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Preliminary Assessment of the Potential for, and Limitations to, Terrestrial Negative Emission Technologies in the UK

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Given the aspirational target of limiting global temperature rise to below 1.5°C compared to pre-industrial temperatures agreed in Paris in December 2015, and the UK's recently stated target of net zero emissions, there is urgency among UK policy makers to assess the technical potential for, and limitations of, Negative Emissions Technologies (NETs) in the UK. In this study we assess the maximum technical potential for a range of NETs, namely Bioenergy with carbon capture and storage, direct air capture of CO_2 from ambient air, enhanced weathering of minerals, afforestation / reforestation, soil carbon sequestration and biochar. We also assess the impact of NET implementation on land, greenhouse gas balance, energy requirements, water use, nutrient use, albedo and cost.

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Preliminary Assessment of the Potential for, and Limitations to, Terrestrial Negative Emission Technologies in the UK

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The aggregate technical potential for land-based negative emissions technologies (NETs) in the UK is estimated to be 12-49 MtC-eq./yr, representing around 8-32% of current emissions. The proportion of this potential that could be realized is limited by a number of cost, energy and environmental constraints which vary greatly between NETs.

Introduction

Future increases in global average temperature will be determined largely by cumulative emissions of CO_2 [1]. As a result, net global CO_2 emissions will need to reach near zero in order to limit temperature change. Negative Emissions Technologies (NETs) are likely to be important in reaching net zero emissions, or below, given the difficulty in completely eliminating greenhouse gas (GHG) emissions from all human activities. In order to avoid warming of more than 2°C with a >50% chance, most recent scenarios from Integrated Assessment Models (IAMs) include the large-scale deployment of NETs within a few decades[2-9]. More stringent temperature limits imply an even greater need for NETs, deployed on shorter timescales[10]. Since society must decide which mitigation pathways are desirable to tackle climate change, information on the potential risks and opportunities afforded by all NETs is necessary.

Two recent studies have examined the global technical potential for terrestrial NETs, and their impacts on land, greenhouse gas balance, energy requirements, water use, nutrient use, albedo and cost. First, Smith et al.[11] reviewed and analysed the biophysical and economic limits to implementation for a number of NETs: (1) Bioenergy (BE[12]) with carbon capture and storage (CCS; together referred to as BECCS[13]), (2) direct air capture of CO_2 from ambient air by engineered chemical reactions (DAC[14,15]), (3) enhanced weathering of minerals (EW[16-18]) where natural weathering to remove CO_2 from the atmosphere is accelerated, and the products stored in soils, or buried in land/deep ocean and (4) afforestation and reforestation (AR[19-21]) to fix atmospheric carbon in biomass and soils. Second, Smith[22], examined other land based options, namely (5) soil carbon sequestration (SCS) through changed agricultural practices (which include activities such as less invasive tillage with residue management, organic amendment, improved rotations / deeper rooting cultivars, optimized stocking density, fire management, optimised nutrient management and restoration of degraded lands[23,24]), and (6) converting biomass to recalcitrant biochar, for use as a soil amendment[25]. IAMs have so far focused primarily on BECCS[5,26,27] and AR[28-30]. For reasons of tractability, the analysis of Smith et al.[11] did not consider (7) manipulation of uptake of carbon by the ocean either biologically (i.e. by fertilizing nutrient limited areas[31,32]) or chemically (i.e. by enhancing alkalinity[33]).

Figures 1 depicts the main flows of carbon among atmospheric, land, ocean and geological reservoirs for fossil fuel combustion (Fig. 1a), BE (Fig. 1b), CCS (Fig. 1c), and the altered carbon flows for BECCS (Fig. 1d), for DAC (Fig. 1e), EW (Fig. 1f), AR, SCS, biochar, and sequestration in construction materials (Fig. 1g – the latter not assessed here), ocean fertilization (Fig 1h – not assessed here), and biochar addition to soil as part of BECCS (Fig. 1i).

In this study, the per-t-C impacts of negative emissions derived in [11,22], and areas available in the UK for land based NETs, are used to make preliminary estimates of the potential for, and impacts of, terrestrial NETs in the UK. The estimates consider the use of UK land specifically; they do not consider possible imports and exports of resources from land outside the UK.

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Systemic, holistic issues need to be considered for NETS deployment[34] and are probably the most immediate aspects of developing these technologies which need to be addressed. It must be noted that this is a preliminary, technology focussed assessment that takes no account of such socio-political aspects of NETs deployment, which when considered would be expected to lower considerably the technical potentials estimated here. Further, whilst the best available data have been used, different technologies are at different stages of development (e.g. AF and SCS widely applied already; DAC yet to be demonstrated at scale), and the quantity and quality of data varies greatly between technologies[11].

