Beyond carbon pricing: policy levers for negative emissions technologies

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Beyond carbon pricing: policy levers for negative emission technologies

Abstract

This paper explores policies for Negative Emissions Technologies (NETs), in an attempt to move beyond the supply-side focus of the majority of NETs research, as well as the current dominance of carbon pricing as the main NETs policy proposal. The paper identifies a number of existing policies from four key areas - energy/transport, agriculture, sub-soil, and oceans - which will have an impact on three NETs: Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Capture (DAC), and terrestrial Enhanced Rock Weathering (ERW). We propose that non-climate co-benefits may be valuable in terms of the policy 'demand pull' for NETs; in particular, we find that ERW may provide multiple co-benefits which can be mandated through existing policy structures. However, interaction with numerous policy areas may also create barriers, particularly where there is tension between the priorities of different government departments. On the basis of existing and analogous policies from a range of geographical contexts and scales, this paper proposes four options for NETs policy that could be reasonably implemented in the near-term. We also argue that ERW demonstrates the importance of scale and framing, because the policy environment depends on whether it is framed as a soil amendment at local scales or as a climate stabilisation technique at international scale.

Key policy insights

- Co-benefits may assist the 'demand pull' for novel technologies by providing multiple policy angles for incentivisation rather than relying on a 'fix-all' policy such as a high carbon price.
- DAC with storage might be overly reliant on a high carbon price, because it only provides one core benefit – that of atmospheric carbon reduction.
- ERW may provide multiple co-benefits which can be mandated through existing policy structures, but should focus on using waste rock rather than mining virgin material.
- We propose four near-term options for NETs policy: funding for small-scale BECCS demonstration and an international biomass certification mechanism; small-scale loans for ERW on farms and promotion of locally-sourced rock residues; amendment of fertiliser subsidy schemes to include silicate rock; and a clearer framework for licensing sub-soil access for CO_2 storage.

Keywords: NETs; carbon dioxide removal; co-benefits; BECCS; enhanced rock weathering; direct air capture

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1 Introduction

It has been increasingly suggested that in order to meet ambitious global climate change targets, there will be a need to remove previously-emitted carbon dioxide (CO_2) from the atmosphere using negative emissions technologies (NETs) (EASAC, 2018; IPCC, 2018). Because of this, policy and academic interest in NETs has grown significantly over the past few years, with the academic literature focusing on an increasingly diverse range of NETs (Minx et al., 2018). As pointed out by Nemet et al. (2018), the vast majority of existing NETs research focuses on the supply-side (for instance, R&D and technology potentials), whilst very little focuses on demand-side issues such as public acceptability and policy. These demand-side policy issues, however, will be critical to successful NETs deployment. Bellamy and Healey (2018) demonstrate that the current governance challenges for NETs can be characterised as more of an 'uphill struggle' than a 'slippery slope', therefore there is a need to begin examining options for responsible incentivisation. Long lead times for innovation also mean that it may be sensible to pay attention to policy levers sooner rather than later, because often the most challenging part of the innovation process is the move from development to large-scale deployment. This paper uses analogues from existing policies to explore potential policy routes for some major NETs and the various scales and actor dynamics which they may entail.

One of the main proposed routes for NETs incentivisation is through large-scale emissions reductions markets, such as emissions trading schemes (ETS). Existing schemes do not currently incentivise negative emissions: to do so would require issuance of credits for negative emissions, rather than just emissions reductions (Berg et al., 2017). These amendments to ETS have been hypothesised but are not currently apparent in any trading scheme. In the EU, ETS reforms alone are unlikely to be enough to finance large-scale deployment of BECCS (Berg, 2016), although they might go some way to reduce uncertainty and risk for investors. Honegger and Reiner (2018) argue that the new Sustainable Development Mechanism (Article 6.4 of the Paris Agreement) could incentivise NETs by harnessing financial transfers to mobilize the NET potential in countries that are unable to afford the capital costs. This would require Article 6.4 to incorporate agreed methodologies to quantify the sequestered CO_2 and the permanence of its storage, and would require the NETs to deliver verifiable co-benefits for the UN Sustainable Development Goals (SDGs). The viability of incentivising NETs under any carbon trading policy relies on the accuracy of monitoring, reporting and verification (MRV) of carbon sequestration and life-cycle emissions.

