Going deeper into negative emissions: A general review and limitations

Daniel Dones[1,*]

[1]TEP4300 Klimavern, NTNU, Trondheim, Norway
[*]daniedo@stud.ntnu.no
[*]daniel.dones.ruiz@alumnos.upm.es

ABSTRACT

Since climate target of limiting maximum temperature increase below 2 °C has been accepted, there is a crucial necessity of reducing CO_2 total emissions in order to achieve the goal by the end of the century. This paper aims to introduce negative emissions as a helpful way for mitigation, presenting the main research carried out and a general review of the main technologies (NETs) available for a large-scale deployment. Most of these technologies' potentials have been assessed, followed by different costs and other related problems. The limit ranges reviewed for different NETs highlight that there is still a lack of maturity, but NETs also provide a high possibility for total emissions reduction and are intended to become part of new, more efficient mitigation policies.

keywords: climate change mitigation, negative emissions, carbon capture

Introduction

Since there is a remaining bucket CO_2 budget established to reach a maximum temperature increase *well below* 2^oC (IPCC Climate Change 2014; Smith et al. 2016)[1,2], not greater than 1,200 $GtCO_2$, at current emissions level that point will be met within a few decades. Reducing greenhouse gas (GHG) emissions may not be enough to mitigate climate change. Thus, and in order to achieve the climate targets, not only a decreasing fossil CO_2 emissions it has become indispensable, but a large-scale deployment of negative emissions technologies (NETs), which result in the removal of GHGs from the atmosphere. Different scenarios have been presented in IPCC reports introducing this concept, where the cumulative budget surplus will be compensated by the removal of emissions from the atmosphere. Different pathways are represented in Figure 1.

These technologies will play an essential role in stabilizing total emissions to reach climate goals, as they pretend to achieve a negative balance of carbon into the atmosphere. Based on our diffuse knowledge about NETs (Minx et al. 2018)[3] and, provided climate change targets depend principally on their future development, the aim of the study is: reviewing and introducing the most developed NETs; bioenergy with carbon capture and storage (BECCS), afforestation and reforestation (AR), direct air carbon capture and storage (DACCS) and enhanced weathering (EW), while arguing and examining the role of negative emissions in the mitigation scenarios, with greater focus on the overall potential of the techniques, limits and other side effects.

Defining NET: considering negative emissions as "intentional human efforts to remove CO_2 emissions from the atmosphere" (2018)[3], NET can be defined as any technology capable to accomplish that target in the atmosphere in order to reduce the levels that would have resulted without their deployment. As CO_2 separation involves a higher operational cost, NETs bring an interesting opportunity to capture CO_2 from any activity emitted at different locations and time (Archer et al. 2009; Azar et al. 2006)[4,5], a possibility to avoid transport costs (capture might occur near storage station) and the absence of pollutants involved in the process. All these technologies involving CO_2 can be clustered into carbon dioxide removal (CDR) for further analysis.

Methodology

This paper encompass the work for the course *TEP*4300 *Klimavern*, taught at the Norwegian University of Science and Technology (*NTNU*). The study was performed by searching review articles (September-November 2019) using ScienceDirect and Google Scholar databases and combining the next keywords: "negative emissions", "negative emissions technologies", "indirect air capture", "carbon capture". In addition, the materials and different references provided along the course have also been notably considered. Due to such the vast literature existing on climate change and related topics, the main focus were review articles, filtered by relevance, where the main research questions were defined. The exclusion criteria about other scientific articles has been carried out by terms of extension, guidelines and complexity. 4 different NETs have been assessed with integrated scenarios depending on: (1) biophysical potentials for carbon sequestration; and (2) economic costs and other side effects derived from their deployment. The findings shown are the result of the most developed and compromising technologies. Some data are based on highly simplified assumptions, and as such, the comparison between technologies would not be completely fair and certain. Since mitigation scenarios are extremely complex and interdisciplinary, there are so many unanswered questions on the matter. However, the most trustworthy available materials will be taken into account.