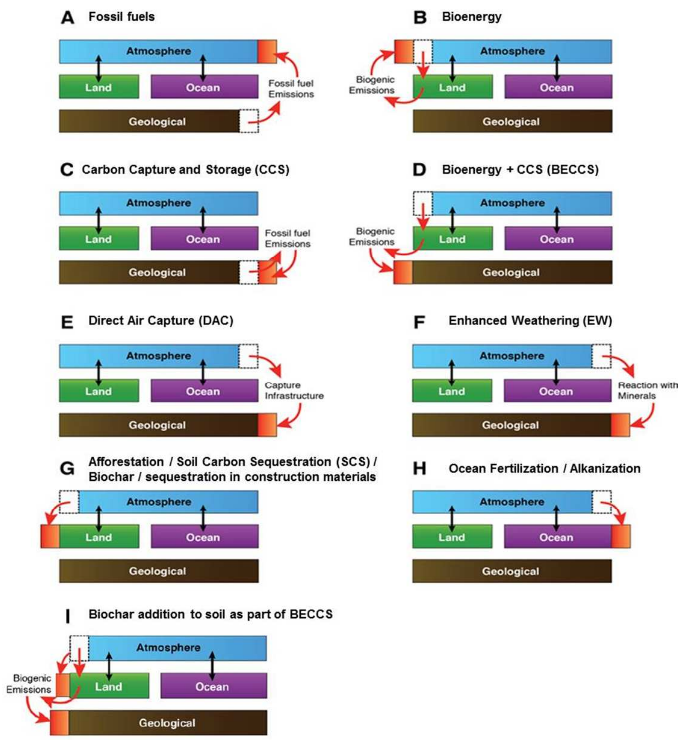

Figure 1. Schematic representation of carbon flows among atmospheric, land, ocean and geological reservoirs. See text for details (adapted from [11,22]).

Materials & Methods

Sources of data used to estimate impacts of NETs on a per-t-Ceq. are described in [11] and [22] except for values for EW where a detailed UK study exists[35] and values from this study are used. For BECCS, dedicated energy crops are assumed as in [11]. Impact were scaled to the UK level by multiplying per-t-C-eq. impact values by available land areas for each technology defined from the UKERC spatial modelling of bioenergy study in the UK described in Lovett et al. [36] using a similar approach to that used for NETs at the global scale[11,22]. The difference in approach here is that available areas in the UK were used to constrain the potentials, rather than using exogenously estimated potentials from IAMs and / or literature values.

Available land areas[36] are: a) 8.5Mha for all land not excluded by all UKERC constraints, including a high naturalness score, 6.4 Mha using “a”, but also excluding all Grade 1 and 2 (prime) agricultural land, and 1.5 Mha using “a”, but also excluding all Grade 1, 2 and 3 (prime and good quality) agricultural land. To put these land grades into context, about half of all agricultural land in England is Grade 3[37], so including grade 3 land is realistic to avoid large scale competition with agriculture[35].

For EW, Renforth[35] lists all of the potential mineral sources in the UK. The total resource suitable for EW available in the UK is 1669 Gt rock, mostly basic silicates with a negative emission potential of 0.082 t C/t rock, and a small proportion of these as ultrabasic rocks with a negative emission potential of 0.218 t C/t rock. The total negative emission potential of the total UK mineral resource is 117 Gt C [35], which is a maximum technical potential; the potential that could ever be realised in reality is likely to be much lower due to a number of constraints[35].

The negative emission potential is largely dependent on the rate at which it is spread onto soils after comminution[18]. Even if spread at 50 t rock/ha/yr, the highest rate considered in Renforth[35] and Taylor et al.[18], only 0.425 Gt mineral would be required to cover the 8.5 Mha of land available – a small fraction of the 1669 Gt rock potentially available in the UK, so the availability of suitable rock in the UK is not limiting. What limits the negative emission potential is the application rate with the rates used by Taylor et al.[18] examined here:

- 0.4 t rock/ha/yr is the rate at which lime is typically applied to agricultural land[35]
- 10 t rock/ha/yr is the “low” rate examined in Taylor et al.[18], similar to nutrient poor soils, even though this is considerably larger than the typical application rate for lime in agriculture
- 50 t rock/ha/yr is the “high” rate noted in both Renforth[35] and Taylor et al.[18]. This would likely be inconsistent with agricultural use of the land, especially with mineral residues.

Results

Impacts of NETs on a per-t-Ceq. removal basis

Values for impact of NETs on a per-t-Ceq. removal basis are shown in table 1. For full details see [11,22].

[Tables attached as separate file]

Table 1. Low and high per-t-Ceq. negative emissions impact values used in the calculation for UK impacts of NETs. All values for SCS and Biochar are from [22]. All values for BECCS, AR, DAC and are from [11], and for EW from calculations based on [35], except for Potassium values for AR which were calculated from values in Ovington and Madgwick[38], and Potassium values for BECCS (Miscanthus) calculated from values in Roncucci et al.[39]. All estimates are nominally for 2100 except for costs which are for 2050.

