Carbon Dioxide Capture and Sequestration to Achieve Paris Climate Targets

Pushp Bajaj and Saurabh Thakur

Abstract The Paris Climate Agreement, signed by over 190 countries at COP21 of the UNFCCC in 2015, set a unique precedent in the global fight against climate change. The signing parties agreed to limit global warming well below 2 °C, aiming for 1.5 °C, which poses a herculean task for the international community. Studies have shown that this target could only be achieved through drastic cuts in global greenhouse gas emissions and large-scale removal of excess carbon dioxide from the atmosphere. In this context, this chapter highlights the latest developments in the science and technology of carbon capture and storage techniques, including land-based and ocean-based techniques, bio-energy with carbon capture and storage (BECCS), and direct air capture (DAC), which would be critical in our efforts to mitigate climate change. The chapter also discusses the technological, financial, ethical, and socio-political challenges and limitations that would need to be addressed for large-scale deployment of carbon capture and storage technologies. As global carbon emissions continue to rise unabated, the need for carbon dioxide removal technologies will grow simultaneously. More research and development is needed to solve the outstanding problems and make these technologies safe, sustainable, and economically feasible for large-scale deployment.

Keywords Carbon dioxide capture · Carbon sequestration · Paris agreement · Negative emissions · BECCS · Direct air capture

1 Introduction

In 2015, the global average temperature rose 1 degree Celsius (°C) above pre-industrial levels (1850–1900 average) for the first time. Last year, 2020, tied with 2016 for the hottest year ever recorded at 1.25 °C above the 1850–1900 average (Carrington 2021). This marked an important milestone; the last time the planet was more than 1 °C warmer was during the last interglacial period around 1,20,000 years ago (NEEM Community Members 2013). While 1 °C may appear to be a small

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change, on average, it corresponds to a very different climate on planet Earth. This 1 °C rise in temperature has modified the hydrological cycle, the carbon cycle, and other natural cycles. The global mean sea level has increased by about 21–24 cm (cm) since 1880 (Lindsey 2020). Extreme weather events, such as heatwaves, droughts, extreme rainfall, cyclones, storm surges, etc., have become more common, more intense, and less predictable.

What is more worrisome is that the temperature rise is accelerating. With the increase of every fraction of degree, the impacts on the natural cycles grow larger and, in turn, the socio-economic impacts on human civilisations increase exponentially. This temperature rise is being fuelled primarily by the relentlessly rising greenhouse gases in the atmosphere primarily emitted by the burning of fossil fuels by humans (Mann et al. 2016; Hansen and Stone 2016; UCSUSA 2017). Among them, the most important greenhouse gas is carbon dioxide (CO_2) due to its long 'lifetime' in the atmosphere. Once emitted, CO_2 stays in the atmosphere for several hundreds to thousands of years before being removed by natural processes (Archer et al. 2009). In other words, planetary temperatures will continue to rise as long as we continue to emit CO_2 into the atmosphere and this warming will be irreversible on the order of hundreds to thousands of years considering the long lifetime of CO_2 in the atmosphere.

In this context, this chapter will highlight why CO_2 capture and storage are absolutely essential in humanity's efforts to mitigate climate change by bringing down the atmospheric CO_2 concentration to "safe levels". And how it can be achieved using a combination of nature-based and technological methods. Section 2 will outline the ambitious 2015 Paris Climate Agreement targets and how they can only be achieved with large-scale use of carbon dioxide removal (CDR) techniques in addition to drastic reductions in greenhouse gas emissions. The major CDR techniques that are currently being explored and implemented, albeit at small scales, by the international community, will be critically analysed in Sect. 3. Finally, Sect. 4 will discuss the ethical, political and economic challenges and discuss potential future pathways for successful large-scale deployment of CDR in order to accomplish the daunting task of restoring the climate to normalcy.

2 The Key to Achieving Paris Climate Targets

The Paris Climate Agreement, signed by over 190 countries in Paris at the 21st Conference of Parties (COP21) of the United Nations' Framework Convention on Climate Change (UNFCCC), is a unique and unprecedented international climate agreement. For the first time, almost all nations of the world came together and agreed that climate change poses a serious threat to global security and prosperity. The signatories of the agreement pledged to limit global warming well below 2 °C, aiming for 1.5 °C, in order to avoid some of the worst impacts. Following that, the United Nations' Intergovernmental Panel on Climate Change (IPCC) was tasked to quantify the physical and socio-economic impacts of climate change that will occur if the global average temperature rises by 2 and 1.5 °C above pre-industrial levels.

