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COMPARATIVE ANALYSIS OF THREE DIFFERENT NEGATIVE EMISSION TECHNOLOGIES, BECCS, ABSORPTION AND ADSORPTION OF ATMOSPHERIC CO_2

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Abstract

Negative Emission Technologies (NETs) are generally considered as vital methods for achieving climate goals. To limit the rise in the global average temperature below 2 °C, a large number of countries that participated in the Paris agreement was virtually unanimous about the effective collaboration among members for the reduction of CO_2 emissions throughout this century. NETs on the ground that can remove carbon dioxide from the atmosphere, provide an active option to achieve this goal.

In this contribution, we compare limiting factors, cost, and capacity of three different NETs, including bioenergy with carbon capture and storage (BECCS), absorption and adsorption. Although there are several advantages for capturing CO_2, still some constraints regarding the high operational cost of NETs and industrial condition of these technologies as a method of climate change mitigation is not clear. Thereby no single process can be considered as a comprehensive solution. Indeed, any developed technologies, in turn, have a contribution to the reduction of CO_2 concentration. Extensive research needs to be done to assess and decrease NETs costs and limitations.

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Keywords: negative emission technology, climate change, BECCS, absorption, adsorption, CO_2

1. INTRODUCTION

Undoubtedly, global warming has arisen from rising greenhouse gas (GHG) concentration in the atmosphere is the paramount important environmental concern throughout the world [4,76,88]. the high concentration of greenhouse gases in the atmosphere causes various environmental problems such as floods, the increasing number of ocean storms, continuous rise of water level in the sea, melting the ice cap, etc. [2,17,55,61,95].

CO_2 as one of the greenhouse gases has a higher contribution to global warming than other gases which accounts for almost more than 55% of global warming [32]. After the industrial revolution, the atmospheric concentration of CO_2 has risen rapidly by 50% [3,35,89].

Despite efforts have been done to mitigate negative consequences of CO_2 emissions and other greenhouse gases (GHGs) since two decades ago, the rate of greenhouse gas emissions in the 2000s increased more than in comparison to the previous decade and by 2010 had reached approximately to 50 Gt CO_2 per year [54,67]. The zero tolerance policy should be considered for the reduction of global atmospheric CO_2 concentration to reach the international goal of limiting warming to less than 2°C compared to before the industrial era [1,11,25].

Recently, a large proportion of climate mitigation efforts focus on reducing emissions of CO_2 to the atmosphere, for example by increasing the energy efficiency of technologies, switching to low or zero-carbon fuel sources, and negative emission technologies[22,26,49,77,90].

A large number of scenarios was assessed by the international panel on climate change (IPCC) to reduce atmospheric CO_2 concentration, these scenarios used to estimate the 2 °C with 66% likelihood carbon budget showing the necessity of negative emissions technologies [20,23,46,74,79,93].

Based on estimates was done by Rogelj et al [79] in 2011, two main urgent actions are set to be required; more reductions in fossil fuel utilization or more carbon dioxide removal.

Negative emissions technologies as feasible solutions provide effective ways to capture and reduce the amount of CO_2 in the atmosphere to achieve the international target of CO_2 concentration in the atmosphere. It is essential to note that the deployment of NETs needs to be received financial aids by governmental due to the lack of tax incentive financed by fossil energy users [6].

There are two different methods of NETs, direct air capture and indirect air capture, as shown in table 1, distinct techniques exist regarding to these methods such as: (1) BECCS [13,15,45,53,57], (2) afforestation and reforestation (AR)

[36,85], (3) absorption [40], (4) adsorption [5], (5) biochar [27,99], (6) soil carbon sequestration [80,101], (7) ocean fertilization [50,97], (8) ocean alkalinity enhancement (OAE) [56,75], and (9) algae culture [10,12].

This paper summarizes an overview of the options and the current status of the three main different NETs, such as BECCS, absorption, and adsorption for capturing atmospheric CO_2. Also, in this paper, we examine three distinct features of each technology, including limiting factors, potential capacity, and cost estimate.