UK land available for use for NETs

Since implementation of BECCS and AR use land that can no longer be used for food production, the areas available for BECCS and AR in the UK are assumed to be those defined in the UKERC mask that excludes Grades 1-3 agricultural land (1.5 Mha). Similarly, land used for growing feedstock for Biochar cannot be used for food so is assumed to be the same (1.5 Mha). BECCS feedstock from agricultural residues would reduce competition for land, but only dedicated crops were considered here. SCS, however, can be practised on land without changing its land use, so is assumed to be any area not excluded by the UKERC mask (8.5 Mha). DAC has no land footprint (if one excludes area used to generate energy to power the process), so is not constrained by land availability. The ground rocks from the EW process can be spread onto land without changing its land use, so when applied at low rates of 10 t rock/ha/yr (thus not interfering with agricultural use of the land – though these rates are still higher than those regularly used in agriculture for liming[35]), could be used on 8.5 Mha of land. If applied at high rates of 50 t rock/ha/yr, rock for EW could only be applied to land not used for agriculture (since the rates are incompatible with agriculture). Low and high rates are from Taylor et al.[18].

[Tables attached as separate file]

Table 2. Summary of areas, negative emission potentials, impacts of NETs on water use, energy requirement, nutrient (N, P and K) requirements and albedo, and bottom-up estimates of cost in the UK. EW may supply nutrients such as P and can have variable impacts on albedo depending on the mineral used, though these effects are not quantified. See text for further details. *DAC potential is not constrained by area so impacts assessed at same level of implementation as BECCS (i.e. area of 1.5 Mha; 4.5-18 MtCeq/yr). ** EW – high rate of application (50 t rock/ha/yr) applied only to non-Grade 1-3 land = 1.5 Mha; low rate of application (10 t rock/ha/yr) applied to available Grade 1-3 land = 7.5 Mha. High and low rock application rates from Taylor et al. (2016)[18].

Negative emissions potential of terrestrial NETs in the UK

Negative emissions potential for BECCS, AR and Biochar implemented on 1.5 Mha of land in the UK are: 4.5-18, 5.1, 1.73-11.25 MtC-eq./yr, respectively. SCS, implemented on 8.5 Mha of land, would deliver 0.255-8.5 MtC-eq./yr. EW can be implemented on 1.5/8.5 Mha of land, delivering 7.0-16.5 MtC-eq./yr. If 50 t rock/ha/yr is applied to 1.5 Mha of non-agricultural land, and 10 t rock/ha/yr is applied to the remaining 7.5 Mha, the combined total potential of EW is 16.36 + 6.14 = 22.5 Mt C/yr.

The technical potential for DAC, while not assessed directly here, is high. In addition to land constraints being low, constraints from available storage sites for CO_2 are also low in the UK. Around 21 GtC (equivalent to 210 MtC-eq./yr over a century) storage potential exists in UK coastal waters[40]. This would, however, be reduced for DAC by other CCS technologies (including BECCS) requiring access to the same storage sites.

Environmental impacts of NETs in the UK

For comparison of impacts of across all NETs (as in [11]), DAC is compared at the same level of implementation of negative emissions as BECCS, i.e. 4.5-18 MtC-eq./yr. All other NETs are compared at the negative emission potentials described above. Table 2 summarises the impacts on water use, energy requirement, nutrient (N, P and K) requirements and albedo, and bottom-up estimates of cost (but see discussion for caveats regarding bottom-up calculation of costs).

Discussion

Total UK negative emissions potential

The negative emissions potential for individual NETs in the UK range from ~0.3 (low estimate for SCS) to ~23 MtC-eq./yr (for EW applied to all available land). Most NETs have potential in the order of magnitude range of 1s – 10s Mt Ceq./yr, though DAC potential could be greater. Total UK emissions for all GHGs during 2010-2014 amounted to ~560 MtCO2-eq./yr (=153 MtC-eq./yr)[41], so potentials in the range of 10 MtC-eq./yr would represent around 7% of current total UK emissions. The results here for BECCS, biochar and DAC are similar to those found in another study of UK technical potential[42]: for BECCS the estimate here of 4.5-18 MtC-eq./yr compares to 5-22 MtCeq./yr, while for biochar the estimate here of 1.7-11 MtC-eq./yr compares to 3-13 MtC-eq./yr.

Not all of the potentials of the individual NETs are additive. In particular, BECCS, AR and biochar are alternative uses of the same land / biomass resource, meaning deployment of one of these technologies precludes deployment of the others. The maximum aggregate land-based UK NETs resource is estimated to be 12-49 MtC-eq./yr (BECCS plus SCS plus EW), assuming no interaction between practices to increase soil organic carbon storage, the spreading of powdered rock onto soils for EW and the growth of biomass as a feedstock for BECCS. Though there is no literature explicitly examining potential interactions between these NETs, several can be hypothesized (such as EW raising soil pH and thereby decreasing the efficacy of soil organic carbon storage; acidity is known to slow decomposition[43]), so the values presented here should be regarded as the maximum aggregate potential range. This optimistic aggregate technical potential for land based NETs in the UK represents ~8-32% of current UK GHG emissions. DAC could increase this total further. The potentials should be regarded as preliminary since large uncertainties remain in the data used in this assessment[11].

An important limitation of this study is that it excludes the potential for national negative emissions from imported and exported resources. Compared to the global per-capita average, the UK has high energy demand and low land availability. Biomass is already imported into the UK for energy generation, and proposed strategies for meeting the UK's emissions targets include the possibility of the UK importing up to 800 PJ/yr by primary energy in the 2030s[44]. To the extent that the UK does become a net importer (or exporter), and depending on where emissions savings are credited, it could have greater (or lesser) negative emissions potential.