Existing policy research mainly focuses on the few NET policies that already exist, generally confined to the carbon mechanisms discussed above, and upstream R&D**.** We argue that interesting insights can be gained by looking *beyond* explicit policies on climate mitigation, because many NETs operate across multiple sectors. As an illustration of this, it is worth briefly exploring the assumed major driver of future NETs deployment: high global carbon prices. The majority of Integrated Assessment Models (IAMs) as used by the Intergovernmental Panel on Climate Change (IPCC) assume perfect-foresight discounting over a 100-year time horizon; this, combined with a limited carbon budget, leads to exponentially increasing carbon prices and a prevalence of NETs (Obersteiner et al., 2018). Carbon prices are indeed emerging in various jurisdictions around the world, but are enormously variable and act mainly as reflections of national priorities. For example, Sweden, with its abundant biomass resources, prices carbon at $139/tonne, whereas Norway (with its vital domestic gas industry) prices some fuels at $64/t but others at zero (World Bank, 2018). IAMs also do not consider the revenue source for these carbon prices: NETs produce *negative* emissions, meaning that the 'tax' becomes a subsidy. The revenue from this subsidy would presumably be sourced from carbon taxation and thus would decrease as decarbonisation advances, so beyond a certain point net carbon removal would be politically highly challenging and potentially unpopular with taxpayers (Royal Society and RAEng, 2018). Furthermore, carbon taxes are naturally regressive, a feature that can theoretically be counteracted using the principle of revenue neutrality (Metcalf, 2009), but as NETs would not produce any revenue, this would no longer be possible. Most importantly, regardless of whether a carbon tax would be most economically efficient in an ideal world, history demonstrates that it is implausible that any one policy would be the actual outcome. Experience shows that transitions do not follow complex modelling studies, but instead tend to result from national or regional political considerations (Geden et al., 2018a). Thus, whilst we do not dispute that a carbon price would be beneficial for carbon reduction and carbon removal innovations, our starting point for this paper is that it would not necessarily provide the promised panacea. There is value in exploring whether other policies and mechanisms – including but not limited to taxes, subsidies, trading schemes, regulations, and voluntary mechanisms – could be relevant for incentivising NETs. Furthermore, existing climate policy experience (for example, the introduction of Nationally Determined Contributions [NDCs] in the Paris Agreement) suggests that policies are likely to emerge piecemeal and will vary between jurisdictions (Beck and Mahony, 2018). The heterogeneity of proposed NETs also suggests the need to discuss a suite of policy perspectives that account for the diversity of techniques and contexts, rather than relying on a 'one-size-fits-all' approach.

This paper focuses on three major proposed NETs, described in more detail in Table 1: Bioenergy with Carbon Capture and Storage (BECCS); terrestrial Enhanced Rock Weathering (ERW); and Direct Air Capture with Storage (DACS). These were chosen because, according to the latest meta-analysis of existing research, they are the three proposed NETs with the largest long-term sequestration potential (Minx et al., 2018: Fig. 6). This is not to suggest that these three are the most promising, or should be the priority for policy-makers; merely that, in terms of thinking about policy overall, a useful starting point may be to consider the options with the biggest potential for CO_2 removal. There is also much uncertainty regarding sequestration potentials, with a large range and frequent updating of estimates, therefore policy planning should be mindful of the need to avoid closing down particular approaches and to enable competitive technology learning. It is also worth emphasising that there is still open discussion on the impacts and side-effects of most NETs, and thus our attempts to identify relevant policy areas for incentivising NETs should not be read as support for these *per se*. For many novel NETs, more needs to be known about potential environmental and social impacts, therefore the 'R&D-first' stance adopted by most policy-makers (and many academics) is in some ways pragmatic. However, this approach clearly has a supply-side bias, assuming as it does that techno-economic R&D must take precedence over socio-political R&D. Exploring analogous policy areas and outcomes may also help to anticipate side-effects. Co-benefits and co-costs can be socio-political as well as biophysical in nature, particularly in the way that interventions are framed and perceived, therefore there may be a need for real-world experimentation by practitioners and communicators, as well as for scientific research.

