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The political economy of negative emissions technologies: consequences for international policy design

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ABSTRACT

Negative emissions technologies (NETs), especially bioenergy with carbon capture and storage and direct air capture and storage, have been invoked as necessary to achieve the aspirational 1.5°C target of the Paris Agreement. However, currently their costs are estimated to be very high, NETs do not seem to offer co-benefits besides mitigating climate change and there are significant concerns regarding possible negative impacts of their large-scale implementation on sustainable development. Costs can vary significantly due to locational factors such as availability of biomass resources and geological storage capacity. It will be up to progressive industrialized countries to take first steps to mobilize the mitigation potential of NETs.

In order to understand whether NETs can provide a significant contribution to mitigation, financial incentives are needed that allow implementing the most attractive NET activities at the global scale. We see the market mechanism under Article 6.4 of the Paris Agreement – colloquially called 'Sustainable Development Mechanism' – as a possible cornerstone of such a policy instrument. While initially NETs will not be competitive on the free market, the mechanism can facilitate bilateral financial transfers for NETs, where mitigation units accrue to the financier. We discuss the functions and design elements that an international policy instrument may need to fulfil to successfully mobilize NETs. This includes in particular robust quantification of removed carbon under international oversight and preventing social and environmental conflicts particularly on land and water use by NETs to ensure long-term acceptability.

Key policy insights

- International policy instruments that mobilize negative emissions technologies are inexistent despite most mitigation pathways relying on large-scale NETs implementation later this century.
- Feasibility of NETs at large-scale is highly uncertain due to high expected costs and political economy challenges. Practical experience is necessary for better understanding feasibility.
- For cost-effective global deployment of NETs, a policy instrument would need to mobilize international financial flows and implement safeguards concerning sustainable development impacts.
- The sustainable development mechanism established in Article 6.4 of the Paris Agreement could be a good basis for this if it includes a robust approach to evaluating sustainable development impacts building on the sustainable development goals.

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1. Introduction

International climate policy is at a crossroads. The Paris Agreement's target to hold warming to 'well below' 2 degrees and pursue efforts towards a 1.5-degree limit (UNFCCC, 2015, Article 2) means that the remaining carbon budget is severely limited (Horton, Keith, & Honegger, 2016; Millar et al., 2017; Rogelj et al., 2016). Given current global emission trends and projections for the implementation of GHG mitigation policies, aggressive deployment of so-called negative emissions technologies (NETs) is needed to meet the Paris Agreement targets (Geden, 2015; IEA, 2016), not least that of limiting warming to 1.5 degrees, which is of particular interest to this article. It is questionable, however, whether Parties, in agreeing to that target, willingly committed to the future deployment of NETs. These technologies remain very costly and are largely untested (Geden, 2016) and political support of the constituent technologies such as carbon capture and storage (CCS) has been lacklustre (Lipponen et al., 2017).

In this article, we view the potential deployment of NETs as a subset of wider climate change mitigation policies, in that the issues surrounding them partly resemble those associated with conventional mitigation, but they also come with additional challenges. The NETs that we focus on include bioenergy with carbon capture and storage (BECCS) and direct air capture and storage (DACS),[1] although we acknowledge that other technologies or practices might emerge. We identify design considerations for a potential international policy instrument that would incentivize the development of such NETs at large scale with a view to achieving the 1.5-degree target.

First, we summarize why NETs are needed to achieve any scenario for 1.5 degrees. Then, we assess the economics of BECCS and DACS, and potential future cost reductions in these technologies, to better understand the levels of financial incentives necessary in the short, medium and long-term to mobilize NETs. This is followed by an analysis of wider political economy barriers to deploying NETs. We then put forward design considerations for a proposed international policy instrument on NETs, and we discuss where it could be placed in the architecture of the Paris Agreement, focusing on the Agreement's so-called Sustainable Development Mechanism (Article 6). We then develop suggestions for the governance of such a policy instrument, and in particular propose strengthening sustainable development assessments and voluntary payment of a NETs premium to overcome the lack of near-term competitiveness of NETs in comparison to already ongoing mitigation activities.

Our methodology is based on a review of the literature, applying concepts of economics and political science as well as practical experience from the history of mitigation technology deployment and development of the international climate policy regime. To our knowledge, it is the first attempt to combine these approaches and disciplinary perspectives to derive policy recommendations for mobilizing NETs under the Paris Agreement.

2. The need for scaling up NETs to keep the 1.5-degree target in reach

NETs represent a unique subset of climate change mitigation measures. They can complement technologies that lead to emissions reductions and thus help bend the curve of atmospheric CO_2 concentrations. Regardless of whether the remaining future global emissions budget to stay on a 1.5-degree-compatible path is 165 Gt CO_2 at the beginning of 2017 as suggested by the IPCC's fifth assessment report (IPCC, 2014; Le Quéré et al., 2016), or 915–1980 Gt as postulated by Millar et al. (2017), at a current emissions level of 50 Gt/year, this budget is used up within the next few decades at most.

Only by full decarbonization of all economic activity within one generation or less (Rogelj et al., 2015) would there remain a small chance at reaching the 1.5-degree target without NETs. The only other alternative would be the still poorly understood and highly controversial geoengineering option solar radiation management (SRM) (Nicholson, Jinnah,& Gillespie, 2017, NRC, 2015a; Pasztor, Scharf, & Schmidt, 2017; Royal Society, 2009).

Once CO_2 emissions and CO_2 sequestration reach the same level (as expressed by the Paris Agreement's wording in Article 4.1 to reach a 'balance between anthropogenic emissions by sources and removals by sinks'), any additional deployment of NETs can lead to an actual reduction of atmospheric CO_2 concentrations (Honegger, Sugathapala, & Michaelowa, 2013). Without NETs, scenarios of 'overshoot and decline' of atmospheric GHG concentrations (such as Azar, Lindgren, Larson, & Mollersten, 2006; Kriegler et al., 2014; Peters, 2016) are virtually impossible.

The scale of NETs foreseen in such scenarios is mindboggling. Removals would have to reach 10–20 Gt CO_2 per year, with eventual cumulative volumes of 444–1000 GtCO_2 by 2100 (Boysen, 2017). To illustrate the challenge, removing 10 Gt CO_2 annually through BECCS would mean increasing power generation capacity from biomass tenfold to 1000 GW (see EIA, 2017 for current capacity) and equipping all these plants with CCS technology.

How could NETs be scaled up to a billion-ton scale within two to three decades? Such a dramatic expansion would rival or exceed past record-breaking transformations in the energy sector, such as the rollout of nuclear power in France with capacity increasing by 42 GW in the 1980s (EIA, 2017), or the scale-up of coal-fired capacity in China by about 600 GW in 1990–2015 (EIA, 2017; Torvanger, Lund, & Rive, 2013).

A massive deployment of NETs as suggested by the scenarios outlined above will only be possible if the NETs are economically attractive, or with the introduction of policy instruments that can make NET deployment attractive by generating revenues linked to the amount of CO_2 captured and safely stored.[2] We will look at each of these issues in turn in the sections below.

3. The economics of NETs

Integrated Assessment Model scenarios see a steep increase of mitigation costs over time and thus view NETs as necessary for cost-optimal paths to cap warming at 1.5 degrees (Peters et al., 2017). How does the situation look in the short and medium term?

To answer this question, we explore the individual technology elements of BECCS and DACS that incur costs and generate returns. We also discuss how geographical factors are expected to influence regional differences in these costs. Our analysis starts from a situation in which there are no financial incentives for the service of removing and storing carbon. We therefore focus on the other cost and revenue elements to identify how high these carbon removal incentives would need to be in order to render NETs economically attractive.