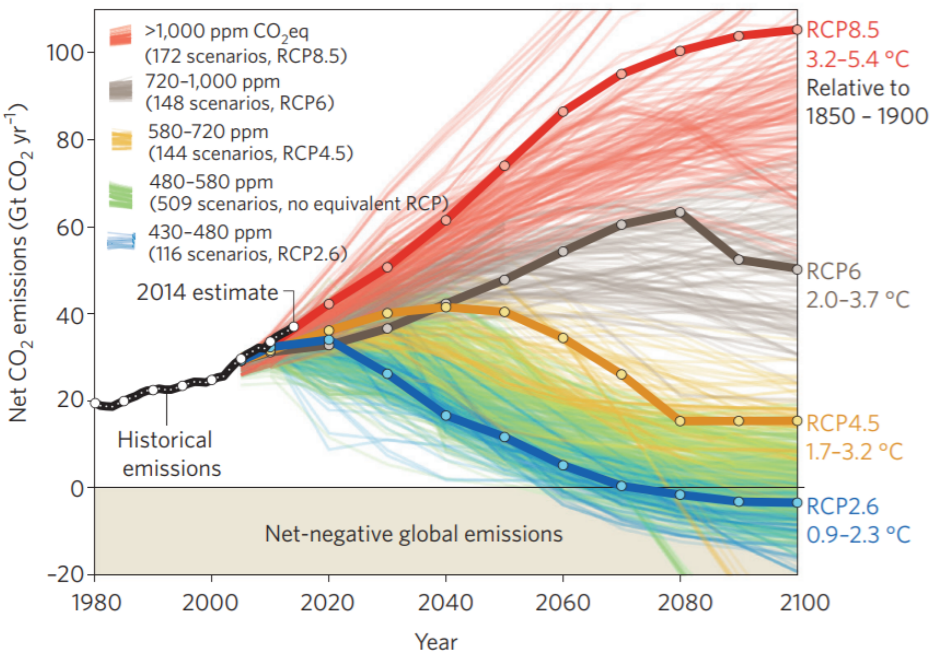

Figure 1. Scenarios including NETs for each category. Scenarios with no technology constraints are shown in colour and all other scenarios from the IPCC AR5 database are shown in grey. Sources: IPCC AR5 database, Global Carbon Project and Carbon Dioxide Information Analysis Center[61]

Results

Bioenergy with carbon capture and storage (BECCS)

BECCS is the preferred negative emissions technology to mitigate the climate, by the majority of integrated assessment model (IAM) scenarios oriented to keep global warming below 2ºC (Fuss. et al. 2018)[7]. It is based on the carbon-neutral bioenergy with CO_2 capture (emitted by combustion) and storage (geological/ocean). It consists of CO_2 transfer from the atmosphere to geological layers, with no use of fossil-fuel sources. Classified in the indirect air capture technology group, it will cover the focus on this review.

The atmospheric CO_2 capture by plants and other microorganisms through photosynthesis is the responsible for the biomass production. Later, biomass can be used to generate electricity. The carbon capture applied to biomass provides the possibility to finally have a negative carbon balance. However, impact assessment scenarios including BECCS are widely varied and uncertain, and bioenergy is currently used at a lower scale, where main researches have been run by developed EU countries. Approximately half of BECCS scenarios exceed 5% of primary energy supply, but with a potential net positive emission level at the end of the century. The reason for assessing this technology is highly influenced by its inherent importance, due to its potential to mitigate climate when stabilization levels are reached, specially with possible near-term delays.

Considering different scenarios, negative emissions would need to be set by 2070, and later for other higher stabilization levels. For IAMs, they will be part of the optimization solution driven by emissions reduction and BECCS.

Potential. Mainly based on the availability of land and biomass. Potential estimations for 2050 cover the range from 60-1548 EJ yr^{-1} (Kraxner and Nordström 2015)[8], with an agreement on the minimum estimates. The potentials will increase

as more productive land is included: 130-216 EJ yr^{-1} (Beringer, Lucht, and Schaphoff 2011)[9]. Other optimistic estimates start from 350 EJ yr^{-1} (Cornelissen, Koper, and Deng 2012)[10], where algae is included as a feedstock (90 EJ yr^{-1}). It reaches 370-1500 18 EJ yr^{-1} for the most (Smeets et al. 2007)[11], considering much more potential from dedicated bioenergy and increasing yield factor among others.
Literature shows consense that there is sufficient potential available around the globe to store such amount of CO_2 as 2ºC mitigation scenarios suggest (James J. Dooley 2013)[12]. Global estimates for total storage are widely dispersed from 320 (Koide et al. 1993)[13] to 50,000 GtCO2. The lowest estimate assumes a 1% suitable sedimentary basin for storage. However, taking aquifers as other trapping mechanisms, other regional estimates have provided good support to values as high as 35,000 and 50,000 GtCO2 (James J. Dooley et al. 2005)[14].

Costs. Estimate costs on BECCS are near to US$30-400/tCO2 (Arasto et al. 2014; Luckow et al. 2010)[15,16]. Most sources are focused on some specific source of CO_2 storage, so it may vary depending on different assumptions. Biomass is assumed as zero life-cycle emissions, while land use is carries a as 10-30% efficiency penalty on carbon reduction. This field entails great uncertainty and there is poor agreement about it (mainly markets variability and livelihoods).

Side effects. The effects on climate studied involve those caused by biomass use, resource needs, and environmental and sustainability effects due to land and energy operation.
Land use: Direct land use change, indirect land use change and albedo effects are categorized here, including previous changes in use for economic interests. Considering a big impact for first-generation bioenergy (ethanol), overall emissions tend to be low range from cellulosic, woody sources, food waste and forest residues (2016)[2]. Low emissions mean a considerable efficiency loss in BECCS, where calculations on different land uses need to be done in order to reflect more accurate estimates and abatement effects.
Global albedo effects vary depending geography. At higher latitudes, biomass acts as a snow cover, causing a compensatory effect on mitigation (Bright et al. 2015)[17]. Different land use and land cover change forcing covers from -0.06 to -0.29 Wm^{-2} by 2070 depending on different assumptions on crop yields and afforestation versus future bioenergy crop deployments (Jones et al. 2015)[18].
Bioenergy raises important concerns regarding land use, impact on the food industry and biodiversity. It is recommendable to assess the large-scale deployment on food industry; from prices and market, to limits and security. There are some studies that argue competition could lead to increases and variations in food prices (Popp et al. 2011; Zilberman et al. 2013)[19,20]. Ethanol could impact food prices because of competition among peers, while sugarcane's impact would be lower. A possible policy is limiting deployment to marginal land, but it is also related to impacts on biodiversity. However and, at same time, it may contribute to prevent from erosion and to soil restoration (Lemus and Lal 2005).[21].
BECCS has the possibility to improve rural income, as there is a great number of small-holder farmers in society, which are highly influenced by agricultural prices, but also the risk of headwinds or tailwinds on them, such as displacement and market volatility. (Buck 2016)[22]. Local actors are more likely to leverage bioenergy systems while other from more marginalized environments, might lose.

