aims (i) to summarize the various popular DAC methodologies – solvent, solid sorbent, electro-swing, cryogenic, and humidity/moisture swing – based on the identified indicators, and (ii) to evaluate the DAC technology to identify the preferred sites in India for developing DAC facilities in the near and long term. All states and union territories of India are evaluated from the short- and long-term perspectives based on clean energy and sequestration capacity. The proposed framework will help the government agencies and private investors to take informed decisions on the preferred sites for developing DAC facilities.

Keywords
Direct Air Capture (DAC), Climate change, Carbon sequestration, Carbon storage capacity, and Clean energy.

1. Introduction
Global warming and climate change is one of the serious problems being faced by the earth right now. Greenhouse gas emissions (GHG) is increasing rapidly due to the industrial growth. Carbon dioxide (CO_2) is one of the major contributors to climate change. The concentration of CO_2has rose from 280 parts per million (ppm) in the pre-industrial period to 412 ppm in 2020 (Dlugokencky and Tans 2022). The increased CO_2 emission has contributed to the global temperature rise. According to scientists at NASA's Goddard Institute for Space Studies, the average global temperature has risen by 1.1 °C since 1880 (World of Change: Global Temperatures 2022). The increased temperature is causing climate anomalies and adversely affecting the various species living on the planet. India alone accounts for 7.02% of total annual CO_2 emissions of the world (Ritche et al. 2022). Globally, researchers are working on improving the current industrial processes to reduce emissions, developing newer technologies to reduce

emissions and improving the existing technologies to bring them to scale and reduce costs. Worldwide government authorities and private sectors are also committing to ambitious goals to reduce the carbon footprint of their countries and companies, respectively. During conference of parties (COP) 26, the Indian government declared that India will aim to get to net-zero by 2070 and reduce the carbon intensity below 45% by 2030, and also pledged to cut down emissions by one billion tonnes. This requires a massive 22% reduction in carbon output by 2030, which need an innovative approach (Climate Pledge: On COP Summit in Glasgow 2021).

Negative emission technologies (NETs) have a crucial role in achieving these targets. NETs were included in the framework of the United Nations Framework Convention on Climate Change (UNFCCC) during the Kyoto protocols of 1997 (UNFCCC 2013). Most of the integrated assessment models (IAMs) rely on NETs to have more than 50% chance of achieving these targets (Sykes et al. 2020). There are various negative emissions technologies. National Academies of Sciences Engineering and Medicine (NASEM) exhaustively reviews various NETs (NASEM 2019). DAC is one of the negative emissions technologies that is getting a lot of recognition as a potential solution to offset carbon emissions. Experts believe that DAC is a promising technology that can help in achieving the climate goals by complementing the decarburization efforts. DAC gives a unique advantage as it can help in offsetting emissions from hard-to-decarbonize sectors like aviation.

A DAC facility aims to capture carbon dioxide from the atmosphere and either utilize it as a feedstock or sequestering it permanently in geological formations. As of 2021, 19 DAC plants are operating all over the world which capture more than 0.01 Mt CO_2/year. A DAC plant with a capacity to capture 1 Mt CO_2/year is under development in the United States (IEA 2021). However, as the CO_2 concentration in the atmosphere is very low, the process is energy-intensive and costly but as the technology matures, experts believe the cost of capture will reduce.

1.1 Objectives
This study is intended to review the various DAC methodologies based on technology readiness, materials used, cost of capture, capture efficiency, working principle, energy required, and advantages as criteria. Further, all states and union territories of India are evaluated for their suitability to adopt DAC technology from short- and long-term perspective. The identification of suitable location is based on the energy mix of the states (clean energy) and the carbon dioxide sequestration capacity. The existing evaluations of NETs in literature are primarily for Europe and North America. The evaluation from Indian perspective will provide government agencies and private investors to take informed decisions on the preferred sites for developing DAC facilities to mitigate climate change.