[INSERT TABLE 1 AROUND HERE]

This paper is structured around four policy areas with which the three NETs interact considerably: energy/transport, agriculture, sub-soil, and oceans. This list is by no means exhaustive: there are others with which these NETs interact (such as manufacturing, health and waterways), and further research could examine other contexts and sectors. It is also worth noting that they are interlinked and overlapping, particularly in the case of climate policy which is often the responsibility of multiple policy departments. For each policy area, we looked for examples in the literature of policies that may impact the three NETs discussed, and selected or deselected policies based on our goal of representing a diversity of geographical contexts, scales and actors, within a limited space. The sources used were all online, comprising policy and legislation documents, peer-reviewed literature and grey literature. Searches were carried out using Web of Knowledge, google scholar and google.com. Our search terms included terms relating to each policy area (e.g. 'energy' 'electricity' and 'transport'), and including the words 'policy/policies', 'regulation', 'legislation' and 'govern/governance'. In the following section, we discuss the four policy areas in turn, illustrating existing policies from around the world which could impact upon the three NETs. Section 3 then shifts to a technology-based approach, focusing on each of the three NETs to identify opportunities and barriers for policy-making in the near term; we propose four options for NETs policy which could reasonably be implemented in the near-term. We conclude by reflecting on the importance of how NETs are framed in policy discussions, particularly in terms of scale.

2 Policies relevant to negative emissions technologies

2.1 Energy and transport

In energy terms, the bioenergy component of BECCS provides a revenue stream which may be larger than those available to other NETs (Platt et al., 2018). This also makes it eligible for support from bioenergy policies, which are established in many jurisdictions around the world. For example, the EU's Renewable Energy Directive (RED) sets a target to supply 14% of transport energy from renewables by 2030, and the Fuel Quality Directive stipulates a 6% reduction in emissions from transport by 2020 (Berg et al., 2017). Currently, the majority of this is met by biomass. Several US States have implemented low-carbon fuel standards which provide an incentive for emissions abatement in biofuel production, and California is currently developing protocols to enable the use of CCS in fuel standards and potentially in its cap-and-trade programme (Sanchez et al., 2018). BECCS is most commonly discussed in relation to electricity (discussed in more detail below), but options for carbon capture at plants producing liquid bioenergy for transport are also being explored. However, the capture rate for liquid fuel is only 40-50%, as opposed to around 90% in electricity (IPCC, 2018), therefore electricity sector policies will be crucial for large-scale CO_2removal via BECCS. It is worth noting that bioenergy policies in electricity and transport sectors may not be mutually reinforcing, because competition for limited biomass resource could drive up prices, while incentivising biofuels in transport could also retard the electrification of transport systems.

Electricity from biomass is non-intermittent, meaning that in theory any policy to promote the use of flexible renewables instead of fossil fuels in the power sector could benefit bioenergy.[1] A large number of jurisdictions have implemented capacity mechanisms as part of national energy security strategies (including France, Germany, Italy, UK and numerous US States), although the success of bioenergy in an auction-type system depends on the structure of the domestic market. However, incentivising bioenergy as flexible or peaking capacity would limit the running hours, because it would be used mainly when supply is tight, which could make the high capital cost of BECCS even less economically feasible. Furthermore, this would significantly reduce the ability of BECCS to remove CO_2 from the atmosphere (Fajardy and Mac Dowell 2017), thus rendering its use as a NET largely pointless. Thus on the face of it, BECCS can provide system balancing capabilities as well as climate benefits, but in reality, such policies would potentially incentivise the use of bioenergy but not necessarily combined with CCS. Therefore proposals to incentivise BECCS using technology-neutral capacity mechanisms or other system management policies will likely be limited, and revenue from ancillary services markets are unlikely to be enough to make BECCS cost-competitive. Overall, there are cheaper options for system balancing, and options such as demand-side response and storage are experiencing significant cost reductions. BECCS also has system drawbacks in terms of the increased energy requirements for carbon capture, thus the energy co-benefits of BECCS are unlikely to provide a viable policy route for incentivisation unless aligned with ambitious emissions-reduction policies.

Trade-offs may exist between energy security of supply, and the NETs discussed here. DACS and ERW in particular have high energy requirements – DACS for the running of the capture units, and ERW for crushing

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[1] Note the distinction of flexible *renewable* capacity: capacity mechanisms generally incentivise any flexible capacity, meaning that bioenergy competes against cheaper gas and coal. Renewable incentives are offered separately, and do not tend to incentivise flexible capacity.

rocks. This power intensity could create tensions with domestic energy security and demand-reduction policies, especially for emerging economies with rapidly-increasing energy demand, and for countries such as Japan and Singapore which already struggle to site low-carbon electricity capacity. In many emerging economies, the energy requirements could also be hampered by a lack of adequate transmission infrastructure. Proponents of DACS argue that it could run intermittently, using power during times of oversupply to avoid curtailment or negative power prices. Yet current trends indicate that advances in electricity storage and demand-side flexibility could significantly reduce supply peaks in the future. In cases where there is tension between energy security and NETs objectives, overall it is likely that domestic energy security policies will take precedence, because the short-term political and economic risk from an energy shortfall is significantly higher than any risks which might accrue from a lack of domestic NETs capability.