In 2018, the UN IPCC produced a comprehensive special report titled "Global Warming of 1.5 °C" with a detailed comparison between the impacts of 1.5 and 2 °C of global warming above pre-industrial levels (IPCC 2018). The report also outlined a science-based action plan to achieve the 1.5 °C target. One of the central conclusions of the report was that, in order to halt global warming below 2 °C the global annual carbon emissions must drop by 25% by the year 2030 relative to 2010 levels and further to net-zero by 2070. The emission cuts would have to be even more dramatic to stay below 1.5 °C, global annual carbon emissions must be reduced to nearly half of their 2010 value by 2030 and to net-zero by 2050. This represents a herculean task which would require an urgent and drastic transformation in almost all sectors of the global economy. Notably, some sectors of the economy such as the aviation and shipping sectors are particularly difficult to decarbonise because there are currently no alternative zero-carbon fuels for airplanes and large cargo ships.

This sobering conclusion has rightfully gained significant attention from academics, journalists, policy makers, and climate change activists. However, the less appreciated fact is that the report also found that all scenarios limiting global warming to 1.5 °C or 2 °C require the use of CDR on the order of 100–1000 giga tonnes of CO_2 ($GtCO_2$) over the twenty-first century (Rogelj et al. 2018). That is more than 2–20 times the current global annual CO_2 emissions. This is largely meant to offset emissions from sectors that cannot be easily decarbonised with current technologies as mentioned above. Moreover, the more we delay significant cuts in carbon emissions, the more we will have to rely on CDR technologies to make up the difference. According to a recent estimate by the International Energy Agency (IEA), currently there are 21 large-scale commercial CDR facilities around the world, almost half of them located in the United States, absorbing only up to 40 million tonnes of CO_2 ($MtCO_2$) each year (IEA 2020). Considering that the current, non-binding pledges made by most nations are grossly incompatible with the Paris targets, it would be wise to assume that CDR would become increasingly necessary in the coming decades.

3 Current Techniques to Carture and Store Cabron Dioxide

When it comes to carbon capture and sequestration, the natural systems are highly efficient at the task. On land, soils and terrestrial vegetation sequester large amounts of carbon from the atmosphere throughout their lifetimes. The oceans, too, absorb large quantities of carbon through a number of physical, chemical and biological processes. These natural "carbon-sinks" are critical components of the carbon cycle of the planet and regulate the atmospheric carbon dioxide levels which, in turn, regulates the climate. However, with rapid urbanisation and the growing impacts of climate change the natural carbon sinks are diminishing at an alarming rate while the anthropogenic carbon dioxide emissions are increasing. As long as this imbalance continues growing, the atmospheric carbon dioxide levels will continue increasing at accelerating rates and consequently the planetary temperature will continue rising.

Of course, the obvious way to counteract this imbalance would be to protect and conserve the natural carbon sinks and/or enhance their capacity to extract more carbon dioxide the atmosphere. So, for terrestrial systems this could be achieved through reforestation and afforestation, and restoration of soils for enhanced carbon storage. For marine systems, it would involve conservation of marine plants and forests starting from the microscopic phytoplankton colonies to other coastal ecosystems such as mangroves, seagrass, corals, etc. Additionally, scientists and engineers have developed artificial/ technological methods to supplement the natural processes to remove carbon dioxide directly from the atmosphere or capture it at the source (such as industrial exhausts) and prevent it from entering the atmosphere (National Research Council 2015). The captured carbon is then concentrated and disposed, either by storing it deep underground or in the ocean or by using it to produce other commercial products. Traditional Carbon Capture and Storage (CCS) (from industry, fossil-fuel power plants, etc.), sometimes also referred to as Carbon Capture Utilisation and Storage (CCUS), Bio-Energy with Carbon Capture and Storage (BECCS) and Direct Air Capture (DAC) are some examples of technological solutions. This section will provide an overview of some the most promising CDR techniques that are either being actively implemented currently or have the potential to be implemented at scale in the future.

3.1 Terrestrial Reforestation and Afforestation

The term Reforestation refers to restoration of forest on recently deforested land and Afforestation refers to forestation of previously unforested land or land that has been deforested for 50 years or more. Any climate change mitigation strategy is incomplete without a comprehensive plan for land-use and forestry. According to global models-based estimates, land-use and land-use change resulted in around 5.2 $GtCO_2$ emissions per year during the 2007–2016 period, accounting for around 13% of the global CO_2 emissions (IPCC 2019). These emissions are mainly driven by deforestation and land degradation and partly offset by reforestation/ afforestation and soil restoration. While preventing deforestation is critical to reduce global annual CO_2 emissions, carefully planned reforestation and afforestation activities could remove significant amounts of CO_2 from the atmosphere over long time scales resulting in "negative emissions".

However, there are a number of nuances that must be considered in order to maximise the CO_2 from afforestation and reforestation. Different forest ecosystems, such as the boreal, temperature and tropical forests, could have very different rates of net annual CO_2 uptake, ranging from 1.5 tCO_2/ha to 30 tCO_2/ha (IPCC 2019). It is important to note that this net uptake of CO_2 follows a bell-curve over time which reaches the maximum value in around three to four decades followed by a gradual decline. The timing of the maximum also depends on the specific type of the forest.

However, this natural profile could be disrupted by natural or man-made disasters such as forest fires, droughts or pest attacks, which are, ironically, becoming more frequent and extreme due to climate change.