Limitations of NETs

As for the global analyses[11,22], the main technical limitations of NETs in the UK are high cost and energy requirements for DAC; landscape, large areas logistics, energy requirements, and costs for EW; competition for land, water and nutrients (and potentially albedo impacts) for BECCS and AR; lower per unit potential for SCS; and albedo, land competition (and possibly) cost for biochar. For AR, changes in albedo could reduce the efficacy of the benefits through negative emissions. In Norway, about 50% of the benefit of the net C sink is lost when short vegetation is replace by needle leaved trees (largely due to snow cover disruption)[45]. At more southerly latitudes, such as the UK, one would expect the impact to be <<50% of the net C sink offset – due to both possibility of planting deciduous trees, and the decreased prevalence of snow. A full spatial assessment should be undertaken to quantify the impact.

Bottom-up costs are known to be unreliable since they do not account for the effect of lowering costs through learning during implementation and economies of scale. Nevertheless, the per-t-Ceq. estimates show the likely relative costs of each technology, suggesting that SCS is the least expensive, but with biochar also having potential for cost negative implementation (through economic benefits realised from productivity co-benefits) in part of the cost range, but also high upper estimates of cost. DAC is the most expensive NET, with upper estimates of cost also high for EW (wide cost range) and biochar. BECCS and AR have relatively low cost. Most of the costs (except for the upper estimates for DAC, biochar and EW) are in the range estimated in the AVOID programme which noted "costs in the order of magnitude of $US 100/tCO2"[42], which is equivalent to ~$US 370/tC-eq. Costs for specific technologies (converted from CO_2-eq. to C-eq.) estimated in the AVOID programme[42] were $US 110-150/tC-eq. for biochar; >$US 460-550/tC-eq. for BECCS; and ~$US 550-730/tC-eq. for DAC.

SCS and biochar provide negative emissions with fewer potential disadvantages than many other NETs, though additional nutrients could be required unless the SCS is achieved by adding organic material. Though the negative emissions potential is lower than for DAC and BECCS, it is not insignificant, and is comparable to the potential for AR[11].

Permanence of emissions removal

Carbon removals with any technology using liquid CO_2 for CCS are subject to the integrity of the storage reservoir. CCS demonstration projects worldwide appear to be performing well at 30 $MtCO_2$/yr[46]. UK reservoirs for liquid CO_2 CCS have been mapped[40], and are assessed to be ready for use. Storage of captured carbon dioxide in solid form as carbonate minerals, by injecting liquid CO_2 into basaltic rocks, may be rapid (95% in less than 2 years) and has been shown to be feasible in a small pilot study[47]. Solid storage is generally considered to be more permanent with lower risk of reversal. Permanence (and sink saturation) is more of an issue for SCS, AR and biochar.

A drawback of SCS and AR is that of sink saturation. We express SCS and AR negative emission potential here as a yearly value, but the potential is time limited. SCS and AR potential is large at the outset (which trees are growing and while soil carbon stocks are increasing), but decreases as forest biomass / soils approach a new, higher equilibrium value[24], reaching zero when the new equilibrium is reached. This sink saturation occurs after 10-100 years, depending on the SCS / AR option, soil / tree type and climate zone (slower in colder regions), with IPCC using a default saturation time of 20 years for soil sinks[48,49]. Since sinks derived from SCS and AR are also reversible[24], practices need to be maintained, even when the sink is saturated, so any yearly costs will persist even after the negative emission potential has reduced to zero at sink saturation. Sink saturation also means that SCS implemented in 2020 will no longer be effective as a NET after 2040 (assuming 20 years for sink saturation). The importance of this for NETs, is that NETs are most frequently required in the second half of this century[3,11], so SCS and AR, may no longer be available after 2050, or will be less effective, if they are implemented for mitigation relatively soon. The same sink saturation issues apply partly to biochar, though the issue is less pronounced as biochar is more recalcitrant, and equilibrium (if it occurs) would be expected to take much longer, so that biochar should still be effective as a NET in the second half of this century even if implemented relatively soon.

Conclusions

The aggregate technical potential for land-based negative emissions technology (excluding direct air capture and imports/exports of resources from land outside the UK) is estimated to be 12-49 MtC-eq./yr, which is around 8-32% of current total UK emissions. The proportion of this technical potential that could be realized is limited by a number of cost, energy and environmental constraints, which will need to be overcome if the full potential of NETs is to be realized in the UK. More detailed, spatially explicit studies will help to better constrain the wide ranges presented here based on literature values. Further, systemic and holistic issues relevant to NETS deployment[34] were not considered in this study and need to be addressed, and public acceptance for a variety of reasons (including perceived threats to health and safety) were not considered. Nevertheless, the methods applied in this study are useful in providing a preliminary technological / environmental assessment of the potential for, and limitations of, NETs at a national scale, allowing for more in-depth research and development to be targeted in future, to overcome the current barriers to implementation.