Carbon Capture and Storage (CCS) is central to pipeline and storage elements of both BECCS and DACS. CCS technology, however, has suffered from a serious lack of policy and financial support worldwide, with significant implications for the viability of CCS-based NETs. The Global CCS Institute (2018) currently lists 18 operational plants, the majority of which use the captured CO_2 for Enhanced Oil Recovery (EOR), resulting in increased fossil fuel supply and net-positive emissions. The US recently reformed their tax credit system to incentivise CCS, with tax credits now available at $35/tonne for EOR and $50/t for geological storage (Bushman et al., 2018). However, the deadline for commencing construction is January 2024, thus a limited number of DACS projects may be eligible in time, and it has been argued that the main beneficiaries will probably be EOR projects (Buck, 2018). Similarly in China and India, CCS is increasingly popular in policy discourse and the opportunity for CCS retrofits on coal plants could reduce costs; however, this will not necessarily be low-carbon, because EOR is simultaneously expanding (IEA, 2016). CCS also significantly reduces power station efficiency, meaning that for many emerging economies, inadequate electricity capacity will be a significant barrier to conventional CCS, let alone energy-intensive NETs such as DACS. Current policy thus suggests that incentivising air capture via market mechanisms is dependent on a high carbon price, or will lead simply to increased carbon production in the form of EOR. This leads Haszeldine et al. (2018) to suggest that an important first step could be the issuance of certificates for long-term CO_2 storage for large emitters.

Air capture technology is being developed in conjunction with Carbon Capture and Utilization (CCU), which may provide a market for cost reductions; however, this runs a high risk of becoming locked into net positive emissions from the re-release of CO_2 during utilization. The term ‘CCU’ includes many diverse technologies, including EOR, synthetic fuels, horticultural activities, carbonated drinks and wood in construction, each of which provides a different storage longevity, therefore climate policy will need to differentiate between levels of support for these. There may also be a temptation on the part of developers and even policy-makers to frame DAC with usage (DACU) in terms of negative emissions, therefore there is a need for clarity that most types of CCU do not remove CO_2 from the atmosphere in the long-term. This will require further development and use of life-cycle emissions assessment, because emissions produced by usage further downstream in the value chain may not currently be fully recognised as part of the DAC process (Assen et al., 2013).

CCS is usually governed by energy departments because of its alignment with the fossil fuel industry, but its main function is emissions reduction, and it in fact creates a rather substantial energy penalty. It thus illustrates some of the tensions between departmental remits, because there may be little inherent incentive within energy departments to promote CCS: there are cheaper ways of reducing energy system emissions. This may be particularly the case for places such as India where responsibility for emissions reduction sits mainly with the department for environment rather than energy. Japan is a particularly salient example of this sort of tension: the Ministry of Environment (currently responsible for CCS demonstration) and the Ministry of Economy (responsible for energy) appear to have fundamentally different views on climate policy (Climate Action Tracker, 2018). Government departments with responsibility for CCS may need to offer direct incentives, for instance in funding allocated via competitions, or in periodic omnibus legislation such as mandates introduced via Energy Bills (Sanchez et al., 2018). We are not the first authors to argue this, and there is increasing pressure on governments to support CCS as a means to eventual NETs deployment; carbon pricing mechanisms and trading schemes have not succeeded, thus direct intervention (most likely at national or State/regional scale) is required (Haszeldine et al., 2018).

2.2 Agriculture

The agricultural context will be a crucial one for many types of land-based NETs, including BECCS and ERW. The agriculture sector in many jurisdictions is strongly supported by powerful lobbying and is often a priority sector for governments. This creates interesting actor dynamics: on the one hand, agriculture tends to be well-supported in terms of revenue, especially in large food-exporting nations; on the other hand, implementing measures such as environmental regulations can be near-impossible. Environmental measures can be very unpopular with farming lobbies, for instance if they require substantial changes to embedded practices, and therefore they often take the form of incentives rather than regulations.

