FROZEN ARCTIC:

Compendium of interventions to slow down, halt, and reverse the effects of climate change in the Arctic and northern regions

A University of the Arctic
Rapid Response Assessment

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Contents

Stabilizing glaciers by cloud seeding

Issue being addressed	Up to 50% of the world’s glaciers are set to disappear this century, with many more at risk if emission reduction targets are not met (Rounce *et al.* 2023).	
Description of the technology/ measure	Increasing precipitation on a glacier would serve two goals. Firstly, it would add to glacier mass, thereby directly countering the melting. Secondly, the snow that falls would increase glacial albedo, and thereby reduce the amount of absorbed energy. Precipitation enhancement could potentially be done by “glaciogenic” cloud seeding (see Snowfall enhancement). This technique introduces silver iodide (AgI) particles into supercooled clouds. This encourages nucleation and growth of particle size thereby allowing more water to leave the cloud in the form of precipitation.	
Technological readiness	High	Glaciogenic cloud seeding is already being carried out at sites around the world. Wang *et al.* (2020) suggest that cloud seeding over glaciers could help to stabilize them or even reverse their melt. They conclude this after a successful experiment using ground-based silver iodide (AgI) smoke generators on the Central-Asian Muz Tau glacier which appeared to significantly enhance snowfall over the glaciers, accounting ‘for at least 79 % of the total snow measured’. However, as is more extensively discussed under the section *Snowfall enhancement,* there are still significant issues with attributing the effectiveness of these measures.
Scalability	low	Cloud seeding can only be done if the right clouds are present, and even if seeded, there is only a limited amount of potential extra precipitation to be gained from specific clouds. Moreover, given the relatively small area of many of the most endangered glaciers, it is doubtful if precipitation can be targeted to fall precisely over them. Such technology would probably also only be possible for glaciers close to the required infrastructure like airfields, thereby excluding much of the Northern regions. Wang *et al.* (2020) furthermore also admit that enhancing precipitation over a specific area would reduce it over another, thereby potentially limiting the measure’s feasibility over larger areas.
Timeliness for near-future effects	Medium	The basic technology already exists, yet, it is unclear if it could be feasibly expanded to make a significant difference.

Potential to make a difference in Northern + Arctic	Medium	The technology might be applied to help slow the melt of particularly valued glaciers. Ongoing experiments by Oerlemans *et al.* (2017), for example, suggest glacier melt can be stabilized by adding artificial snowfall. Wang *et al.* (2020) suggest that precipitation enhancement on a broad scale might especially reduce summer melt.
Potential to make a global difference	Low	Mountain glaciers store enough water to cause about 50-60 cm of global sea level rise. But given the described uncertainties around effectiveness and difficulties with scalability, increasing glacier mass would likely not make a global difference
Cost - Benefit	High	Cloud seeding is generally expensive to do (see Snowfall enhancement). Moreover, Abermann *et al.* (2022) make the general comment that most glacier stabilization techniques are far too costly for almost all of the world's glaciers, even the most visited ones.
Likelihood of environmental risks	Low	Cloud seeding is already routinely done to provide water for agriculture and does not pose direct toxic risks. However, Wang *et al.* (2020) admit that ‘a potential concern is that artificial precipitation activities might redistribute the natural precipitation over a region’.
Effects on local/ indigenous communities	Neutral	As described above, cloud seeding is already routinely done to provide water for agriculture, but it could potentially lead to a competition over water redistribution. Due to the high costs associated with cloud seeding, this would only be carried out to enhance especially valued resources.
Ease of reversibility	easy	Cloud seeding is reversible by default as it stops when the seeding stops.
Risk of termination shock	Low	
Suitability within current legal/ governance structures	high	Cloud seeding is already practiced by companies and states around the world. The main provision is that it cannot be used for military purposes following the 1977 Environmental Modification Convention. Some commentators warn that cloud seeding could lead to major geopolitical tension around water redistribution in the future (Chen *et al.* 2017; Shevchenko and Horiacheva 2017; de Guglielmo 2021).
Amount of attention in scientific journals	low	Historically, the literature on weather modification has always been rather limited (see Snowfall enhancement). The specific application

and public media and currently ongoing research programs		to glaciers does not appear to have been picked up after the study by Wang *et al* (2020).

Increasing glacier thickness by local artificial snow production

Issue being addressed	Up to 50% of the world's glaciers are set to disappear this century, with many more at risk if emission reduction targets are not met (Rounce *et al*. 2023).	
Description of the technology/ measure	Oerlemans *et al.* (2017) suggested using localized surface technologies to create artificial snow coverage on mountain glaciers. Financed by a Swiss grant, there are currently ongoing experiments to explore the feasibility of different such technologies on the Swiss Morteratsch glacier (see mortalive.ch/, and glaciersalive.ch, and coverprojectfoundation.ch).	
Technological readiness	medium	Due to reduced amounts of snowfall, many of the world's ski resorts are already heavily reliant on artificial snow (Gerbaux *et al*. 2020; Joksimović, 2021). Amongst several snow producing methods, snow cannons are most often used. This is effective on a local scale (Fischer *et al.* 2016), although it requires large amounts of energy and water. Alternatively, less wealthy ski areas sometimes resort to so-called snow farming, in which previously fallen snow is stored and redistributed when needed (Wolfsperger *et al*. 2019). The MortAlive project seeks to use technologies that do not require external energy sources and water from a glacial lake. In this, they collaborate with several Swiss commercial companies.
Scalability	low	Like with other mountain glacier stabilization techniques (see for example Huss *et al*. 2021; and Stabilizing glaciers by cloud seeding) technical requirements, and especially cost, make such technologies only relevant for particularly valuable glaciers, and not feasibly scalable.
Timeliness for near-future effects	High	Snowmaking technology already exists, and ongoing experiments like the one on Morteratsch will likely provide clear answers as to how to best employ those.
Potential to make a difference in Northern + Arctic	low	The technology might be applied to help slow the melt of particularly valued glaciers, but due to technical requirements, and especially cost, such technologies would, if at all, only be deployable on particularly valuable glaciers.

Potential to make a global difference	Low	Mountain glaciers store enough water to cause about 50-60 cm of global sea level rise. But given the described uncertainties around effectiveness and difficulties with scalability, increasing glacier mass would likely not make a global difference.
Cost - Benefit	High	Abermann *et al.* (2022) clearly show that most glacier stabilization techniques are far too costly for almost all of the world's glaciers, even the most visited ones.
Likelihood of environmental risks	low	Such measures are already commonplace in ski resorts. Such actors generally have strong incentives to avoid damage, and are under close scrutiny. The projects named above emphasize their use of technologies that would not require external water and energy sources, and thereby potentially prevent related negative environmental side effects.
Effects on local/ indigenous communities	beneficial	Some of the sites on which this technique would be deployed might be of particular importance to local communities. For instance because of religious or financial reasons, or because it is a source of drinking water. The protection of such a glacier could therefore be important to such a community. Although it has to be ensured that the water and energy requirements of this measure would not interfere with local needs.
Ease of reversibility	Medium	This measure would probably be reversible by default, but the thickened glacier would only slowly return to its original state. It would likely have to be deployed constantly to prevent a sudden warming of the glacier under normal climatic circumstances.
Risk of termination shock	low	
Suitability within current legal/ governance structures	high	It would mainly be a local issue. Artificial snow making is already practiced at ski resorts worldwide.
Amount of attention in scientific journals and public media and currently ongoing research programs	Medium	The suggestion by Oerlemans *et al.* (2017) has received quite a lot of attention in the international media. Given the large financial importance of winter tourism, future funding and interest in such measures are likely to rise.

Glacier Albedo increase		
Issue being addressed	Up to 50% of the world’s glaciers are set to disappear this century, with many more at risk if emission reduction targets are not met (Rounce *et al*. 2023). The surface of many mountain glaciers has moreover significantly darkened due to a general increase in atmospheric black carbon and other kinds of aerosols.	
Description of the technology/ measure	It has recently been suggested that hollow glass microspheres (HGM, see also see sea ice albedo increase) could be used to increase the albedo of mountain glaciers and thereby slow their melt. The non-profit organization Bright Ice Initiative (https://brighticeinitiative.org/) is currently exploring this idea in collaboration with several other US and Indian organizations like the Healthy Climate Initiative (https://healthyclimateinitiative.org/) and Climformatics (https://climformatics.com/).	
Technological readiness	Medium	This measure faces similar issues as sea ice albedo enhancement does: the material already exists, but there remain large uncertainties around effectiveness, material behavior, and environmental issues. While the application of HGM on sea ice has been the subject of several studies, there have been no peer reviewed publications of its use on high mountain glaciers yet. In collaboration with scientists from IIT Indore, a field experiment is scheduled to start on the Chhota Shigri Glacier in North India in the summer of 2023 (Project Himalayas Brochure 2023).
Scalability	Low	This measure would only serve to reduce the melting of specific glaciers on land and is likely most effective on relatively flat surface areas (Project Himalayas Brochure 2023). If HGM is found to work, there could be possible scaling advantages in the production process that reduce costs.
Timeliness for near-future effects	Medium	The suggested material already exists, but there is no certainty if this measure would actually work.
Potential to make a difference in Northern + Arctic	Low	Apart from the issues that also face the application of HGM on sea ice, the vast expanse of the Arctic and Northern regions would likely make widespread operationalization difficult.
Potential to make a global difference	Low	It would mainly concern targeted interventions with limited global effects.
Cost - Benefit	High	There are no current estimates of the price of deployment, although the figures for the application of HGM on sea ice indicate high costs. To this, it must be added that the proposed surface area to

		be treated is far smaller than what Arctic Ice Project envisions for the Arctic sea ice, and that the potential sites of distribution would be many smaller surfaces instead of a single large area, which probably would come with increased costs.
Likelihood of environmental risks	Medium	There have been no studies on environmental risks. In a recent unpublished manuscript on the behavior of various HGM's in the Arctic, Farkas *et al*. (2023) found that some variants in their experiment leached in seawater overtime. Since mountain glaciers are generally of great importance to ecosystems and human drinking water (Cauvy-Fraunié and Dangles 2019), this would be an essential element to investigate further.
Effects on local/ indigenous communities	Unknown	Some sites where this technique might be deployed may be of particular significance to local communities, such as areas of religious or economic importance, or, especially in the context of Asian high mountain ranges, sources of drinking water. The protection of such a glacier could, therefore, be important to such communities. However, it must be ensured that the HGMs are environmentally safe and do not pose a risk to human health.
Ease of reversibility	Easy	This measure would likely stop when the HGMs are washed away or buried, although they would potentially need to be cleaned up if suddenly found undesirable.
Risk of termination shock	Low	
Suitability within current legal/ governance structures	Medium	Although these measures could be undertaken by States on whose territory the glaciers exist, it is likely that environmental issues would arise related to the spreading of particles on protected areas.
Amount of attention in scientific journals and public media and currently ongoing research programs	Medium	The promoters of this idea have been quite vocal and even organized an online benefit concert to raise awareness and gain sponsors for their idea. So far the idea seems not to have been picked up in scientific circles. A recent article in The New Yorker likely provided it great public exposure (Riederer 2023).

Glacier insulation with fabrics

Issue being addressed	Up to 50% of the world's glaciers are set to disappear this century, with many more at risk if emission reduction targets are not met (Rounce *et al*. 2023).