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Tables

Table 1. Low and high per-t-Ceq. negative emissions impact values used in the calculation for UK impacts of NETs. All values for SCS and Biochar are from Smith (2016). All values for BECCS, AR, and DAC are from Smith *et al.* (2016) and values for EW were calculated from Renforth (2012), except for Potassium values for AR which were calculated from values Ovington & Madgwick (1959), and Potassium values for BECCS (*Miscanthus*) calculated from values in Roncucci *et al.* (2014). All estimates are nominally for 2100 except for costs which are for 2050.

Technology	NET rate per land		Land area		Water use		Energy input		Nitrogen		Phosphorus		Potassium		Albedo impact		Cost	
	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
	t-Ceq./ha	t-Ceq./ha	ha/t-Ceq.	ha/t-Ceq.	1000m^3/t-Ceq.	1000m^3/t-Ceq.	GJ/t-Ceq.	GJ/t-Ceq.	kgN/t-Ceq.	kgN/t-Ceq.	kgP/t-Ceq.	kgP/t-Ceq.	kgK/t-Ceq.	kgK/t-Ceq.	unitless	unitless	US$/t-Ceq.	US$/t-Ceq.
BECCS	3	12	0.1	0.4	2	2.5	-38.6	8.7	11	20	0.8	20	5.7	22	0	0.04	132	132
AR	3.4	3.4	0.1	0.6	1.18	2.35	0	0	2	5	4	5	0.4	3.12	0.002	0.62	65	108
SCS	0.03	1	1	33	0	0	0	0	80	80	20	20	15	15	0	0	-165	40
Biochar	1.15	7.5	0.13	0.87	0	0	-50	-20	30	30	10	10	70	70	0.08	0.12	-830	1200
DAC	1818	1818	0.001	0.001	0.073	0.11	2.6	45.8	0	0	0	0	0	0	0	0	1600	2080
EW	0.82	10.91	1.22	0.09	0.0015	0.0015	3	46.2	0	0	0	0	0	0	0	0	92	5887

Table 2. Summary of areas, negative emission potentials, impacts of NETs on water use, energy requirement, nutrient (N, P and K) requirements and albedo, and bottom-up estimates of cost in the UK. See text for further details. * DAC potential is not constrained by area so impacts assessed at same level of implementation as BECCS (i.e. area of 1.5 Mha; 4.5-18 MtCeq/yr). ** EW – high rate of application (50 t rock/ha/yr) applied only to non-Grade 1-3 land = 1.5 Mha; low rate of application (10 t rock/ha/yr) applied to available Grade 1-3 land = 7.5 Mha. High and low rock application rates from Taylor *et al.* (2016)[18].

	Area applied	Negative Emission Potential		Water use		Energy required		Nitrogen		Phosphorus		Potassium		Albedo		Cost	
		Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Technology	Mha	Mt Ceq./yr	Mt Ceq./yr	km^3/yr	km^3/yr	PJ/yr	PJ/yr	ktN/yr	ktN/yr	ktP/yr	ktP/yr	ktK/yr	ktK/yr	unitless	unitless	B$US/yr	B$US/yr
BECCS	1.5	4.5	18	9.00	45.00	-173.7	156.6	49.5	360	3.6	360	25.7	396	0	0.04	0.59	2.38
AR	1.5	5.1	5.1	6.02	11.99	0	0	10.2	25.5	20.4	25.5	2.0	15.9	0.002	0.62	0.33	0.55
SCS	8.5	0.255	8.5	0	0	0	0	20.4	680	5.1	170	3.8	127.5	0	0	-0.04	0.34
Biochar	1.5	1.725	11.25	0	0	-86.3	-225	51.8	337.5	17.3	112.5	120.8	787.5	0.08	0.12	-1.43	13.5
DAC		4.5*	18*	0.33	1.98	11.7	824.4	0	0	0	0	0	0	0	0	7.2	37.44
EW	1.5/8.5**	7.0	16.5	0.01	0.04	20.9	755.9	0	0	0	0	0	0	0	0	0.64	96.32

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Response to reviewers' comments - EM-COM-06-2016-000386

Reviewer 1 comments to the editor:

Comment: "However, its framing has a number of implicit implications which might be interpreted inappropriately by a policy audience and result in unintended consequences. This reviewer has relayed his concerns in the comments to authors, but to the editor, I would like to emphasize the following:
Response: Thank you for this thoughtful assessment. We have revised the manuscript to address all of your points, as detailed below.

Comment: • The paper takes a very `static', `silod' technological perspective of negative emissions technologies and is devoid of socio-political dimensions. Though it is a technical assessment and the academic community understands this the likely role of the socio-political aspects of negative emissions technology deployment in lowering potential must be emphasized for the policy audience.
Response: We are not able to assess the likely role of the socio-political aspects of negative emissions technology deployment in lowering potential, since to our knowledge, this research has not yet been done, but we agree that it is a critical point and we have added it both to the framing in the introduction and again in the discussion – in the introduction: "Systemic, holistic issues need to be considered for NETS deployment[47] and are probably the most immediate aspects of developing these technologies which need to be addressed. It must be noted that this is a preliminary, technology focussed assessment that takes no account of such socio-political aspects of negative emissions technology deployment, which when considered would be expected to lower considerably the technical potentials estimated here."