Recent models-based estimates suggest that the upper limit of the carbon capture potential from reforestation and afforestation could be in the range of 1–7 $GtCO_2$ per year by 2050 (de Connick et al. 2018). Of course, to achieve the maximum potential we would have to address the implementation challenges related to land requirements, water and nutrient (fertiliser) requirements, governance and legal issues, etc. Cost estimates are significantly lower than other CDR techniques (discussed below) and there would likely be ecosystem-services related benefits if species-diversity is taken into account in reforestation and afforestation efforts. Arguably, there are some concerns regarding the reduced albedo of forest canopies that may lead to more warming and the fact that forests will, in general, become more vulnerable to climate-change-induced forest fires and pest attacks, as mentioned before. Therefore, there is a need for careful planning and identifying synergies with other climate change mitigation strategies in order to make the case for reforestation and afforestation stronger.

3.2 Ocean-Based Carbon Sequestration

In protecting humans from global heating, the oceans are silently playing a very crucial role. Oceans act as massive natural carbon sinks, absorbing excess CO_2 from the atmosphere through multiple mechanisms. Scientific estimates suggest that, since the beginning of the industrial revolution, oceans have absorbed nearly one-third of all anthropogenic carbon dioxide emissions (Gruber et al. 2019). Carbon is stored in the oceans in two main forms- organic and inorganic. At the air-ocean water interface, there is constant exchange of CO_2 between the air and ocean water. Some of it gets dissolved into the ocean water and forms a weak acid, called carbonic acid, this comprises the inorganic carbon. The organic carbon, on the other hand, is that which is captured by coastal and marine plants and micro-organisms primarily through the process of photosynthesis. Considering the vast expanse of the oceans there is huge potential for large quantities of CO_2 sequestration which has motivated scientists and experts to find ways to enhance these natural processes and increase the CO_2 storage capacity of the oceans.

One way to increase the surface absorption of ocean water is through a process called “ocean alkalinisation”. The idea is to distribute ground up rock material (consisting of calcium and silicon primarily) in the surface waters where, under the right temperature and chemical composition of the water, they combine with CO_2 to produce dissolved alkaline bicarbonates and carbonates over time. This method could, in principle, be used to sequester large quantities of carbon but it is limited by the logistical aspects involved in extracting and distributing the rock minerals. Some estimates suggest that the carbon capture potential could be in the range of 1–6 $GtCO_2$ per year, however, the estimates are preliminary due to limited studies on the subject and the wide-ranging parameters that determine the potential (Kohler et al. 2013; Hauck et al. 2016; Renforth and Henderson 2017).

Ocean fertilisation through added nutrients is another approach to enhance carbon fixation in the ocean. Phytoplankton are microscopic marine plants that live in the surface waters. Just as terrestrial plants do, they absorb carbon dioxide from the atmosphere and sunlight for photosynthesis and release oxygen in the process. They are, in fact, the primary oxygen producers on the planet, they produce over 80% of the oxygen that we breathe. Phytoplankton are produced in the oceans in what are called “blooms” under specific atmospheric conditions. Their growth also relies on dissolved nutrients in the water, such as iron, nitrogen and phosphorous, which are in low supply. Scientists believe that, we could, in principle, enhance the growth of phytoplankton species by artificially adding these nutrients to ocean water. This process is referred in the scientific literature as “ocean fertilisation” (Harrison 2017). However, this has only been tested in laboratory settings, no large-scale field experiments have been conducted yet. There are also some outstanding questions regarding the impact that enhanced fertilisation could have on the broader marine food-web and in turn the marine biodiversity (Williamson et al. 2012). Simply considering the vast area that the ocean covers, the potential for carbon sequestration through the surface is quite significant, with more research and experimentation it could become a strong candidate for large-scale carbon dioxide removal from the atmosphere.

3.3 Bio-Energy with Carbon Capture and Storage (BECCS)

BECCS corresponds to a hybrid, natural-technological methodology in which ‘biomass’ is first generated by growing energy-intensive crops and then consumed (by burning or chemical conversion) to produce energy in the form of heat, electricity, and/ or liquid or gas fuels; the CO_2 that is generated during the consumption process is captured and stored, completing the process of BECCS. This is considered to be a ‘net-negative’ emissions technique, since, when the crops grow they absorb CO_2 from the atmosphere via photosynthesis and then when the matured crops are burnt, the emitted CO_2 is captured and stored (generally underground), thereby resulting in a net reduction of atmospheric CO_2. Due to the wide range of applications of bioenergy and the potential for net negative emissions when combined with CCS, BECCS is by far the most widely studied CDR technique (Kemper 2015). It is also extensively incorporated in the Integrated Assessment Modelling (IAMs) studies that are used by the UN’s IPCC to make projections for future climate change.