Storage and carbon leakage. Among the different NETs available, one of the less vulnerable technologies to post-variations is BECCS. The decision on CO_2 capture and storage depend no more on management and operation, which is the main advantage regarding the others. The problem on leakage needs to be addressed, but it is not considered a hard obstacle, but as high carbon leakage could compromise the future development of BECCS, it just needs to be examined.
Against running a single and unrealistic model based on BECCS, a number of different NETs were proposed and studied (including BECCS, afforestation/reforestation, enhanced weathering, direct air capture, altered agricultural prices and biochar production) as long as it is expected to require a combination of NETs to achieve mitigation. Assumptions were made with different leakage time scales of 300, 1000 and 10,000 years, and 80% or more was permanently stored. The study concluded that "leakage would not significantly compromise the benefits of negative emissions unless leakage is substantial and rapid" (Lyngfelt, Johansson, and Lindeberg 2019)[23]. Other more specific researches showed remediation on leak detection (Bui et al. 2018)[24] and concerns related with effectiveness of the technology and viability (Plevin et al. 2010)[25].

Direct air carbon capture and storage (DACCS)

It is the process in which CO_2 is captured in the ambient air, opening a wide variety of techniques to achieve it, mainly focused on hydroxide sorbents (calcium hydroxide). Many efforts have been put into a way to improve contact surfaces to sequestrate more CO_2. As the process requires, energy is needed to release CO_2 from the sorbent and for the post pressurization for its transportation.

Potential. As long as DACCS potential can be considered unlimited, estimates need to be done in order to have a global NETs assessment. Ranging from 10-15 $GtCO_2$ yr^{-1} in 2100 (2018; McLaren 2012)[7,26] there is a higher potential (Sanz-Pérez et al. 2016)[27] for other studies assuming low probability on long-term mitigation scenarios by the end of the century. The discussion about DACCS potential is strong dependent on costs and on the possible viability of the technology.

Costs. General review on the topic (2016)[27] has come with the evidence that DACCS cost are based on: capital investment, costs of capture , operation and regeneration, and sorbent maintenance. Other potential factor is the location for the storage facilities, optimizing losses and costs. A great place is considered to be near to renewable energy plants, where the maximum amount of CO_2 will be captured and avoided. General costs range from $US30-1000/tCO_2$. The low estimates assume proximity to industry and do not include overall cost of components. Higher range are driven by different thermodynamic considerations with no particular guidelines. Nonetheless, most scientific outcomes show results close to higher values (2016)[2].

Side effects. Land areas are not such a big issue, nor is storage capacity as it has been revised. (de Coninck and Benson 2014; Keith 2009)[28,29]. However, geological storage presents a series of different effects (as BECCS). In solvent-based separation, the use of potassium hydroxide has been studied accordingly through several years, accomplishing minimal wastes in production (Holmes and Keith 2012)[30]. Environmental implications will be similar to those as the reclaimer in terms of solid waste build-up.

Storage and carbon leakage. As DACCS has not been deployed (except in small units), there are no comparable assessments to other technologies. It is clear that its biggest problem is the cost, where different cost-effective studies and other conventional option have been examined (Kittner, Lill, and Kammen 2017)[31] showing that is matter of time that DACCS becomes profitable economically and produced at high volumes to the market. However, DACCS plants and structure required could be quite challenging in remote locations, which might be pressure by the need of this technology to achieve a global and developed network of NETs.

Afforestation and reforestation (AR)

Afforestation refers to planting trees on land which has not been afforested in recent history (last 50 years). Reforestation refers to replanting trees on recently deforested land. Negative emissions are practiced by CO_2 sequestration from the atmosphere of the additional biomass.

Potential. Yearly mid-century potential shows a range 0.5-7 $GtCO_2$ yr^{-1} (2012)[26] and by late-century covers 1-12 $GtCO_2$ yr^{-1} (2016)[2]. New IAMs give a range of 5.83-9.56 $GtCO_2$ in 2100 for 2580 Mha afforested (Kreidenweis et al. 2016)[32]. Other earlier estimates are between 0.47-4.88 $GtCO_2$ yr^{-1} by that year (2010)[25] assuming that abandoned land can be used for AR. (Richards and Stokes 2004)[33] reviewed older literature concluding that more than 7 $GtCO_2$ could be sequestered for the first decades. Since there is a big discrepancy on this, it is not easy to extract some clear evidence on its potential.