3.1. The anticipated economics of BECCS

While there are several options for technical processes summarized under the term BECCS, they all comprise the following basic steps: Biomass production, processing into fuel or electric power, and CO_2 storage. The costs of BECCS accruing along this chain of processes are seen from the perspective of the plant operator and include the investment in the power plant or biofuel production facility; the capture and storage infrastructure, general operating and maintenance costs; the cost of biomass production; and the transportation of biomass to the plant as well as transportation of CO_2 to a sequestration site. Potential revenues would include the sale of electricity, fuel or heat and waste-processing fees (Azar et al., 2010; Muratori, Calvin, Wise, Kyle, & Edmonds, 2016).

Costs are expected to vary geographically owing to different kinds of biomass sources as well as storage options. Biomass waste from forests and agricultural or industrial processes is available in limited quantities, but is likely to be lower cost (Boysen et al., 2017). Dedicated agricultural energy or forest crops could theoretically generate large quantities, but this would incur higher costs, especially if indirect effects on food production are taken into account (Azar et al., 2010; Kato & Yamagata, 2014; Smith et al., 2015). Bioenergy power plant as well as CO_2 capture costs depend on the plant size and are thus intricately linked to the biomass supply potential. A non-negligible part of costs involves the high energy demands of capture and storage processes. The cost of CO_2 transport and storage depends on the availability of suitable geological formations on land or under the seabed, but also on the purity of CO_2, which again depends on the biomass input (Fajardy & Mac Dowell, 2017). For example, under ideal conditions, the costs of capturing and storing CO_2 from sugarcane fermentation and sugarcane bagasse flue gas could be around \$50/tCO_2 (IEA GHG, 2011; Moreira, Romeiro, Fuss, Kraxner, & Pacca, 2016), whereas most other BECCS processes are estimated to be costlier: The review of existing research by Kemper (2015) finds that most studies see BECCS operating at costs of \$50–\$150/tCO_2. While Luckow, Wise, Dooley, and Kim (2010) estimate that significant volumes of BECCS would occur at costs well below \$100/tCO_2, they also find that, in order to equip over 90% of new bioenergy plants with CCS, a carbon price in excess of

\$150/tCO_2 would be needed to cover the costs. However, any estimates of future operating costs are rough approximations, given that BECCS is still at an exploratory stage (IPCC, 2014). Power plant technology as well as CCS costs are expected to decrease over time due to technology learning, potentially leaving the cost of biomass as the largest variable cost element. Once large-scale BECCS leads to greater scarcity of land and water resources, indirect costs due to competition with food and other crops over land or water will rise significantly.

The economics of BECCS over time therefore appear to be essentially driven by two conflicting forces: (i) economies of scale, where technology learning and mass production can reduce costs of power plants, capture equipment, transport and storage infrastructure, and (ii) resource scarcity, where increasing biomass demand causes rising operating costs especially when biomass supply cannot be increased easily. An equivalent effect would relate to the availability of storage sites. The latter effect should not be underestimated once BECCS is scaled up to deployment levels anticipated in global models.

Global scenarios compatible with cost-effective achievement of the Paris targets suggest that comparable amounts of bioenergy may be sourced from agriculture and forestry by-products, as opposed to dedicated energy crops (Azar et al., 2010), which would require land on the order of several hundred million hectares, or about a third of global croplands (NRC, 2015b).

Such large-scale BECCS deployment would have significant effects on food prices. Muratori et al., (2016, p. 1) have shown that, in a world that has a carbon pricing level set to achieve an ambitious temperature target, the carbon price and biomass and food crop prices are directly related, and the availability of BECCS (and CCS more generally) would actually reduce 'the upward pressure on food crop prices by lowering carbon prices and lowering the total biomass demand in climate change mitigation scenarios'. So, despite BECCS competing with food production, food prices could actually experience less pressure in scenarios that include BECCS applications compared to those that do not – if ambitious temperature targets are to be met (Muratori et al., 2016).

3.2. The anticipated economics of DACS

DACS is a group of technologies all of which are currently at laboratory scale. A process to capture CO_2 from ambient air via biological, chemical or physical processes would need to be combined with CO_2 storage (NRC, 2015b).

The economics of DACS differ from BECCS in that the primary resource needed is electricity rather than biomass. This means that the full CO_2 benefit will only accrue if the production of that electricity does not generate GHG emissions. A DACS plant running on high-carbon power would likely result in a regional increase of emissions rather than the intended negative emissions (Socolow et al., 2011). Even if the electricity used for DACS is zero-carbon, indirect effects on electricity production elsewhere need to be considered.

The costs of DACS include the air capture infrastructure cost, the cost of power to operate this equipment, and transport and storage costs. Transport costs could be kept low if the DACS plants are sited on top of storage sites; this could be done if sufficient renewable electricity is available near the storage sites. Cost estimates are even less reliable than those of BECCS, as air capture technologies have not yet been tested at large scale and the number of studies in the public domain is substantially smaller compared to BECCS. Current estimates of full DACS costs range from \$400 to \$1000/tCO_2 (NRC, 2015b).

Costs of DACS are thus exceedingly high compared to classical mitigation options. How far technology learning can reduce the cost of DACS, remains to be seen. Given that huge volumes of air need to be moved to extract a small volume of CO_2, the potential for cost reduction seems limited.

3.3. Costs of NETs and mitigation alternatives over time

Given that the current costs of BECCS and DACS are orders of magnitude above costs of classical GHG mitigation options, they are highly unattractive under current conditions. This is accentuated by the likely lack of obvious co-benefits besides mitigation. Whereas conventional mitigation action – done unilaterally or with international climate finance – is regularly motivated by non-climate-related co-benefits (such as health improvements), it is

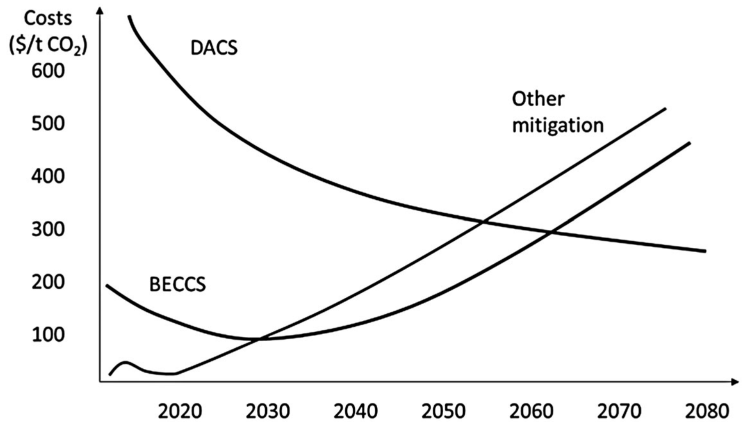

Figure 1. Development of costs of BECCS, DACS and classical mitigation over time assuming strong political will to cover mitigation costs.
Note: Curves are indicative.

rather unlikely that, for example, adding a CO_2-storage component to a bioenergy plant would result in highly visible co-benefits.

The upscaling of mitigation ambition would bring in higher-cost options, such as measures in the transport sector where mitigation costs frequently exceed 100 USD/tCO_2e (IPCC, 2014, p. 604; Solano Rodriguez, Drummond, & Ekins, 2017), at which point some NETs would arguably become more attractive options. Such trends could result in cost developments as shown in Figure 1 below, provided that policymakers are willing to introduce policy instruments that would cover the respective mitigation costs.