Most modelling scenarios that limit global warming below 1.5 and 2 °C consist some combination of Afforestation and Reforestation with BECCS. According to the 2018 IPCC Special Report on “Global Warming of 1.5 °C”, median values of BECCS deployment is estimated to be around 3, 5 and 7 $GtCO_2$ per year in 2050, depending on whether the global average temperature rise stays below 1.5 °C, slightly overshoots 1.5 °C, or highly overshoots 1.5 °C. The rates ramp up to 6, 12 and 15 $GtCO_2$ per year in 2100 (Rogelj et al. 2018). It is important to understand that these are median deployment rates; there are some scenarios compatible with 1.5 °C of global warming which do not rely on BECCS, but instead use afforestation and reforestation for CDR or do not rely on any form of CDR but instead assume deep cuts in global carbon emissions in the short-term. Some of these hypothetical scenarios are likely only of academic value and do not represent practical real-world possibilities. As mentioned before, it is highly likely that we would need large-scale deployment of CDR technologies during the twenty-first century and BECCS would almost certainly be one of these technologies.

According to a 2013 study which considered switchgrass as the energy crop for BECCS, in order to remove 1 Peta gram of Carbon per year (PgC/yr) equivalent to 3.7 $GtCO_2$/yr, it would require 200 million hectares of land, 20 Terra gram per year (Tg/yr) of Nitrogen, and consume 4000 cubic kilometres per year (km^3/yr) of water (equal to current global water withdrawals for irrigation) (Smith and Torn 2013). Of course, these demanding land and resources requirements pose a major challenge for large-scale deployment of BECCS, particularly considering the ever-growing land requirement for food crops and feedstock for cattle to feed the growing population. Large-scale biomass plantations may have to replace existing forests and grasslands which would not only affect the biodiversity but also release the CO_2 stored in these forests when they are cleared. Additionally, if the biomass plantations adopt a monoculture practice that would be detrimental to the soil quality and reduce their natural capacity to store CO_2 and eventually lead to land degradation. Considering this, scientists are trying to explore better energy crops and/ or better practices that require less resources and may not compete with food crops (Kline et al. 2016).

Nonetheless, once the CO_2 has been captured and concentrated it needs to be stored away permanently in order to complete the carbon dioxide removal process. One popular option in this case is geological sequestration, which is to inject concentrated CO_2 deep underground in depleted hydrocarbon reservoirs or saline aquifers. Several studies in recent years have estimated the potential global geological CO_2 storage capacity, the estimates range from a few thousand $GtCO_2$ to tens of thousands of $GtCO_2$ (Benson et al. 2012; Dooley 2013). In comparison, the total anthropogenic carbon emissions to date are on the order of ~2000–2500 $GtCO_2$. So, in principle, there is enough capacity underground to sequester human-caused carbon emissions. There are, however, some challenges in implementation and potential side-effects that must be taken into account.

The current global CO_2 capture and storage capacity of large-scale facilities, including those that are in the development stages, is on the order of ~100 mega tonnes of CO_2 ($MtCO_2$) per year (Global CCS Institute 2020). There is a long way to go before we reach the scale that is necessary to achieve the Paris Climate targets, which would be on the order of ~ 10$GtCO_2$/year. The CO_2 captured has to be transported from the source (typically fossil-fuel or biomass-based power generation facility) to the sequestration facility in pressurized containers or through pipelines. There are also important considerations regarding the long-term integrity of the geological carbon sinks that must be considered. Some studies have shown that leakage of CO_2, depending on the characteristics of the reservoir, is possible, however, the probability decreases over time as the CO_2 is sequestered through secondary trapping mechanisms (GEA 2012). Studies also show that large amounts of injected CO_2 could increase the risk of seismic events (earthquakes) which in turn could destabilise the reservoir and lead to CO_2 leakage (National Research Council 2013; Gan and Frohlich 2013; Zoback and Gorelick 2012). There are some proposals of sequestering carbon dioxide under the ocean depths as well, at 1000 to 3000 m depth where it could be stored for hundreds to thousands of years before it returns to the atmosphere through natural ocean circulation (Rau 2011). However, there are a few unknowns in terms of the biological impacts, potential costs, and long-term efficacy of this approach, hence it has primarily been discussed at the academic level so far and not been demonstrated at scale yet. A lot more research is needed to identify practical solutions to the problems mentioned above in order to make BECCS an effective CDR option that can be deployed at large-scales (Stavrakas et al. 2018).

3.4 Direct Air Capture

Direct Air Capture (DAC) and Storage (DACS) is a relatively new and purely technological methodology that is being debated more and more in climate mitigation discussions. As the name suggests, it is a process in which CO_2 is captured literally out of thin air and concentrated before it is utilised in other processes or sequestered underground. The separation of CO_2 from air is typically carried out using chemical sorbents (amine- or hydroxide-based), which must then be regenerated to produce a stream of pure CO_2 (Sans-Perez et al. 2016). There is a very important difference between DACS and conventional CCS or BECCS which is that conventional CCS extracts carbon from a ‘point source’ such as an exhaust at a fossil-fuel power generation plant while in DACS CO_2 is captured from ambient air. A point source is, of course, much more concentrated in CO_2 than air which makes DACS a much more challenging task.