2. Literature Review
The increasing threat of climate change has shifted the focus of governments to reduce their carbon footprint. Various steps are being taken to shift to renewable energy and more sustainable methods of manufacturing. However, it is very difficult to control emissions for industries like aviation, agriculture, and other land use. Considering this challenge, it is helpful to use negative emissions technologies to reach the targets of global climate. NETs can be viewed as a part of the portfolio of methods to tackle climate change (Pires 2019).

Negative emissions technologies are techniques that aim to remove the emissions already present in the atmosphere since it is very difficult to completely eliminate GHG emissions, although researchers are continuously trying to minimize them. The latest IPCC report recognizes bioenergy with carbon capture and storage (BECSS), afforestation and reforestation (AR), soil carbon sequestration (SCS), biochar (BC), enhanced weathering (EW), ocean alkalization, direct air carbon capture and storage (DACCS), and ocean fertilization (OF) as carbon dioxide removal (CDR) techniques or NETs (Lecocq 2022). Afforestation and soil carbon sequestration technologies are well researched while others are still in the developing stage. Minx et al. (2018) categorized the NETs based on various variables including technology category, methods of implementation, interaction with the earth systems and storage medium. BECSS and AR can have a direct impact on food security and prices, OF has unknown impact on the marine ecology and food chains, use of OF and SCS can also lead to an increase in N_2O and CH_4 emissions from ocean and soil, respectively. DAC stands out as one of the most effective technologies. DACCS provides a solution with less spatial requirements as compared to AR and BECSS, and can easily be scaled by increasing the capacity of an existing DAC facility (Fuss 2018). DAC technology has low land requirements as compared to other net negative technologies like afforestation and BECSS and can eliminate the need for long pipelines to take the captured CO_2 by installing DAC systems near the storage sites (NASEM, 2019). DAC systems can be co-located with renewable energy parks which will limit the transmission losses (Erans et al. 2022). The end effect of DAC is highly dependent on the end-use of CO_2 which is removed from the ambience. If the captured $CO_2$is utilized as a feedstock for other industries then the true effectiveness of the removal will depend on the life cycle of the product produced by using the capturedCO_2. Currently, enhanced oil recovery is one of the potential uses of the removedCO_2. However, one can argue that using CO_2as an excuse to extract more fossil fuel does not serve the purpose of DAC. Alternatively, sequestering the captured CO_2 in geological formations can serve as a long term solution for locking away the emissions. Nevertheless, irrespective of the final use of captured CO_2, DAC still acts as a negative emissions technology as the CO_2 is captured and cut out from the ambience. The commercial viability of DAC is being tested by multiple companies that have heavily invested in DAC, and each company is developing a different method or working on improving the operational efficiency of an existing process. As of now five major DAC methodologies are being investigated and are at different stages of development: solvent, solid sorbent, electro-swing, cryogenic, and humidity/moisture swing. The review by Erans et al. (2022) comprehensively summarizes the developments of the different DAC methodologies. Solvent and solid sorbent based methods are the most mature technologies as of now and companies like Carbon Engineering and Climeworks are already operating pilot plants using these methods. A life cycle assessment done by Terlouw et al. (2021) found that for various energy sources, the efficiency varied from 9%-97%, with the best-case scenario being when waste heat and low carbon grid electricity were used. The authors also recommended an all-electric DAC system better for improving efficiency. Moreover, the location of the DAC plant should be in a region where low carbon grid electricity and CO_2sequestration location are available. Thus it is important to strategically decide the location before establishing a DAC facility.

Based on the literature reviewed, it is evident that DAC technique has a long way to go before it can be scaled to a level where it can help in achieving the climate targets. Most of the studies are done from the perspective of the western countries. Developing nations like India still heavily rely on fossil fuels for their energy needs. It has not yet been evaluated if direct air capture can be used by India to meet their climate targets. Moreover, there is a lack of knowledge of sequestration potential in India which makes it even more difficult to consider setting up a DAC facility in India. Nemget et al. (2018) in their study concluded that although a lot of literature is available on DAC but more relevant literature on post research and development topics like early deployment, niche markets, scale-up, etc. is still lacking.