Table 1. Negative Emission Technologies

Method	Technique	CO_2 Removal Mechanism	CO_2 Storage & utilization Method
Indirect air capture	BECCS [13]	Biological + CO_2 Capture	Deep Geological Formations
	AR[85]	Biological	Soils
	Ocean fertilization [97]	Biological	Ocean
	Biochar [27]	Biological	Soils
	Algae culture [10]	Biological	Energy production
Direct air capture	Absorption[40]	Chemical	Deep Geological Formations
	Adsorption [5]	Physical	Deep Geological Formations
	Soil carbon sequestration [101]	Biological	Soils
	Ocean Alkalinity [56]	Chemical	Ocean

2. INDIRECT AIR CARBON CAPTURE

Atmospheric CO_2 is captured in the natural process of the carbon cycle and then converts into the organic carbon by the photosynthesis reaction, while oxygen is made as a product of this reaction [28]. Compared to direct capture methods, the most important advantage of the biological route is that it requires less energy [59]. Moreover, the operating and investment cost of direct air capture is expensive, and until now the long-term efficiency of it has unproven [24].

The indirect air capture can be separated into five different processes: (1) ocean fertilization, (2) biochar, (3) AR, (4) Algae culture, and (5) BECCS. Because the BECCS process received more attention in the last two decades in comparison to the indirect carbon capture processes, it is described in the next section.

2.1. Bioenergy with carbon capture and storage

BECCS is a geoengineering technique to remove carbon dioxide from the atmosphere that is the combination of biomass combustion and Carbon Capture and storage (CCS). It is possible to use biomass as a fuel source in two different ways, combustion of it as single fuel for power generation or using it in combination with other conventional sources of energy such as natural gas or coal (co-fired generation) [9,38,69]. CCS is a technology that can capture carbon dioxide emissions produced from the use of fossil fuels in industrial processes, preventing carbon dioxide from entering the atmosphere. The CCS consists of three parts; capturing carbon dioxide, transporting the carbon dioxide, and securely storing carbon dioxide emissions, underground in deep geological formations. Whereas the combination of CSS and biomass reduces the atmospheric CO2 by taking it temporarily locked in plants and then storing it permanently in geological formation, it is known as negative emission technology [8,16,83].

BECCS technology is considered an appropriate way to respond to the problems caused by global warming in the current century [42,62]. According to some studies, the BECCS has the potential of capturing an acceptable rate of atmospheric CO2 that if combined with other mitigation options, could help to reduce CO2 concentration to pre-industrial level [51,72], while contributing to global economic growth [91]. Creutzig et al [15] examined the strength of BECCS as a long-term mitigation approach. They declared that this method can use for a large number of technologies with various CO2 emissions range such as biomass refineries, power plants or biomass gasification plants [92]. BECCS as one of the significant technology among the negative emission technologies can help to reach the international temperature goal. Moreover, negative emissions that arise from the deployment of the BECCS process can compensate for the residual emissions in other sectors, such as paper, cement, and steel industries or in the transportation sector.

The extensive demand for land is considered as one of the main side-effects of BESSC. This can weaken both the capability of negative emissions if greenhouse gas emissions from biomass supply chain are considered [92] and also the potential of land for use of food production and other purposes [92]. Thereby, it is crucial to allocate the marginal land as well as waste biomass feedstocks to benefit more from BECCS implementation. The BECCS potential has been evaluated by the different countries throughout the world, for example, using organic waste from the forestry, agricultural, and municipal sectors was implemented by Australia [70].

Recently, some studies identified the environmental and economic impacts of four BECCS options; bagasse, solid waste of municipal, forest residual, and landfill gases which are combusted in a gas turbine. The cost-effectiveness of negative

emission was studied in Brazil using sugar cane, bagasse, and other residuals to produce ethanol and electricity simultaneously [63]. The Nordic countries have the largest potential of biomass in the world, this feature facilitated the deployment of BECCS in this region [81]. Moreover, the use of biomass is widespread in other regions of the world. In Korea [44] and Austria [84], domestic biomass use as a bioenergy source. In North America, the use of agricultural residues and wastes are common because they have the potential to achieve a 145% emission reduction by 2050 compared to 1990s levels [82].
The concept of BECCS depicts in fig 1. In this process, CO_2 produces after the combustion of biological materials (biofuel, biomass, and biogas) and then captures from flue gas via one of the three different CO_2 capture technologies, namely Post combustion, pre combustion, and oxy combustion [18]. Finally, approximately pure CO_2 which is released can be used in different industrial processes or stored in the geological formations, these two processes lead to neutral emissions and negative emissions, respectively.