Description of the technology/ measure	One method to increase the albedo of individual glaciers already in use is to wrap them in reflective materials. Most cover projects focus on the European Alps (see, for example, Senese *et al*. 2020), where coverage is also used for skiing areas. However, there are also studies on the potential of non-tourism-related glacier coverage in Asia (Liu *et al*. 2022) and Eastern Antarctica (Engel *et al*. 2022).	
Technological readiness	high	Glaciers are already being covered at several sites and it seems to be able to reduce some of the melt. Such glacier coverage by various forms of materials has been relatively well studied (Olefs and Lehning 2010; Huss *et al*. 2021). Many studies and existing projects use geotextiles consisting of polyester or polypropylene fibers (Senese *et al*. 2020). Liu *et al*. (2022) found that nanofibres hold specific advantages over geotextiles, and some speculate that radiative cooling techniques could hold great promise for the future (Li *et al*. 2022, See passive radiative cooling).
Scalability	low	Due to high costs it seems likely that this measure could only serve to reduce the melting of specific glaciers. Perhaps the mass scale production of covering material could drive down costs and make it more feasible to apply large amounts of material over many more glaciers. Practically, the protection of glaciers would furthermore likely be limited to the more accessible glaciers that could also be easily maintained and restored if needed.
Timeliness for near-future effects	High	Coverage is already being used on specific glaciers.
Potential to make a difference in Northern + Arctic	low	Engel *et al.* (2022) found that 'the protection of glacier surface with non-woven geotextile covers reduced the snow and ice ablation by 40 to 69%' in Antarctica, suggesting specific glaciers in the Arctic and Northern regions might benefit from such a measure. In a study on 9 Swiss sites where the technology is used, Huss *et al*. (2021) found that only '300,000 m3 yr−1 of ice have been saved… [i]n comparison to roughly 1 km3 yr−1 of total Swiss glacier mass loss'. This is only a reduction of 0.03%. For any meaningful reduction in glacier melt deployment would have to be done at a very large scale.
Potential to make a global difference	Low	The global effects of covering these glaciers will likely be very limited.
Cost - Benefit	High	Huss *et al.* (2021) found a price of 0.6 and 7.9 CHF m−3 of saved glacier ice per year. If applied on all Swiss glaciers, they conclude this measure would cost more than 1 billion CHF per year, which,

		at a carbon cost of 30 CHF per ton of CO2, is more than would be needed to compensate for all the country's CO2-emissions. This prohibitively high price tag confirms the findings of Abermann *et al.* (2022) that glacier stabilization techniques are far too costly for almost all of the world's glaciers.
Likelihood of environmental risks	low	Huss *et al.* (2021) warn that 'Geotextiles placed on glacier ice might have a suite of negative effects for the local environment and downstream water quality' and that these effects need to be researched further if larger areas were to be covered.
Effects on local/ indigenous communities	beneficial	Some sites where this technique might be deployed may be of particular significance to local communities, such as areas of religious or economic importance, or sources of drinking water. The protection of such a glacier could, therefore, be important to these communities. However, it must be ensured that such coverage would not be objectionable to local communities for cultural or other reasons, and that the material used does not pose a threat to local ecosystems or human health if it degrades.
Ease of reversibility	easy	Ideally, the cover would be designed so it could be removed and reused, or, if needed, destroyed.
Risk of termination shock	low	
Suitability within current legal/ governance structures	High	This technique is already being applied on glaciers in Europe and Asia.
Amount of attention in scientific journals and public media and currently ongoing research programs	High	There have been many scientific studies on glacier insulation, and there is large commercial interest from the tourism industry. This measure has received significant attention in popular media, likely because of the importance of Alpine glaciers to tourism and the European context.

Artificial glaciers

Issue being addressed	Up to 50% of the world's glaciers are predicted to disappear this century, with many more at risk if emission reduction targets are not met (Rounce *et al*. 2023). Furthermore, the melting of mountain glaciers impacts the rates and seasonality of meltwater abundance and scarcity.

Description of the technology/ measure	Several high mountain communities around the world have a long history of building barriers and other constructions that trap or hold meltwater by refreezing it (Nüsser *et al*. 2019b). Nüsser et al (2019a) distinguish three different kinds of artificial glaciers in the Hindu Kush-Himalaya area. The most famous of these is the “ice stupa” which was developed in Ladakh (http://www.icestupa.org/) and is being studied in the European Alps (https://glaciersalive.ch/en/projekte-2/). As the name suggests, ice stupas take the form of the Buddhist religious structures and are formed during winter by letting layers of water freeze over a previously constructed frame. The water used in this process is glacial meltwater that is deviated and sprayed over the frame by the force of gravity alone, without any extra energy requirements. The structure then slowly melts as temperatures rise, thereby providing a temporary but steady source of water for local communities. Artificial glaciers have also been built for cooling purposes, most famously in a large-scale project in Ulaanbaatar, Mongolia (Watts 2011).	
Technological readiness	High	There are several different kinds of artificial glaciers already in use, with experiments ongoing to improve upon the ice stupas (see http://www.icestupa.org/).
Scalability	Low	Experiments in the European Alps found that their ice stupas were far lower than the ones built by their peers in the Indian context due to geophysical factors related to humidity and air temperature (Nüsser *et al*. 2019a; Oerlemans *et al*. 2021). It appears that ice stupa construction is most feasible in dry mountain areas (Balasubramanian *et al*. 2022). So far, artificial glaciers have been relatively small-scale. Because they are dependent on the time and energy of many local people to construct them, they likely are not easily scalable in their current form. Artificial glaciers are moreover dependent on the availability of water, and are therefore limited to specific areas. Although global warming will temporarily produce an increase in meltwater, at some point many glaciers will have largely disappeared and meltwater will no longer be available for artificial glaciers.
Timeliness for near-future effects	High	Many of these measures are already in use.
Potential to make a difference in Northern + Arctic	Low	Although Clouse (2014) describes artificial glaciers as a 'low-tech form of geoengineering', they can best be seen as adaptation measures. To a limited degree, they might be able to reduce problems around water availability in areas that rely on glacial meltwater but will not significantly mitigate climate change or its wider effects (Nüsser *et al*. 2019a). The low population density and different freshwater context of the Arctic and Northern regions will

		make such measures far less effective there than in the high mountain regions like the Hindu Kush-Himalaya.
Potential to make a global difference	Low	These would be localized structures that will likely not have a major effect beyond the very local area.
Cost - Benefit	Medium	Although the structure of artificial glaciers is mainly used with limited local materials, often without significant extra energy input, Nüsser *et al.* (2019a) note that ice stupas require a lot of maintenance, investment, and construction labor. They also state that in addition to the significant costs to local communities, ice stupas can only store limited amounts of water.
Likelihood of environmental risks	low	Most artificial glaciers would only store or redirect melt ater, and would therefore have limited environmental effects. However, because ice stupas divert water away from rivers, they could have negative effects on downstream ecosystems and communities (Nüsser et al. 2019a).
Effects on local/ indigenous communities	Beneficial	The ice stupas are generally lauded as examples of local grassroots climate action that build on traditional local and religious knowledge and benefit local communities (Clouse 2016).
Ease of reversibility	Easy	In their present form, artificial glaciers are very easily removed if needed.
Risk of termination shock	Low	
Suitability within current legal/ governance structures	High	There are already many such projects in existence, and they would likely only fall under local or national governance and legal systems.
Amount of attention in scientific journals and public media and currently ongoing research programs	High	There have been several social and natural science studies on artificial glaciers, including on their potential role outside of the Himalaya. Ice stupas have been broadly covered in public media. Ladakhi engineer Sonam Wangchuk, for example, received a Rolex Awards for his work on and design of the ice stupa.

Ice sheet stabilization via seabed curtains		
Issue being addressed	One of the potentially most catastrophic effects of contemporary global warming would be the dramatic increase in sea levels as a result of the melting Greenland and Antarctic ice sheets. Even if all current emissions were immediately stopped, sea level rise could still occur because of locked-in warming (State of the Cryosphere report 2022).	
Description of the technology/ measure	There have been several suggested "Glacier geoengineering" measures (Lockley *et al.* 2020). The only one that is being seriously explored at this time would attempt to increase ice sheet stability by blocking the warmer deep water access from the ocean to terminating glaciers or floating ice sheets. Although larger physical dams have been previously suggested (Wolovick and Moore 2018; Hunt and Byers 2018), a curtain design is considered more feasible. These curtains would be anchored to the ground and would block most of the warmer waters, whilst still being flexible enough to allow icebergs to pass over them (Keefer *et al*., 2023; Wolovick *et al*. 2023). Research is still being done on how to best deploy such a measure, and which sites would provide the greatest benefit whilst still being feasible to build.	
Technological readiness	low	Although the project is still in an initial state, it is seeing rapid expansion, and now includes several private engineering firms that aim to provide more clarity about pending questions about preferred materials and design elements (see akersolutions.com/news/news-archive/2022/aker-solutions-explores-first-of-a-kind-engineering-solution-to-slow-melting-of-glaciers/). The feasibility of the underwater curtain design has been shown in other applications in which it separates water at different temperatures. After model and computer simulations, a small variant of the curtain could be tested at accessible fjords, for example on Svalbard, after which larger construction projects in more difficult locations could be done.
Scalability	Medium	There are only a handful of glaciers where a curtain deployment could potentially prevent metres of global sea level rise. The project could advance, step-by-step, to more challenging locations from easily accessible Arctic locations to Greenland and eventually to Antarctica. However, because of increasing atmospheric temperatures, it is not clear how effective such curtains ultimately would be in each of the suggested locations.

Timeliness for near-future effects	Medium	It might take two to three decades of development before this measure could be deployed in Antarctica. As the most serious Antarctic instability is not predicted until later this century, if research were to start now, this would still be timely.
Potential to make a difference in Northern + Arctic	Unknown/high	Apart from the positive effect of potentially mitigating sea level rise through a deployment in Antarctica, seabed curtains could potentially also be installed in Greenland. However, this method might be less effective there, as, in contrast to Antarctica, at least half of the melt in Greenland is due to atmospheric warming, which this measure would not be able to mitigate.
Potential to make a global difference	High	Global sea level rise will be one of the most impactful results of current global warming. West Antarctica alone holds enough water to potentially raise sea levels by 6 metres. Any intervention that would prevent or reduce sea level rise would, therefore, be highly significant.
Cost – Benefit	Low	The cost estimates for curtain construction crucially depend on several variables like location, size, and depth. Hunt and Byers (2018) earlier gave a figure for the final cost of a barrier as US$ 68.9 billion, with submerged dams built at a cost of US$ 337.1 billion, Keefer *et al.* (2023) estimate that an 80 km curtain at 600 m depth could be built at Pine Island and Thwaites glaciers for $40–80 billion plus $1–2 billion/yr maintenance. Although this sounds expensive, they note this would also be needed yearly to build global protections as a result of the sea level rise that would follow the collapse of both glaciers. The costs for this measure, therefore, would ultimately only be 1 to 2 % of the total amount of money that would be needed for global coastal protection this century if sea level rise is left unmitigated.
Likelihood of environmental risks	Unknown	The environmental effects of such constructions are unknown. The earlier conceived physical dams would likely have had a much greater environmental impact, although the construction of curtains will also inevitably cause disturbances. A curtain, for example, could interfere locally with glacial runoff regimes thereby influencing marine bioproductivity that thrives on the associated nutrients. However, these potential effects of deployment will have to be weighed against the major ecological disturbances that ice sheet retreat and potential collapse will have.
Effects on local/ indigenous communities	Unknown	The project has attempted to co-create and build collaborations in Ilulissat, Greenland (see http://arcticcentre.org/EN/grisco). Depending on the environmental and ecological effects of

		deployment, local livelihoods might be positively or negatively impacted.
Ease of reversibility	Medium	In contrast to dams or other fixed constructions, the curtain is only fixed to the seafloor at the anchoring points and could, therefore, be relatively easily removed, if desired (Keefer *et al*. 2023).
Risk of termination shock	Medium	If suddenly removed there might be some risk of destabilization.
Suitability within current legal/ governance structures	Medium	Corbett and Parson (2022) conclude that such intervention would currently not fit into Antarctic governance structures, but they say they are very hopeful it will adjust to include it in the future.
Amount of attention in scientific journals and public media and currently ongoing research programs	Medium	The idea has received some public attention and has for example been featured in the New Scientist (www.newscientist.com/article/2343633-engineering-firms-explore-plan-to-slow-melting-of-greenland-glacier/). The research program is mostly led by John Moore at the University of Lapland, Finland, with international collaboration.

Ice sheet stabilization via buttressing

Issue being addressed	One of the potentially most catastrophic effects of contemporary global warming would be the dramatic increase in sea levels as a result of the melting Greenland and Antarctic ice sheets. Even if all current emissions were immediately stopped, sea level rise could still occur because of locked-in warming (State of the Cryosphere report 2022).	
Description of the technology/ measure	It has been suggested that ice sheets could be stabilized by building physical structures that could artificially support and buttress them. These pinning points would provide places for the ice sheet to stabilize, and encourage the growth of new ice (Wolovick and Moore 2018). Another idea would be to increase ice sheet thickness which would allow increased contact with already existing points (Lockley *et al*. 2020).	
Technological readiness	low	This was one of the first ice sheet stabilization ideas (MacAyeal 1983), and is now proposed again as a research topic (MacAyeal pers comm.). However, as of yet, buttressing as a means to stabilize ice sheets has not been studied or explored further.
Scalability	low	Such constructions would be very difficult to build. Moreover, They would require vast amounts of materials, almost as much as for the

		construction of artificial islands in Dubai and Hong Kong (Wolovick and Moore 2018). Because larger designs are likely to be more effective than smaller ones, material constraints will probably limit scalability even further.
Timeliness for near-future effects	low	The idea is not currently being actively explored. Considering that the most serious ice sheet instability in Antarctica is probably still decades away, deployment of buttressing, like undersea curtains (see undersea curtains), could still be timely if research started immediately.
Potential to make a difference in Northern + Arctic	Low	Reductions in global sea level rise by stabilizing Antarctica would be felt in the Arctic as well, but in itself this method would not likely be effective in the Arctic as the region holds few ice sheets that could be buttressed.
Potential to make a global difference	High	Global sea level rise will be one of the most impactful results of current global warming. West Antarctica alone holds enough water to potentially raise sea levels by 6 metres. Any intervention that would prevent or reduce sea level rise would, therefore, be highly significant.
Cost - Benefit	High	Given the huge amount of required materials and the incredible logistical and construction challenges, the cost of this project will likely be prohibitively high. However, it should be also noted that unmitigated sea level rise would require investments in coastal defenses that could be two to three orders of magnitude higher (Keefer *et al*. 2023).
Likelihood of environmental risks	High	There are likely significant environmental effects due to the construction of such buttressing points (Wolovick and Moore 2018). However, these potential effects will have to be weighed against the major ecological disturbances potential ice sheet collapse will have.
Effects on local/ indigenous communities	Neutral	Construction of such buttressing points could have effects on local populations. However, as there are few ice shelves in the Arctic with any local populations, these effects will be limited.
Ease of reversibility	Hard	It is likely that these structures would be hard to tear down once built and the impacts of their collapse or damage are unknown. Given the force behind calving processes and the size of icebergs, the integrity of such structures would have to be ensured.
Risk of termination shock	High	If they collapse, this would likely have a massively destabilizing effect on the ice sheet.