BECCS costs would initially fall as the technology matures, and rise again as the resource scarcity of biomass (and to some extent storage) kicked in. DACS costs would decrease steadily provided sufficient renewable electricity could be procured near storage sites. Classical mitigation costs are expected to increase continuously from current levels as 'low-hanging fruit' are depleted and given the necessary increase in ambition compared to current mitigation action. The resulting 'scissors' – falling NETs costs combined with rising classical mitigation costs - could close some time in the second half of this century. All values considered are orders of magnitude above current levels of carbon pricing (World Bank, Ecofys & Vivid Economics, 2016), which means that decisive policy measures would be required to trigger mitigation at such cost levels.

Figure 1 shows that the case for wide-scale deployment of NETs becomes compelling only in the long term even presuming a willingness to pay for increasingly costly mitigation. Moreover, this assessment does not yet include non-economic factors, which we consider in the following section.

4. The difficult political economy of NETs

Economics are not the only factor that determine the deployment of a mitigation option. History shows that public perceptions of, as well as interest group struggles and preferences for (or against), certain technologies could have a major impact on the feasibility of NETs. We focus here on existing technologies, namely, biomass use for fuel and electricity production, and CCS, both of which have been promoted as mitigation technologies and which form the building blocks of key NETs. Therefore, these emissions reduction technologies are well-suited to illustrate the political economy challenges that prominent NETs are likely to face in terms of public acceptance and potential resource competition. The design of any policy instrument needs to take into account these experiences in addition to the economic costs of the NETs.

Additionally, discussions on NETs have been dominated by concerns over their presumed scale and associated risks, in particular where they have been framed as 'geoengineering' (Scheer & Renn, 2014). We thus start with a reflection on the role of perceptions as well as interest groups in the political economy of NETs before looking at the lessons that can be drawn from the specific cases of bioenergy and CCS.

4.1. The role of perceptions

The images or analogues that the public and key stakeholders find most evocative with regard to each of the NETs will have an impact on their likely acceptability and prospects for wide-scale deployment. Some terms that have to date been used are relatively neutral (e.g. 'backstop technology') or hopeful (e.g. 'Plan B'), whereas many others are dismissive, derisive or otherwise negative (e.g. 'unicorn', 'dead end road', 'magical thinking', or 'moral hazard') (Anderson & Peters, 2016). Focussing the conversation on the gradual rollout of a specific technology such as BECCS and advancing research (including on its distinct social, environmental and political dimensions) would emphasise the limited contribution of NETs and move away from largely negative framings of NETs as 'large-scale technological interventions' (Caviezel & Revermann, 2014). A focus on research and the first plants would help clarify that NETs do not offer a 'silver bullet' or 'get out of jail free card' and reveal real-world challenges, e.g. in terms of technological development, costs or limiting factors such as resource conflicts or local opposition (Buck, 2016). There is some fear that research on NETs would crowd out funding of other relevant climate technologies. However, given the minimal attention paid to NETs outside of modelling circles to date, and the possibility that they could contribute meaningfully, though to a lesser extent than some scenarios suggest, to addressing the challenge, we argue that virtually any RD&D into NETs using realistic assumptions could have a significant social payoff.

4.2. Interest groups and their positions

BECCS will face stiff opposition from established stakeholders in the power sector if they fear that regulations would impose additional costs on themselves. However, industry stakeholders may come to view NETs favourably, if they offer greater flexibility in reaching mandated emissions limits by compensating for emissions elsewhere. If NETs reached a certain scale, new interest groups such as producers of NETs technologies would emerge. These would then increasingly seek to influence policies and market conditions to enhance demand for NETs and to maximize profits. At the same time, environmental NGOs are likely to highlight potential environmental and social risks. A key interface with the wider public will be transport and storage, since that is the part of the CCS infrastructure closest to most residents (Ashworth, Wade, Reiner, & Liang, 2015). In the case of BECCS, transport of the biomass into the plants may additionally act as a source of tension (van der Horst, 2007). Whether one of these groups will dominate or whether a healthy equilibrium will be found cannot be forecast at this point in a credible manner.

4.3. Insights from bioenergy

The experience of biofuels (Sorda, Banse, & Kemfert, 2010) demonstrates some of the political economy challenges of BECCS. The recent history of biofuels shows rising concerns over competition with existing food crops associated with the rapid increase in biofuel production in the early to mid-2000s and environmentalists' concerns over the sustainability of the biomass being harvested (Tilman et al., 2009). The debate came to a head in 2007–8 as global food prices were rising along with concerns over deforestation and impacts on endangered species (notably orangutans in Borneo). Political attention in the food–fuel debate was most protracted in various European countries. Other countries such as China also backpedalled from ambitious proposals to rollout biofuels in the face of concerns over food security. By contrast, in countries where there already were significant levels of biomass production, and food security could be retained, such as Brazil or Thailand, the political dynamics were different – there is continued support for ever-growing levels of biofuels still today.

The environmental impacts of biofuels were debated from the start. Conversion of existing ecosystems in Brazil, Southeast Asia, and the United States to crop-based biofuels were seen as running the danger of releasing '17 to 420 times more CO_2 than the annual GHG reductions that these biofuels would provide by displacing fossil fuels' (Fargione, Hill, Tilman, Polasky, & Hawthorne, 2008).

Technological attempts to resolve these conflicts – for example, by turning to particular crops such as *Jatropha Curcas* that could be grown on marginal land – have had limited success. One study, for example, found that Jatropha was neither profitable nor in the interests of poor local populations (Ariza-Montobbio, Lele, Kallis, &

Martinez-Alier, 2010). Further, concerns over 'land grabs' by government agencies, agribusiness or sovereign wealth funds further eroded the reputation of biofuels (Cotula, 2012).

The denouement of traditional biofuels in Europe happened remarkably rapidly: In 2007, Jean Ziegler, UN special rapporteur on the right to food at the time, stated that biofuels might result in increased hunger. He decried the 'ill-conceived rush' to convert food crops into biofuels as a 'crime against humanity' (Ferrett, 2007) and called for a five-year moratorium on expanding biofuels (UN News Centre, 2007). By late 2008, the European Parliament voted to cut the target for the share of biofuels in the EU transport sector from 10 to 5%. This vote however never became law. In 2013, the European Parliament voted to limit the use of conventional land-based biofuels in the European transport fuel mix to 6% and to report on indirect emissions caused by land-use change. The final nail in the coffin for first-generation biofuels in Europe came in 2014 as the more ambitious transport sector targets were removed post-2020. Instead, a nominally lower target was set, but one based on tighter sustainability standards that prevented counting traditional biofuels towards the 2030 target, and pointed the way towards the development of biofuels still being driven by regulatory targets, but at a slower-than-expected pace addressing environmentalist concerns. This experience indicates a clear limit to the *political* potential of biofuels and could foreshadow political reluctance in Europe towards BECCS, particularly if close attention is not paid to the links between wider sustainability considerations and deploying BECCS at scale.

Aside from biofuel use in transport, the complementary histories of bioenergy power plants and biorefineries have also revealed entrenched opposition in some locations, provoking significant concerns from local citizens (van der Horst, 2007; Upreti, 2004). However, in regions that are more heavily reliant on bioenergy, public sentiment has tended to be more supportive (Kortsch, Hildebrand, & Schweizer-Ries, 2015) since it is associated with perceived benefits to the local stakeholders. In other cases, bioenergy development has been linked to problems with past environmental damages associated with prior industrial policy (Eaton, 2016).

The biofuel and bioenergy power cases show that political economy considerations can be an obstacle to deployment of mitigation options, but that support, or opposition, is not necessarily universal or homogenous. Certain contexts and participatory approaches with involvement of various local stakeholders have led to greater likelihood of support.