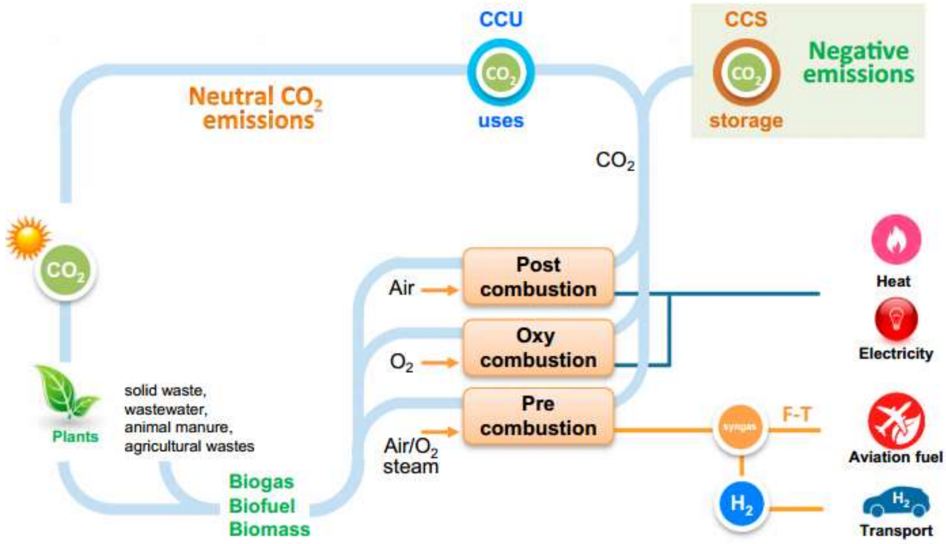

Fig.1. Bioenergy with carbon capture and storage [60]

Biomass has been used generally as an energy source in the history of humankind. The combination of biomass and CCS for the first time was identified by Williams et al [98] in the hydrogen production process, and by Herzog for power generation in 1996 [30].
According to the scientific predictions the contribution of biomass use in the energy system can exceed by 27% in 2050 [21]. In the shorter term, Panoutsou et

al [66] and Hoefnagels et al [31] estimated the potential share of biomass in Europe's energy system in 2020 to increase to 10.6% and 14.0%, respectively. Besides, Schakel et al [83] identified the technical potential of six different BECCS options that co-fired with other sources of fuels.

Although Biomass has some limitations such as lower heating value compared to coal and higher moisture content, it has low NO_X and SO_X emissions. Moreover, owing to the assessment of this technology that has been done recently, the capability of deployment this technology on a commercial scale is still unclear [25,94]. Besides, one of the most concerning issues regarding the CCS is the safety of the CO_2 storage process that still does not accept by the general public [94].

3. DIRECT AIR CARBON CAPTURE

Formulae, In addition to indirect capture, DAC is considered as an alternative route for capturing CO_2 from the atmosphere. In this approach atmospheric CO_2 captures via industrial processes [7,47]. DAC is a relatively new and innovative technology in early commercial stages [65], which can help humankind to mitigate the dire consequences of global warming by using conventional technologies in the long term [39,64].

The economic feasibility of DAC systems have investigated in several pieces of literature. They reported costs ranging from \$ 30 to \$ 1000 per ton of removed CO_2 [33]. According to the arguments on physics, thermodynamics, and entropy, the cost of this technology has been widely criticized [73]. However, there is still no comprehensive agreement on the economic feasibility of this process. For example, Simon et al [86] argued that owing to climate mitigation scenarios DAC can be cost-effective in the future, while Ranjan and Herzog [71] asserted that the costs of DAC systems in comparison to other mitigation approaches is high. The atmospheric CO_2 can be directly captured by the following methods [96,105]: (1) absorption and (2) adsorption.