Suitability within current legal/ governance structures	Low	Corbett and Parson (2022) say such intervention would currently not fit into Antarctic governance structures. This scheme would likely be far more objectionable than other glacier stabilization ideas due to the extent of the constructions required.
Amount of attention in scientific journals and public media and currently ongoing research programs	low	This idea has been suggested a few times but has not seriously been explored further.

Ice sheet stabilization by draining water or bed freezing

Issue being addressed	One of the potentially most catastrophic effects of contemporary global warming would be the dramatic increase in sea levels as a result of the melting Greenland and Antarctic ice sheets. Even if all current emissions were immediately stopped, sea level rise could still occur because of locked-in warming (State of the Cryosphere report 2022).	
Description of the technology/ measure	It has been suggested that ice sheets could be stabilized by reducing the lubrication effect of water below the ice sheet. This is known to occur naturally and could be done artificially by either pumping the water out or attempting to freeze it (Wolovick and Moore 2018; Lockley *et al*. 2020). To freeze water, the water at the base would need to be cooled. Lockley *et al.* (2020) suggest this might be done through thermosyphons (see Enhancing permafrost refreezing with air pipes and Thermosyphon technologies) or refrigerants like liquid CO2 which might be captured relatively efficiently in the colder Antarctic climate (see Antarctic CO2 Capture).	
Technological readiness	low	This idea has not been explored seriously. Deep drilling has been done in ice sheets before: the U.S. Amundsen–Scott South Pole Station drilled 2.5 km deep, and a Russian attempt reached a lake at 3.6 km depth (Wolovick and Moore 2018). Many drilling points would likely be needed across the ice sheet. The ice motion would mean new holes being drilled every year. The basal hydrology will change naturally and would be also affected by the drying. The water pumped out would also have to be disposed of and might require treatment.
Scalability	Low	Locating places to drill on a moving glacier with variable basal hydrology would require extensive geophysical knowledge. Multiple

		holes would have to be drilled and maintained across the ice sheet, likely limiting scalability.
Timeliness for near-future effects	Low	
Potential to make a difference in Northern + Arctic	Low	This measure is likely not able to make significant differences to ice sheet melting rates.
Potential to make a global difference	Low	
Cost - Benefit	High	Apart from material and human expenses, drilling to a depth of 2.5 km at the US station required 450,000 litres of fuel. As is the case with other Ice Sheet ideas, this project would likely be very expensive.
Likelihood of environmental risks	medium	There could be multiple environmental effects, for instance related to the large amounts of fuel that would need to be transported and burnt on-site.
Effects on local/ indigenous communities	neutral	The potential to impact Greenland glaciers is likely low, and the global effects minimal.
Ease of reversibility	easy	The holes would likely freeze if discontinued.
Risk of termination shock	low	Although there would be low risk of termination shock, this measure would likely have to be continued once started since the drilled holes will freeze if they are not maintained. The same will be true for any basal freezing measure.
Suitability within current legal/ governance structures	medium	Corbett and Parson (2022) say such intervention would currently not fit into Antarctic governance structures, but they are very hopeful they will be adjusted to include it in the future.
Amount of attention in scientific journals and public media and currently ongoing research programs	low	This has been mentioned in several scientific articles, and also featured in the science fiction novel Ministry for the Future, by Kim Stanley Robinson (2020).

Pumping of water on ice sheets		
Issue being addressed	One of the potentially most catastrophic effects of contemporary global warming would be the dramatic increase in sea levels as a result of the melting Greenland and Antarctic ice sheets. Even if all current emissions were immediately stopped, sea level rise could still occur because of locked-in warming (State of the Cryosphere report 2022).	
Description of the technology/ measure	This scheme specifically targets ice sheet melting. The aim is to directly increase ice mass by pumping water or snow on top of the ice sheet (Frieler *et al.* 2016; Feldmann *et al*., 2019). This could be done by using large wind-powered pumps, possibly with desalination plants, to pump seawater to the top of the ice sheet (3 km thick, on average). It could then be distributed in different ways. Although snow cannons might be preferable, the water would need to be desalinated first, leading to major increases in energy requirements (Frieler *et al*. 2016). The other option, directly pumping sea water on the ice sheet, could lead to unfrozen water collecting in ponds, or bare ice patches, which could significantly reduce albedo. This water could furthermore drain towards the bottom to further lubricate and thereby speed up the ice sheet discharge rate. There have been various slightly differing proposals for this project. In a recent book, it was suggested to desalinate the seawater first through reverse osmosis, and then spray it onto the ice caps. (Khandelwal 2019; Chauhan *et al*. 2019)	
Technological readiness	low	Although the model studies of Frieler *et al.* (2016) and Feldmann *et al.* (2019) show that such a measure might be effective in stabilizing ice sheets or reducing sea level rise, the technology would be prohibitively expensive and complicated to install and maintain due to extreme weather conditions and the remote nature of these ice sheets. Although similar kinds of pumps exist, nobody has done further engineering studies into how they might be adjusted and adapted to these conditions as they would require far too much energy to be feasible. The Feldmann *et al.* (2019) model study shows that lifting the water 640 m on average to cover an area ‘similar to the size of the state of Costa Rica or half the size of Iceland' would already require a significant amount of currently used global energy, and that this would roughly double if the water had to be desalinated first. An option could be to build 12,000 wind turbines, similar to those described in ambitious macro-engineering projects to generate energy on a large scale in Antarctica (Bolonkin and Brook 2008). But given difficulties in constructing and maintaining them, this seems to make this project very unattractive as opposed to other schemes.

Scalability	Low	Snow accumulation is a low sensitivity knob of the climate system, and melt rates are often far greater than deposition rates. Even if successful in increasing glacier mass, this could eventually accelerate the ice sheet melt and thereby negate any positive effects this measure would have had. Apart from these geophysical objections, the costs and investments are likely too high for this idea to be scalable.
Timeliness for near-future effects	Low	Construction of the required infrastructure would be a major undertaking, whilst continuously rising global temperatures would require ever greater volumes of water to be pumped onto the ice sheets.
Potential to make a difference in Northern + Arctic	Low	This measure seems “plausible” only in Antarctica where lower surface temperatures prevent much surface melt and would likely be futile in Greenland where surface melt is already extensive. However, if effective in Antarctica it would also reduce sea levels in the Northern and Arctic regions.
Potential to make a global difference	Low	Although water disposition on top of ice sheets could reduce sea level rise (Frieler *et al.* 2016), ice sheet dynamics would evolve because of it, and it is doubtful it would have a significant global effect in the long run (Moore *et al.* 2020).
Cost - Benefit	high	Frieler *et al.* (2016) state that the ‘costs cannot be reliably estimated’, but would be extremely high. Moore *et al.* (2020) therefore conclude it is an ‘entirely implausible use of resources’.
Likelihood of environmental risks	High	Feldmann *et al.* (2019) state that '[t]he building of the wind turbines and the further infrastructure, as well as the extraction of the ocean water itself, would mean the loss of a unique natural reserve, with serious effects on its sensitive marine and coastal ecosystems'.
Effects on local/ indigenous communities	neutral	As noted above, this measure would likely not be deployed in Northern regions.
Ease of reversibility	Hard	Feldmann *et al.* (2019) warn that it would be very hard to deal with potential negative effects and hazards of such an enterprise. Any snow accumulated will stay until melted away (potentially over thousands of years).
Risk of termination shock	low	
Suitability within current legal/	medium	The Protocol on Environmental Protection to the Antarctic Treaty (Secretariat of the Antarctic Treaty 1991) means to protect the Antarctic, and would most certainly be a major obstacle for the

governance structures		deployment of such measures on the continent. In the Arctic, such an intervention on the Greenland ice sheet would likely mainly have to deal with Greenlandic national governance systems (Corbett and Parson, 2022)
Amount of attention in scientific journals and public media and currently ongoing research programs	low	This idea is sometimes mentioned in public media, and occasionally in scientific literature, but generally not considered a serious option.

Increasing humidity around glaciers and ice sheets

Issue being addressed	Up to 50% of the world’s glaciers are set to disappear this century, with many more at risk if emission reduction targets are not met (Rounce *et al.* 2023).	
Description of the technology/ measure	Engineer Paul Klinkman has suggested increasing the water content around glaciers and ice sheets to increase precipitation over them (see klinkmansolar.com/knightfog.htm#U2). Although it is unsure how this would work exactly, Klinkman suggested constructing ‘fog-creating ponds’ that would increase the moisture content of the air. Klinkman has also suggested increasing moisture content by using a ‘water vapour chimney’ (See klinkmansolar.com/kchimney.htm#H14). Alternatively the increased warmth associated with open water will increase ablation and calving rates in Greenland. This has been proposed as a likely mechanism for variations in terminus position. Historical mass loss is correlated with heat flow from surrounding seas (Yue *et al.* 2021; Moore *et al.* 2019)	
Technological readiness	low	
Scalability	low	This would likely only be effective near the coast.
Timeliness for near-future effects	low	
Potential to make a difference in Northern + Arctic	low	

Potential to make a global difference	low	
Cost - Benefit	unknown	
Likelihood of environmental risks	low	
Effects on local/ indigenous communities	neutral	
Ease of reversibility	easy	
Risk of termination shock	low	
Suitability within current legal/ governance structures	high	
Amount of attention in scientific journals and public media and currently ongoing research programs	low	Although the idea surfaced several times in the Geoengineering Google Group, it seems to not have been picked up.

Iceberg management

Issue being addressed	With rising Arctic temperatures, there have been major changes in iceberg production rates of marine terminating glaciers. These icebergs drift into warmer sea waters where they will slowly melt.
Description of the technology/ measure	In a series of posts to the Geoengineering Google Group in 2009, Veli Albert Kallio suggested the possibility that 'suspension cabling could hold ice in place and prevent it moving into the warm waters'. These cables would potentially sink or be removable. The original post suggested placing the cables in the Robeson Channel between Canada and Greenland. Several

	responses remarked it might be worthwhile to look into the use of such cables to reduce the outflow rate of ice in other areas.	
Technological readiness	low	The plan has not been explored seriously in the scientific literature.
Scalability	low	
Timeliness for near-future effects	low	
Potential to make a difference in Northern + Arctic	low	The effects of such management would probably be limited.
Potential to make a global difference	low	This would only be applicable to specific iceberg producing regions.
Cost - Benefit	high	
Likelihood of environmental risks	medium	The original post already encouraged further research into the environmental effects of this measure.
Effects on local/ indigenous communities	neutral	
Ease of reversibility	easy	
Risk of termination shock	low	
Suitability within current legal/ governance structures	high	
Amount of attention in scientific journals and public media and currently ongoing research programs	low	The idea has likely been abandoned after the original series of posts.

Modular iceberg creation by submersibles		
Issue being addressed	Arctic sea ice extent has rapidly decreased over the last few decades, with most multi-year ice disappearing altogether. This has already had major effects on local communities and ecosystems. The disappearance of the relatively reflective sea ice also leads to a dramatic decrease of albedo in the Arctic and subsequent high energy uptakes by the darker water during the Arctic summers.	
Description of the technology/ measure	In 2019, an Indonesian design team came up with the idea of a submersible device that could take in sea water, desalinate it, and then have it freeze into a solid block they called a “new ice baby” (Griffiths, 2019). Although the idea received a second prize in a 2019 international design competition, and the related video gained much media attention, it is not clear what exactly the designers tried to achieve with their device. Most likely these modular icebergs would replace Arctic sea ice, but it is not specified how this would be done. In the project’s description, the designers explain they see this as an analogue to tree planting programs in tropical forests, without stating how this would have climate positive effects. Moreover, they confuse the Arctic and Antarctic several times, and seem to be unaware of the basics of sea ice physics.	
Technological readiness	low	This idea only exists on a drawing board, and no serious research has been done.
Scalability	low	
Timeliness for near-future effects	low	
Potential to make a difference in Northern + Arctic	low	
Potential to make a global difference	low	
Cost - Benefit	high	Thousands of such devices would be needed, generating equal concerns about costs, sustainability, and possible ways to transport. Furthermore, these submersibles would require energy, and although the design features solar panels, it is not sure how these would work.