Since the CO_2 concentration is very low in air, the amount of work required to ‘capture’ it is significantly greater compared to conventional CCS or BECCS where the CO_2 concentrations are much higher (Wilcox et al. 2014, 2017). Therefore, DACS is more energy intensive, it requires at least 2 to 10 times the amount of energy required to capture CO_2 from point sources. Of course, the energy for operation must come from CO_2-free renewable sources in order to be optimal as a CDR technique. Another consequence of the low CO_2 concentration in air is that the absorption device must have a large cross-sectional area, in order to get the most exposure, and be very shallow, in order to avoid a pressure-drop. In comparison, a similar device for point-source capture is likely to be tall and thin. DACS facilities, therefore, tend to be much larger in size and require bigger land areas. Due to these reasons, the costs associated with DACS are prohibitively high in comparison to other CDR techniques and current estimates range widely (on the order of a few hundred US dollars per tonne of CO_2 to a thousand US dollars per tonne of CO_2) depending on the underlying assumptions and the type of air capture methodology considered (House et al. 2011; APS 2011; Mazzotti et al. 2013).

Finally, once the CO_2 is captured, it needs to be sequestered or utilised in some way, as is the case in BECCS described in Sect. 3.3. In this context, there is one advantage of DACS over BECCS which is that a DACS facility, in principle, does not have a site-specific limitation. In other words, a DACS facility can be installed with or close to a carbon sequestration or utilisation facility and minimise transportation costs. The DACS technology is at a very nascent stage of development with only small-scale experiments carried out to date. Before it could be implemented at a large-scale, carbon sequestration technologies would have to be well established and the energy-land requirements would have to be addressed. For DACS to make commercial sense, it would have to be supported by effective policies that incentivise negative carbon emissions even as the technology approaches optimal efficiency.

4 Current Challenges and Way Forward

As was also discussed in Section II, the Working Group three (WG3) of the IPCC AR5 as well as the IPCC SR15 presented an elaborate explanation for the need for the Negative Emissions Technology (NET). The achievement of both the 2 °C target as well as the aspirational target of 1.5 °C by 2050, according to nearly 900 mitigation scenarios generated through integrated assessment models (IAMs), will heavily rely on the use of NETs. As the remaining "carbon budget" continues to deplete at a fast pace, the debate on negative emissions, which is fraught with political and ethical concerns, has gained momentum in the face of accelerated pace of emissions (Hilaire et al. 2019; Rogelj et al. 2018; Quere et al. 2018; Fuhrman et al. 2019). Although the projected benefits of these technologies provide a hopeful picture, most of them have not moved beyond small-scale demonstrations on the ground to be viewed as cost-optimal alternatives. Several studies have argued that NETs cannot be viewed as panacea to overcome the political inertia which dominates our current responses to the problem of anthropogenic climate change (Anderson and Peters 2016). NETs cannot and should not be viewed as an insurance policy, but rather an unjust and high stakes gamble which is likely to raise a number of other concerns both moral and socio-economic in nature. In this climate of political and scientific uncertainty, it is important to flesh out these concerns which are likely to raise as large-scale deployment of NETs become feasible.

4.1 Ethical Concerns

Although the debate surrounding the NETs is fairly recent in its origins, but they are rooted in a longstanding discourse which began in the post-World War II period and posed the question regarding the role of modern technology in dealing with the social issues and environmental problems. At the birth of the environmental debates in the 1960s, the technological solution to the problems of ecology became a paramount concern as scientists, engineers, innovators and policymakers emerged as the lead actors in society. The technological fix was seen at the time as the logical solution to the problems, but it proved to be a short-sighted way of tackling the ecological issues, especially as their complexity of the challenge grew and several ethical concerns were raised with regards to the role of unfettered technological fixes in an unequal world. Much of the criticism focused upon the reductionistic nature of such solutions, wherein the rational decision-making approaches overlooked the key concerns that emerged from an ethical and socio-political standpoint. The primary concern with technology, from an ethical standpoint, was the asymmetry of power between the states, and inequity between individuals. This criticism has been extended to the debates surrounding the NETs as well, wherein it is viewed as myopic in its understanding the scope of the problem, which carries the risk of disempowering the marginalised voices and their concerns, all in the name of universal good.