In an attempt to bridge this gap, the current study aims to identify suitable locations in India from a short term and long term perspective where a DAC facility can be operated. Location selection of a plant is an old problem that the industry has been solving using various frameworks like factor rating method (FRM), weighted factor rating method (WFRM), load-distance method (LDM), etc. Two factors: clean energy and sequestration capacity, are considered for identifying the sites in India for DAC facilities installment. Each of these factors are explained in detail below.

2.1 Clean Energy
Clean energy in this study represents the amount of energy which is generated from clean energy sources including solar, wind, biomass, nuclear, and hydro. The benefits of the DAC strongly depend on the source of energy used to operate the plant (Deutz and Bardow 2021). In an ideal scenario, the plant should operate solely on clean energy, however that can be challenging as most of the DAC methods require energy in the form of both heat and electricity. Therefore, for a DAC facility to operate in India it will have to draw electricity from the grid, and it will become crucial to understand the electricity mix of the grid.

2.2 Sequestration Capacity
In order to store the captured CO_2in permanent geological structures it becomes important to assess if there is ample sequestration capacity near the DAC facility. The vicinity of storage sites with ample capacity will minimize emissions, energy, and costs associated with long distance transportation of capturedCO_2. However, sequestration capacity in India is not fully surveyed and literature provides only estimates of the sequestration capacity. Vishal et al. (2021) did a systematic evaluation of sequestration capacity in India and the data for this study are taken from their research. In the study, the researchers calculated the sequestration capacity for the 26 basins in India for four sequestration methods, enhanced oil recovery (EOR), enhanced coalbed methane recovery (ECMR), saline aquifers, and basalt formations. Another study argues that EOR and ECMR will lead to the development of technologies for storage in saline aquifers and basalt formations(Kearns et al. 2017).

2.2.1 Enhanced Oil Recovery (EOR)
Enhanced oil recovery is a mature and economical method for sequesteringCO_2. In this method, CO_2 is injected at high pressure in depleted oil fields or active oil fields (Voormeij and Simandl 2004). Typically, oil fields go through different primary and secondary phases of recovery and as a tertiary recovery method CO_2 injection can be used to

recover the gas reserves (Jimenez and Chalaturnyk, 2003). Moreover, repressuring the reservoir can help extract enough natural gas to compensate for the cost of CO_2 capture and injection (Davision et al. 2001).

2.2.2 Enhanced Coalbed Methane Recovery (ECMR)

Similar to EOR, carbon dioxide can be injected into coal beds to extract any methane present in the coalbed and store the CO_2 permanently. Along with the carbon dioxide sequestration benefit, methane production rate can be enhanced up to 90% with the help of injecting CO_2. Although this technique has problems associated with it like- injected gas breakthroughs, swelling of the coal matrix, and resulting in variable permeability (Sloss 2015).

2.2.3 Storage in Saline Aquifers

Saline aquifers are geological formations in which CO_2 can be stored in the pores of the sedimentary rocks inside the earth. CO_2 leakage is an issue associated with it, hence CO_2 trapping mechanism becomes a key point of consideration. According to a detailed review, geochemical trapping is an effective process for the short term, whereas mineral trapping is a more economically sound and safe mechanism in the long term (De Silva 2015).

2.2.4 Storage in Basalt Formation

Storage in basalt formation is a more permanent form of storage and a form of mineral trapping. The method is also known as mineralization or mineral carbonation. In this method, the injected carbon dioxide slowly reacts with metal oxides inside the earth to form carbonates and a solid byproduct like silicates which provide CO_2 on a geological timescale (IPCC 2005). This method is a better way of storing CO_2 permanently.

3. Methods

The current study aims to identify state wise sites in India that can be the most preferred location for setting up a DAC plant. Thus, a weighted factor method is used in the study and the two factors taken into consideration are clean energy mix and sequestration capacity.

For this study, two scenarios are considered as near term and long term which are explained in section 3.1 and 3.2 respectively. The clean energy factor is quantified using the installed capacity and estimated potential of clean energy from the Indian perspective. For the sequestration capacity factor, EOR and ECMR capacities are considered in near term as these methods are already mature and being used in many parts of the world. Saline aquifers and basalt formation capacities are considered for the long term scenario. Based on this data collected, the following equations are used to calculate the score for the different states and union territories of India.