Likelihood of environmental risks	medium	
Effects on local/ indigenous communities	neutral	
Ease of reversibility	easy	
Risk of termination shock	low	
Suitability within current legal/ governance structures	medium	
Amount of attention in scientific journals and public media and currently ongoing research programs	low	Although the project has not been developed further, it is still relatively frequently mentioned in blog posts and less critical news media.

<table>
<tr><th colspan="3">Sea ice thickening</th></tr>
<tr><td>Issue being addressed</td><td colspan="2">Arctic sea ice extent has rapidly decreased over the last few decades, with most multi-year ice disappearing altogether. This has already had major effects on local communities and ecosystems. The disappearance of the relatively reflective sea ice also leads to a dramatic decrease of albedo in the Arctic and subsequent high energy uptakes by the darker water during the Arctic summers.</td></tr>
<tr><td>Description of the technology/ measure</td><td colspan="2">Sea ice thickening is an idea to slow or reverse the decline of Arctic sea ice by artificially thickening it. Desch <i>et al.</i> (2017) suggested this could be done by pumping sea water on top of already existing ice during winter and letting it freeze. This thickened sea ice would then melt later, or even survive the summer to become multi- year ice. Desch <i>et al.</i> (2017) suggested a large amount of floating wind-powered pumps could be used as pumping devices.</td></tr>
<tr><td>Technological readiness</td><td>low</td><td>This idea is still at a very early stage of development. Desch <i>et al.</i> (2017) provided a rough design for the pumps. A recent Master's thesis by Laura van Dijke (2022) at the University of Delft further</td></tr>
</table>

		explored some engineering questions and the company Real Ice (https://www.realice.eco/) is trying to develop this design for real world application after its founders worked on the idea during their studies. However, apart from design issues, many questions remain, such as how to produce, distribute, and maintain such devices.
Scalability	medium	Desch *et al.* (2017) suggest that millions of pumps spread across the Arctic Ocean could remain frozen in the ice and operate throughout winter. There would likely be scaling benefits associated with increased pump production, although it is unclear how distribution and maintenance could be effectively organized.
Timeliness for near-future effects	medium	With many questions around the technology remaining, and large parts of the ice already gone, the potential window to implement such an intervention seems increasingly limited.
Potential to make a difference in Northern + Arctic	High	If, as model studies by Zampieri and Goessling (2019) and Pualing and Blitz (2021) suggest, the technology could postpone the melt of Arctic sea ice, this might be very beneficial to the Arctic as it would give more time to adapt to the effects of climate change and would perhaps allow further research into other schemes.
Potential to make a global difference	Low	If more Arctic sea ice could actually be preserved, this might have some effect on the global energy budget. The Zampieri and Goessling (2019) model study found a global - 0.08 W/m2 forcing effect for the period of 2061–2100. However, both Zampieri and Goessling (2019) and Pualing and Blitz (2021) also find that although certain pumping strategies might lead to better results, they would only delay the eventual disappearance of Arctic summer ice under expected warming scenarios.
Cost - Benefit	Medium	Desch *et al.* (2017) give a rough estimate of $50 billion per year to increase ice thickness by one metre over 10% of the Arctic. The accuracy of this estimate, however, is highly uncertain as there are many unknowns: for example, how the pumps would behave in the Arctic, how they could be maintained and repaired, and how this could be done without causing extra emissions that could break existing ice or spread albedo reducing particles. It should, however, be noted that Hao *et al.* (2023) estimate that the melting of the sea ice would cost the world an average of 6.7–13.3 trillion USD annually over the period 2020 to 2100, when the costs of the forcing effects of the ice are calculated in terms of equivalent costs of the forcing that is the result of GHG emissions.

Likelihood of environmental risks	Medium	Miller *et al.* (2020) note that this kind of thickening would affect Arctic marine biochemistry in multiple ways. The pumping process would, for example, release aerosols which would alter atmospheric chemistry, might increase or decrease temperatures, and 'could have myriad contrasting impacts on the Arctic atmosphere'. They also note that this scheme might affect the availability of light for photosynthesising algae under the ice, thereby reducing marine productivity, or reduce algae production directly by removing shallow, algae-rich waters, and pumping them on top of the ice. Furthermore, the distribution and maintenance of the pumps could be a major source of Arctic GHG emissions, and the pumps would have to be made out of non-toxic materials.
Effects on local/ indigenous communities	Unknown	The worries about the potential biochemical effects of sea ice thickening expressed by Miller *et al.* (2020) might have significant effects on the livelihoods of local and indigenous communities who rely on hunting and fishing. Desch *et al.* (2017) suggested that the pumps might be maintained by local and indigenous communities, thereby providing social co-benefits, but it is unclear if this could actually be done in practice.
Ease of reversibility	Medium	If the scheme is found to be undesirable, the pumps could probably be removed at some cost.
Risk of termination shock	medium	The technology would need to be continuously deployed, as the ice would most likely rapidly melt without it (Pualing and Blitz, 2021).
Suitability within current legal/ governance structures	medium	Although it is not clear how the deployment of such pumps would be governed on the High Seas, the five Arctic coastal states would likely be able to deploy such pumps if they wanted to within their Exclusive Economic Zones (Moore *et al.* 2020). Both Argüello and Johansson (2022) and Bennet *et al.* (2022) have recently called for discussions on security, ethical, and governance issues around sea ice thickening and other Arctic ice management techniques.
Amount of attention in scientific journals and public media and currently ongoing research programs	Medium	Sea ice thickening has been featured in popular media (See for example the prominent reports of Desch' 2017 plan by Mc Kie in The Guardian and by Bukszpan on CNBC). There has been limited academic coverage of this idea besides the studies already cited here, and the company *Real Ice* seems to be the only commercial research project devoted to it.

Sea ice Albedo Modification

Issue being addressed	Arctic sea ice extent has rapidly decreased over the last few decades, with most multi-year ice disappearing altogether. This has already had major effects on local communities and ecosystems. The disappearance of the relatively reflective sea ice also leads to a dramatic decrease of albedo in the Arctic and subsequent high energy uptakes by the darker water during the Arctic summers.	
Description of the technology/ measure	Apart from thickening sea ice by directly adding mass to it (see sea ice thickening), it has been suggested that the ice could also be protected by increasing its albedo and thereby reducing the amount of absorbed energy (Field *et al*. 2018). The non-profit organization Arctic Ice Project is currently studying the feasibility of increasing albedo by spreading hollow glass microspheres (HGM) on top of sea ice (https://www.arcticiceproject.org/the-project/).	
Technological readiness	Low	HGM are already used for different purposes, and these kinds of microspheres made out of silica are commercially produced and available (Field *et al*. 2018). The global demand of HGM is, however, rather limited and production would have to be significantly increased if substantial parts of Arctic sea ice were to be covered with them. Current research is looking at whether these HGM could effectively preserve Arctic sea ice without causing unwanted side effects. Through the non-profit organization Ice911, Leslie Field, who first suggested using HGM, started conducting several field trials in North America, mainly on freshwater ponds. Field, however, recently left the organization and is now exploring the possibility to use HGM on mountain glaciers (see glacial albedo enhancement). Ice911 has since been renamed Arctic Ice Project. The organization works together with private companies like Climformatics and Harvey Mudd College for their modeling and simulations, and are currently in a 'multi-year, multi-million dollar' collaboration with Norwegian organization SINTEF aimed at 'materials testing, safety, performance testing and methods for deployment' (https://www.arcticiceproject.org/the-project/). Arctic Ice Project's white paper (Zornetzer *et al*. 2021) estimates their HGM idea to be at Technology Readiness Level 3, stating 'that the main features have undergone successful proofs of concept, including successful initial demonstrations of the effectiveness, practicality, and safety of the approach.In a recent pre-peer review manuscript, Farkas *et al*. (2023) describe that their experiment found significant differences in properties between different kinds of

		HGM, and established that some materials leached into seawater overtime. Research is, therefore, still needed about HGM's environmental impacts, lifetime, and behaviour, especially under harsh weather conditions. It also remains to be seen how the organization responds to a damning verdict by Warren and Webster (2022) that claimed that HGM would be detrimental to overall Arctic sea ice albedo and whether this sets back its development.
Scalability	Medium	Field *et al*. (2018) wrote that current supplies of HGM are insufficient for a large-scale deployment, but that production could likely rapidly be enhanced if needed, thereby also driving down costs. The idea would be to distribute the material at strategic locations in the Arctic, like the Beaufort Gyre, where they would incur greatest effect. However, since it is unclear if the material will be effective outside an experimental setting, and would not be blown away as suggested by Warren and Webster (2022), uncertainties remain about possible scalability.
Timeliness for near-future effects	Medium	Publications related to the Arctic Ice Project are more optimistic about the potential timeliness of this scheme (see for example Zornetzer *et al*. 2021). However, even though HGM already exists, due to the many technical issues and large parts of the ice already gone, the potential window to implement such an intervention seems increasingly limited.
Potential to make a difference in Northern + Arctic	Unknown	A report by Arctic Ice Project states that their experiment showed that a treatment with HGM increased an area's average albedo from 0.17 to 0.36, and that the observed '30% reduction in radiative energy into the pond from surface modification with HGMs cause[d] a proportional 30% reduction in ice melt rate' (Johnson *et al*. 2022). Zornetzer *et al*. (2021) furthermore claim that modeling has shown 'that yearly application of the material on the Arctic sea ice over the period 2000–2040 would cause/ have caused ice volume to increase 0.5 percent to 1 percent per year, with increased ice thickness of 20 cm to 1 m15', and that this would lead to Arctic temperature decreases of up to 1.5°C. Warren and Webster (2022), however, strongly question these findings and argue that Arctic Ice Project's studies did not take ice and snow specificities and weather into consideration, and that this technology would in fact not slow, but rather increase the overall rate of melting. Although completely non-absorbing microspheres could perhaps increase ice albedo, the authors write in an AGU joint release (2022): 'this might still not solve the problem' because it would require 360 million tons per year to prevent melt and cool

		the climate, ‘and that’s assuming the non-absorbing microspheres could be manufactured and dispersed without contamination or other unintended effects.’ Apart from this production and distribution problem, the potential to form a functional layer of reflective particles is also questioned because winds would likely blow them away or clump the particles together, a phenomenon the authors say is already observed in the very small experimental ponds. Model studies suggest that even though HGM might lead to some ice preservation (Cvijanovic *et al*. 2015), the ice will probably completely disappear anyway if current warming trends continue (Zampieri and Goessling 2019). Moreover, Zhao *et al*. (2020) found that Marine Cloud Brightening (see Arctic Marine Cloud Brightening) could have a 40% greater forcing efficacy than surface albedo modifications like HGM application along with the extra benefit of also reducing shortwave heating of the lower atmosphere.
Potential to make a global difference	Unknown	If significant amounts of Arctic sea ice could be preserved, this could have a major effect on the global energy budget. However, in absolute terms, the global radiative forcing effects of HGM sea ice modification will likely remain limited (Cvijanovic *et al*. 2015).
Cost - Benefit	Low	The HGMs are intended to be applied at strategic locations where they would have maximum effect. The cost of such limited application would still remain high. Field *et al*. (2018) estimate that production costs for a treatment of 25,000 km2 with microspheres would be around $300,000,000 at current prices, with some 10 million UDS added for transportation. It should be noted that these costs would likely decline if production were to be scaled. Moreover, Hao *et al*. (2023) estimate that the melting of the sea ice would in any case costs the world an average of 6.7–13.3 trillion USD annually over the period 2020 to 2100, when the costs of the forcing effects of the ice are calculated in terms of equivalent costs of the forcing that is the result of GHG emissions.
Likelihood of environmental risks	Medium	The Arctic Ice Project claims their material is non-toxic (see for example Zornetzer *et al*. 2021). This is important, as Farkas *et al*. (2023) found that some HGM variants they tested in their experiment leached into seawater over time. Miller *et al*. (2020) still warn about the project’s potential effects on biochemistry because, like sea ice thickening, this measure would likely increase aerosol levels in the atmosphere leading to changes in air temperature due to cloud formation and could influence bioproductivity in the ocean by limiting light availability. The use of silicon-based spheres could

		moreover have a fertilization effect and thereby impact the blooming of algae.
Effects on local/ indigenous communities	Unknown	The Arctic Ice Project emphasizes that it wants to collaborate with indigenous groups. On their website they write they want to 'do no harm' to 'the environment, nor the tribes, communities, and animals that call the Arctic home in the attempts to restore ice' (www.arcticiceproject.org/the-project/). However, in early 2022 the organization faced criticism after indigenous-led protests at a fundraising event (see Elliott, 2023), which was followed by a letter of protest that called for a termination of all the companies intended activities in the Arctic (https://docs.google.com/document/d/1G5b-MSKyV5cI96lyBV140jhyfE-SaPTEt85aVZC5TjM/edit).
Ease of reversibility	Medium	The distribution of material could be halted at any point. Depending on the reason for reversing, the material would potentially have to be removed at some cost.
Risk of termination shock	Low	The ice would probably melt away quickly without continuous treatment.
Suitability within current legal/ governance structures	Medium	Although it is not clear how the deployment of HGM would be governed on the High Seas, the five Arctic coastal states would likely be able to distribute them within their Exclusive Economic Zone if they wanted to (Moore *et al*. 2020), albeit with likely many objections from various local interests. The project would face difficulties in terms of governance because distribution areas would be both on states' territorial and international waters, and would therefore be liable to both national and international legislation. Argüello and Johansson (2022), therefore, call for active research to see how Arctic ice management techniques might be governed.
Amount of attention in scientific journals and public media and currently ongoing research programs	High	This idea is often listed as one of the main Arctic geoengineering plans and has received a lot of attention in international public media and at fora like the Arctic Circle. Several scholars unrelated to the Arctic Ice Project have looked into this, although academic interest remains limited. It remains to be seen how the project will respond to the damning verdict by Warren and Webster (2022) which was picked up widely in the scholarly community.