3.1. Absorption

Absorption technology for capturing carbon dioxide using alkaline solution has been explored since half a century ago. [19,104]. For the first time, using large scale scrubbing of CO_2 from ambient air as a climate mitigation technology was suggested by Lackner in the late 1990s [48]. In wet scrubbing techniques, CO_2 is absorbed into a solution of sodium hydroxide (NaOH) or potassium hydroxide (KOH). According to fig 2, two successive cycles can happen simultaneously for aqueous solutions.

In the first cycle, the ambient air enters to the process with the help of existing fans in the system and then in contact with the NaOH which is sprayed as a solvent in the process and sodium carbonate (Na_2CO_3) is formed by reaction of CO_2

molecules and sodium hydroxide (Eq. 3.1). Then, the rich-CO_2 solution is sent to the regeneration cycle and the air with a lower concentration of CO_2 leaves the column.

In the regeneration cycle, NaOH is recovered as a result of the reaction between Na_2CO_3 with calcium hydroxide ($Ca(OH)_2$) in the causticiser unit (Eq. 3.2). Then NaOH is sent back to the absorption cycle. Simultaneously, in the most energy-intensive step, pure CO_2 is released by a reaction that $CaCO_3$ is heated up to about 900 °C and CO_2 collected afterward (Eq. 3.3).

In the last step, water is mixed with CaO in the slaker unit for $Ca(OH)_2$ regeneration (Eq.3.4).

Contactor	$2NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O$	(3.1)
Causticiser	$Na_2CO_3 + Ca(OH)_2 \rightarrow 2NaOH + CaCO_3$	(3.2)
Calciner	$CaCO_3 + Heat \rightarrow CaO + CO_2$	(3.3)
Slaker	$CaO + H_2O \rightarrow Ca(OH)_2$	(3.4)

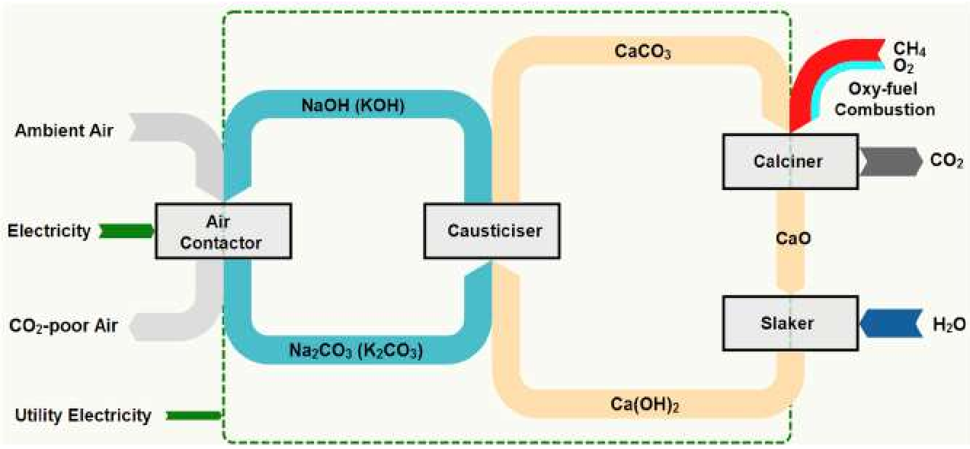

Fig.2. Absorption air capture with sodium hydroxide (NaOH) and potassium hydroxide (KOH) [41]

According to literature reports, the efficiency of CO_2 absorption on new materials based on amide polymeric ionic liquids is currently being investigated. New class of amide-based polymer ionic liquids, which are characterized by high CO_2 capture efficiency, it may be characterized by low costs and high CO_2 capture efficiency.

3.2. Adsorption

In this process, air is pumped and then passed through the filter that is coated by alkaline adsorbents. Regeneration of filters is the most important financial limitation in the desorption process. To decrease the recovery cost of CO_2, using regenerable adsorbents that can be utilized in multiple cycles paramount important [52]. Pressure swinging adsorption (PSA) and temperature swinging adsorption (TSA) are common methods for CO_2 desorption. PSA is a technology for gas separation under high pressure according to the gas characteristics in the adsorption process, then the desorption process happens at a pressure close to the atmospheric pressure. In TSA, hot air or steam is injected to raise the system temperature to regenerate the solid adsorbents from absorbed CO_2 [52]. Although the regeneration time for TSA is much longer than PSA, some features of TSA such as the potential for high recovery of CO_2 with a relatively pure concentration that is reduced the energy demand to pressurized CO_2 is considered as the main advantage of this process.