3.1 Near Term Score Calculation

Near term scenario considers the current clean energy capacity and relatively mature sequestration methods for evaluation. In the near term scenario, it is operationalized by considering the percentage of installed electricity capacity coming from nuclear, hydropower plants or renewables like solar and wind.

$$\text{Clean Energy Score} = \frac{\text{Factor Weightage}\,.\,((\text{Clean Energy }\%)_{State\ or\ UT} - \text{Min}(\text{Clean Energy }\%))}{\text{Range (Clean Energy }\%)}$$

Where,

Factor weightage = 50 and 75 in case I and case II, respectively
Clean electricity % is taken from Table 1

$$\text{Mature Sequestration Capacity Score} = \frac{\text{Factor Weightage} \cdot ((\text{MSC} \cdot \text{SPM})_{State\ or\ UT} - \text{Min}(\text{MSC} \cdot \text{SPM}))}{\text{Range}(\text{MSC} \cdot \text{SPM})}$$

Where,

Factor weightage = 50 and 75 in case I and case II, respectively
Mature sequestration capacity(MSC) and sequestration prospectivitymodified(SPM) are taken from table 2

3.2 Long Term Score Calculation

Long term scenario considers the estimated potential clean energy capacity in future and potential sequestration methods that are still under development. In the long term scenario, the clean energy factor is operationalized by considering the estimated potential capacity of clean energy from solar, wind, biomass, and small hydropower plants in the future as per estimates.

$$\text{Potential Clean Energy Score} = \frac{\text{Factor Weightage} \cdot (\text{CEP}_{\text{State } or\ UT} - \text{Min (CEP)})}{\text{Range (CEP)}}$$

Where,

Factor weightage = 50 and 75 in case I and case II, respectively
Clean energy potential(CEP) is taken from Table 1

$$\text{Potential Sequestration Capacity Score} = \frac{\text{Factor Weightage} \cdot ((\text{PSC} \cdot \text{SPM})_{State\ or\ UT} - \text{Min(PSC} \cdot \text{SPM}))}{\text{Range(PSC} \cdot \text{SPM)}}$$

Where,
Factor weightage = 50 and 75 in case I and case II, respectively
Potential sequestration capacity(PSC) and sequestration prospectivity(SPM) modified are taken from table 2

4. Data Collection

Data for the clean energy factor was taken from a dashboard developed by NITI Ayog (https://www.niti.gov.in/edm/#elecCapacity, https://www.niti.gov.in/edm/#elecPotential). Table 1 shows the clean energy data taken for the near and long term. In the table, clean electricity percentage gives the percentage of clean energy in the electricity mix of the state, clean electricity capacity (GW) gives the capacity of clean energy installed in the state as of 2020 in GWh and clean energy potential (GW) gives the estimated clean energy capacity that the states can have in future in GWh.

Table 1. Indian clean energy for different states and union territories

S. No.	**State/Union Territory**	**Clean Electricity (in percentage)**	**Clean Electricity Capacity (GW)**	**Clean Energy Potential (GW)**
1	Andaman and Nicobar Islands	29.82	0.0170	0.00
2	Andhra Pradesh	33.79	10.0150	114.3000
3	Arunachal Pradesh	100.00	0.9520	11.1000
4	Assam	18.32	0.4570	14.4000
5	Bihar	4.91	0.3450	16.0000
6	Chandigarh	35.00	0.0420	0.00
7	Chhattisgarh	2.21	0.6730	19.9000
8	Dadar and Nagar Haveli	6.98	0.0060	0.00
9	Delhi	6.63	0.2170	2.2000
10	Diu and Daman	68.97	0.0200	0.00
11	Goa	2.40	0.0050	0.9000
12	Gujarat	29.67	13.7870	179.8000
13	Haryana	6.59	0.5870	6.4000