4.4. Insights from CCS

Carbon capture at large CO_2 point sources (such as fossil-fuel power plants) combined with CO_2 transport and geological storage can provide essential insights for BECCS, as both share capture, transport and storage processes and the challenge of requiring large-scale storage reservoirs for CO_2. Much like the shorter history of NETs, the theoretical need for CCS deployment was clear from mitigation scenario development before the first policy discussions on this technology took place (Krey, Luderer, Clarke, & Kriegler, 2014). The IPCC's Fifth Assessment Report (2014) found that constraints on deployment of CCS would more than double the global costs of meeting a 450 ppm target. Omitting CCS is far costlier than constraints on other low-carbon options because of its potential versatility in addressing emissions from existing power plants and industrial processes, for which there are few other attractive alternatives.

Implementation of CCS has been slow and stymied by a lack of adequate policy frameworks and corresponding funding (Reiner, 2016). Reiner and Herzog (2004) found that local opposition often impedes progress if not proactively addressed by an inclusive and transparent decision-making process and benefit-sharing. The first large-scale (>1 million tonnes/year) CO_2-storage facility began operations over twenty years ago at the Sleipner field in the North Sea. However, it was not until 2015 that the first commercial-scale power plant equipped with CCS began operation at Boundary Dam in Saskatchewan, Canada. Other recent large-scale projects include the Petra Nova power plant in Texas, Emirates Steel in Abu Dhabi and a coal-to-liquids facility in China. These all rely, to differing degrees, on revenues from enhanced oil recovery. Although other projects such as Tomakomai in Japan or Quest in Alberta, Canada, have not relied on revenues from CO_2 utilization, it is notable that the successful early projects relied on a constellation of commercial factors to incentivize projects, rather than on, say, a voluntary commitment to climate action or dedicated public funding.

Despite the slow pace of deployment of CCS, there are valuable lessons to be learned from both its successes and failures. From 2010 to 2017, the number of operational large-scale CCS projects rose from fewer than 10 to just over 20, with the annual CO_2 capture capacity of operational projects more than doubling to 40 Mt (Global CCS Institute, 2017). Yet at the same time the number of projects in the pipeline has halved from 77 to 38. The reasons for projects being shelved include local opposition (e.g. in Germany and the Netherlands), political opposition (e.g. Futuregen in the US), cost overruns, and technological problems (e.g. Kemper County in Mississippi). Many of these dimensions are of course interrelated: project economics are, for instance, frequently challenged by unexpected technological difficulties or by local protests prolonging costly planning processes.

In Europe, onshore storage, in particular, has led to protests in Germany (e.g. Schleswig-Holstein has banned CO_2 storage after protests against several projects across the country) and the Netherlands (where opposition led to the shutdown of the proposed Shell project at Barendrecht and then extended a moratorium to all onshore storage) (Ashworth et al., 2012; L'Orange Seigo, Dohle, & Siegrist, 2014; Terwel, ter Mors, & Daamen, 2012). By contrast, in North America, the economic value associated with enhanced oil recovery has led to interest in using the revenues from CO_2 sales to oilfields to help support project economics (Herzog, 2011; Reiner, 2015).

Reiner and Herzog's (2004) finding that early failures could irreparably damage the standing of CCS is especially pertinent, since reaching large-scale NET application requires starting with a few pioneering installations, the success or failure of which will have a far greater impact on the fate of NETs than later ones.

Given the potential for resource conflicts in addition to the general difficulty of establishing novel technologies, effective policy instruments are not, in themselves, sufficient to ensure the smooth rollout of a technology, but rather they are a necessary pre-condition. We turn to these considerations in the next section.

5. Design considerations for an international policy instrument to mobilize NETs

In this section, we introduce three key considerations relevant for how to design an international policy instrument that would help mobilize NETs: (i) the scale of the financial incentives needed; (ii) the differentiation of financial contributions between countries at various stages of development; and (iii) the need for economic flexibility in mobilizing NETs in a least-cost manner.

5.1. Financial incentives

As shown in Section 3 above, a major challenge for NETs is their dependence on high and continuous payments to cover capture and storage costs. For BECCS specifically, another cost component would be the differential between electricity production costs using biomass and the costs of alternative power generation technologies with which the BECCS plant is competing. No private entity would cover these costs without direct government intervention. On a national level, this support could take various forms: direct carbon pricing through a carbon tax, emissions trading, provision of subsidies or technology mandates (IPCC, 2014, chapter 13).

As shown by the World Bank, Ecofys and Vivid Economics (2016), currently over 75% of emissions covered by carbon pricing instruments are facing prices below \$10/tCO_2e. In a few countries, notably Sweden, Switzerland, Finland, and Norway, carbon pricing exceeds \$50/tCO_2e – a level which could theoretically be sufficient to mobilize some of the (limited) least-cost BECCS options. At the moment at least, the political will to increase carbon prices for mitigation without demonstrated co-benefits beyond this level does not exist even in the most ambitious jurisdictions. So, at current prices, NETs will not be implemented. If NETs are to play a relevant role in the medium to long term, governments will need to increase carbon prices, or subsidy levels will need to be very high, at least initially to stimulate learning, much as has been the case for renewables such as solar or offshore wind.

Given the existence of varying carbon pricing policy instruments at the national level, and highly variable costs of BECCS and DACS according to plant location, it is crucial to develop an international policy instrument that incentivises NET deployment, regardless of where it takes place. Otherwise, there might be a few jurisdictions where high-cost NET implementation would happen, whereas in other jurisdictions, low-cost NET options would not be implemented because there is no possibility to cover even these lower costs.

5.2. Industrialized countries to take the lead on funding NETs

Wealthier and more advanced countries are generally expected to take the lead in mitigation and support poorer, developing countries in their efforts.[3] Given the high costs of NETs, this would mean that at least the initial financial stimulus to mobilize NETs needs to be introduced by rich countries (Füssler et al., 2015). Poor countries that install NET plants would benefit from direct transfers ('climate finance') or get revenue from the sale of carbon credits. As these countries get richer, they are increasingly expected to also introduce carbon pricing and ramp it up over time.

A credible mechanism to mobilize NETs will require high levels of support from rich countries sustained over decades. Experience with government tenders to purchase carbon credits abroad (e.g. in Norway, Sweden or Switzerland) indicates that the public is sensitive to potential sustainability co-benefits or potential harm caused by such transactions. This sensitivity has led many programmes to select only very specific, reputable activities abroad (Dransfeld et al., 2017). In recent years, this tendency has resulted in more and more project types being side lined (Hoch et al., 2015). Eventually, costs of NETs need to fall dramatically and carbon credit demand will have to increase by several orders of magnitude to enable NETs to fully compete in a market mechanism (see Figure 1 and discussion below).

5.3. Economic efficiency of mitigation

As we have shown above, pursuing the 1.5-degree target requires mobilizing the full potential of mitigation including NETs. International cooperation enables reduction of mitigation cost differentials between countries and thus can increase the global efficiency of mitigation. This increased efficiency can help reduce overall costs and/or enhance the ambition of global mitigation efforts.

Under the United Nations Framework Convention on Climate Change (UNFCCC), market mechanisms have been developed that allow carbon prices to function as an incentive for mitigation throughout the world, even if there is no carbon pricing in a specific jurisdiction. The 1997 Kyoto Protocol (KP) introduced three such mechanisms (UNFCCC, 1998). The Clean Development Mechanism (KP Article 12) allows mitigation projects in developing countries to produce emission credits that could be used by industrialized countries to reach their mitigation targets. Joint Implementation (KP Article 6) and International Emissions Trading (KP Article 17) allow generation of emission credits through projects in industrialized countries and the direct transfer of emission units between such countries.