ERW may improve soil fertility (Beerling et al., 2018), meaning that it may be politically attractive in food-exporting economies if proposed benefits emerge. Agricultural subsidies including direct payments are present in most food-producing economies, and these could provide a revenue stream to ERW, particularly where farmers are offered low-cost loans for new inputs or machinery.[2] For example, in Brazil, generous agricultural credit is available for new techniques; in Canada, the Growing Forward Initiative provides funding for developing new technologies; in Turkey, subsidies are provided to improve farm production capacity (Allen, 2016). Loans for the rock material would encourage farmers to shift from current soil amendment practices, such as liming, to ERW, and loans for spreading machinery could assist smaller farmers to start using rock amendments. However, these types of targeted interventions would have to compete with other farming priorities; for example, it is common for agricultural policy to focus on supporting particular crops for strategic reasons such as export markets. Nevertheless, small-scale subsidies (for instance at local level) could support the use of ERW on small numbers of farms, thus increasing visibility and familiarity amongst the farming community; if these amendments were successful at improving yields and soil quality without damaging ecosystems, loan schemes could be introduced more widely.

Depending on the rock product used, ERW may provide benefits such as reduced soil pH and improved nutrient uptake in plants, meaning that it may be a partial replacement for some conventional fertilisers (Beerling et al., 2018). This may be particularly relevant for nutrient-poor tropical soils, for instance in South-East Asia where many governments offer fertiliser subsidies. In Thailand, the health ministry has called for an outright ban on certain agricultural chemicals (Bangprapa, 2018), which if enacted could benefit non-chemical fertilisers such as crushed rock. Meanwhile, Malaysia already imports large quantities of phosphate rock to use as fertiliser; however, the government is also promoting a shift away from mineral fertilisers. In India, urea is heavily subsidised and there is a lack of regulation of run-off (Abrol et al., 2017). These examples illustrate the fact that fertiliser policies are highly heterogeneous, meaning that ERW development needs to pay attention to the particular fertiliser policies in any area. In most countries, silicate rock is not

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[2] One exception to this is New Zealand, which eliminated agricultural subsidies in the mid-1980s.

currently included as an eligible fertiliser because of its relatively novel status, thus schemes would need to be amended to include it. Berg et al. (2017) argue that organic standards could represent a barrier to ERW because they only permit certain types of soil amendments; however, the literature review conducted for this paper did not uncover examples of any organic standards that would prohibit basalt applications.[3] Finally, tests are underway to establish whether ERW may enable crops to use nitrogen more efficiently, reducing the need for nitrogen fertiliser. Pressure is building on governments to enact stronger environmental nitrogen-reduction policies, which could benefit ERW; yet implementing strict regulations is challenging in the face of powerful agricultural lobbying, and will depend on the power dynamics between the state and the private sector, and in most cases, between the agriculture and environment ministries. The applicability of nitrogen policies to ERW would also require crushed rock to be used *instead* of nitrogen-based fertilisers, with the degree of substitution depending on the attitudes and actions of farmers, the cost of the various options (including subsidies), and the extent of lock-in to nitrogen-based fertiliser practices.

Whilst BECCS could be incentivised using biomass policies from the agriculture sector, such policies have had their share of unintended consequences, which may provide useful lessons for future policy-making (cf. Buck, 2016). The land-use changes associated with biofuel planting can result in greater carbon emissions than they absorb, and there is considerable evidence that biofuels can cause severe ecological and social impacts in the areas from which they are sourced. They may also result in trade-offs with the SDGs (Honegger et al., 2018). These issues impacted the EU Renewable Energy Directive, which initially mandated increased use of crop-based biofuels, but after considerable debate, such use was eventually capped at no more than 7% of all transport fuels until 2030 (Geden et al., 2018b). These lessons are also important for ERW, which could operate alongside biomass production, opening up incentives and cost reductions under agricultural policies but also leaving ERW vulnerable to the substantial drawbacks of some of these policies. A potential challenge to BECCS may come from increasing concern over the sustainability of bioenergy, which could put pressure on its inclusion in schemes for ‘renewable’ energies and in agricultural support mechanisms, particularly in the EU.

2.3 The sub-soil

The three NETs discussed in this paper all interact strongly with issues relating to the subsoil. DACS and BECCS both rely on the same storage processes into deep geological formations, requiring the piping of pressurised CO_2 deep underground. The status of policy on geological storage differs considerably from place to place. The EU has already established a fairly comprehensive CCS Directive (EurLex, 2009), which enforces rules regarding safety, security, permits and liability; developing this Directive was problematic because of significant public opposition to CO_2 storage in Germany and the Netherlands, resulting in strict regulation of storage sites. In the US, EOR is already well-established, meaning that much of the regulatory apparatus already exists; however, there will be a need for near-term support to incentivise storage, most likely at State-level due to the federal government’s current opposition to climate change regulation. Meanwhile in Asia, CCS policies are largely absent; Wu et al. (2014) argue that the EU Directive provides a model for the development of a CCS framework in China, alongside a mandatory ETS to incentivise CCS deployment.