In a 2012 study conducted to understand the divergent claims and opinions on the NETs, an ethical matrix of carbon capture and storage was created, wherein principles of justice and a set of actors, including the non-human actors, were selected to understand the diverse framings of justice in the context of carbon capture and storage. It particularly considered the divergent concerns of different actors, including the non-human actors were assessed to frame the problem (Boucher and Gough 2012). The study found that the ethical framing of negative emissions technologies will require a mapping of, "a global network of localised researchers, communicating regularly with each other to understand the relationship between different actors' understandings of principles and the technology's compliance with and deviation from them with sensitivity to the significant cultural and linguistic diversity that would be encountered." CCS presents a more complex ethical problem than the other alternative of renewable energy and the reasons for this include- Firstly, the accrued benefits of the CCS are tied to its storage and the effects of the stored CO_2 persists for a long time. Secondly, the CCS technology carries the risk of extended dependence on fossil fuels rather than fuel a just and green transition. Thirdly, both its costs and benefits will be unevenly distributed, where the poorest people will be unevenly impacted by the transition. Finally, the detractors of the CCS point towards the intergenerational legacy of its impact, especially in terms of waste management, where strong parallels have been drawn with risks involved in nuclear waste management (Brown 2011).

Compared to CCS, BECCS is held up as a greener alternative which overcomes the limitation of storage. However, it raises a whole different set of problems and ethical complications such as, "the costs of low-carbon energy will ultimately have to be met by consumers with knock-on effects on pricing and fuel poverty" (Gough et al., Social and Ethical Dimension of BECCS 2018). Like CCS, BECCS carries the risk of promoting the business-as-usual rates of fossil fuel consumption and hinder the growth and transition in poorer countries, who may lose land and resources at the altar of unchecked consumption in the developed world (Gough et al. 2018). Bioenergy production at scale will require large scale deployment of land and other resources to meet the carbon sequestration demands, which carries the risk of creating a food-water-energy nexus, especially in poorer countries where technologies like BECCS will compete with agricultural lands for meeting such demands (Kato and Yamagata

2014). The large-scale deployment of BECCS could endanger, “terrestrial species losses equivalent to, at least, a 2.8 °C temperature rise, leading to difficult trade-offs between biodiversity loss and temperature rise” (Anderson and Peters 2016).

The carbon sequestration technology also becomes difficult to implement from a procedural justice point of view (Ambrose and Arnaud 2005). While a business-as-usual scenario will raise legitimate concerns and claims from countries and communities who are facing the risk of extinction, but on the other hand a hard push for the such technologies could promote extractivist activities, particularly coal, and add to the vicious circle of poverty in many parts of the world (McLaren 2012). Unlike the nuclear power discourse, where level of public awareness and emotiveness is high, CCS and other similar technologies have not generated widespread public debates. Therefore, the debate on the ethics and public debate regarding the NETs has ranged from ‘prudent pessimism’ to unshaken optimism in technological solutions at large. Yet another criticism of the NETs emerges from the underlying assumptions about the reversibility of the problem and management of Nature through technology. This has been criticised as a case of hubris, where political and ethical solutions to the problem are sidestepped in the name of effectiveness. While it is true that NETs are not the pure cases of manipulation of Nature, such as the solar radiation management (SRM), but it is equally true that, “achieving the more stringent 1.5 °C target requires between 400–1000 $GtCO_2$ to be removed from the atmosphere via NETs. At current rates, utilizing BECCS or DAC to achieve this would imply storing 10–25 years of global CO_2 emissions under the Earth’s crust. There are great dangers in overestimating our ability to do this justly, safely or effectively” (Lenzi 2018).

4.2 Political Economy of Carbon Sequestration

If the negative emissions technologies grow over the next a few decades, it will be driven by two contrasting forces- firstly, the economies of scale will be a critical factor in achieving any mass scale production and reducing cost of production over time. Secondly, as is case with all technological shifts, there will be a set of losers and winners in this transition. Resource scarcity is one of the central concerns that are likely to emerge in developing and poor countries where several socio-economic factors are critically linked with the climate policy. It is important to understand both these factors, in order to predict the fate of negative emissions technologies.

4.2.1 The Problem of Scale

A 2014 study by Mercator Institute found that an annual average of 6 billion tonnes of atmospheric CO_2 removal by the year 2050 would require a scale up rate of close to 60%. This figure is far lower than the one the IPCC AR5 of 2014 suggests between the range of eight and twelve billion tonnes. If the carbon removal technologies have to emerge as an alternative, they require a rapid scaling up of operations to be commercially viable and politically feasible. A key strategy to meet this target would require heavy investments in research and innovation, which, in this context, includes supply-side research and development of technologies and a demand side uptake, which is subject to greater public acceptance of such technologies. Most NETs are currently in nascent stages of production, often limited to small scale experimentation. The projected levels of carbon dioxide removal and storage through 'sinks' varies from 100 to 1000 $GtCO_2$, depending on the how well the Paris pathways to zero net emissions are met through traditional, biological and geochemical processes over the next decades (Geden 2019).