S. No.	**State/Union Territory**	**Clean Electricity (in percentage)**	**Clean Electricity Capacity (GW)**	**Clean Energy Potential (GW)**
14	Himachal Pradesh	95.85	10.7700	37.6000
15	Jammu and Kashmir	94.78	3.6490	112.8100
16	Jharkhand	4.15	0.3220	18.5000
17	Karnataka	56.89	20.1370	153.7000
18	Kerala	65.50	2.3660	10.0000
19	Lakshadweep	100.00	0.0010	0.0000
20	Madhya Pradesh	20.31	7.4540	79.3000
21	Maharashtra	30.02	14.8500	165.2000
22	Manipur	76.32	0.1160	10.7000
23	Meghalaya	83.26	0.3680	6.1000
24	Mizoram	38.78	0.0380	9.3000
25	Nagaland	100.00	0.1070	7.5000
26	Odisha	10.74	2.7210	34.6000
27	Puducherry	3.03	0.0080	0.4000
28	Punjab	24.31	2.5650	6.9000
29	Rajasthan	45.90	11.5190	271.2000
30	Sikkim	100.00	2.2210	5.2000
31	Tamil Nadu	49.30	20.7410	88.2000
32	Telangana	41.39	6.4890	45.3000
33	Tripura	2.16	0.0250	2.1000
34	Uttar Pradesh	13.32	4.2340	25.0000
35	Uttarakhand	82.65	4.4340	18.6000
36	West Bengal	10.26	1.8340	8.2000

Table 2. Sequestration capacity data and storage perspectivity (Vishal et al. 2021)

S. No.	**State/Union Territory**	**Sequestration Capacity (Gt)**		**SequestrationProspectivity**	
		Mature Sequestration (Gt)	**Potential Sequestration (Gt)**	**Initial**	**Modified**
1	Andaman and Nicobar Islands	0.00	12.35	3.00	0.33
2	Andhra Pradesh	0.9000	27.63	3.00	0.33
3	Arunachal Pradesh	0.6978	46.46	1.00	1.00

S. No.	State/Union Territory	Sequestration Capacity (Gt)		SequestrationProspectivity	
		Mature Sequestration (Gt)	Potential Sequestration (Gt)	Initial	Modified
4	Assam	0.6784	46.46	1.00	1.00
5	Bihar	0.1672	13.68	4.00	0.25
6	Chandigarh	0.00	0.00	4.00	0.25
7	Chhattisgarh	0.4242	8.12	4.00	0.25
8	Dadar and Nagar Haveli	0.00	0.00	4.00	0.25
9	Delhi	0.00	0.00	4.00	0.25
10	Diu and Daman	0.00	0.00	4.00	0.25
11	Goa	0.00	25.3300	3.00	0.33
12	Gujarat	2.2545	80.7300	3.00	0.33
13	Haryana	0.00	0.00	4.00	0.25
14	Himachal Pradesh	0.00	0.00	4.00	0.25
15	Jammu and Kashmir	0.00	0.00	4.00	0.25
16	Jharkhand	0.00	13.6800	4.00	0.25
17	Karnataka	0.0995	41.8200	4.00	0.25
18	Kerala	0.0995	41.4100	3.00	0.33
19	Lakshadweep	0.00	25.3300	4.00	0.25
20	Madhya Pradesh	0.2315	255.3100	4.00	0.25
21	Maharashtra	1.6819	258.9000	4.00	0.25
22	Manipur	0.00	32.3000	1.00	1.00
23	Meghalaya	0.0045	8.7700	4.00	0.25
24	Mizoram	0.00	32.3000	1.00	1.00
25	Nagaland	0.0005	32.3000	1.00	1.00
26	Odisha	0.4975	3.2500	4.00	0.25
27	Puducherry	0.0002	0.00	4.00	0.25
28	Punjab	0.00	0.00	4.00	0.25
29	Rajasthan	0.3125	19.1400	3.00	0.33
30	Sikkim	0.00	0.00	4.00	0.25
31	Tamil Nadu	0.1355	16.0800	1.00	1.00
32	Telangana	0.2360	6.1400	4.00	0.25
33	Tripura	0.00	32.3000	1.00	1.00