Subsoil ownership is also an important factor to consider for CO_2 storage. In many areas, ownership has yet to be determined, resulting in uncertainty over permits for CCS operations. In Alberta (Canada), the

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[3] We reviewed organic standards for the following jurisdictions: EU, UK, US, China, India, Japan, Thailand, Australia and Israel. Because of import/export rules, national organic standards have a high degree of similarity.

provincial government resolved this by declaring State ownership, whereas in the US, the subsoil is owned by the landowner above, meaning that compensation is necessary (UCL, 2019). It should be noted that the US ownership structure actually benefitted sub-soil fracking operations, because the compensation gave landowners a financial incentive; in the UK, where the subsoil is owned by the Crown, attempts to gain public support via compensation have been largely unsuccessful (Whitton et al., 2017). An immediate task for policy-making on NETs should be to establish an understanding of the politics of the subsoil, including how different ownership structures could impact project siting and how public opposition could delay or prevent projects, according to the relative role of civil society in different jurisdictional and societal contexts.

ERW requires rock resource for spreading, and in order for it to provide a significant emissions-reduction benefit, at least some of this would need to be mined (Strefler et al., 2018). Mining regulations could create serious constraints: in most countries, mining is governed by many levels of local, national and regional law, and opening new mines and complying with all relevant environmental legislation tends to be a complex and expensive process. Environmental regulations may be less stringent in many developing countries, but this trades off against damage to ecosystems, environments and communities. Mineral mines are responsible for hundreds of ongoing conflicts, particularly in India, Brazil, Colombia, Ecuador, Peru, Nigeria and the Philippines (EJOLT, 2018). There is also a risk that mining and dust spreading activities could cause health problems for workers, especially in countries with less developed regulatory infrastructure, and as such could trade off against other policy goals such as the SDGs (Honegger et al., 2018). Better regulation and governance of mining activities is crucial for local communities, and should be a priority for ERW projects to be carried out in a socially sustainable manner. Overall, the most pragmatic route for ERW in the near-term – in legal, economic and ethical terms – may be to avoid mining virgin material altogether and use waste materials such as volcanic ash, glacial till or leftovers from the core activities of an existing mine. This, however, means that the sequestration potential of ERW may be more limited than has been previously suggested.

2.4 Oceans

ERW in particular could interact with policies governing watercourses and the ocean. However, as the weathered material is technically a run-off rather than an addition, it would not fall under the Law of the Sea (UNCLOS, 1982) or the London Convention (1972) which prohibit ocean-based NETs. ERW would add alkalinity to oceans; at present, the ecosystem impacts of this are poorly understood, although in theory it could benefit coral reef and coastal areas by reducing ocean acidification (Renforth and Henderson, 2017). Ocean acidification could in theory fall under the remit of the United Nations Framework Convention on Climate Change (UNFCCC) process for reducing atmospheric CO_2 concentrations, although it has never been officially discussed in negotiations, and only appears specifically in the NDCs of 14 small island states (Spence et al., 2018). Legislative action on ocean acidification has been taken in the US by Maine and Washington State because of impacts to coastal fisheries (Cooley et al., 2016). There is also interest in coral reef protection from numerous national and global institutions, including the UN Environment Programme (UNEP) International Coral Reef Initiative; if ERW succeeds in protecting reefs from ocean acidification, it could be eligible for funding under programmes such as these. However, governance from international bodies such as UNEP is at a very early exploratory phase, and considering the controversies involved, governance at UNEP level is likely to be cautious and incremental. This is illustrated by the blockage and subsequent withdrawal in March 2019 of a Swiss-proposed resolution for UNEP to undertake an assessment of geoengineering methods and governance frameworks. A range of marine NETs approaches propose to add alkalinity directly to the oceans, via a range of mechanisms including ocean-based ERW and ocean liming; however, these are beyond the scope of this paper (see GESAMP, 2019, for a review).

DACS and BECCS also interact with ocean policies, although here the policies may create barriers rather than incentives. CCS offshore will require building pipes and platforms to access deep geological storage, which would need to be regulated to avoid negatively impacting ocean ecosystems. For offshore storage, the regulatory environment will depend on whether storage takes place in territorial waters or the high seas. Some jurisdictions have already implemented policies governing storage in territorial waters, but these are limited to a handful of industrialised economies (e.g. Australia, Scotland), not including any in Asia (UCL, 2019). Meanwhile storage in the high seas would be governed by UNCLOS, which does not prohibit CCS but which does constrain activities considered to be 'polluting'. Finally, it is important to remember that policies – particularly in democratic countries – are influenced by public attitudes. Research demonstrates that people consider oceans to be a particularly precious environment in terms of emotional connection and perceived 'naturalness' (Spence et al., 2018), and that offshore CO_2 storage could be an issue for public contestation (Mabon et al., 2014). Thus, it should not be assumed that utilising offshore sites will circumvent public concerns regarding CCS, and policy (particularly in terms of licensing and regulation) needs to be mindful of potential barriers to deployment at local and possibly national levels.