Apart from the scale of economic investments, one key factor that will drive the innovation process is the political will to engage in the process. Artificial sinks are currently viewed as an additional option which can enhance the existing sink capacity that is available in the form of the natural ecosystems like tropical forests, peatlands and oceans (Peck et al. 2010; Ma et al. 2012; Nabuurs et al. 2013; Pan et al. 2011). The rapid decline of the natural equilibrium of ecosystems around the globe is leading to a disruption in the carbon cycle and increased accumulation of carbon in marine and terrestrial carbon sinks, disrupting the critical carbon budget estimates. The terrestrial sinks and oceans removed nearly 32.6 and 25.3% of fossil fuel based industrial emissions, respectively, in the brief period of 2007 to 2017 (Kennan and Williams 2018; Le Quere et al. 2018; Penuelas et al. 2017). In an extensive study of Peruvian Amazon, one of the largest natural existing sinks in the world, found that, much like the loss of peatlands in Siberia, South-East Asia and Canada, these peatland ecosystems are losing peat carbon to the atmosphere at a rapid pace due to external pressures such forest fires, intensive agriculture, and deforestation, which puts them at a risk of transforming into carbon sources rather than sinks (Wang et al. 2018).

Therefore, as the stresses on natural ecosystems increase, an important factor in scaling up carbon dioxide removal operations will be pace of innovation and their removal efficacy. A number of recent studies have yielded the results that favour a joint implementation of different kinds of technologies to maximise the negative emissions potential (Chen and Tavoni 2013; Marcucci et al. 2017). NETs technologies pose a different scaling up challenge, wherein BECCS will require massive upscaling on the ground and wider resource mobilisation, both of which are currently on short supply due to legislative and legal factors (Kemper 2015). In the case of Direct Air Capture with Carbon Storage (DACCS), the primary challenge remains the mass manufacturing. In the absence of large-scale demonstration, both feasibility and investment come into question for new technologies. Therefore, in order to attract investments, challenges related to feedstock availability, transportation, and system integration will have to be addressed on the supply side. The demand-side will require a greater emphasis on the construction of demonstration plants which can overcome the investor anxieties in a niche market that is both volatile and riddled with uncertainties due to factors like climate change policies (Iyer et al. 2015; Gough and Upham 2011).

In a recent survey conducted on the topic of socio-political mobilisation for the NETs, it was found that while BECCS feature extensively in the IAM projections, there is very little policy attention given to this topic, especially compared to nuclear power, thus raising concerns about their short-term uptake and feasibility (Fridahl 2017). The survey further found that, “if political, industrial, and public priorities result in preconditions for BECCS that disfavour deployment, then allowing an overshoot in pathways to limit temperature increase to well below 2 °C will have to rely either on other CO_2-removal technologies or on relatively cheap but unproven and potentially dangerous solar radiation management technologies.” Recent studies have argued that full decarbonisation within a single generation is critical in order to meet the 1.5° target in the Paris Agreement. It is argued that an estimated 10–20 Gt CO_2 will have to be removed annually, which adds up to staggering 444–1000 Gt CO_2 removal by the year 2100 (Boysen et al. 2017). Such a massive scale of operation makes NETs virtually unavoidable for stakeholders, although such an expansion remains unprecedented in history. A peculiar trend is anticipated from a rapid and massive scaling up operations wherein, “costs would initially fall as the technology matures, and rise again as the resource scarcity of biomass (and to some extent storage) kicked in… Classical mitigation costs are expected to increase continuously from current levels as ‘low-hanging fruit’ are depleted and given the necessary increase in ambition compared to current mitigation action” (Honegger and Reiner, The political economy of negative emissions technologies: consequences for international policy design 2018). In their 2011 study of climate mitigation options, Gough and Upham (2011) favoured a smaller scale CCS or BECCS innovation as an exaggerated scale will eventually run into issues such as accessible infrastructure, resource scarcity. Their study further argued that bioenergy potential should not be projected extensively, given the lack of data on, “the cost of connecting bio-processing (combustion, gasification or other) infrastructure with CO_2 storage sites.”

The uptake of new technology will, therefore, depend on overcoming the key constraints in the path to maturation of NETs, which includes the absence of capital, lack of political will, the near absent public demand and teething issues such as the free rider problem in the sector which inhibit innovation. This failure to grow is often described as a ‘valley of death’ problem, wherein new start-ups, and new technologies often fail to demonstrate their reliability at scale, which deters financial investors and results in such technologies never reaching the commercial markets where could expand (Nemet et al. 2018; Ford 2007).

4.2.2 The Resource Scarcity Question

While the NETs offer a critical pathway to the Paris Agreement targets, they will run up against a number of ecosystem-based constraints which includes the emerging food-water-energy nexus, massive changes in land use change (LUC) across the world, governance of artificial carbon sinks and anthropogenic climate change. Therefore, the technological transition cannot merely be seen as a technical transition; rather they have to be understood in the broader socio-technical landscape, where the impact of transition of socio-economic lives as well as planetary boundaries will be enormous (Creutzig et al. 2015; IPCC 2019). BECCS offers great prospects in meeting the Paris targets, their implications for a broad range of issues such as LUC, food security, energy security, water security, socio-political systems are relatively under researched (Fuhrman et al. 2020). It is an important aspect of the transition that NETs are attempting to bring about and highlight the often-neglected regional scale of these technologies. While the economic thinking and IAM projections are more focused on upscaling, a resource constraint on regional scale will pose a parallel, but equally vexing challenge for states and policymakers (Tian et al. 2016; Fuss et al. 2014; Zilberman 2015). The IAM projections which are highlighted in the IPCC AR5 rest on the assumptions based on perfect knowledge of yet unseen technologies and their cost-optimisation. One important consequence of this method is that it gives less weightage to future expenditure, in comparison with the present-day costs, thereby creating an impression that delay in action is a favourable strategy in the short run (Brack and King 2020; Bednar, Obersteiner and Wagner 2019).