S. No.	**State/Union Territory**	**Sequestration Capacity (Gt)**		**SequestrationProspectivity**	
		Mature Sequestration (Gt)	**Potential Sequestration (Gt)**	**Initial**	**Modified**
34	Uttar Pradesh	0.00	13.6800	4.00	0.25
35	Uttarakhand	0.00	0.00	4.00	0.25
36	West Bengal	0.5967	60.3500	3.00	0.33

Data for sequestration capacity was taken from the recent study by (Vishal et al. 2021). Table 2 shows the sequestration capacity for each states and union territories in India. This data was given basin wise in the source article, based on the location of each basin the state wise data is calculated. In this table, mature sequestration capacity (Gt) gives the sum of CO_2 storage capacity in EOR and ECMR in gigatonnes, and potential sequestration capacity (Gt) gives the sum of CO_2 storage capacity in saline aquifers and basalt formations. The sequestration prospectivity provides a classification of the sequestration location with 1 (representing very high potential) to 4 (representing very low potential), to use this in weighing the sequestration capacity. This classification is converted to a weightage metric by taking the reciprocal of the sequestration prospectivity. The new weightage factor is given in the sequestration prospectivity modified column.

5. Results and Discussion

Based on the literature review ((NASEM (2019), Erans et al. (2022), Fasihi et al. (2019), van der Giesen et al. (2017)), a comparison of various DAC methodologies was carried out to understand the strengths and weaknesses of each DAC methodology with respect to each other, as shown in table 3. The factors defined for the evaluation are technology readiness, cost of CO_2 capture, material used, capture efficiency, energy requirements, and advantages.

5.1 State Wise Total Score for Short Term and Long Term Perspectives

In the case of equal weightage (case I) and near-term scenario, Anurachal Pradesh was found the most preferred location based on the framework being used. Figure 1 gives the total score of each state. As shown in the chart following states- Arunachal Pradesh, Gujarat, Assam, Nagaland, and Lakshadweep are the most preferred locations. On a deeper inspection it was found that, in Arunachal Pradesh 100% of installed electricity capacity comes from clean sources and the total installed electricity capacity is less than 1 GWh which is significantly less as compared to states like Gujarat and Maharashtra. Although Arunachal Pradesh gets a very high score as it has 100% clean grid electricity, it may not be the favorable location for a DAC facility as the installed capacity is less.

Similarly Assam, Nagaland, Lakshadweep, and Sikkim all have a high score but low installed capacity, thus might not be preferred as suitable DAC locations. Practically it can be assumed that Gujarat will be the most preferred location followed by Himachal Pradesh, Jammu & Kashmir, Maharashtra, and Uttrakhand. It is also worth noting that Gujarat has the least clean electricity percentage among the top 5 states but it still is most preferred due to available sequestration capacity.

Maharashtra is the most preferred location in the long-term scenario as it has high clean energy potential and is a home to basalt formations, which have high potential sequestration potential. In the long-term scenario, instead of the percentage of clean electricity directly the capacity is used to score so an additional inspection is not required. However, in the case of Assam, the potential clean energy is low compared to the other top 4 preferred states, this is because the potential sequestration capacity in Assam is high and has high modified sequestrationprospectivity. Therefore it is ranked higher than other states.