[INSERT TABLE 2 AROUND HERE]

3 Discussion and Conclusions

Current research on NETs is dominated by the supply side, as opposed to demand-side topics such as policy, and policy discussions tend to focus on the need for a high (global) carbon price. This paper has attempted to move beyond this, by exploring existing policy levers, mechanisms and concepts from multiple policy areas and at multiple scales which could be relevant to NETs. We suggest that co-benefits may be valuable in terms of the 'demand pull' for novel technologies, for instance because they provide multiple policy angles for incentivisation rather than relying on a 'fix-all' policy such as a high carbon price which has thus far proven rather elusive. The preceding section took a sector-based approach, examining existing policies from diverse spatial contexts. Table 2 summarises the examples we identified. This section now shifts to a technology-based approach, focusing on each of the three NETs to identify opportunities and barriers for policy-making in the near term.

A major conclusion which may be drawn from the preceding sections is that DACS might be overly reliant on climate policies such as a high carbon price, because it only provides one core benefit – that of atmospheric carbon reduction. At the moment, air capture technology is being developed in conjunction with CO_2 utilization for oil extraction, synthetic fuels and horticultural activities; this may provide valuable learning effects and potentially cost reductions, but without a high carbon price or targeted policies there may be little incentive to shift from CO_2 utilization (which may not lead to long-term CO_2removal) to CO_2 storage. There is a considerable body of existing research which points out that targeted state-led support may be necessary to incentivise CCS; this could take many forms, but the overriding lesson from previous experience is that 'technology-neutral' market mechanisms do not seem to be working. We also argue that support needs to be more transparent about the difference between utilization and long-term storage, particularly in cases where CCU technologies with diverse sequestration longevities are discussed under a blanket term.

BECCS has a biomass component which produces energy, and which is already well-established in existing policy frameworks. However, the previous section demonstrated that despite this co-benefit, the policy options for incentivising BECCS from within the energy sector may be somewhat limited. Another important factor to consider is that biomass is increasingly globally traded, thus a policy priority should be for adequate rules governing the sustainability of imports of biomass feedstocks; a possible first step could be a certification scheme similar to the Forestry Stewardship Council, with an international membership of individuals and organisations. At present, the externalities of feedstock production are increasingly shifted to the Global South, with environmental and climate impacts often going unreported. Thus Thornley and Mohr (2018) suggest that BECCS requires overlapping policy mechanisms at different scales, to focus attention on local actors and supply chain nodes and impacts that are often below the scope of national/international frameworks. Bellamy and Healey (2018) argue that responsible BECCS incentivisation should consider 'bottom-up' approaches that pay attention to local and national differences as well as collective ambitions. There may be potential for supporting BECCS using local waste feedstock such as residues or municipal waste, thus reducing ecological consequences and supporting the domestic waste sector. There is already interest in this at demonstration scale, for instance at Klemetstrud in Oslo (Norway), supported by state subsidies (Pour et al., 2018). This could involve sub-national actors such as local councils or county governments and waste management organisations (public and private, depending on the jurisdiction), as well as academics and private-sector institutions interested in supporting R&D.

Proponents of ERW promise numerous co-benefits, and the scientific challenge will be to identify which of these are the most robust, requiring positive results from years of field trial research. If the anticipated co-benefits do emerge, policies relating to agriculture and oceans in particular could provide a revenue stream for ERW. For instance, funds for ocean protection could also be viable if increased alkalinity were shown to be beneficial for ecosystems such as coral reefs; the actors involved could be international (e.g. UNEP), national (e.g. fisheries departments), or sub-national (e.g. Maine, Washington State). Agricultural subsidy schemes could realistically support ERW deployment on farms; however, agricultural policies can be notoriously political, tough to amend, and highly diverse in reflection of specific national priorities. In particular, fertiliser policies are complex and varied, with some countries promoting the use of mineral fertilisers as an alternative to chemicals, and others promoting the use of organic waste products such as farm residues and manure. In general, reform to national fertiliser schemes could promote the use of silicate rock amendments if the benefits were clearly evident. Importantly, many of the relevant policy actors for ERW may be small-scale and sub-national; for example, agricultural departments and regional/local farm support schemes. This raises questions about the extent to which ERW could ever make a significant contribution to CO_2 removal – its use as a soil amendment can take place on a small scale, governed by sub-national policies and actors, but its use as a significant NET would likely require deployment on a much larger scale requiring national or even international mandates and raising major MRV challenges.