Article 6 of the Paris Agreement has defined two international market mechanisms: one regulated individually by participating countries (Article 6.2) and one subject to international rules and oversight (Article 6.4). The latter is known as the 'Sustainable Development Mechanism' (SDM). As we argue below, the SDM could become a 'natural home' for mobilizing NETs globally, given that it is subject to more stringent international oversight, which seems important in view of the challenging political economy of NETs. Fundamental design questions, however, need to be resolved to make the SDM operational. In the next section, we will discuss how the SDM could be structured to enable the deployment of NETs, taking into account their high costs and difficult political economy characteristics. As stated, our focus is on the international level, given that national and sub-national policies to mobilize NETs can be introduced independently.

6. A possible approach to mobilizing NETs: the sustainable development mechanism (SDM)

We first outline the fundamental characteristics of the SDM as a market mechanism intended for voluntary international collaboration on mitigation under the Paris Agreement. We then specify the functions that the SDM might need to fulfil to mobilize NETs. Finally, we describe how specific decisions could be taken in ongoing negotiations to account for these functions so that the SDM would best be suited to mobilize NETs.

We are aware that both NETs as well as market mechanisms are contentious topics in international climate policy, and as a consequence it might take several years until the SDM would be ready to host NET activities. Given that NETs appear inevitable for reaching ambitious temperature targets, however, we think an approach through an international market mechanism is necessary (though not necessarily sufficient) for the reasons we have given in the previous section.

6.1. The basic concept of the SDM

Under the Paris Agreement, national governments have defined their countries' respective mitigation targets through their NDCs, which are to be strengthened over time in five-year periods. Article 6 recognizes that Parties may want to voluntarily cooperate on mitigation efforts. The SDM established in paragraph 4 of Article 6 is to promote mitigation and foster sustainable development. Activities are to be authorised by participating Parties and contribute to a reduction of emissions levels in the host Party, which can be used by another Party to fulfil its NDC. The activities are to deliver overall mitigation in global emissions and paragraph 5 specifies that the reduction can only be counted toward one Parties' NDC. The rulebook that will specify the operating procedures and institutional responsibilities of the SDM is still being written by the Parties to the Paris Agreement (to be adopted at the Conference of the Parties (COP) 24 in December 2018). A plausible scenario, however, is that the SDM would allow for voluntary transfers of mitigation units in return for payment of a price for each tonne of CO_2 of avoided emissions by the country that receives the units. In the logic of our proposal, this could be expanded to analogously include payment of a price for each ton of CO_2 removed. The received units might then be counted towards the buyer country's mitigation target or its climate finance pledges. This would create the flexibility to fund mitigation activities including NETs outside of national borders in a way that they contribute to the funders' mitigation target.

6.2. Key functions that the SDM would need to fulfil in order to harness significant amounts of carbon removal

Based on our assessment of the limited political attractiveness of NETs and their high costs, we identify the following as key functions that the SDM would need to fulfil if it were to mobilize significant amounts of NETs:

1. Harness financial transfers to mobilize the NET potential in countries that are unable to afford the costs of NETs
2. Ensure credible quantification and accounting under the Paris regime
3. Provide an effective administrative process with limited transaction costs
4. Prevent social and environmental conflicts.

This list is likely not exhaustive. In the following section, we describe how each of these functions could be achieved in the ongoing negotiations under the Paris Agreement.

6.3. Steps in negotiations that could help make the SDM fit for NETs

Each of the functions outlined above can be reflected in some form in the rules that are currently under negotiation and scheduled to be finalized by the end of 2018.

1) Financial transfers to mobilize NETs: Given the limited attractiveness of NETs, it seems important that no limits are placed on the use of mitigation units by the acquiring country. The SDM rules should not preclude voluntary payments in addition to the market price: Given that, in the short-term, NETs would not be able to compete on an international market with the cheapest mitigation options, governments willing to fund NETs activities in other countries would need to pay a premium for NETs on top of the market price for mitigation units. This premium could be offered via bilaterally-agreed transfers that cover NET-specific additional costs, in the context of the framework for non-market mechanisms under Article 6.8.[4] Over time, the most ambitious NDCs might include a specific pledge to mobilize NETs, which could be operationalized in form of NET-premium payments.

2) Credible quantification and accounting under the Paris regime: Credibly demonstrating the results of activities is particularly important in the case of NETs due to their challenging political economy. This would require agreed and conservative methodologies to quantify CO_2 removed by each activity and monitor whether it remains in the storage site. As under the Clean Development Mechanism (CDM), methodologies could be proposed both by market participants as well as by the body supervising the SDM to maximize the ability of various institutions and companies to contribute. Methodologies for CCS already exist under the CDM, but their approval took several years due to concern regarding the permanence of storage. They could be modified to appropriately quantify negative emissions accruing from BECCS (Krüger, 2017). In order to be reliable, the accounting approach would require a centralized registry and international oversight, similar to that under the Kyoto Protocol. Proposals for robust accounting in view of different possible uses of mitigation units[5] are described in much greater detail elsewhere (Schneider, Broekhoff, Cames, Füssler, & La Hoz Theuer, 2017).

3) Effective administrative processes with limited transaction costs: The responsibilities of various entities involved in the SDM need to be defined to ensure effective administration. In order to prevent a loss of accumulated experience (and thus valuable time), national project approvals could be done by the same designated national authorities that performed this task under the CDM. The SDM supervisory body could be modelled on the CDM's Executive Board. The task of this body would, in this case, likely be the tracking of activities and transactions, approval of innovative project types, as well as approval of the corresponding baseline and monitoring methodologies.

4) No conflicts with sustainable development objectives: A robust and credible process for this – be it voluntary or mandatory – is crucial but could prove very challenging, given countries' historical reluctance to accept international procedures and criteria for evaluating sustainable development impacts. Many countries see this as violating national sovereignty and thus vigorously oppose any such procedures. There is an extensive literature on the mixed successes of environmental and social safeguards under various climate policy instruments (REDD+, NAMAs, the CDM, the voluntary carbon market and other areas) and it is crucial to learn from these experiences (Arens, Beuermann, et al., 2015; Chhatre et al., 2012; Dransfeld et al., 2017; Olsen, 2007). For example, the UNFCCC Secretariat has created a sustainable development assessment tool under the CDM (Arens et al., 2014; Arens, Mersmann, Beuermann, & Rudolph, 2015), but it has been used only to a limited extent. Specific safeguards have been considered mostly in the context of avoided deforestation (Kossoy et al., 2015). The easiest approach has been for mitigation unit buyers to exclude certain activity types, which are seen as not sufficiently aligned with sustainable development, but this has also proved controversial (Füssler et al., 2015).

A principal reason for the mixed outcome has been the lack of a common understanding of what constitutes sustainable development and how an activity's sustainable development performance should be assessed. However, the 17 goals and 169 targets of the Sustainable Development Goals (SDGs) now offer an internationally agreed normative framework against which sustainable development contributions can be measured ex-post (Dransfeld et al., 2017; Honegger & Toussaint, 2017). Of course, the multi-dimensional nature of these goals and proliferation of targets does mean that this will be a daunting challenge, particularly given the complex potential interactions across goals and targets (Nilsson, Griggs, & Visbeck, 2016). Thus, a safeguard procedure would need to operationalize selected goals, targets and indicators of the SDGs in a way that addresses key concerns over NETs (Fuso Nerini et al., 2017). Consistent application of such a procedure would likely be a prerequisite to strengthening the acceptability of large-scale NET deployment among environmental NGOs and local populations.

7. Conclusions and further research needs

Limiting global warming to 1.5 degrees requires large-scale deployment of NETs alongside conventional mitigation measures. Currently BECCS and DACS are more than an order of magnitude more expensive than current mitigation technologies. However, with near-term political support, technology learning and innovation could bring costs down over time, while other mitigation actions become more expensive, as cheaper options are exhausted. If there is political willingness to pay for such expensive mitigation, NETs would eventually become more competitive mitigation options. Any international policy instrument for mobilization of NETs needs to allow for a NETs premium to render NETs economically viable in the near term until NETs can compete financially with other mitigation options.