Costs. Range between US$2-150/$tCO_2$ (2004)[33] (IAMs are not included in this range, it is expected to increase with further literature). It was also showed that costs for developing countries are expected to be lower than for industrialized countries. However, there are so many factors involved in the matter, such as yield rates and land prices, that still need to be clarified. Following an optimization approach, cost range is US$10-237/$tCO_2$, while bottom-up studies range US$0.1-15/$tCO_2$. Other previous literature range from US$7.50-50/$tCO_2$.

Side effects. The main issue with AR is albedo change, when there is a clear evidence that low albedo of boreal forests make AR in high latitudes inefficient, increasing local warming and losses of ice and snow. (Anderson et al. 2011)[34]. Regarding tropical areas, it presents greater chance for evaporative cooling than boreal forests per unit of land. In addition, the impact on biodiversity of AR needs to be addressed. Nonetheless, the use of native species for afforestation is considered superior compared to habitat quality plantations and species diversity (Hall et al. 2012)[35]. It might have lower performance but it is less vulnerable to climate alterations and provides a wide range of products and services. Furthermore, there are other issues like the effects on soil organic carbon and large-scale deployment of AR in terms of limit extensions.

Storage and carbon leakage. In contrast to geological storage, biogenic CO_2 has a much shorter permanence, the ratio is thousands of years versus decades or centuries for this technology (2016)[2]. Other potential problems may be natural and human action i.e. forests fires or pests. Considering this high vulnerability, AR will become less attractive over time than other NETs. However, new land area will need to be found in order to achieve the total additional negative emissions at the end of the century, where free-meat diet would play an important role. (Röös et al. 2017)[36].

Enhanced weathering (EW)

Weathering, whether it is terrestrial or ocean, is the natural decomposition of rocks, from chemical to physical processes. It is ruled by several factors depending on biota interaction, water composition and temperature. EW is the purpose of stimulating one of these factors to accelerate rock decomposition, at the same time geogenic nutrients and alkalinity are being released. Cutting down the period and bringing it closer to human scale, it favors different chemical reactions that have the potential to capture and sequester atmospheric CO2. It could be also used with other mine waste materials or alkaline waste. Since it has a high potential in many tropical regions which have poorer nutrient soil levels, temperatures make them highly interesting. Basalt application of 3 Gt yr-$^{-1}$ may sequester 1 $GtCO_2$ yr^{-1} (Strefler et al. 2018)[37]. Considering the ocean alkalinisation as the addition of alkalinity to marine areas in order to increase the CO2 buffering capacity, it could be a technology grouped here as it follows similar geological and chemical processes. An issue that still needs to be addressed is the overall impact of EW on biomass, soil and other biogeochemical cycles.

Potentials. Reports show a wide range of different potentials, from regional to global scale models, with the highest potential of 88.1 $GtCO_2$ yr^{-1} for pulverized rock over the tropics (Taylor et al. 2016)[38]. Regarding crop areas for dunites and basalt; 95 and 4.9 $GtCO_2$ yr^{-1} respectively. (2018)[37]. Estimation approaches about land areas are highly uncertain, mainly due to different considerations and conditions. Thus, there is still research to do in this field.

Costs. Dependent on the defined technology; from the rock grind and material for transportation, to the rock source. It is also unclear and difficult to make some assumptions but the range for inorganic CO_2 sequestration is US$14-40/t$CO_2$ to US$3460/t$CO_2$. (2016; Köhler, Hartmann, and Wolf-Gladrow 2010)[38,39]. EW costs are influenced by their way of extraction, other interdisciplinary drivers (e.g. technical and economic) and means of transportation. This last starting from US$0.0016/t rock/km for inland waterway and high-scale ship distribution and climbing to the most expensive, which is road transport (US$0.079/t rock/km) (Renforth 2012)[40]. The feedback extracted from that assessment is the relevance of the infrastructural conditions usually omitted by other studies. Other global report remits costs at US$60/t$CO_2$ for dunite and US$200/t$CO_2$ for basalt (2018)[37].

Side effects. Driven by rock powder source, ecosystem, soil and climate characteristics. Land applications reflect an increase in water *pH* (2016)[38]. An inappropriate material use results in the release of heavy metals and plant nutrients. Other point, such as computing, that impacts on carbon cycle and total alkalinity are showed to be too far away from reality. (2010)[39]. Soil applications alters its properties, when again, water impacts might be observed (e.g. groundwater, river and coastal water). Possible negative side effects on the marine biology and ecosystems are missing at the current knowledge.

Storage and carbon leakage. EW storage can be carried through different pools. It is firstly kept in soil solution as dissolved inorganic carbon, where possible saturations are contemplated, resulting in a residence time order of 10^6 years (Wilson et al. 2009)[41]. If precipitation does not occur in land system, the products would be stored as ocean alkalinity. (2016)[38].

Discussion

Global analysis sequestration levels of 3.3 GtC yr^{-1} in 2100 is proposed for BECCS and DAC (2016)[2]. For other NETs is not possible to achieve this value in terms of mean annual levels (1.1 GtCeq yr^{-1} for AR and 0.2 GtCeq yr^{-1} for EW). Results showed that CDR technologies such as DAC and EW tend to require much less land and water. Also CDR technologies require a considerable energy and economic investment per unit of negative emissions. Among BECCS options, forest feedstocks require less nitrogen than crops, with higher risk of changes in albedo and less energy generated. Other NETs such as ocean fertilization, soil carbon sequestration and biochar could be also evalued. However, the most emerging and recurrent NETs in IAMs reports have been covered.