3.1 Options for NETs policy

Any discussion of co-benefits comes with the significant caveat that some proposed co-benefits might not emerge as promised; the case of the environmental impact of biofuels provides an important cautionary tale in this regard. Nevertheless, co-benefits can be socio-political as well as biophysical, and sometimes technological learning requires real-world implementation, otherwise promising technologies may struggle to transition from basic R&D to deployment, and implementation at smaller scales can sometimes improve knowledge regarding the extent of co-benefits and co-costs. With this caveat in mind, we propose the following options for NETs policy in the near term:

- Increased funding for BECCS demonstration projects at local scales using locally-produced wastes and residues, and an international certification mechanism for biomass feedstocks to support sustainable imports.
- The introduction of small-scale loans for purchase of ERW rock material or machinery for use on farms, implemented at local scale in areas where there is a nearby supply of waste rock material, and the promotion of locally-sourced volcanic, glacial or mining residues for ERW as alternatives to large-scale mining and grinding.
- Amendment of fertiliser subsidy schemes to include silicate rock as a viable soil amendment.
- A clearer framework for licensing sub-soil access for CO_2 storage, giving increased clarity over ownership rules and the rights of local citizens.

As a closing remark, it is worth emphasising the critical importance of framing in policy discourse, particularly when discussing NETs at different scales. Starting with the influential Royal Society report in 2009, NETs such as BECCS, DACS and ERW have followed a particular route in policy discourse which has viewed them as part of a suite of ‘geoengineering’ techniques. This positioned NETs in the same category as highly controversial technologies such as Solar Radiation Management, with impacts on the discourse surrounding their implications and risks (Cox et al., 2018). Yet methods such as afforestation and soil carbon sequestration were never really tied into the political and ethical debates around geoengineering in the same way, because they tend to fall under the language of ‘carbon sinks’. As pointed out by Geden et al. (2018b), definitional questions are crucial for the framing of NETs in climate policy, because NETs will likely attract much less criticism if they are seen as additional mitigation measures rather than as a distinct third category. ERW is a particularly salient example of this crucial framing question, because as we have shown, the policy environment looks rather different if it is considered as a soil amendment at local scales, rather than as a climate stabilisation technique at international scale. In light of this, we feel it is worth some critical reflection on our decision to focus on the three NETs with the greatest estimated sequestration potential, because this may not always be the most useful way to think about policy mechanisms for NETs. Any framing will open up certain avenues and close down others; further research could explore whether discussing NETs at the scales required for stabilising the climate may act to close down alternative routes to incentivisation at smaller scales.

This is an exploratory paper in which we have taken a necessary first step in defining the policy environment for NETs, focusing on existing policy regimes rather than hypothetical future ones. Context is clearly important, and what works for one area may be counterproductive for another; in our research, some contexts received more attention than others, particularly the EU, US, China and India, stemming from their status as the world’s largest or fastest-growing emitters. Nevertheless, we do not mean to rule out the prospect that NET development could happen in other areas, and some methods might be particularly suited for locations not covered in this paper, for instance ERW in Brazil or DACS in the Persian Gulf.[4] This paper also raises the question of the potential *magnitude* of the effects of co-benefits, because some might result in significant effects on carbon reduction or other measures of progress, whilst others might be small or incidental. There is therefore scope for further research to explore whether this magnitude can be reasonably quantified or ranked, a task for which we would propose using multi-criteria analysis to avoid the drawbacks of attempting to monetise and aggregate complex social and environmental benefits and risks

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[4] Brazil could be suitable for ERW, because it has highly-weathered soils, a hot and humid climate, and large tracts of agricultural land (Strefler et al., 2018). Places such as Saudi Arabia and the UAE may be suitable for DACS, because they have abundant renewable resource potential, geological storage capacity and capital availability (Chen and Tavoni, 2013).

(see UNEP, 2011). Fundamentally, the development of effective NETs policy will require dedicated and ongoing research to identify projects, proposals and policies which might achieve genuine co-benefits. A critical area for further research could be how to balance carbon goals with goals from other sectors, including being mindful of the need to prioritise across different timescales.

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