Sea ice breakup in winter		
Issue being addressed	Sea ice can be an effective insulator between colder winter air and the warmer ocean below, thereby reducing the potential dissipation of heat into space.	
Description of the technology/ measure	There have been occasional undeveloped references to the idea to break up sea ice in winter with ice breakers to increase the amount of outgoing radiation (see for example: McCracken 2009; and groups.google.com/g/geoengineering/c/XMR75eB77c8/m/aJrf6Zp3okcJ). Apart from such isolated references, Hunt *et al*. (2020) provide some back-of-the-envelope calculations on the potential radiative effects of sea ice breakup, and suggest several methods by which to do this. Many of the authors' ideas about Arctic sea ice removal are reminiscent of earlier plans by Russian and Soviet scientists and engineers to melt the Arctic in order to "ameliorate" the northern climates. Hunt *et al*. (2020) even directly cite some of these earlier ideas to legitimize their plan. They ultimately consider the following options: (1) Pumping freshwater down to make it less likely for ice to form, (2) Reducing the melting of the Greenland ice sheet thereby limiting freshwater inflow, and (3) Deviating the rivers in the Northern Regions to reduce freshwater inflow into the Arctic.	
Technological readiness	Low	Apart from the highly questionable assumption that it would be beneficial to get rid of Arctic ice, and setting aside the question whether this would require enormous engineering projects in face of already rapidly declining ice levels, the plans suggested by Hunt *et al*. (2020) belong to the realm of speculative mega-engineering projects that are nowhere close to being operationalised.
Scalability	Low	
Timeliness for near-future effects	Low	Many of these engineering projects would take a very long time to develop and implement, if they are at all feasible.
Potential to make a difference in Northern + Arctic	High	Although there are no clear technological pathways to do so, and it is highly questionable if it would be desirable to remove Arctic sea ice, this measure would clearly have a huge impact on the Arctic. Apart from the removal of the ice itself, the increased release of heat from the Arctic ocean would likely warm surrounding air temperatures and have a significant warming effect on the Arctic.
Potential to make a global difference	Unknown	Hunt *et al*. (2020) do not attempt to provide any definitive calculations on this. Removing sea ice in winter could increase outgoing radiation, but it is unsure how much this would be. The

		resulting lack of sea ice in spring would undoubtedly lower the earth’s albedo and thereby increase ocean energy absorption.
Cost - Benefit	High	Hunt *et al*. (2020) admit that the costs for such projects would be prohibitively high.
Likelihood of environmental risks	High	Apart from side effects of the chosen method to remove the ice, the destruction of Arctic ice would severely endanger local ecosystems. The warming in the Arctic as a result of increased outgoing radiation would likely be equally disastrous for the region.
Effects on local/ indigenous communities	Negative	Hunt *et al*. (2020) seemingly uncritically copy the ideas of Soviet scientists about the amelioration of the North and assume that a warming Arctic would be desirable. But the destruction of Arctic ice and further warming of the region would be disastrous for already severely endangered local livelihoods.
Ease of reversibility	Hard	Many of the suggested means by which the ice would be removed would be near-permanent constructions, and there are many doubts if Arctic winter sea ice could regrow if removed (see for example the discussion of Arctic winter sea ice as a tipping point in Armstrong McKay 2022).
Risk of Termination shock	low	
Suitability within current legal/ governance structures	medium	Given the huge objections against it, it is highly unlikely that the removal of Arctic sea ice and the technologies required to do so could become part of international legal and governance structures. The sea ice within the Exclusive Economic Zone of individual countries may however be modified under domestic laws, e.g., by the river freshwater outflows.
Amount of attention in scientific journals and public media and currently ongoing research programs	low	Apart from Hunt *et al*. (2020), there have been several independent references to the breaking up of sea ice in winter. However, this remains a very niche idea that is not given much credible attention.

Pykrete usage		
Issue being addressed	Arctic sea ice extent has rapidly decreased over the last few decades, with most multi-year ice disappearing altogether. This has already had major effects on local communities and ecosystems. The disappearance of the relatively reflective sea ice also leads to a dramatic decrease of albedo in the Arctic and subsequent high energy uptakes by the darker water during the Arctic summers.	
Description of the technology/ measure	Pykrete is a 6:1 mix of ice and sawdust that has the property of melting slower than regular ice. Several references have been made online to the use of pykrete as an artificial barrier, as artificial sea ice, or as blockers of moulins.	
Technological readiness	Medium	Pykrete was designed in the twentieth century. During the Second World War, it was even suggested that an aircraft carrier could be built from it. However, there have been no serious studies into its feasibility for any of the suggested purposes.
Scalability	Medium	
Timeliness for near-future effects	Medium	
Potential to make a difference in Northern + Arctic	Low	
Potential to make a global difference	Low	
Cost - Benefit	Low	
Likelihood of environmental risks	Medium	Sawdust might cause unwanted marine bioproductivity.
Effects on local/ indigenous communities	Neutral	
Ease of reversibility	Medium	

Risk of Termination shock	Low	
Suitability within current legal/ governance structures	Medium	
Amount of attention in scientific journals and public media and currently ongoing research programs	Low	There have been isolated online references on the use of pykrete. It has, for example, been featured on the online blog by Joseph Cannon on his blog CANNONFIRE https://cannonfire.blogspot.com/2009/10/global-warming-cannon-saves-world.html. Cannon reports that a similar idea has also been mentioned in TED talks.

Sea Ice growth management

Issue being addressed	Arctic sea ice extent has rapidly decreased over the last few decades, with most multi-year ice disappearing altogether. This has already had major effects on local communities and ecosystems. The disappearance of the relatively reflective sea ice also leads to a dramatic decrease of albedo in the Arctic and subsequent high energy uptakes by the darker water during the Arctic summers.	
Description of the technology/ measure	In 2010 Veli Albert Kallio suggested the use of ‘floating cables or levees, even platforms’, to act as ‘seeding points to fasten the seasonal growth of the Arctic Ocean's sea ice.’ (https://groups.google.com/g/geoengineering/c/XMR75eB77c8/m/aJrf6Zp3okcJ) Even if multiyear ice disappeared, he claimed such schemes might be used to stimulate the growth of ice, which would then lead to thicker ice the next year which would reflect more sunlight for a longer time.	
Technological readiness	Low	This idea was probably not explored further.
Scalability	Low	
Timeliness for near-future effects	Low	

Potential to make a difference in Northern + Arctic	Low	
Potential to make a global difference	Low	
Cost - Benefit	Low	
Likelihood of environmental risks	Medium	
Effects on local/ indigenous communities	Unknown	
Ease of reversibility	Easy	
Risk of Termination shock	Low	
Suitability within current legal/ governance structures	Medium	
Amount of attention in scientific journals and public media and currently ongoing research programs	Low	The idea seems not to have been picked up after having been suggested.

Ice shields and “Volcanoes”

Issue being addressed	Arctic sea ice extent has rapidly decreased over the last few decades, with most multi-year ice disappearing altogether. This has already had major effects on local communities and ecosystems. The disappearance of the relatively reflective sea ice also leads to a dramatic decrease of albedo in the Arctic and subsequent high energy uptakes by the darker water during the Arctic summers.

Description of the technology/ measure	Similar to other ideas to pump water on sea ice (see Sea Ice Thickening), engineer Sev Clarke and engineering student Katy Cartlidge both came up with designs to artificially produce sea ice. In both schemes, water is pumped up through a central pipe and allowed to freeze onto previously-grown ice. This ongoing process then slowly forms a thicker mass of ice that would hopefully be able to survive over longer periods. Many of these “icebergs”, which Clarke calls Ice Shields and Cartlidge dubbed ice volcanoes, could together form larger surface areas that could have multiple benefits for ecosystems and the climate.	
Technological readiness	Low	Both ideas have been suggested by their authors but have not been explored further.
Scalability	Low	
Timeliness for near-future effects	Low	
Potential to make a difference in Northern + Arctic	Low	
Potential to make a global difference	Low	
Cost - Benefit	Medium	Hao *et al*. (2023) estimate that the melting of sea ice would cost the world an average of 6.7–13.3 trillion USD annually over the period 2020 to 2100, when the costs of the forcing effects of the ice are calculated in terms of equivalent costs of the forcing that is the result of GHG emissions.
Likelihood of environmental risks	Medium	
Effects on local/ indigenous communities	Unknown	
Ease of reversibility	Medium	
Risk of termination shock	Medium	
Suitability within current legal/	Medium	

governance structures		
Amount of attention in scientific journals and public media and currently ongoing research programs	Low	Both ideas are isolates and have not yet been subject to further study.

Snowfall enhancement

Issue being addressed	With the exception of some regions like Antarctica, global snowfall amount and frequency have decreased, and the timespan during which snow cover remains has shortened (Zender 2012). This has multiple effects on human and natural systems as it influences widely diverging processes such as reducing surface albedo and changes in the hydrological cycle.	
Description of the technology/ measure	There have been sparse references to the use of cloud seeding over Arctic and Northern areas as a means of countering some of the effects of climate change (see for example https://groups.google.com/g/geoengineering/c/dm7DqAanhhA/m/JsjYMQKA4CQJ). Some have suggested using it specifically over glaciers (see Stabilizing Glaciers by Cloud Seeding). Yet, most studies focus on cloud seeding as a means to ensure water security. Precipitation enhancement and weather modification has a long history, with the first modern field trials with the “seeding” of clouds by airplanes starting after WW2. The idea behind “glaciogenic” cloud seeding is that introducing silver iodide (AgI) particles into supercooled clouds will encourage nucleation and growth of particle size, thereby allowing more water to leave the cloud in the form of precipitation.	
Technological readiness	High	The history of research into weather modification is quite expansive, and saw significant expansion in the second half of the twentieth century (Fleming 2010). The technology already exists and is being used commercially around the world, especially to encourage rainfall. However, the main and longstanding issue with snow enhancement experiments is that it is extremely difficult to show whether specific cloud seeding missions resulted in a significant increase in snowfall, or if this was already expected to fall without any active seeding action (Geerts *et al*. 2010; Geerts and Rauber 2022). In cloud seeding circles, belief in the potential of the technology has always been strong (see for example Huggins 2009 or most other articles in the main weather modification

		journal *The Journal of Weather Modification*), and promises that definite proofs would be delivered within years have been often repeated since the 1970s (Fleming 2010). More recently there has again been much excitement in the cloud seeding community as a combination of several measurement advances may finally be able to definitively prove the effect of seeding (Friedrich *et al*. 2020). There have been several major studies in the US, such as the Seeded and Natural Orographic Wintertime Clouds – the Idaho Experiment (SNOWIE), but the most expansive study with glaciogenic seeding was The Wyoming Weather Modification Pilot Program which ran from 2005 to 2014. The project initially reported major precipitation increases, although a statistical evaluation study four years later found that the project was not statistically significant as it had failed 'to reject the null hypothesis that there is no seeding effect' (Rasmussen *et al*. 2018).
Scalability	Low	Cloud seeding can only be done if the right clouds are present, and even if seeded, there is only a limited amount of potential extra precipitation to be gained from specific clouds. This limitation is exacerbated by the requirement for extensive seeding infrastructure which would need enormous investments in the sparsely populated and isolated Northern and Arctic regions. This would make it difficult to scale up such a measure without enormous investments.
Timeliness for near-future effects	Low	The technology for glaciogenic cloud seeding already exists, but it is not sure if it would be able to make a significant climate impact, even if it would be sufficiently scaled up.
Potential to make a difference in Northern + Arctic	Low	Cloud seeding could have major effects on water availability, yet its specific climate effects are very much understudied. Given the difficulties around scalability, it seems unlikely that snowfall over the entire regions could be enhanced significantly, although local applications on specific glaciers could be more feasible (see Stabilizing Glaciers by Cloud Seeding).
Potential to make a global difference	Low	The seeding would likely have a primarily local effect.
Cost - Benefit	High	Cloud seeding is likely relatively expensive to do at scale, with the project in Wyoming reporting low estimates of ‘$27 to $214 per acre-foot and higher costs ranging from ‘$53 to $427 per acre-foot.' So although it might be financially feasible for areas with particularly high water prices, or in specific glacial regions, large-scale seeding across large areas is likely to be prohibitively expensive.