BECCS might be limited by nutrient demand and water use, therefore more developments are required to improve energy conversion and distribution, followed by the cost of infrastructure and transportation.For DAC, costs and energy requirements guide to slow deployment, where more research is needed. EW presents the highest demand for large areas, which next to the low carbon removal potential, poses an important barrier. AR appears to be inexpensive, but competition for land and the decreasing albedo in high latitudes slow down the growth. There is a need to create and develop socio-economic governance systems for NETs, promoting research and implementation in the most sustainable way. Priorities should include investing in renewable and low-carbon technologies, performing different systems of achieving a mature network of NETs and providing the best complement for mitigation. In the meantime, emission reduction policies must be addressed and continuously proposed, assuming the main role of reducing global emissions.

Different climate change results from the addition of geological carbon to the atmosphere through combustion or other processing of fossil fuels for energy are represented in Figure 2. There are some differences in the materials and energy requirements for each process to remove a given mass of carbon.

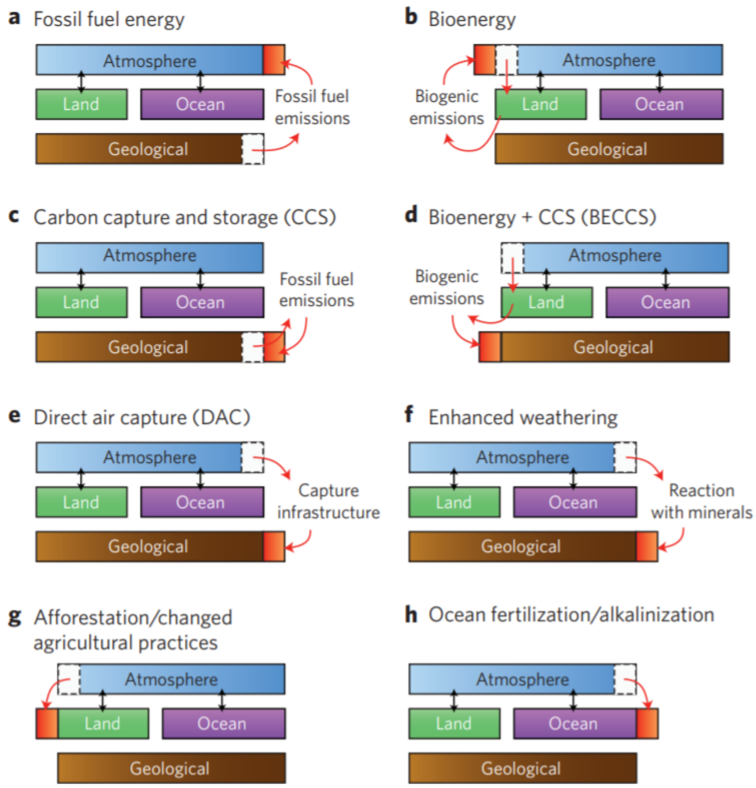

Figure 2. Schematic representation of carbon flows among atmospheric, land, ocean and geological reservoirs. Source:[2]

Ethical aspects

On one hand, many concerns about negative emissions, specially BECCS, have been expressed such as the implications of large-scale bioenergy production, where the role played by fossil fuels is expected to be replaced by biofuels, as they are known as sustainable and low-carbon technologies. Critics appears as it would be unacceptable to let such an appropriation of ecosystem services and nature by human actions. Pushing the land competence mark and the requirement for organism regulations. (Gomiero et al 2010; Creutzig 2017)[42,43]. For DACCS, conditions are more permissible as the effects are easily localized. Same rule it applies to other terrestrial NETs (e.g. AR).

On the other hand, the point that NETs may cause is considerably justified compared to any alternative existing, since side-effects are small in comparison to those produced by the fossil-fuels. Other calls for "historical responsibility" and the need for a large-scale deployment will be the focus of most arguments and discussions.

Moral hazard and hubris

The existence of NETs, as a possibility to rely on and reduce or soften the reduction of emissions could lead to a hubristic position, where supporting the NETs could justify the importance of mitigation policies, acting as a "mitigation obstruction", so it could turn into a counter-productive fact (2006)[5]. Represented in Figure 3, it is necessary to know that NETs potential is likely to be too optimistically projected and could vary a lot, where real displace will differ depending on the research design, since the assessments are based on so many different assumptions and uncertainty. This gross negative emissions deployment ranges within an ensemble of 450 ppm scenarios. Thus, near-term mitigation is greater than 9 $GtCO_2$ yr-1 by 2030 when NETs are excluded, creating a path dependency to the inclusion of negative emissions (Riahi et al. 2017)[44].