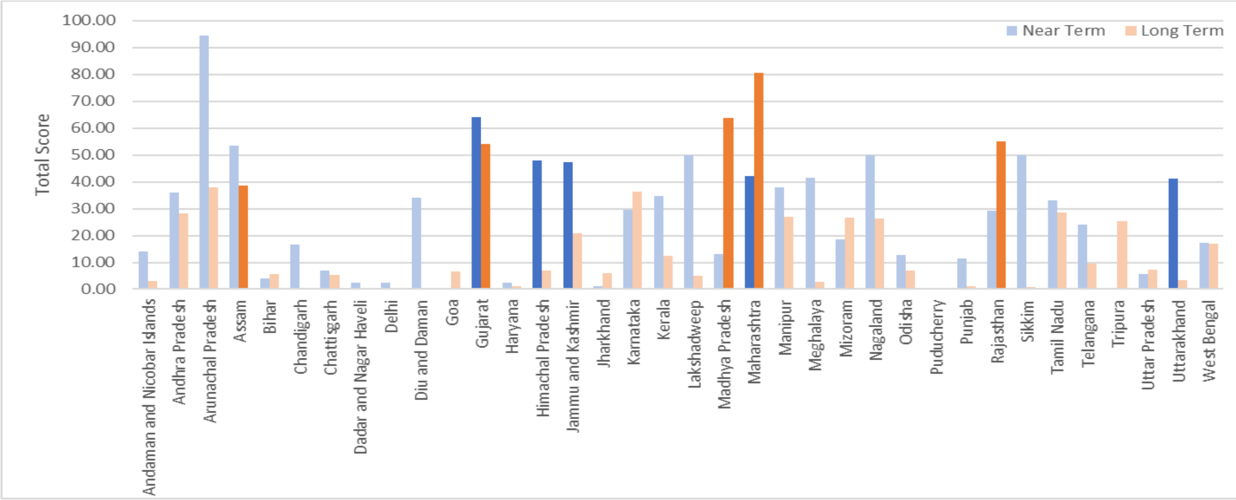

Figure 1. The state-wise total score for case I

In case II, clean energy is given a 75% weightage thus it drives the preferred location. However, it is not known what are the exact weights of the two factors should be but this scenario helps in testing how the weightage may change the results. Similar to case I, although the north eastern states rank high according to the framework may not be best suited as the installed electricity capacity in these states is low. However, a change can be seen in the ranking of the states like Himachal Pradesh, Jammu & Kashmir, and Uttarakhand are above Gujarat in this scenario as they have a higher percentage of clean electricity. Figure 2 shows the score for all the states and union territories.

In case II and long-term scenarios, states with higher estimated clean energy potential are ranked higher. Rajasthan is the most preferred location instead of Maharashtra. As the weightage to clean energy has increased for this case.

Table 3: Comparison of various DAC methodologies

Factor for Comparison	**DAC methodology**				
	Liquid Solvent Based	**Solid Sorbent Based**	**Cryogenic**	**Electro Swing**	**Humidity and Moisture Swing**
Principle of Working	Absorption	Adsorption and desorption	Sublimation of CO_2	Redox-active adsorption	Sorbent CO_2 holding capacity based on humidity
Technology Readiness	Pilot demonstration by carbon engineering	Pilot demonstration by clime works	Proof of concept to lab-scale plant	Proof of concept to lab-scale plant	Proof of concept to lab-scale plant
Material Used	Solvent KOH and $Ca(OH)_2$ for available regeneration	Amine based sorbent and polymer used by clime works and global thermostat.	NA	Quinone based electrodes	Polymer-based material

Factor for Comparison	**DAC methodology**				
Cost of Capture	\$94-\$232/tonne of CO_2	\$600/tonne of CO_2	Very high cost if used as a standalone.Integrated with liquefied air energy storage to reduce cost	NA	NA
Energy Required	Heat: 1458 kWh/tCO_2 + Electricity: 366 kWh/tCO_2	Low Grade Heat: 1170-2000 kWh/tCO_2 + Electricity: 150-300 kWh/tCO_2	NA	NA	Electricity: 377.6 kWh/tCO_2
Capture Efficiency	Depends on the energy sources. Multiple life-cycle assessments show that in the case of low carbon energy sources the capture efficiency can go above 90% and can be as low as 10% if coal is used as a fuel source				
Advantages	Mature technology	Allow utilization of low-grade heat	Can be linked with liquid air energy storage (LAES) plant	Electrified,Does not require heat energy	Relatively low energy consumption than all other methods