Comment: • It assumes that the knowledge that informs the numbers for each technology is of the same level of development when in fact the assumptions and research needs for the technologies are very different - making a like for like comparison inappropriate - but understandably necessary for this particular analysis. This should be emphasised better in the paper.
Response: We have now emphasised this in the introduction, by adding the following: "Further, whilst the best available data have been used, different technologies are at different stages of development (e.g. AF and SCS widely applied already; DAC yet to be demonstrated at scale), and the quantity and quality of data varies greatly between technologies[11]."

Comment: • Some of the calculations have used metrics which are questionable when transposed to a UK context and could have a substantial impact of overestimating some of the calculations.
Response: The metrics questioned by the reviewer (EW potential and land available for each NET) have been reworked (EW) – see response to "comments to the authors" below.

Comment: • Finally the paper completely avoids the systemic, holistic issues that need to be considered for NETS deployment – see Lomax, et al 2015 – which are probably the most immediate aspects of developing these technologies which need to be addressed. These points, if not addressed, may result in policy makers interpreting the work in a manner which is inconsistent with the needs of the sector to inform UK decarbonisation strategy."
Response: This is a very good point – we now cite Lomax et al. (2015) and note the need to address the systemic, holistic issues for NETs deployment in the introduction (and again in the conclusions). See further responses below.

Referee: 1

Comments to the Author

Comment: This paper presents quantitative results (in Tabels 1 and 2) that are essentially those found in Smith et al. 2016 (Nature Climate Change) downscaled to the UK given UK constraints on land area, as well as qualitative results (e.g. Limitations of NETs) that are repeating those found in that other paper. I suppose that the results for any particular country are worthwhile knowing, although it would be much more useful knowing the results for any given country in the context of results for other countries as well. Being based on the same assessment methods as the previous paper I do not have any serious critique about their validity.
Response: Thank you for this observation. We have now been more circumspect in our statement of potentials and have added more discussion on uncertainties and systemic and holistic constraints to NETS deployment.

Comment: I find the results to potentially misleading in terms of their level of certainty. All of these technologies are untested at large scale, implying large ranges of uncertainty in several respects. The cost estimates rely on other studies (in particular, reference 40, which appears not to be peer-reviewed), and yet to me appear to be overly optimistic in terms of the width of the uncertainty band for some technologies (e.g. BECCS has a single point estimate, DAC has low and high estimates differing by only 30%, despite the fact that it is untested at scale).
Response: We agree that uncertainty was not adequately flagged in the original submission, and we now refer to the levels of uncertainty (often quite large) in the estimates in the discussion, e.g. this sentence added to the section on potentials: "The potentials should be regarded as preliminary since large uncertainties remain in the data used in this assessment[11]".

Comment: What is driving the overall finding (30 - 130 MtC-eq / yr) is the range of estimates for Enhanced Weathering (EW), and yet these are the results that are the least transparent. If I multiply the NET rate per land in Table 1 (which for EW is a point estimate, which contradicts the level of uncertainty that I understand to exist) to the available land area listed in Table 2, I arrive at a value of 2023 t-Ceq / yr for EW. It is completely unclear how the authors then derive a range of 25.5 - 102 MtCeq/yr. Aside from EW, which we don't even know the feasibility of, Table 2 suggests a range of 5 - 25 MtC-eq/yr. This in turn corresponds to about 3 - 18% of current UK emissions.
Response: The EW estimates have been reworked to include only mineral resource from the UK, to make the estimate comparable with the estimate for other NETs (where domestically available land is the limiting factor). Values from Renforth (2012) are now used.

Comment: I find the presentation of the limitations of NETs to be overly simplistic, and ultimately not appropriate for this article. In addition to costs, land availability, energy and water requirements, there are also issues of a lack of public acceptance for a variety of reasons (including perceived threats to health and safety). This is a subject for a review article, or a research article focused on any of these issues. It would be better to remove it here.
Response: We disagree that the biophysical and cost limitations should not be presented – we feel that this adds considerable value to the article – but we acknowledge that we did not address public acceptance at all – this we have now addressed in a caveat included at the end of the discussion – to emphasise again (since it appears this was not clear) that we are assessing only the biophysical and cost limitations to NETs and that public acceptance for a variety of reasons (including perceived threats to health and safety) are another consideration not quantified in this article.

Comment: I found Figure 1, which was essentially copied from Smith et al. (2016) to be unnecessary. In Table 1, I assumed that the values for "Land area" should be the inverse of those for "NET rate per land," and yet the numbers didn't really fit.
Response: The land area is determined from land availability (Lovett et al., 2014), and land area error for EW has been corrected (reviewer2 also spotted this). While stylistically and superficially similar,

Figure 1 differs from that in Smith et al. as it includes soil carbon sequestration, biochar and biochar as a by-product of BECCS. It has not been published before and we feel it is a useful explanatory figure to help the reader understand the mechanism by which each NET removes carbon from the atmosphere and the reservoirs in which that carbon is stored.