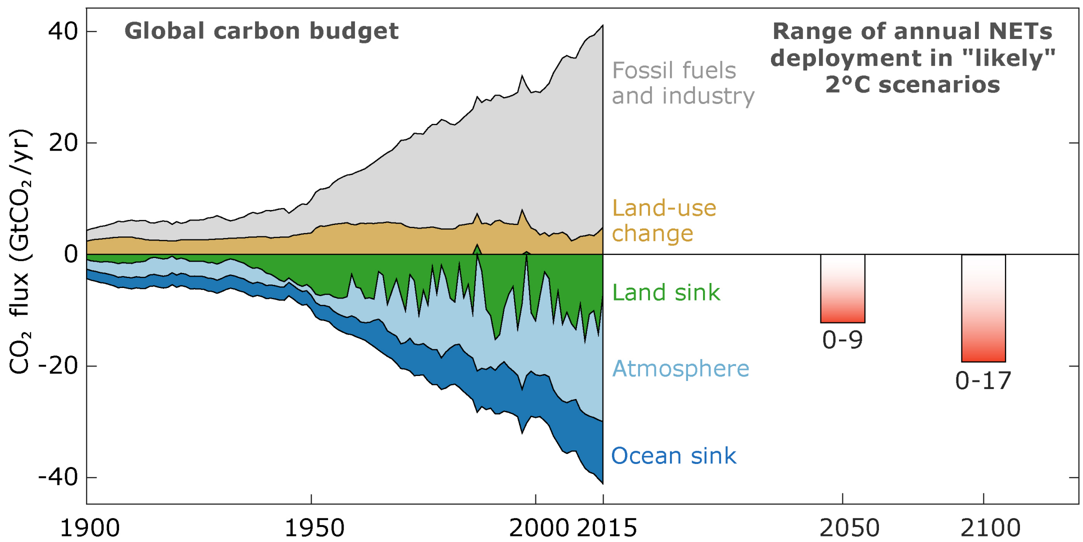

Figure 3. Hubris and negative emissions. Gross negative emissions deployment ranges within an ensemble of 450 ppm scenarios with an at least 66% probability of limiting global mean temperature rise below 2°C by the end of 21st century. Data and figure design of historic emissions obtained from the Global Carbon Project. Source:[44]

Conclusion

The large-scale deployment of NETs still needs to be clarified and some matters must be solved before. BECCS is presented as one of the most promising technologies, but more research is required concerning land and biomass needs, food security and biodiversity effects. General response of natural lands and ocean carbon sinks present the same problem for this deep deployment, considering there is some uncertainty about that. In addition, overall costs of untested technology present a problem, due to much reports are only based on estimates that are expected to vary a lot.

There are other obstacles as social, economic and institutional factors that could constrain implementation and development, where huge efforts will need to be done in terms of awareness, clarification and public debate. Scientific research must take the responsibility of dissemination and spreading the need of these technologies, to mitigate climate change and reduce as much as possible the derivate effects.

Climate target of 2^{o}C has been accepted and the importance of negative emissions has been explained, it is clear that a large-scale deployment of NETs is needed, in order to design the most efficient mitigation policies. It is also known that NETs could cause and imply different side-effects which would have to be dealt with, from different assumptions to unknown factors and emerging problems. Nonetheless, it has been accorded that these problems are much more acceptable than any potential alternatives. NETs are a necessary and helpful tool for mitigation scenarios, and as a consequence, its large-scale deployment would need to take place as soon as possible. Moreover, future research in the field must continue in order to clarify some uncertainties, improve different technologies and drive the deployment of NETs.

References

1. Change, I. P. o. C. (2015), *Climate Change 2014: Mitigation of Climate Change* (Cambridge University Press, 2015). Google-Books-ID: JAFEBgAAQBAJ.

2. Smith, P. *et al.* (2016). Biophysical and economic limits to negative CO2 emissions. *Nat. Clim. Chang.* **6**, 42–50, URL http://www.nature.com/articles/nclimate2870.

3. Minx, J. C. *et al.* (2018). Negative emissions—Part 1: Research landscape and synthesis. *Environ. Res. Lett.* **13**, 063001, URL https://doi.org/10.1088%2F1748-9326%2Faabf9b.

4. Archer, D. *et al.* (2009). Atmospheric Lifetime of Fossil Fuel Carbon Dioxide. *Annu. Rev. Earth Planet. Sci.* **37**, 117–134, URL https://www.annualreviews.org/doi/10.1146/annurev.earth.031208.100206.

5. Azar, C., Lindgren, K., Larson, E. & Möllersten, K. (2006). Carbon Capture and Storage From Fossil Fuels and Biomass – Costs and Potential Role in Stabilizing the Atmosphere. *Clim. Chang.* **74**, 47–79, URL https://doi.org/10.1007/s10584-005-3484-7.

6. Boden, T. A., Andres, R. J. & Marland, G. Global, Regional, and National Fossil-Fuel CO2 Emissions (1751 - 2014) (V. 2017). Tech. Rep., Environmental System Science Data Infrastructure for a Virtual Ecosystem; Carbon Dioxide Information Analysis Center (CDIAC), Oak Ridge National Laboratory (ORNL), Oak Ridge, TN (United States) (2017). URL https://www.osti.gov/dataexplorer/biblio/dataset/1389331.

7. Fuss, S. *et al.* (2018). Negative emissions—Part 2: Costs, potentials and side effects. *Environ. Res. Lett.* **13**, 063002, URL https://doi.org/10.1088%2F1748-9326%2Faabf9f.