Likelihood of environmental risks	Low	The seeding material, AgI, has been used in experiments for a long time and has not been subject to much criticism. A main environmental effect of extensive seeding is related to changes in the hydrological cycle, as increases in precipitation over one area will likely lead to reductions over another.
Effects on local/ indigenous communities	Neutral	
Ease of reversibility	Easy	The effects of this measure cease after each application.
Risk of termination shock	Low	Because the snow would melt overtime, seeding would need to be actively continued.
Suitability within current legal/ governance structures	High	Cloud seeding is already practiced by companies and states around the world. The main provision is that it cannot be used for military purposes following the 1977 Environmental Modification Convention. Some commentators warn cloud seeding could lead to major geopolitical tension around water redistribution in the future (Chen *et al*. 2017; Shevchenko and Horiacheva 2017; de Guglielmo 2021).
Amount of attention in scientific journals and public media and currently ongoing research programs	Medium	Weather modification has been a relatively niche topic over the last several decades as successes failed to materialize. However, it is gaining increased global attention due to the increasing amounts of droughts. Interest seems to be especially great in China, Australia, the US, and countries in the Arabian peninsula.

Arctic winter High latitude seasonal stratospheric aerosol injection

Issue being addressed	GHG emissions reductions and future negative emissions are the only sustainable solutions to stabilize or even reverse global warming as they counter the cause of the problem. However, the required actions will likely take time to materialize, and inertia in the climate system and locked-in warming already ensures major changes in global temperatures and the nearing of several tipping points. Solar radiation management (SRM) techniques seek to reduce global temperatures by reflecting incoming solar

	radiation. They would thereby not fix the underlying issue of the warming effects of GHGs but are, according to the United Nations Environment Programme (UNEP) Review on Solar Radiation Modification Research (2023), ‘the only known approach that could be used to cool the Earth within a few years’.	
Description of the technology/ measure	Stratospheric aerosol injection (SAI) is an idea to inject particles in the stratosphere to reduce the amount of incoming solar energy (Rasch *et al*. 2008; Irvine *et al*. 2016). The principle behind SAI is well understood as it is analogous to some naturally occurring volcanic eruptions which have been consistently observed to cool global temperatures over year-timescales if they deposit material high enough into the atmosphere (Robock *et al*. 2013; IPCC Ar6 Wg1, chapter 4). Although multiple aerosol types have been suggested for SAI, the most studied idea would burn or inject sulfur into the stratosphere where it would form SO2 which would then oxidize into sulphuric acid and form a relatively stable layer. Due to the high seasonality in the higher latitude regions, specific strategies look at injection rates that see greatest injections in spring and summer, and no injections before and during winter (Lee *et al*. 2021).	
Technological readiness	Low	At the moment, SAI studies are mostly limited to model simulations. There have recently been several controversial small-scale initiatives that have prompted major debate within the community (See the coverage of the launches of Make Sunsets in the US and Mexico and the SATAN project launch in the UK), but so far no major or substantial outdoor tests have been conducted (Low *et al*. 2022). Model studies allow scholars to get an increasingly accurate understanding of the effect of SAI on the climate system and a formulation of potential injection scenarios. These models have become more sophisticated, and are also jointly investigated in the Geoengineering Model Intercomparison Project (GeoMIP) and the Geoengineering Large Ensemble Simulations (GLENS). However, many topics like aerosol behaviour and aerosol–cloud–radiation interaction are still poorly understood (IPCC AR6 Wg3, chapter 14) and would be hard to study without outdoor experiments. There have been several suggestions with regards to injection devices, with specific aircraft generally considered as most probable for altitudes up to 20 km (Smith and Wagner 2018). Although higher injections would be more effective according to model studies, Smith *et al*. (2022) warn 'raising the deployment altitude from 20 to 25 km entails a step change in both costs and safety hazards'. Deployment seems far off, and although Smith *et al*. (2022) call a high latitude injection program 'logistically feasible', they envision such a program to be a 'decadal time-scale project'. Opinions on if and how to pursue further research vary widely, with a call for a

		moratorium on further research being broadly signed in 2022 (https://www.solargeoeng.org/), whilst on the other side calls intensify for further research, most notably in a recent UNEP (2023) report and in an open letter signed by, amongst others, James Hansen (https://climate-intervention-research-letter.org/). Such research projects could either be national or international, with a report by the US National Academies of Sciences, Engineering, and Medicine for example suggesting that 'the U.S. should pursue a research program for solar geoengineering — in coordination with other nations' (NASEM, 2021). There seems to be an increasing attention to the inclusion of different actors in a previously global North dominated field, as exemplified by the Degrees Initiative (https://www.degrees.ngo/) that seeks to encourage the evaluation of SAI in “developing countries”.
Scalability	Medium	The scalability of SAI is limited in one sense as the effectiveness of injections decreases with increased injection rates (Kleinschmitt *et al*. 2018). These effects are, however, most pronounced at high injection rates that would be required for the complete mitigation of high forcing scenarios. The distribution of aerosols in the stratosphere at low latitudes would ensure a near-global coverage and a global reduction of surface temperatures. If aerosols were to be specifically injected at higher latitudes, they would have more focussed effects over those parts, as stratospheric dynamics move the particles polewards. Although estimates vary, it is estimated that a relatively manageable fleet of hundreds of aircraft would be needed to achieve significant surface cooling (Smith and Wagner 2018).
Timeliness for near-future effects	High	Although there are currently no feasible injection measures for SAI, the development a new kind of aircraft to release aerosols in the stratosphere is likely to be a relatively straightforward task (Smith and Wagner, 2018), and Smith et al (2022) consider a high latitude injection program to be a 'decadal time-scale project'. A lot would depend on the proposed SAI injection strategy and goal. UNEP (2023) distinguishes broadly between two framings of SRM deployment, either as an emergency measure, or as a durable part of global climate action strategies to reduce the worst of the warming effects and provide more time for emissions reductions and negative emission technologies to be employed.
Potential to make a difference in Northern + Arctic	High	Model studies have consistently shown that SAI could cool surface temperatures and slow or reverse the thawing of the cryosphere in the Northern and Arctic (Robock *et al*. 2008; Berdahl *et al*. 2014; Chen *et al*. 2020; Lee *et al*. 2023; Chen *et al*. 2023). This cooling

		could furthermore have multiple other benefits for the region. For example, Tang *et al*. (2023) for it would reduce wildfires (see Wildfire Management) and Irvine *et al*. (2019) conclude that SAI could generally significantly decrease climate hazards. Irvine *et al*. (2018), however, note that effects of SAI are different from simply reversing GHG forcing. It is, for instance, not certain if and how injections may counter sea level rise and marine ice shelf instability, as Moore *et al*. (2010) showed that only very high injection scenarios would be able to delay sea level rise significantly. Yue *et al*. (2021) equally found that the Icelandic Vatnajökull ice cap's melt can be reduced somewhat by SAI, although it remains relatively insensitive to solar geoengineering. Concerning the wider cryosphere, Zhao *et al*. (2017) find SRM could also slow melt in other areas like in the “Third Pole” region.
Potential to make a global difference	High	Multiple model studies and historical analogues of volcanic eruptions show SAI could swiftly reduce global temperatures when initiated (IPCC AR6 WG3, chapter 14). The amount of cooling would be dependent on injection strategies and on the total amount of sulfur injected, with larger injection amounts achieving a progressively lower efficacy (Kleinschmitt *et al*. 2018). The IPCC AR6 WG1 (2021) report, therefore, attains they have high confidence that SRM technologies like SAI could offset some of the effects of GHG forcing, and gives maximum forcing potentials ranging from –5 to –2 W m–2 (Chapter 6) and a global mean radiative forcing potential of 1–8 W m–2 (Chapter 4).
Cost - Benefit	Low	In comparison to the effects of global warming, the costs of SAI are extremely low, with Smith and Wagner (2018) providing a rough estimate of $2.25 billion yr−1. Smith (2020), therefore, writes that 'SAI continues to appear remarkably inexpensive, even if we extend our gaze out to the end of this century'. Economist Gernot Wagner even considers this as a reversal of the free rider logic, as SAI is so cheap that it creates a “free driver” problem (2021).
Likelihood of environmental risks	Medium	Some of the major objections against SAI relate to this measure’s possible environmental and ecological effects. The expected ones are still relatively under-researched (Zarnetske *et al*. 2020) and there may be several unknown risks related to global deployment. A first expected consequence of SAI would be an effect on rainfall patterns and a weakening of monsoons (Bala *et al*. 2008; Krishnamohan and Bala 2020; Riky 2023). Such disturbance would be especially strong in the case of uneven global cooling and could be lessened by specific injection strategies (IPCC, AR6 WG1, 2021 Ch. 4). Nalam *et al*. (2018), for instance, found that SAI

		geoengineering in the Arctic alone would significantly alter precipitation patterns around the globe but that this could be largely balanced out by a mirrored cooling of the Antarctic. Although there have been fears of acid rain due to the use of sulfur, the earliest estimates on SAI by Budyko (1974) indicated that the total amounts of sulfur used are negligible in comparison to other anthropogenic emissions, while a recent study indicated that even in the most ambitious emission pathways, global sulfur depositions would not vary much from present levels (Visioni 2020). The use of sulfur as aerosol could also impact stratospheric ozone levels (Tilmet *et al*. 2008). The IPCC AR6 WG1 report (chapter 4) says it is “likely” SAI would delay the recovery of the Antarctic ozone hole and model studies find that this effect could be particularly pronounced in the first decade, and delay recovery by several more (Tilmes *et al*. 2021; Times *et al*. 2022). Sustained deployment could have significant impact on the lower and middle stratosphere, and UNEP (2023) writes this could have 'unknown consequences for the environment on and near Earth’s surface.' Since SAI would reduce the amount of available energy for photosynthesis on the Earth’s surface and in the oceans, the IPCC 2021 AR6 WG1 report states it has medium confidence that SAI would ‘cause a reduction in plant and soil respiration and slow the reduction of ocean carbon uptake due to warming.’
Effects on local/ indigenous communities	Unknown	There is a lack of research on the potential effects of SAI on local communities. Of the many understudied topics, the potential impact of SAI on human health has started to be explored (Tracy *et al*. 2022), with Carlson *et al*. (2022), for example, finding it could have a significant impact on malaria distributions. More research has been done on perceptions of geoengineering, with some studies on the relation of indigenous peoples to geoengineering (Whyte 2012; Whyte (2018), and on the perception of geoengineering by Northern communities (Buck 2018; Mettiäinen 2022). Certain events also reveal that there is significant skepticism against SAI amongst some communities. This showed especially clearly in the 2021 protest against the Harvard SCoPEx group in North Sweden by Sami and environmental activists. In addition, statements like Smith *et al*.’s (2022) that ‘an SAI program with global benefits that would entail deployment directly overhead of far less than 1% of the world's population and nearly none of its agriculture may prove an easier sell to a skeptical world than a full-on global deployment’, further highlight the need for more research

		into the opinions and possible effects of potential SAI deployment in the Arctic and Northern regions.
Ease of reversibility	Easy	The lifetime of sulfur particles in the stratosphere is generally considered to be around two years (UNEP 2023). So although the particles would in time naturally disappear, the cooling effect would not disappear instantly. This could be a major concern if the effects are found to be undesirable.
Risk of termination shock	High	A major issue with SAI is the potential of a termination shock when the technology is abruptly halted for whatever reason (Jones *et al*. 2013; IPCC AR6, WG1, chapter 4; UNEP 2023). The C2G2 risk analysis report on SRM (2022) states clearly that 'A sudden and sustained termination of large amount of SAI or MCB under a high GHG emission background would cause a rapid increase in temperature and precipitation at a rate that far exceeds that predicted for future climate change without SRM.' For the Arctic specifically, Berdahl *et al*. (2014) show that in a RCP4.5 scenario, a sudden termination would negate all geoengineered benefits in terms of retained snow and ice within a decade.
Suitability within current legal/ governance structures	Low	A main objection that many opponents of SAI have is that it would be ungovernable as countries and actors would dispute over target temperatures and struggle to find common ground with regards to compensation of negative effects of SAI (Biermann *et al*. 2022). Others, including NASEM (2021) and UNEP (2023), instead argue for further research into the governance of geoengineering and geoengineering research. There are already several governance proposals (Reynolds 2019) and further research is being conducted, perhaps most prominently by the Carnegie Climate Geoengineering Governance Initiative (C2G2 (https://www.c2g2.net/). UNEP (2023), however, urges increasing emphasis on the need to include previously excluded voices, especially in the global South and that decision be made ‘in a globally inclusive, equitable and transparent manner’.
Amount of attention in scientific journals and public media and currently ongoing research programs	High	SAI is the most researched and written about climate intervention/ geoengineering measure. Apart from several rogue field trials, there are increasing numbers of scholars around the world doing modeling work on SAI and studying the governance issues around research and deployment.