Referee: 2

Comments to the Author

<u>Comment</u>: Overall this reviewer considers this to be a useful set of analysis that helps to inform the debate, and I agree with most of the analysis. The work:

- Clearly states assumptions for system boundary of assessing the scale of UK based negative emissions technologies potential.
- The analysis is clearly based on literature reviews and explicitly stated as such.
- The demerits of bounding an analysis for UK based negative emissions technologies is well made in the paper as are the flaws of setting the system boundary at this loci.

The reviewer has a number of concerns which I would recommend are addressed before the paper is published. These have been broken into general issues and those relevant to the analysis and calculations.

<u>Response</u>: We thank the reviewer for this overall assessment – and we address their specific concerns below.

<u>Comment</u>: General Issues:

- The paper is very good at highlighting the weaknesses in its assessment of the technologies but omits one very important flaw. The work implicitly assumes that the technologies are at the same level of development such that they may be considered: (1) to be directly comparable now; and (2) that they will all be able to ramp up in a linear rate to 2050. The need for varied levels of further research, different levels of uncertainty of assessments / assumptions and the differences in the level of investment and value chain development for the different technologies will be highly varied. This must be emphasised in the work to avoid miss-interpreted by the policy community.

<u>Response</u>: We acknowledge that both the differences in the level of development of each NET and that the uncertainties in the assessments / assumptions were not adequately dealt with in the original submission (as also pointed out by reviewer 1). We have now addressed both issues in the framing of the paper at the end of the introduction.

<u>Comment</u>: Direct comparability of land footprint of the technologies is inconsistent – most significantly for the following technologies:

DAC footprint is not comparable with the other technologies p5 line 6 due to the lack of accounting for the energy generation footprint required which could be substantial.

<u>Response</u>: We acknowledge that the energy generation footprint is not included and we state this explicitly: “DAC has no land footprint (if one excludes area used to generate renewable energy to power the process), so is not constrained by land availability”. If the energy were to come from nuclear power the UK land footprint would be negligible, but if from wind or solar would be prohibitive.

<u>Comment</u>: The EW role is a little unclear as it is unlikely that it will be feasible at scale in the UK unless the minerals are imported which blurs a system boundary. The footprint of the value chain is also not included and therefore questions the direct comparability of this metric with other technologies. The reviewer appreciates that these calculations are fraught with substantial variations for these particular technologies depending on the assumptions used but the need to explicitly state that some metrics are not directly comparable should be made in the paper.

Response: We agree that the system boundaries were blurred by not considering only UK mineral sources for EW. We have remedied this by reworking the EW figures so that they only include EW available from domestically (UK) mined minerals, now largely using the values from Renforth (2012).

Comment: The work tends to be technology centric and siloed in its assessment of the environmental and policy implications and completely avoids the systemic, socio-political issues that need to be considered for negative emissions deployment; though it does allude to markets p6 line 2-3 - it fails to explore this further. This concern is most salient in the conclusion which states that further analysis of this type as this being a fundamental basis to advance the negative emissions agenda. It is simply one very small component, the most significant being to advance the integration of negative emissions into current policy to calibrate - in a bottom up manner - the opportunities for NETS which is likely to establish a lower bound capacity for each technology. Arguably this is the most important aspect of understanding their future role - see Lomax, et al 2015
Response: We agree that these aspects were inadequately dealt with in our original submission, with the very same issues also raised by reviewer 1. We now cite Lomax et al. (2015) and note the need to address the systemic, holistic issues for NETs deployment – in the introduction and in the conclusions. See also responses to reviewer 1.

Comment: Though this reviewer is aware that the authors have stated that this is a technical assessment which will be appropriately contextualised by the academic community. The reviewers comments are seeking to address the capacity for miss-interpretation of the paper by policy makers and those who consider negative emissions as a mechanism to continue combusting fossil fuels in the medium term. The nascent state of understanding of these technologies by many audiences is such that the latter is prevalent and needs to be addressed for the sake of a more balanced discourse in this sector.
Response: We agree that these aspects were inadequately dealt with in our original submission, with the very same issues also raised by reviewer 1. We have addressed this in our enhanced introduction (framing) and in the conslusions.

Comment: Comments relating to the calculations
It is difficult to critique numbers too deeply as they are taken directly from literature reviews in some of the main author's previous published papers here and here.
Response: Thank you for this comment – indeed the potentials and impacts are from previously published papers. We have replaced the EW values largely with those from Renforth (2012).

Comment: Generally the numbers in the paper seem appropriate. However, three points are worth raising, one of might make a substantive difference to the final computations.
Response: See detailed responses below.

Comment: Most importantly, their estimate of sequestration per hectare per year for Enhanced Weathering seems orders of magnitude too high (238 tC-eq/ha/year).
Response: We have replaced the values used in the global analysis with those from a UK specific study reported in Renforth (2012) – the per-hectare values are indeed much smaller. Thank you for pointing out this error.