8. Kraxner, F. & Nordström, E.-M. (2015). Bioenergy Futures: A Global Outlook on the Implications of Land Use for Forest-Based Feedstock Production. In Westholm, E., Beland Lindahl, K. & Kraxner, F. (eds.) *The Future Use of Nordic Forests: A Global Perspective*, 63–81 (Springer International Publishing, Cham, 2015), URL https://doi.org/10.1007/978-3-319-14218-0_5.

9. Beringer, T., Lucht, W. & Schaphoff, S. (2011). Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. *GCB Bioenergy* **3**, 299–312, URL https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1757-1707.2010.01088.x.

10. Cornelissen, S., Koper, M. & Deng, Y. Y. (2012). The role of bioenergy in a fully sustainable global energy system. *Biomass Bioenergy* **41**, 21–33, URL http://www.sciencedirect.com/science/article/pii/S0961953411006684.

11. Smeets, E. M. W., Faaij, A. P. C., Lewandowski, I. M. & Turkenburg, W. C. (2007). A bottom-up assessment and review of global bio-energy potentials to 2050. *Prog. Energy Combust. Sci.* **33**, 56–106, URL http://www.sciencedirect.com/science/article/pii/S0360128506000359.

12. Dooley, J. J. (2013). Estimating the Supply and Demand for Deep Geologic CO2 Storage Capacity over the Course of the 21st Century: A Meta-analysis of the Literature. *Energy Procedia* **37**, 5141–5150, URL http://www.sciencedirect.com/science/article/pii/S1876610213006723.

13. Koide, H. *et al.* (1993). Underground storage of carbon dioxide in depleted natural gas reservoirs and in useless aquifers. *Eng. Geol.* **34**, 175–179, URL http://www.sciencedirect.com/science/article/pii/001379529390086R.

14. Dooley, J. J. *et al.* (2005). - A CO2-storage supply curve for North America and its implications for the deployment of carbon dioxide capture and storage systems. In Rubin, E. S. *et al.* (eds.) *Greenhouse Gas Control Technologies 7*, 593–601 (Elsevier Science Ltd, Oxford, 2005), URL http://www.sciencedirect.com/science/article/pii/B9780080447049500604.

15. Arasto, A., Onarheim, K., Tsupari, E. & Kärki, J. (2014). Bio-CCS: Feasibility comparison of large scale carbon-negative solutions. *Energy Procedia* **63**, 6756–6769, URL http://www.sciencedirect.com/science/article/pii/S1876610214025260.

16. Luckow, P., Wise, M. A., Dooley, J. J. & Kim, S. H. (2010). Large-scale utilization of biomass energy and carbon dioxide capture and storage in the transport and electricity sectors under stringent CO2 concentration limit scenarios. *Int. J. Greenh. Gas Control.* **4**, 865–877, URL http://www.sciencedirect.com/science/article/pii/S175058361000099X.

17. Bright, R. M., Zhao, K., Jackson, R. B. & Cherubini, F. (2015). Quantifying surface albedo and other direct biogeophysical climate forcings of forestry activities. *Glob. Chang. Biol.* **21**, 3246–3266, URL https://onlinelibrary.wiley.com/doi/abs/10.1111/gcb.12951.

18. Jones, A. D., Calvin, K. V., Collins, W. D. & Edmonds, J. (2015). Accounting for radiative forcing from albedo change in future global land-use scenarios. *Clim. Chang.* **131**, 691–703, URL https://doi.org/10.1007/s10584-015-1411-5.

19. Popp, A. *et al.* (2011). The economic potential of bioenergy for climate change mitigation with special attention given to implications for the land system. *Environ. Res. Lett.* **6**, 034017, URL https://doi.org/10.1088%2F1748-9326%2F6%2F3%2F034017.

20. Zilberman, D., Hochman, G., Rajagopal, D., Sexton, S. & Timilsina, G. (2013). The Impact of Biofuels on Commodity Food Prices: Assessment of Findings. *Am. J. Agric. Econ.* **95**, 275–281, URL https://academic.oup.com/ajae/article/95/2/275/69530.

21. Lemus, R. & Lal, R. (2005). Bioenergy Crops and Carbon Sequestration. *Critical Rev. Plant Sci.* **24**, 1–21, URL https://doi.org/10.1080/07352680590910393.

22. Buck, H. J. (2016). Rapid scale-up of negative emissions technologies: social barriers and social implications. *Clim. Chang.* **139**, 155–167, URL https://doi.org/10.1007/s10584-016-1770-6.

23. Lyngfelt, A., Johansson, D. J. A. & Lindeberg, E. (2019). Negative CO2 emissions - An analysis of the retention times required with respect to possible carbon leakage. *Int. J. Greenh. Gas Control.* **87**, 27–33, URL http://www.sciencedirect.com/science/article/pii/S1750583618308235.

24. Bui, M. *et al.* (2018). Carbon capture and storage (CCS): the way forward. *Energy & Environ. Sci.* **11**, 1062–1176, URL https://pubs.rsc.org/en/content/articlelanding/2018/ee/c7ee02342a.