Past experiences with CCS and bioenergy suggest that the political economy of NETs will be challenging. An international policy instrument thus would need to transparently demonstrate the GHG impacts of NETs and include safeguards to avoid social and environmental conflicts. Furthermore, it needs to be communicated clearly that NETs are very unlikely to be scaled up rapidly even when adequate financial incentives are put in place. Emphasizing the inherently gradual nature of NET rollout could attenuate some of the negative views, and ultimately a popular rejection, of NETs.

We find that the SDM under Article 6.4 of the Paris Agreement could be the cornerstone for an international policy instrument, if combined with a transparent assessment of sustainable development implications. Furthermore, some buyer-countries would have to combine acquisition of mitigation units with bilateral transfers that provide an additional NET-premium as long as NETs cannot compete on a free market with other mitigation options. This would allow the growth of competitive enterprises developing and operating NET activities. Once increased demand for mitigation units results in a market price that enables NETs to compete with conventional mitigation activities, NET deployment will be accelerated as a natural component of mitigation. For BECCS, this could happen when the market price reaches \$100–\$150/t CO_2, i.e. potentially around 2030. For DACS, it would probably take much longer.

More research is needed to better understand the effects of resource scarcity in terms of land, water or power (in the case of DACS), which are likely to result in competition with food production, general power needs or other societal needs. Also, understanding of the political economy of NETs, especially the prospects for ensuring popular support for their implementation, needs to be refined. Empirical evidence on public and stakeholder attitudes needs to be collected (Braun, Merk, Pönitzsch, Rehdanz, & Schmidt, 2017), especially in locations where the theoretical potential for NETs is substantial. It would be particularly helpful to learn the extent to which stakeholders will invoke the same arguments as in the case of bioenergy and CCS, and whether these would result in dogmatic opposition or allow deployment in cases where conflicts with sustainable development can be resolved.

Ultimately, we need to understand whether the international community, in formulating mitigation targets, can rely on the near-term and future availability of NETs at large scale. We need to avoid a situation where decades could be lost waiting for NETs rather than pursuing more aggressive traditional mitigation strategies that would attempt to achieve almost complete decarbonization in the 2020 and 2030s (Larkin, Kuriakose, Sharmina, & Anderson, 2017). A credible policy instrument channelling resources into NETs implementation at the most cost-effective locations worldwide would be an important stepping stone to understanding whether NETs can help move the needle toward the 1.5-degree target, or whether they serve as a dangerous distraction.

Notes

1. Please note that we use the term Direct Air Capture and Storage (DACS) as opposed to Direct Air Capture (DAC). This is to prevent confusion with direct air capture of CO_2 and utilization without long-term storage. For example, the Swiss start-up Climeworks captures CO_2 and uses it in greenhouses (Marshall, 2017). This does not result in negative emissions. While NETs could also take the form of enhanced weathering (Taylor et al., 2015; Köhler, Hartmann, & Wolf-Gladrow, 2010) and ocean liming (Renford and Henderson, 2017; McLaren, 2012), these technologies are still speculative and have not been tested at scale. Afforestation (Grassi et al., 2017) and biochar (Woolf, Amonette, Street-Perrott, Lehmann, & Joseph, 2010), while leading to 'negative emissions' relative to a counterfactual, are sometimes seen as part of 'classical' mitigation and thus not covered in this article.
2. For NETs with revenues, the gap between costs and revenues would have to be covered.
3. The principle of equity and common but differentiated responsibilities and respective capabilities (CBDR-RC) has evolved throughout the history of climate negotiations (Voigt & Ferreira, 2016). As a cornerstone of the international climate policy system it is enshrined in Article 3.1 of the UNFCCC and has entered the Paris Agreement with the qualifier 'in light of different national circumstances' (Article 2.2).
4. In principle, all international financial payments for NETs could be undertaken under Article 6.8 of the Paris Agreement. However, in such a case, no mitigation units could be transferred given the 'non-market' nature of Article 6.8. The limited political attractiveness of NETs indicates that hardly any substantial international funding would be mobilized if there was no possibility to help achievement of the donor countries' NDC. We are therefore focussing on the SDM in our core proposal.
5. E.g. toward climate finance pledges, NDC achievement or development cooperation goals.

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References

Anderson, K. W., & Peters, G. (2016). The trouble with negative emission. *Science*, *354*(6309), 182–183. doi:10.1126/science.aah4567

Arens, C., Beuermann, C., Mersmann, F., Rudolf, F., Holm Olsen, K., Fenham, J., … Bakhtiari, F. (2015). Final report of the project "evaluation and development of recommendations on the CDM EB's sustainable development tool including the sustainability requirements of other flexible mechanisms". On behalf of the Federal Environment Agency.

Arens, C., Mersmann, F., Beuermann, C., & Rudolph, F. (2015). *Reforming the CDM SD tool recommendations for improvement*. Berlin: Federal Environment Agency (DEHSt Discussion Paper).

Arens, C., Mersmann, F., Beuermann, C., Rudolph, F., Olsen, K. H., & Fenhann, J. (2014). *Mapping the indicators: An analysis of sustainable development requirements of selected market mechanisms and multilateral institutions*. Berlin: Federal Environment Agency (DEHSt Discussion Paper).

Ariza-Montobbio, P., Lele, S., Kallis, G., & Martinez-Alier, J. (2010). The political ecology of Jatropha plantations for biodiesel in Tamil Nadu, India. *Journal of Peasant Studies*, *37*(4), 875–897.

Ashworth, P., Bradbury, J., Wade, S., Ynke Feenstra, C., Greenberg, S., Hund, G., & Mikunda, T. (2012). What's in store: Lessons from implementing CCS. *International Journal of Greenhouse Gas Control*, *9*, 402–409.

Ashworth, P., Wade, S., Reiner, D. M., & Liang, X. (2015). Developments in public communications on CCS. *International Journal of Greenhouse Gas Control*, *40*, 449–458. doi:10.1016/j.ijggc.2015.06.002

Azar, C., Lindgren, K., Larson, E., & Mollersten, K. (2006). Carbon capture and storage from fossil fuels and biomass – costs and potential role in stabilizing the atmosphere. *Climatic Change*, *74*(1), 47–79.

Azar, C., Lindgren, K., Obersteiner, M., Riahi, K., van Vuuren, D. P., den Elzen, K. M. G., … Larson, E. D. (2010). The feasibility of low CO_2 concentration targets and the role of bio-energy with carbon capture and storage (BECCS). *Climatic Change*, *100*(1), 195–202.

Boysen, L. (2017). *Potentials, consequences and trade-offs of terrestrial carbon dioxide removal* (Doctoral dissertation, Humboldt-Universität zu Berlin, Mathematisch-Naturwissenschaftliche Fakultät).

Boysen, L. R., Lucht, W., Gerten, D., Heck, V., Lenton, T. M., & Schellnhuber, H. J. (2017). The limits to global-warming mitigation by terrestrial carbon removal. *Earth's Future*. doi:10.1002/2016EF000469

Braun, C., Merk, C., Pönitzsch, G., Rehdanz, K., & Schmidt, U. (2017). Public perception of climate engineering and carbon capture and storage in Germany: Survey evidence. *Climate Policy*. doi:10.1080/14693062.2017.1304888

Buck, H. J. (2016). Rapid scale-up of negative emissions technologies: Social barriers and social implications. *Climatic Change*, *139*(2), 155–167.