In commercial sectors for the high concentration of CO_2 in the air, the adsorption process has several practical advantages in comparison to the absorption process. Thermal durability in different conditions, the lower energy requirement for regeneration, resistance to corrosion, and the lower environmental concern for the solid waste compared to the liquid waste are the main superiorities of adsorption. [103].

In the selection of adsorbents three main features such as the regeneration ability, specific surface area, and the selectivity of adsorbents should be considered. Activated carbon and zeolites are two types of adsorbents that have been used recently because they have higher stability and selectivity even at low concentrations [102].

Wurzbacher et al. [100] assessed the performance of amine-functionalized sorbents for the extraction of CO_2 from the air in the adsorption and desorption processes by TSA.

In 2017, the Swiss company, Climeworks, commissioned the world's first commercial DAC plant (fig.3). In this plan which is worked according to desorption and adsorption processes with alkaline adsorbents, CO_2 is chemically bonded to the absorbents located on the filter and then CO_2 desorbed by TSA. During the TSA process, the temperature is raised from 80 to 120 °C while the pressure in the system is decreased simultaneously, thereby captured CO_2 is released. Then the process is repeated after the cooling stage [29].

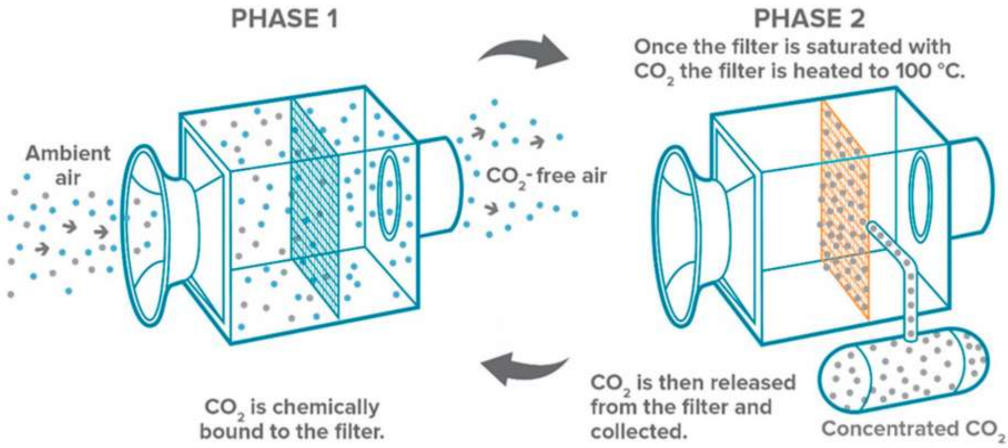

Fig.3. Schematic illustration of Climeworks direct air capture process [29]

According to the climate policies NETs are a valid option for supporting climate change targets. Many accounting frameworks consider these technologies as one of the vital approaches to mitigate the dire consequences of global warming. We already mentioned three different technologies, BECCS, absorption, and adsorption to reach a fairly clear conclusion, the important issues regarding these technologies should be addressed, including limiting factors, the potential capacity of atmospheric CO_2 capture and cost estimates of each technology.
Amine-functionalized solids are other types of adsorbents that have been used recently because they have higher stability and selectivity even at low concentrations.

4. LIMITING FACTORS

In table 2 the limiting factors associated with each technology are represented. The leading limiting factor related to all the NETs is the storage capacity of CO_2 in geological formations [59]. According to the former estimations approximately the storage capacity of 1200 Gt for CO_2 captured by NETs is needed. It seems that it is possible to store around half of this figure with techniques that do not rely on geological storage. BECCS on the ground that it has an energy penalty associated with CCS technology would require more storage approximately between 750-900 Gt CO_2. It might be that the absorption and adsorption also need additional storage, especially when fossil energy were utilized to power wet calcination, a factor of 2.0 might be applied [87]. If alternative methods for storage such as

basaltic injection can be used at acceptable cost instead of geological storage, then this figure may be declined [43].
Moreover, availability of land, water, and fertilizer are other constraints regarding to BECCS, Christopher Consoli [14] estimated that if we want to meet CO_2 emission target, it would need two times more than the annual world use of water for agriculture and twenty times the annual use of nutrients, and also need 300-700 million hectares land. A significant amount of water is lost in the adsorption process (at 15°C and 65% relative humidity, approximately 20 mol H_2O per mol of CO_2), which optimization of system and operation condition can be decreased it. [68].