Comment: From the citation in the original paper here, this number actually relates to in-situ carbonation of peridotite formations in Oman, which is very different to the ex-situ spreading of ground olivine on land that they consider here. As a point of comparison, Kohler et al. 2012 estimates that even in their most optimistic case, ex-situ EW across the Amazon basin could conceivably reach 7.5 tC-eq/ha/year. The UK value would be far lower. Phil Renforth looked at this in more detail for the UK in this paper in 2012.

Response: Thank you. We concur that the UK-specific analysis from Renforth (2102) is more appropriate for use in this study than the values originally used, derived from a global study. We have replaced the values from the global analysis with those from the UK-specific study reported in Renforth (2012) as suggested by the reviewer.

Comment: Ideally it would also be good to consider the life cycle sequestration once mining, milling and distribution are considered.
Response: Mining, milling and distribution are considered under the energy and cost categories. We refer to Renforth (2012).

Comment: Under Soil Carbon Sequestration, it is not clear that this would involve additional input of external nutrients (N, P, K) beyond that already being applied to UK cropland. For example, practices typically reported to increase soil carbon sequestration rates in the literature usually do not involve increases in inputs. It would be valuable to clarify this.
Response: This has now been clarified by adding more detail in the discussion: "SCS and biochar provide negative emissions with fewer potential disadvantages than many other NETs, though additional nutrients could be required unless the SCS is achieved by adding organic material".

Comment: Under Afforestation and Reforestation, the albedo point raises the question of whether the net effect in the UK specifically would likely be positive or negative. The current numbers are drawn directly from the global analysis, which presumably entailed tropical, temperate and boreal effects. It would be useful to clarify where on the spectrum the UK would fall.
Response: Additional information has been added to the discussion. In Norway, about 50% of the benefit of the net C sink is lost, so at more southerly latitudes of the UK, one would expect the impact to be <<50% of the net C sink offset – due to both possibility of planting different species (deciduous trees are possible) and the decreased prevalence of snow which gives the largest impact on albedo when low vegetation is replaced with needle leaved trees. This has been added to the discussion.

Comment: I have no problems with the rest of Table 1 or how they translate the numbers in to Table 2.
Response: Thank you. We hope the above responses / changes address your concerns.

Referee: 3

Comments to the Author

Comment: The authors show in a "crisp" and efficiently written manuscript the potentials of and limits to a variety of NETs for the UK. Given the need and urgency of further research in the area of negative emissions, this short communication, based on 2-3 recently published articles, provides a first-cut assessment of options and opportunities for the UK to contribute substantially to mitigate global warming through their NE potentail. The article will be a great contribution to filling research gaps and national NE emissions assessments and I hence recommend to publish as is.
However, if space allows, it would be beneficial to the reader to consider and further elaborate on following issues:
Response: Thank you for these constructive comments.

Comment: 1) The importance of BECCS and the differences between BECCS from agriculture and forestry could be better explained (both types considered?). Furthermore, the discussion would benefit from a sentence on BECCS from agricultural residuals which would allow for food and energy production from the same arable land area and might reduce competition for land (and food

production) and enhance potentials (and sustainability). This might be implicit from the studies cited (e.g. AVOID), but is not that obvious for the general reader...
Response: The assumption about BECCS for dedicated energy crops has been added to the M&M. These nuances about agricultural residues are now discussed in the discussion section.

Comment: 2) The discussion section might further benefit from the mentioning of the needs for spatially explicit (higher resolution) potentials assessments that e.g. could identify realizable potentials (e.g. by considering different (optimal) technologies for different regions within UK, optimize logistics (one of the main problems for NETs) and suitable formations for storage. Furthermore, such detailed assessments could better consider environmental constraints such as ESS and protection areas etc...
Response: Protected areas are already considered (see M&M), but we have added the need to better spatially explicit assessments to the discussion.

Comment: The intervals between min/max and high/low shares seem to be substantial and combining the authors' approach with more detailed bottom-up assessments might reduce these gaps substantially... literature examples for such approaches possibly to be considered are e.g. Biomass enables the transition to a carbon-negative power system across western North America, Dan Sanchez et al. 2015, Nature Climate Change; BECCS in South Korea – Analyzing the negative emissions potential of bioenergy as a mitigation tool, Florian Kraxner et al. 2012, Renewable Energy; How negative can biofuels with CCS take us and at what cost? Refining the economic potential of biofuel production with CCS using spatially-explicit modeling, Nils Johnson et al. 2013, Energy Procedia;
Response: These are excellent points, which we have now added to the discussion.

Comment: 3) To my understanding, for the presented analysis it is correct to not consider NEs from imported feedstock since otherwise the boundary conditions would possibly need to be defined more accurately (!?) E.g. when considering imported biomass, this might need to be expanded towards consequent/linked AR and SCS activities in the locations of origin of the important biomass etc... would this have to be accounted (at least partially) for UK-produced NEs?
Response: We have now used the UK as the strict boundary condition, since we now only consider domestically (UK) available mineral for EW.

Comment: Congratulations for a great contribution that should be seen as a basic step towards further and more accurate calculations, assessments and modeling approaches.
Response: Thank you very much. We to hope that by providing these preliminary estimates of potentials and biophysical and cost limitations, further studies will refine and improve upon the estimates presented here.