Bioenergy is currently the source of nearly 10% of global energy supply, especially in the poor and developing countries, where people depend on these sources for daily needs like household cooking. These sources of bioenergy, therefore, cannot be shifted towards BECCS without accommodating for the needs of the poorest populations around the world (see Fig. 4.1). One of the major positives for the transition towards NETs relates to their potential to reduce dependency on fossil fuels. This claim, however, remains subject to both scrutiny and criticism. A 2018 study on the energy balance of BECCS highlighted that BECCS energy output will remain lower than the projected rates and returns will vary sharply on a case-to-case basis (Fajardy and Mac Dowell 2018). The study further observed that, "biomass conversion and CCS, followed by transport (road), drying, and farming (including inputs) represented over 80% of the energy losses for high moisture and low yield biomass such as willow pellets. Power plant efficiency, fuel efficiency for transport, transport

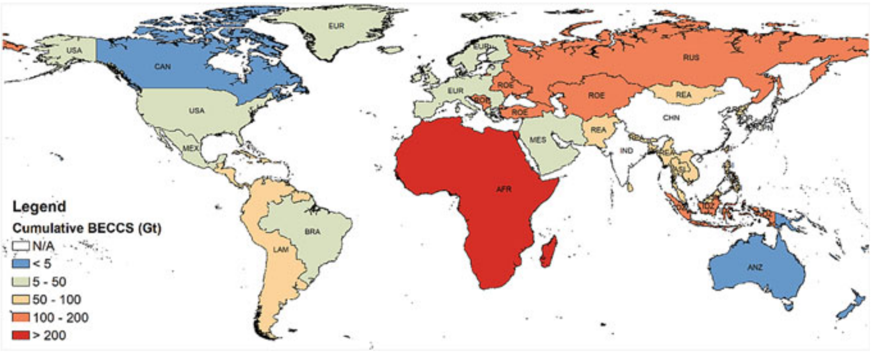

Fig. 4.1 Cumulative CO2 removal from BECCS under 1.5 °C policy with BECCS. 84% of BECCS deployment occurs in developing nations, with 26% alone in Africa. *Source* Fajardy, M., Morris, J., Gurgel, A., Herzog, H., Mac Dowell, N. and Paltsev, S., 2020. The economics of bioenergy with carbon capture and storage (BECCS) deployment in a 1.5 C or 2 C world

distance, moisture content, drying method, as well as yield were thus identified as key parameters that need to be carefully controlled to maximise BECCS net electricity balance." As a way forward, the emphasis should be to disincentivise the usage of fossil fuels and invest in scaling up of operations to build reliable storage of CO_2 to meet the net-zero targets.

Yet another concern regarding the feasibility of such projects relates to their impact on natural resources and their local management. Water is a key point of concern in this regard as NETs projects are likely to lead to an increase in the water usage, which will be diverted towards the irrigation of bioenergy cultivation at a mass scale. Such large-scale shifts in the cropping patterns and potential rise in demand for biofuel crops will lead to higher stress on water tables, degradation of freshwater bodies and loss of biodiversity. In the context of climate change induced stresses, such diversions of key resources of survival will make any NETs project politically and socially unviable, especially in resource stressed regions of the world (Smith et al. 2016; Burns and Nicholson 2017; Gough and Mander 2019; Forster et al. 2020). The 2018 Royal Society report on Greenhouse Gas removal warns about the unintended consequences of the NETs, where, "indirect land-use change can involve spatial leakage—efforts to increase or protect forests in one location, without measures to meet demand for crops or ranching for meat, may push up crop and meat prices, increasing deforestation in another location." (The Royal Society 2018) A 2014 study on the future land-use scenario found that it would take a ten-fold increase in the yield of first-generation bioenergy crops like maize, sugarcane and rapeseed before 2055, thereby raising the demand for nutrient inputs, water, high fertiliser input. In addition to the increased cost of input and higher land use change, BECCS also carries the potential of increased nitrous oxide release into the atmosphere, thereby creating a new set of challenges (Kato and Yamagata 2014; Crutzen et al. 2016).

It is important to understand both the planetary scale impact of NETs as well as their regional, localised impacts, in order to make the right trade-offs. The deployment of CDR technology is projected to rise as the rates of carbon emissions rise, therefore, it has to be subjected to greater scientific scrutiny and socio-political analysis. The challenge for the policymakers will be to find the right equilibrium and appropriate scale for employing such technologies so as to yield their intended benefits.

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