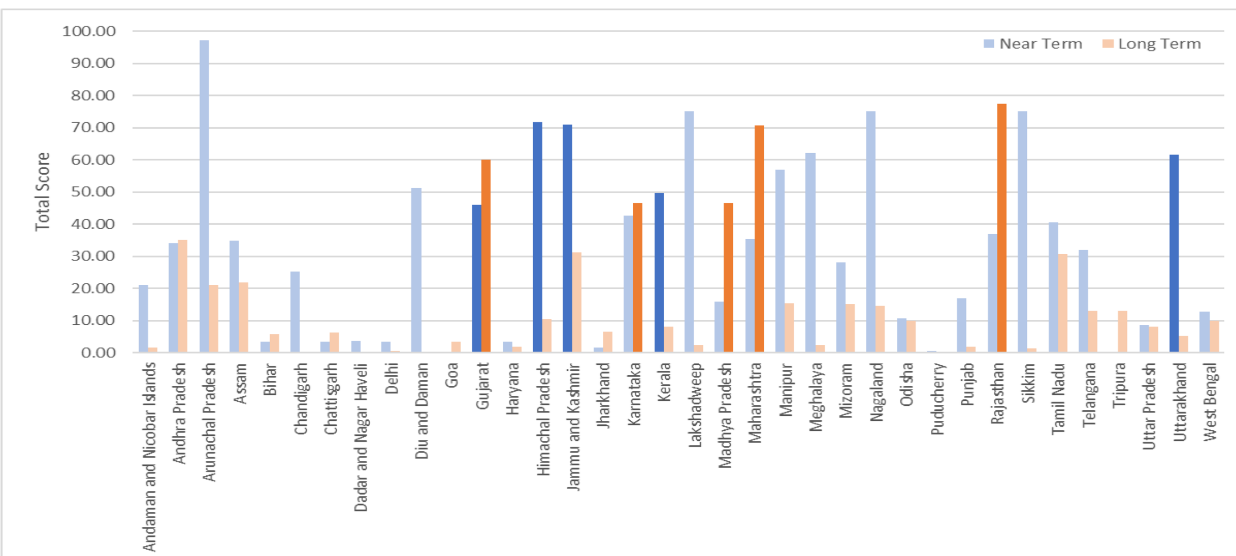

Figure 2. The state-wise total score for case II

6. Conclusions

Direct air capture is an important negative emissions technology having significant potential to combat climate change. DAC is getting a lot of attention from investors, who see a potential in the technology to complement the decarburization efforts being carried out throughout the globe. Different DAC methodologies can be used to remove CO_2 from the atmosphere and each has its advantages and limitations. Solvent and solid sorbent based systems are currently the most mature methods. Companies are trying to scale up these processes and reduce the cost of capture. The study provides a brief comparison of the different DAC methodologies. Available literature pointed out that the energy source and the nearness to the sequestration capacity are two major factors that determine the efficiency of a DAC system. Based on these two factors a weighted factor method is developed in the study to evaluate all states and union territories in India for this potential to set up DAC facilities. It was found that in the near term, Gujarat is most preferred when both factors have equal weightage and Himachal Pradesh is most preferred when clean energy is given a 75% weightage. But considering the geography of Himachal Pradesh which lies in the Himalayas, construction of a DAC facility might be challenging and thus Gujarat will be preferred. In the long term, Maharashtra and Rajasthan are the most preferred states for equal weightage scenarios and 75%-25% weightage scenarios, respectively. Both the locations have significant renewable energy potential and sequestration capacity which makes them suitable for the long term scenario. It is interesting to note that Gujarat is among the top five preferred states in the long term scenario for both cases, thus it is beneficial to establish a DAC facility in Gujarat as it has potential not only in the near term but also in the long term. The current study only uses two factors– clean energy and sequestration capacity– for the evaluation of DAC methodologies. In future, it will be interesting to develop more factors for the evaluation. Moreover, the future studies can be carried out to compare various DAC methodologies based on their maturity and viability. India also requires a more comprehensive survey of sequestration capacity. Currently most of the literature only provides an estimate of the sequestration capacity based on theoretical and empirical formulas. More research on DAC from an Indian perspective can help in increasing the awareness about the process, which can lead to more stakeholders considering DAC to include in India's actions against climate change.

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