Cirrus cloud thinning		
Issue being addressed	Cirrus clouds are high altitude ice clouds. They influence the Earth’s radiation budget as they reflect both incoming and outgoing radiation. However, they ultimately have a warming effect as they are more efficient at trapping outgoing longwave radiation (Kärcher 2017).	
Description of the technology/ measure	Some have suggested artificially thinning cirrus clouds so more long wave radiation can escape into space. Cirrus Cloud Thinning (CCT) could be done by seeding the clouds, which would increase nucleation rates, thereby reducing their lifetime and optical thickness (Storelvmo *et al*. 2013). This technique would only work on ice clouds. Several different seeding materials have been proposed, ranging from environmentally benign sea salt to the toxic but more effective bismuth triiodide (Lawrence *et al*.2018). CCT would be most effective at high latitudes during winter when such clouds do not reflect incoming radiation and only trap outgoing radiation (Gruber *et al*. 2019). Cirrus clouds in the coldest locations are also likely to be the most effectively thinned as they are composed of smaller crystals with larger radiative effects than larger crystals. This makes potential deployment far more effective in mountain and polar regions.	
Technological readiness	Low	There is a lack of research on CCT, and to date no outdoor experiments have been conducted. This means that there are many open questions around CCT. Individual groups of scholars working on CCT are mainly conducting modeling studies. Tully *et al*. (2022), however, recently recommended that the high uncertainties around CCT require ‘more observational evidence … on cirrus formation mechanisms and the impact that natural as well as anthropogenic aerosol have on cirrus properties before further modeling studies proceed.' Research is still continuing, with Smith *et al*. (2023) announcing preliminary results from their modeling of CCT at a conference in early 2023. It is not clear how clouds would be seeded. It has been suggested that already existing commercial jets could have their fuel modified (Mitchell and Finnegan 2009), or that fleets of drones could possibly be used (Mitchell *et al*. 2011).
Scalability	Unknown	CCT would only work on some kinds of cirrus clouds, and it is unsure if it would be feasible on a global scale (Tully *et al*. 2022). Polar and mountainous regions are probably most suitable for potential CCT deployment since clouds in the coldest locations are likely to be the most effectively thinned as they are composed of smaller ice crystals.

Timeliness for near-future effects	Unknown	If deployed, the effects of CCT would be immediate. However, with lack of scientific certainty and distribution technologies it is unsure if this measure would be timely.
Potential to make a difference in Northern + Arctic	High	CCT during winter at high latitudes is generally believed to be able to cause a significant cooling effect (Gruber *et al*. 2019). However, a recent study by Tully *et al*. (2022) using a more sophisticated model contradicts claims from earlier studies by Storelvmo and Herger (2014) and Storelvmo *et al*. (2014) and disputes that winter high-latitude strategies will significantly increase seeding efficacy.
Potential to make a global difference	Unknown	Some studies (Muri *et al*. 2014; Lohmann & Gasparini 2017; Lawrence *et al*. 2018; Gasparini *et al*. 2020) found that CCT could have a significant cooling effect. Muri *et al*. (2014), for instance, state that global CCT could have a −1.55 W m−2 forcing effect and change global mean temperatures by −0.94 K. Lawrence *et al*. (2018) estimate a potential 2 to 3.5 W/m2 forcing effect. However, there are many uncertainties around these numbers (Lohmann and Gasparini 2017). The underdeveloped state of research on CCT is highlighted in the IPCC AR6 WG1 report where they state that they have ‘low confidence in the cooling effect of CCT’ (2021 chapter 4). They write that even though all current cirrus clouds have a net positive radiative forcing effect of around 5 W m–2, maximum CCT cooling potential would only be about 1 to 2 W m–2, and that some model studies found CCT was entirely ineffective and could even have an opposite effect if “over-seeded”. One such adverse effect is described by Liu and Shi (2021) who found that the seeding of cirrus clouds can also influence other clouds, thereby eventually having a warming effect. The complexities around cloud physics would also require further research into many potential side effects and interactions with other suggested measures. Kuebbeler *et al*. (2012), for example, found that stratospheric aerosol injection (SAI) could have an effect on cirrus clouds.
Cost - Benefit	Low	Cirrus clouds are relatively easy to access which could indicate low distribution costs. However, rapid rainout probably means that seeding would need to be continuously maintained.
Likelihood of environmental risks	Unknown	There have been very few studies on the potential environmental effects of CCT. An important issue would be the material used to thin the clouds, as the use of toxic substances would obviously have greater environmental impact. The IPCC AR6 WG1 report also mentions a possible impact due to an increased amount of radiation reaching the Earth’s surface (2021, chapter 4). There have been some studies on the potential effect of CCT on the

		hydrological cycle. Kristjánsson *et al*. (2015) and Muri *et al*. (2018) found CCT would enhance this cycle and lead to increased global precipitation, although regional variation would have to be further studied.
Effects on local/ indigenous communities	Unknown	A cooling of Northern and Arctic winters could have both positive and negative environmental and socio-cultural benefits for local populations.
Ease of reversibility	Easy	Clouds would likely need to be continuously seeded to achieve effect.
Risk of termination shock	High	This would probably be similar to the risk described for Stratospheric Aerosol Injection, as a sudden cessation could lead to rapid temperature increases.
Suitability within current legal/ governance structures	Medium	Cloud seeding is already frequently done to enhance precipitation (see Cloud seeding). Such seeding falls under national or local legislative and governance structures, and CCT could potentially be considered similarly. However difficulties emerge with regards to deployment over the High Seas.
Amount of attention in scientific journals and public media and currently ongoing research programs	Medium	Despite some positive estimates around the potential of CCT and its listing alongside other solar radiation management (SRM) climate interventions in major climate reports (see for example the IPCC AR6 reports of WG1 & WG3), public and academic interest remains minimal. The IPCC AR6 reports clearly state that the lack of research activity on the potential of CCT is a major source of uncertainty (WG1 chapter 6 & WG3 chapter 14).

Mixed phase regime cloud thinning over the polar oceans during winter

Issue being addressed	Clouds play an important role in the Earth's energy system. The effects of clouds are complex and diverse, often having simultaneous cooling and warming effects. Mixed-phase clouds (MPC) are clouds that contain water vapor, ice particles, and supercooled water droplets. MPCs are still poorly understood and 'notoriously difficult to represent in numerical weather prediction and climate models' (Korolev *et al*. 2017).
Description of the technology/ measure	Villanueva *et al*. (2022) suggest that mixed-phase cloud thinning (MCT) could be a potential alternative cloud seeding measure alongside marine cloud brightening (MCB) and cirrus cloud thinning (CCT). The idea of MCT would be to thin MPCs during winter by seeding them. The effect of this thinning would likely be to reduce the capacity of clouds to trap heat and to reflect solar radiation (Villanueva *et al*. 2022).

Technological readiness	Low	This measure has only been suggested recently and has apparently not been explored since. As described elsewhere in this report, cloud seeding is already being done around the world. This might mean MCT could rely on already developed technologies.
Scalability	Unknown	
Timeliness for near-future effects	Unknown	
Potential to make a difference in Northern + Arctic	Unknown	Villanueva *et al*. (2022) found a significant net positive cooling effect for their Arctic model scenario, with temperature decreases of roughly 0.5 to 0.1 degree C over the Arctic Ocean, and an increase in winter sea ice extent. In contrast to CCT, they also did not find the risk of adverse effects due to overseeding.
Potential to make a global difference	Unknown	
Cost - Benefit	Unknown	
Likelihood of environmental risks	Unknown	Villanueva *et al*. (2022) found a slight reduction in global precipitation rates in their model study.
Effects on local/ indigenous communities	Unknown	
Ease of reversibility	Unknown	Villanueva *et al*. (2022) state that MCT seeding aerosols have shorter lifetimes than in SAI, allowing for a more rapid reversal.
Risk of termination shock	Unknown	
Suitability within current legal/ governance structures	Medium	Cloud seeding is already frequently done to enhance precipitation (see Cloud seeding). Such seeding falls under national or local legislative and governance structures, and MCT could potentially be considered similarly. However, difficulties emerge with regards to deployment over the High Seas.
Amount of attention in scientific journals and public media and currently	Low	This measure has only been suggested recently, and not received any substantial investigation..

ongoing research programs		

Arctic Marine Cloud Brightening

Issue being addressed	Roughly one-third of the incoming solar radiation is directly reflected back into space by the Earth’s atmosphere and surface albedo. Clouds play an important role in this, although their role is double as water droplets can also interfere with outgoing longwave radiation, thereby contributing to the greenhouse effect. Over open water clouds can make a particularly big difference as the albedo of the water is below 0.1, thereby absorbing most of the sun’s energy.	
Description of the technology/ measure	Arctic Marine Cloud Brightening (MCB) seeks to enhance the albedo of the Northern oceans during summer months by increasing the amount, lifetime, and reflectivity of clouds over them. MCB makes use of the Twomey effect (Twomey 1977) which stipulates that more and smaller water droplets will reflect more incoming solar radiation than fewer larger droplets (Latham *et al*. 2012). Since clouds form when water droplets accumulate around small airborne particles, the idea is to inject very small particles into stratocumulus clouds. Apart from increasing the albedo of the cloud, they might also lengthen the lifespan of clouds. The aerosols used for MCB are generally conceived to be salt particles that remain from seawater that is sprayed up into the air. Although increased cloud coverage would also reduce the amount of energy radiated out into space in summer, the reduction in incoming radiation is said to lead to a net cooling effect (Latham *et al*. 2014). In winter, MCB would be halted as there would be no energy to reflect.	
Technological readiness	Low	That aerosols contribute to cloud formation has long since been observed in the formation of ship tracks of normal ocean vessels (Hobbs *et al*. 2000), and studies on such “inadvertent” MCB provide valuable analogues for MCB (Patel and Shand 2022). Latham already proposed the idea to use specially designed boats for this in 1990. This idea has since developed in several research programs, including lab experiments (Cooper *et al*. 2014). In 2014, Neukermans *et al*. designed a spray device that would use the salt from seawater. As an alternative distribution method, Claudel *et al*. (2023) recently suggested using UAVs to seed clouds. Research is currently being done in Australia where scientists seek to explore the possibility of using MCB to reduce coral bleaching (Latham *et al*. 2013) and cool the waters around the Great barrier Reef (Tollefson 2021, see for a research project https://gbrrestoration.org/program/cooling-by-cloud-brightening/). A

		novel research project by the Cambridge Centre for Climate Repair and Delft University will specifically also look at the relevance of MCB for attempts to refreeze the Arctic (https://www.cam.ac.uk/news/refreeze-the-arctic-foundation-funds-marine-cloud-brightening-research). The advocacy group Silver Lining's Near-term Climate Risk and Intervention (2023) report suggested 4 to 5 year research programs working on modeling, technical, and outdoor experiments could significantly advance MCB, although the reality of such a timeline is questionable. The IPCC AR6 WG1 notes that many uncertainties remain around MCB, especially since climate models do not represent the relevant cloud processes well (2021, chapter 4). Hoffmann and Feingold (2021) for example found that small differences in particle seeding size could have significant impacts on the effect of MCB.
Scalability	Medium	Arctic MCB advocates envision large, unmanned fleets of vessels operating throughout the season, but until now these ships only exist on the drawing board, and it is unsure if the measure would be scalable (National Research Council 2015). Wood (2021) estimates that 10,000 to 100,000 vessels would need to operate 'over the majority of the 54 % of the Earth's surface that is over ocean and remote from land' to compensate for the forcing caused by a doubling of atmospheric CO2. Moreover, the IPCC AR6 WG1 report cautions that MCB requires the presence of a specific type of cloud' (2021: Ch. 4). It might be that MCB could also be effective in areas regardless of clouds due to the radiative effect of the aerosols themselves (Ahlm *et al*. 2017). Mahfouz *et al*. (2023) coupled model study recently highlighted the need to better understand these interactions between aerosols and solar radiation to determine the effectiveness of MCB. Manshausen *et al*. (2022) note that invisible ship tracks create significant radiative forcing that could be interpreted as suggesting that MCB could have both stronger and earlier detectable impacts on climate than previously expected.
Timeliness for near-future effects	High	The previously mentioned Silver Lining Report (2023) is very optimistic about the potential of MCB, however, with a lack of modeling results and still non-existent means of distribution at scale, this might be wishful thinking.
Potential to make a difference in Northern + Arctic	High	Many studies show that MCB could cause significant cooling over the Arctic. The Parkes *et al*. (2012) model study shows that Polar MCB would allow significantly more sea ice to remain in a CO2x2 world. Latham *et al*. (2012) equally find MCB 'significantly reduces