Caviezel, C., & Revermann, C. (2014). *Climate Engineering: Kann und soll man die Erderwärmung technisch eindämmen?* (Vol. 41). edition sigma, Berlin, Germany.

Chhatre, A., Lakhanpal, S., Larson, A. M., Nelson, F., Ojha, H., & Rao, J. (2012). Social safeguards and co-benefits in REDD+: A review of the adjacent possible. *Current Opinion in Environmental Sustainability*, *4*, 654–660. doi:10.1016/j cosust.2012.08.006

Cotula, L. (2012). The international political economy of the global land rush: A critical appraisal of trends, scale, geography and drivers. *Journal of Peasant Studies*, *39*(3–4), 649–680.

Dransfeld, B., Honegger, M., Michaelowa, A., Bagh, T., Bürgi, P., Friedmann, V., … Wehner, S. (2017). *SD-benefits in future market mechanisms under the UNFCCC*. Umweltbundesamt (UBA), Dessau-Roßlau, Germany.

Eaton, W. M. (2016). What's the problem? How 'industrial culture' shapes community responses to proposed bioenergy development in northern Michigan, USA. *Journal of Rural Studies*, *45*, 76–87.

EIA. (2017). International Energy Statistics, Energy Information Administration. Retrieved from https://www.eia.gov/beta/international/data/

Fajardy, M., & Mac Dowell, N. (2017). Can BECCS deliver sustainable and resource efficient negative emissions? *Energy & Environmental Science*, *10*, 1389–1426.

Fargione, J., Hill, J., Tilman, D., Polasky, S., & Hawthorne, P. (2008). Land clearing and the biofuel carbon debt. *Science*, *319*(5867), 1235–1238.

Ferrett, G. (2007, October 27). Biofuels a crime against humanity. *BBC News*. Retrieved from http://news.bbc.co.uk/1/hi/7065061.stm

Fuso Nerini, F., Tomei, J., To, L. S., Bisaga, I., Parikh, P., Black, M., & Milligan, B. (2017). Mapping synergies and trade-offs between energy and the sustainable development goals. *Nature Energy*, *1*, 2058–7546. doi:10.1038/s41560-017-0036-5

Füssler, J., Michaelowa, A., Honegger, M., Hoch, S., Warland, L., Matsuo, T., … Streck, C. (2015). *Market mechanisms: Incentives and integration in the post-2020 world*. Swiss Federal Office of the Environment (FOEN), Bern.

Geden, O. (2015, December 1). The dubious carbon budget. *New York Times*.

Geden, O. (2016). The Paris Agreement and the inherent inconsistency of climate policymaking. *Wiley Interdisciplinary Reviews: Climate Change*, *7*(6), 790–797.

Global CCS Institute. (2017). *The global status of CCS: Summary report. Canberra*. Retrieved from https://www.globalccsinstitute.com/publications/global-status-ccs-2016-summary-report

Grassi, G., House, J., Dentener, F., Federici, S., den Elzen, M., & Penman, J. (2017). The key role of forests in meeting climate targets requires science for credible mitigation. *Nature Climate Change*, *7*(3), 220–226.

Herzog, H. J. (2011). Scaling up carbon dioxide capture and storage: From megatons to gigatons. *Energy Economics*, *33*(4), 597–604.

Hoch, S., Michaelowa, A., Dransfeld, B., Honegger, M., Englert, D., Bieri, L., … Alt, R. (2015). *Methodology for CDM eligibility criteria definition*. Perspectives on behalf of KfW, Zurich, Switzerland.

Honegger, M., Sugathapala, K., & Michaelowa, A. (2013). Tackling climate change: Where can the generic framework be located. *Carbon and Climate Law Review*, *7*(2), 125–135.

Honegger, M., & Toussaint, P. (2017, May). *SDG-proofing the Paris market mechanisms to unlock mitigation and sustainable development synergies*. IASS Working Paper. doi:10.13140/RG.2.2.35343.69283

Horton, J. B., Keith, D. W., & Honegger, M. (2016). *Implications of the Paris Agreement for carbon dioxide removal and solar geoengineering*. Harvard Project on Climate Agreements Viewpoints Series, Cambridge, MA.

IEA. (2016). *20 years of carbon capture and storage accelerating future deployment*. Paris: International Energy Agency Report.

International Energy Agency Greenhouse Gas R&D Programme (IEA GHG). (2011). *Appendix G factsheet bio-ethanol production in potential for biomass and carbon dioxide capture and storage*. Report 2011/06. Retrieved from http://hub.globalccsinstitute.com/sites/default/files/publications/102121/potential-biomass-carbon-dioxide-capture-storage.pdf

IPCC. (2014). Climate change 2014: Mitigation of climate change. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, … J. C. Minx (Eds.), *Contribution of working group III to the fifth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Kato, E., & Yamagata, Y. (2014). BECCS capability of dedicated bioenergy crops under a future land-use scenario targeting net negative carbon emissions. *Earth's Future*, *2*(9), 421–439. doi:10.1002/2014EF000249

Kemper, J. (2015). Biomass and carbon dioxide capture and storage: A review. *International Journal of Greenhouse Gas Control*, *40*, 401–430.

Kortsch, T., Hildebrand, J., & Schweizer-Ries, P. (2015). Acceptance of biomass plants – Results of a longitudinal study in the bioenergy-region Altmark. *Renewable Energy*, *83*, 690–697.

Kossoy, A., Peszko, G., Oppermann, K., Prytz, N., Klein, N., Blok, K., … Borkent, B. (2015, September). *State and trends of carbon pricing*. Washington, DC: World Bank.

Köhler, P., Hartmann, J., & Wolf-Gladrow, D. A. (2010). Geoengineering potential of artificially enhanced silicate weathering of olivine. *Proceedings of the National Academy of Science (PNAS)*, *107*(47), 20228–20233. doi:10.1073/pnas.1000545107

Krey, V., Luderer, G., Clarke, L., & Kriegler, E. (2014). Getting from here to there–energy technology transformation pathways in the EMF27 scenarios. *Climatic Change*, *123*(3–4), 369–382.

Kriegler, E., Weyant, J. P., Blanford, G. J., Krey, V., Clarke, L., Edmonds, J., … Rose, S. K. (2014). The role of technology for achieving climate policy objectives: Overview of the EMF 27 study on global technology and climate policy strategies. *Climatic Change*, *123*(3–4), 353–367.

Krüger, T. (2017). Conflicts over carbon capture and storage in international climate governance. *Energy Policy*, *100*, 58–67.

Larkin, A., Kuriakose, L., Sharmina, M., & Anderson, K. (2017). What if negative emission technologies fail at scale? Implications of the Paris Agreement for big emitting nations. *Climate Policy*. doi:10.1080/14693062.2017.1346498

Le Quéré, C., Andrew, R. M., Canadell, J. G., Sitch, S., Korsbakken, J. I., Peters, G. P., … Keeling, R. F. (2016). Global carbon budget 2016. *Earth System Science Data*, *8*(2), 605–649.

Lipponen, J., McCulloch, S., Keeling, S., Stanley, T., Berghout, N., & Berly, T. (2017). The politics of large-scale CCS deployment. *Energy Procedia*, *114*, 7581–7595.

L'Orange Seigo, S., Dohle, S., & Siegrist, M. (2014). Public perception of carbon capture and storage (CCS): A review. *Renewable and Sustainable Energy Reviews*, *38*, 848–863.

Luckow, P., Wise, M. A., Dooley, J. J., & Kim, S. H. (2010). Large-scale utilization of biomass energy and carbon dioxide capture and storage in the transport and electricity sectors under stringent CO_2 concentration limit scenarios. *International Journal of Greenhouse Gas Control*, *4*(5), 865–877.