Table 2. Limiting factors of absorption, adsorption, and BECCS

Limiting factors	Technology
CO_2 Storage capacity [59]	BECCS, Absorption, Adsorption
Sustainable supply raw materials [59]	BECCS, supply of biomass. Absorption ,absorbers selection Adsorption ,adsorbers selection
Availability of land, water and fertilizers [14]	BECCS
Corrosion [59]	Absorption
Water loss [68]	Absorption

5. CO_2 CAPTURE CAPACITY

The annual potential capacity of the NETs according to the forecast estimates until 2050, represents in table 3. The figures for both absorption and adsorption was estimated 10 Gt CO_2 per year [57], these figures change according to the adsorbent or solution and percentage of atmospheric CO_2 that use in these processes. BECCS capacity is predicted to be 2.4–10 Gt per year, the total global CO_2 capacity is estimated to be 72-300 Gt CO_2 by 2050 (is predicted for 2020-2050) [34]. This figure varies depending on three distinct factors, kinds of biomaterials using for combustion, the percentage of biomass combined with fossil fuel and the technologies that use for capturing the CO_2 such as; oxy-fuel combustion capture, pre combustion capture, post combustion capture, and chemical looping process [59].

Table 3. Assessment of CO2 capture capacity and cost

Technique	Potential capacity Gt CO_2 Per year	Cost estimates $ per ton CO_2
BECCS	2.4- 10 [59]	15-400 [14]
Absorption	10 [59]	40-600 [68]
Adsorption	10 [59]	40-600 [68]

6. COST ESTIMATES

Table 3 represents the cost estimates of BECCS, absorption and adsorption processes per ton CO_2 stored, these figures have collected according to the literature. Generally, cost estimates mentioned in the literature are changed from \$8 to more than \$1000 per ton of CO_2 is captured by NETs [58].
The BECCS cost was estimated by researchers in different literature according to their criteria and consideration, most of the figures was calculated fairly optimistic for 2020 or even 2030, especially when the deployment of CCS generally remains slow, and a value of \$150/t CO_2 is considered for this process, as presents in table 3 this figure is \$15-400/t CO_2, varying widely according to CCS process and kinds of biomaterial utilizing in this technology [14].
Keith et al [40] report the cost of captured CO_2 around \$70/t CO_2 from the air. While IEAGHG [31] cites costs of \$70–110/t-CO_2 avoided for BECCS, Karlsson et al [37] suggest, more optimistically, costs of BECCS in Sweden between \$75–95/t-CO_2 by 2020, and significantly lower by 2030.
The cost of absorption and adsorption technologies were estimated to be at the range of \$40-600/t-CO_2 according to operation parameters [68]. For example for the only existing commercial direct air capture machine which is depicted in fig 3, CO_2 captures at a cost of \$600/t CO_2 [68].

7. CONCLUSIONS

Despite the low concentration of CO_2 in the atmosphere, CO_2 capture with direct and indirect way from the atmosphere with utilizing negative emission technologies seem to be powerful techniques to mitigate the dire consequence of climate change. According to the findings of this work, the potential capacity of CO_2 capture for absorption and adsorption technologies is more than BECCS. However, the price of capturing CO_2 for these two technologies, in most cases, are more than BECCS. Besides, the constraints regarding the BECCS are much more than two other techniques.
Owing to this assessment, NETs, in turn, failed to be considered as an economically effective alternative for mitigation of global warming in the coming decades. Significant technological development and adequate international subsidization would be necessary to overcome such constraints and reduce the cost of utilizing these technologies.
Indeed, NETs should be seen as a complementary action to achieve climate targets until the end of this century. The combination of these technologies with other conventional methods may reduce the overall costs of the process.

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