25. Plevin, R. J., , M. O., Jones, A. D., Torn, M. S. & Gibbs, H. K. (2010). Greenhouse Gas Emissions from Biofuels' Indirect Land Use Change Are Uncertain but May Be Much Greater than Previously Estimated. *Environ. Sci. & Technol.* **44**, 8015–8021, URL https://doi.org/10.1021/es101946t.

26. McLaren, D. (2012). A comparative global assessment of potential negative emissions technologies. *Process. Saf. Environ. Prot.* **90**, 489–500, URL http://www.sciencedirect.com/science/article/pii/S0957582012001176.

27. Sanz-Pérez, E. S., Murdock, C. R., Didas, S. A. & Jones, C. W. (2016). Direct Capture of CO2 from Ambient Air. *Chem. Rev.* **116**, 11840–11876, URL https://doi.org/10.1021/acs.chemrev.6b00173.

28. de Coninck, H. & Benson, S. M. (2014). Carbon Dioxide Capture and Storage: Issues and Prospects. *Annu. Rev. Environ. Resour.* **39**, 243–270, URL https://doi.org/10.1146/annurev-environ-032112-095222.

29. Keith, D. W. (2009). Why Capture CO2 from the Atmosphere? *Science* **325**, 1654–1655, URL https://science.sciencemag.org/content/325/5948/1654.

30. Holmes, G. & Keith, D. W. (2012). An air–liquid contactor for large-scale capture of CO2 from air. *Philos. Transactions Royal Soc. A: Math. Phys. Eng. Sci.* **370**, 4380–4403, URL https://royalsocietypublishing.org/doi/10.1098/rsta.2012.0137.

31. Kittner, N., Lill, F. & Kammen, D. M. (2017). Energy storage deployment and innovation for the clean energy transition. *Nat. Energy* **2**, 17125, URL https://www.nature.com/articles/nenergy2017125.

32. Kreidenweis, U. *et al.* (2016). Afforestation to mitigate climate change: impacts on food prices under consideration of albedo effects. *Environ. Res. Lett.* **11**, 085001, URL https://doi.org/10.1088%2F1748-9326%2F11%2F8%2F085001.

33. Richards, K. R. & Stokes, C. (2004). A Review of Forest Carbon Sequestration Cost Studies: A Dozen Years of Research. *Clim. Chang.* **63**, 1–48, URL https://doi.org/10.1023/B:CLIM.0000018503.10080.89.

34. Anderson, R. G. *et al.* (2011). Biophysical considerations in forestry for climate protection. *Front. Ecol. Environ.* **9**, 174–182, URL https://esajournals.onlinelibrary.wiley.com/doi/abs/10.1890/090179.

35. Hall, J. M., Van Holt, T., Daniels, A. E., Balthazar, V. & Lambin, E. F. (2012). Trade-offs between tree cover, carbon storage and floristic biodiversity in reforesting landscapes. *Landsc. Ecol.* **27**, 1135–1147, URL https://doi.org/10.1007/s10980-012-9755-y.

36. Röös, E. *et al.* (2017). Protein futures for Western Europe: potential land use and climate impacts in 2050. *Reg. Environ. Chang.* **17**, 367–377, URL https://doi.org/10.1007/s10113-016-1013-4.

37. Strefler, J., Amann, T., Bauer, N., Kriegler, E. & Hartmann, J. (2018). Potential and costs of carbon dioxide removal by enhanced weathering of rocks. *Environ. Res. Lett.* **13**, 034010, URL https://iopscience.iop.org/article/10.1088/1748-9326/aaa9c4/meta.

38. Taylor, L. L. *et al.* (2016). Enhanced weathering strategies for stabilizing climate and averting ocean acidification. *Nat. Clim. Chang.* **6**, 402–406, URL https://www.nature.com/articles/nclimate2882.

39. Köhler, P., Hartmann, J. & Wolf-Gladrow, D. A. (2010). Geoengineering potential of artificially enhanced silicate weathering of olivine. *Proc. Natl. Acad. Sci.* **107**, 20228–20233, URL https://www.pnas.org/content/107/47/20228.

40. Renforth, P. (2012). The potential of enhanced weathering in the UK. *Int. J. Greenh. Gas Control.* **10**, 229–243, URL http://www.sciencedirect.com/science/article/pii/S1750583612001466.

41. Wilson, S. A. *et al.* (2009). Carbon Dioxide Fixation within Mine Wastes of Ultramafic-Hosted Ore Deposits: Examples from the Clinton Creek and Cassiar Chrysotile Deposits, Canada. *Econ. Geol.* **104**, 95–112, URL https://pubs.geoscienceworld.org/economicgeology/article/104/1/95-112/128062.

42. Gomiero, T., Paoletti, M. G. & Pimentel, D. (2010). Biofuels: Efficiency, Ethics, and Limits to Human Appropriation of Ecosystem Services. *J. Agric. Environ. Ethics* **23**, 403–434, URL https://doi.org/10.1007/s10806-009-9218-x.

43. Creutzig, F. *et al.* (2017). The underestimated potential of solar energy to mitigate climate change. *Nat. Energy* **2**, 1–9, URL https://www.nature.com/articles/nenergy2017140.

44. Riahi, K. *et al.* (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Glob. Environ. Chang.* **42**, 153–168, URL http://www.sciencedirect.com/science/article/pii/S0959378016300681.