Marshall, C. (2017). In Switzerland, a giant new machine is sucking carbon directly from the air. *Science*. June 1. doi:10.1126/science.aan6915

McLaren, D. (2012). A comparative global assessment of potential negative emissions technologies. *Process Safety and Environmental Protection*, *90*(6), 489–500.

Millar, R., Fuglestvedt, J., Friedlingstein, P., Rogelj, J., Grubb, M., Matthews, D., … Allen, M. (2017). Emission budgets and pathways consistent with limiting warming to 1.5°C. *Nature Geoscience*, *10*, 741–747.

Moreira, J. R., Romeiro, V., Fuss, S., Kraxner, F., & Pacca, S. A. (2016). BECCS potential in Brazil: Achieving negative emissions in ethanol and electricity production based on sugarcane bagasse and other residues. *Applied Energy*, *179*, 55–63.

Muratori, M., Calvin, K., Wise, M., Kyle, P., & Edmonds, J. (2016). Global economic consequences of deploying bioenergy with carbon capture and storage (BECCS). *Environmental Research Letters*, *11*(9), 095004.

National Research Council (NRC). (2015a). *Climate intervention: Reflecting sunlight to cool earth*. Washington, DC: National Academies Press.

National Research Council (NRC). (2015b). *Climate intervention: Carbon dioxide removal and reliable sequestration*. Washington, DC: National Academies Press.

Nicholson, S., Jinnah, S., & Gillespie, A. (2017). Solar radiation management: A proposal for immediate polycentric governance. *Climate Policy*. doi:10.1080/14693062.2017.1400944

Nilsson, M., Griggs, D., & Visbeck, M. (2016). Map the interactions between sustainable development goals: Mans Nilsson, Dave Griggs and Martin Visbeck present a simple way of rating relationships between the targets to highlight priorities for integrated policy. *Nature*, *534*(7607), 320–322.

Olsen, K. H. (2007). The clean development mechanisms contribution to sustainable development: A review of the literature. *Climatic Change*, *84*(1), 59–73.

Pasztor, J., Scharf, C., & Schmidt, K.-U. (2017). How to govern geoengineering? *Science*, *357*(6348), 231.

Peters, G. P. (2016). The 'best available science' to inform 1.5 [deg] C policy choices. *Nature Climate Change*, *6*(7), 646–649.

Peters, G. P., Andrew, R. M., Canadell, J. G., Fuss, S., Jackson, R. B., Korsbakken, J. I., … Nakicenovic, N. (2017). Key indicators to track current progress and future ambition of the Paris Agreement. *Nature Climate Change*, *7*(2), 118–122.

Reiner, D. M. (2015). Where can I go to see one? Risk communications for an 'imaginary technology'. *Journal of Risk Research*, *18*(6), 710–713.

Reiner, D. M. (2016). Learning through a portfolio of carbon capture and storage demonstration projects. *Nature Energy*, *1*, 15011. doi:10.1038/nenergy.2015.11

Reiner, D. M., & Herzog, H. J. (2004). Developing a set of regulatory analogs for carbon sequestration. *Energy*, *29*(9), 1561–1570.

Renforth, P., & Henderson, G. (2017). Assessing ocean alkalinity for carbon sequestration. *Reviews of Geophysics*, *55*(3), 636–674.

Rogelj, J., Luderer, G., Pietzcker, R. C., Kriegler, E., Schaeffer, M., Krey, V., & Riahi, K. (2015). Energy system transformations for limiting end-of-century warming to below 1.5°C. *Nature Climate Change*, *5*(6), 519–527.

Rogelj, J., Schaeffer, M., Friedlingstein, P., Gillett, N. P., Van Vuuren, D. P., Riahi, K., … Knutti, R. (2016). Differences between carbon budget estimates unravelled. *Nature Climate Change*, *6*(3), 245–252.

Royal Society. (2009). "Geoengineering the climate: science, governance and uncertainty", RS Policy Document 10/09, London.

Scheer, D., & Renn, O. (2014). Public perception of geoengineering and its consequences for public debate. *Climatic Change*, *125*(3–4), 305–318.

Schneider, L., Broekhoff, D., Cames, M., Füssler, J., & La Hoz Theuer, S. (2017). Robust accounting of international transfers under Article 6 of the Paris Agreement. Discussion paper published by the German emissions trading authority (DEHSt) at the German Environment Agency, Berlin.

Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., … Van Vuuren, D. P. (2015). Biophysical and economic limits to negative CO_2 emissions. *Nature Climate Change*, *6*(1), 42–50.

Socolow, R., Desmond, M., Aines, R., Blackstock, J., Bolland, O., Kaarsberg, T. … Siirola, J. (2011). Direct air capture of CO_2 with chemicals: A technology assessment for the APS Panel on Public Affairs. *American Physical Society*.

Solano Rodriguez, B., Drummond, P., & Ekins, P. (2017). Decarbonizing the EU energy system by 2050: An important role for BECCS. *Climate Policy*, *17*, S93–S110.

Sorda, G., Banse, M., & Kemfert, C. (2010). An overview of biofuel policies across the world. *Energy Policy*, *38*(11), 6977–6988.

Taylor, L. L., Quirk, J., Thorley, R. M., Kharecha, P. A., Hansen, J., Ridgwell, A., … Beerling, D. J. (2015). Enhanced weathering strategies for stabilizing climate and averting ocean acidification. *Nature Climate Change*, *6*(4), 402–406.

Terwel, B. W., ter Mors, E., & Daamen, D. D. (2012). It's not only about safety: Beliefs and attitudes of 811 local residents regarding a CCS project in Barendrecht. *International Journal of Greenhouse Gas Control*, *9*, 41–51.

Tilman, D., Socolow, R., Foley, J. A., Hill, J., Larson, E., Lynd, L., … Williams, R. (2009). Beneficial biofuels—the food, energy, and environment trilemma. *Science*, *325*(5938), 270–271.

Torvanger, A., Lund, M. T., & Rive, N. (2013). Carbon capture and storage deployment rates: Needs and feasibility. *Mitigation and Adaptation Strategies for Global Change*, *18*(2), 187–205.

UNFCCC. (1998). Kyoto Protocol to the United Nations Framework Convention on Climate Change, UNFCCC. Retrieved from http://unfccc.int/resource/docs/convkp/kpeng.pdf

UNFCCC. (2015). Decision 1/CP.21 Adoption of the Paris Agreement. In *Report of the Conference of the Parties on its twenty-first session, held in Paris from 30 November to 13 December 2015, Addendum Part two: Action taken by the Conference of the Parties at its twenty-first session*, FCCC/CP/2015/10/Add.1. Retrieved from https://unfccc.int/resource/docs/2015/cop21/eng/10a01.pdf

UN News Centre. (2007). *UN independent rights expert calls for five-year freeze on biofuel production*. Retrieved from http://www.un.org/apps/news/story.asp?NewsID=24434#.WX3OSNPyiRs

Upreti, B. R. (2004). Conflict over biomass energy development in the United Kingdom: Some observations and lessons from England and Wales. *Energy Policy*, *32*(6), 785–800.

van der Horst, D. (2007). NIMBY or not? Exploring the relevance of location and the politics of voiced opinions in renewable energy siting controversies. *Energy Policy*, *35*(5), 2705–2714.

Voigt, C., & Ferreira, F. (2016). 'Dynamic differentiation': The principles of CBDR-RC, progression and highest possible ambition in the Paris Agreement. *Transnational Environmental Law*, *5*(2), 285–303.
Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, *1*, 1–9.
World Bank, Ecofys and Vivid Economics. (2016, October). *State and trends of carbon pricing*. Washington, DC: World Bank.