		sea-ice fraction loss during the summer months'. Latham *et al*. (2014) furthermore find that MCB might help stabilize the West Antarctic ice sheet, and might be a tangible way to cool surrounding permafrost areas and limit methane release from its thaw (see Methane measures). The Kim *et al*. (2020) model study found MCB could produce significant cooling over East Asia and could restore sea ice in the Sea of Okhotsk. Mahfouz *et al*. (2023) equally show that MCB could be effective at cooling Arctic temperatures.In comparison to other measures. Zhao *et al*. (2020) posit that MCB has several climate benefits over surface albedo modification (see Marine surface albedo modification).
Potential to make a global difference	High	Multiple model studies have shown that MCB could cool the oceans and lead to regional cooling, but it is unsure how effective it could be in lowering global temperatures (National Research Council 2015). From their large model ensemble study, Stjern *et al*. (2018) found that MCB would lower temperatures by −0.96K relative to RCP4.5. The Lawrence *et al*. (2018) review found large differences in potential cooling of MCB that ranged from 0.8 to 5.4 W/m2. The IPCC AR6 WG1 report gives 1–5 W m–2 as global mean radiative forcing potential (chapter 4), but expresses low to medium confidence in the reported forcing numbers due to a lack of understanding of the relevant warming processes (chapter 6). Hirasawa *et al*. (2023) suggest that an AI model like the one they used could optimize MCB forcing patterns.
Cost - Benefit	Low	The costs of operationalisation of MCB at scale are still largely unknown but will likely be low in comparison to the projected benefits and costs associated with inaction. The National Research Council estimated logistical costs of around 5 million dollars per week to produce 0.01W/m2 (NASEM 2015). In an interview with the Guardian, David Kind gives a rough estimate that an effective Arctic MCB fleet of 500 to 1000 vessels would cost up to £40bn, with subsequent annual continuation costs of around £10bn (Anthony 2022).
Likelihood of environmental risks	Medium	Like other solar radiation management (SRM) measures, MCB could impact precipitation patterns and the hydrological cycle (IPCC 2021, chapter 4). In their large model ensemble study, Stjern *et al*. (2018) found from MCB would reduce global precipitation by −2.35%, and Bala *et al*. (2012) found equally important effects, although these would be less impactful than those of land-based albedo changes.

		The National Research Council report states that MCB might reduce light availability and thereby affect weather patterns and local ecosystems through reduced photosynthesis (NASEM 2015), and impact ocean circulation and carbon sequestration (Partanen Bala *et al*. 2016; Lauvset Bala *et al*. 2017). Horowitz Bala *et al*. (2020) found that sea salt aerosol distribution by MCB would decrease tropospheric ozone and extend methane lifetime, and although the resulting radiative forcing is minimal, it could influence air quality. The inherent patchiness of MCB (i.e., it is not conducted over land) means that there will be large gradients in radiative forcing. In simulations of global ocean brightening, these radiative changes induce large impacts on downstream precipitation and clouds (Kravitz *et al*. 2018). Few or no global analyses of teleconnection impacts from localized MCB have been done (Ricke *et al*. 2021). MCB could have certain beneficial effects. Although claims from proponents like Kevin Lister and Sev Clarke of the technology firm Winwick Business Solutions are probably too optimistic when they hint at the possibility of MCB to 'influencing where, when, and how much precipitation occurs downwind'. Parkes *et al*. (2015) found MCB and other geoengineering methods could reduce crop failure rates, and Latham *et al*. (2012b) showed it could weaken hurricanes. Moreover, Hirasawa *et al*. (2023) suggest AI models could potentially be used to reduce negative side effects of MCB.
Effects on local/ indigenous communities	Unknown	Diamond *et al*. (2022) recommend 'collaboration between physical scientists, ecologists, social scientists, and ethicists' to explore potential risks to local communities. It could for example be that reduced bioproductivity (see above, Environmental risks) might lead to local fish stocks decline, thereby detrimentally affecting local and indigenous communities and the international fishing industry.
Ease of reversibility	Easy	The effect of MCB would only last a couple of days and would, therefore, be relatively straightforward to reverse.
Risk of termination shock	High	The C2G2 risk analysis report on SRM (2022) states clearly that 'A sudden and sustained termination of large amount of SAI [stratospheric aerosol injection] or MCB under a high GHG emission background would cause a rapid increase in temperature and precipitation at a rate that far exceeds that predicted for future climate change without SRM.' Parker and Irvine (2018) point out that the short time before MCB’s effect wear off would not leave much time to restore the measure in comparison to SAI, whose stratospheric aerosols have a far longer lifetime.

Suitability within current legal/ governance structures	Medium	Cloud seeding under domestic regulation is already practiced widely, and as the MCB experiments in Australia show, it can be done without international consultation.The Carnegie Climate Governance Initiative brief on SRM (2020) states that 'there are no measures, other than soft power, that would stop either researchers or states from taking forward field trials or climate-scale deployments'. They therefore suggest 'early discussions about how these technologies might be governed' and that policy makers do not know enough about the technology to make adequate decisions.
Amount of attention in scientific journals and public media and currently ongoing research programs	High	MCB is probably the second-most discussed SRM technique after SAI. Recently it has attracted more attention, and several research projects are already ongoing, or will start shortly.

Space-based solar radiation management

Issue being addressed	GHG emissions reductions and future negative emissions are the only sustainable solutions to stabilize or even reverse global warming as they counter the cause of the problem. However, such actions will likely take a while to materialize, and inertia in the climate system and “baked-in” warming already ensures major changes in global temperatures and the nearing of several tipping points. Solar radiation management (SRM) techniques seek to reduce global temperatures by reflecting incoming solar radiation. They would thereby not fix the underlying issue of the warming effects of GHGs, but are according to the United Nations Environment Programme (UNEP) Review on Solar Radiation Modification Research (2023) ‘the only known approach that could be used to cool the Earth within a few years’.
Description of the technology/ measure	One of the most intuitive SRM approaches would be to reflect or block some solar energy before it reaches the Earth’s atmosphere. Several space-based ideas have been suggested to do just that (See Baum et al. 2022 for a summary of all ideas). Most of these intend to place something between the Earth and the sun at Lagrange Point L1. These could be space mirrors (Early, 1989), Lightsails (Kennedy et al., 2013), space bubbles (https://senseable.mit.edu/space-bubbles/), sunshades (Angel, 2006), a fleet of self-reproducing space vehicles (Ellery, 2016), or lunar dust (Bromley et al. 2023). Almost all studies share the aim to reduce solar radiation by 1.8%, and claim this would be needed to compensate for a doubling of CO2. Such

	space-based SRM could have certain advantages over other kinds of SRM, as they would lead to less side effects and be more predictable and they could perhaps be focussed on specific areas (Keith, 2000).	
Technological readiness	low	Some of the earliest space based geoengineering ideas were developed during the early 20th century, and were given an impulse by the Space Race, with several wild speculative projects being suggested in the USSR (see Keith, 2000; Fleming, 2010). These past and present ideas are however largely standalone explorations that are very far from development. A 2021 report by RAND estimated the technological readiness of space mirrors as *medium*, but it is unclear why they think so other than that some smaller space mirrors already exist. Bromley et al’s (2023) comments are illustrative of the overestimations around the feasibility of such projects as they write that ‘[r]oughly 10 [to the power of] 10 kg of dust per year is needed for Earth-climate impact, which is approximately 700 times more mass than humans have launched into space', and that the 'easier' alternative therefore would be to use mined lunar dust and launch it ‘on ballistic trajectories that cross near the Earth-Sun line of sight.' In general most reviewers dismiss such techniques as an option. UNEP (2023) observes that the developmental timescales ‘appear prohibitive compared to other approaches’, and NASEM (2015) chose not to consider space-based ideas ‘because of the substantial time (>20 years) … and technology challenges associated with these issues’. Baum et al. (2022) analysis of expert opinions found that although many were ‘broadly positive about the concept itself’, they were ‘unsure about its ultimate workability.'
Scalability	Medium	There would likely not be major physical limitations to scaling as space offers ample room for such measures. In practise, they would however likely scale linearly as greater surface area could reflect more light but would also be more difficult to build and/or get into place.
Timeliness for near-future effects	Low	Most reports and overview studies believe that space-based SRM would take too long to develop to be taken seriously as a means to enact short-term climate gains (NASEM, 2015; Keith et al. 2020; UNEP, 2023).
Potential to make a difference in Northern + Arctic	High	Theoretically, space-based SRM could be targeted to specific regions and could therefore be regionally effective.

Potential to make a global difference	High	Like SAI, it is likely that this measure, if technologically feasible, would be able to cool surface temperatures.
Cost - Benefit	High	Almost all studies agree that such technologies would be very expensive, although it has been suggested that declining space transportation costs could force a reconsideration of some of these estimates (Yonekura, 2022). There are of course differences between suggested plans, and Ellery (2016) for example claims 3D printed self-replicating spacecraft would be a relatively less expensive space-based SRM measure. In an early ‘order-of-magnitude estimate’, Keith (2000) gave $50–500 billion. Baum et al's review comes up with a price tag of $1 trillion to $6–20 trillion (2022), although they elsewhere note side benefits like the potential use of sun shields as a source of renewable energy. Angel (2006) suggested around 1-2% of global world product. For both UNEP (2023) and NASEM (2015) this high cost is at least one major reason not to focus on space-based SRM.
Likelihood of environmental risks	Low	Like other SRM measures, these space based technologies would compensate for long wave greenhouse gas forcing with reductions in incoming solar energy and thereby affect processes like the hydrological cycle and photosynthesis. But there would be no impact from the introduction of either cloud condensation nuclei as in MCB, CCT, nor stratospheric physical-chemical reactions as in SAI.
Effects on local/ indigenous communities	Unknown	
Ease of reversibility	Unknown	It would likely depend on the measure. Some devices could be moved by rockets, while other technologies would be much harder to remove.
Risk of termination shock	High	LIke other SRM measures, there is a high risk of termination shock when such space technologies would for whatever reason be removed. Keith et al (2020) moreover warn that space-based SRM are highly vulnerable ‘to destruction by rogue actors’, and caution that ‘[r]edeployment … after destruction would be a major effort’.
Suitability within current legal/ governance structures	Unknown	There are certain international governmental structures in place with regards to outer space like the Outer Space Treaty of 1967 (Keith et al 2020).
Amount of attention in	Medium	Baum et al (2022) notes that 'the literature on space-based geoengineering is limited', and that only 2% of articles on

scientific journals and public media and currently ongoing research programs		geoengineering consider space-based methods. Some spectacular ideas like Bromley et al’s (2023) space dust from the moon idea have reached the public media, but as Keith et al (2020) write: ‘For the most part [such ideas] are simply left unconsidered.’

Improved fishing practices and management

Issue being addressed	Fisheries contribute to global CO2 emissions by the extraction of fish, disturbance of coastal and oceanic blue carbon ecosystems, and the use of fossil fuels as their main energy source. Fishing vessels are moreover a major source of short-lived climate forcers like black carbon (McKuin and Campbell 2016), which can have a major effect in Arctic and Northern regions (see black carbon mitigation).	
Description of the technology/ measure	There are multiple measures that can reduce emissions related to fishing ranging from technological modifications to reduce fuel consumption, to improved fisheries management and fishing practices, and reduction of waste and improvements with processing further down the value chain (Parker *et al*. 2018; FAO 2022).	
Technological readiness	High	Although new innovations will likely also play a role, many improved technologies and management practices already exist (FAO 2022).
Scalability	Medium	Not all management practices and technological interventions will be equally effective in specific contexts, and high implementation costs hinder the implementation of certain innovations at scale (FAO 2022).
Timeliness for near-future effects	Medium	While some beneficial technological improvements and management approaches can be relatively easily applied, others are more difficult to implement, for example due to high costs, or international political complexities around fishing rights.
Potential to make a difference in Northern + Arctic	Unknown	As most studies around fisheries and climate change focus on potential adaptation strategies to the effects of warming oceans, many uncertainties remain around the potential role of the industry in mitigating the effects of climate change. McKuin and Campbell (2016) calculate that Arctic fisheries will emit 6.9 and 5.9 Tg CO2 equivalent GHG emissions per year from fuel combustion for 20 to 100 year time horizons respectively, but do not estimate how much of this could be mitigated. Although fishing vessels are an important contributor to Arctic black

		carbon (McKuin and Campbell 2016), and improved management practises and technologies can help reduce emissions regionally (Waldo *et al*. 2016; Merayo *et al*. 2018), the ultimate effects will likely be relatively minor in comparison to other sectors.
Potential to make a global difference	Unknown	Parker et al (2018) revealed that fisheries were only responsible for 4% of total global emissions related to food production, and the FAO (2022) clearly notes that '[f]isheries and aquaculture make a minor contribution to global carbon emissions.' Since technological improvements and better management practices would at best be able to mitigate a part of these emissions, the global potential of this measure will likely remain minimal.
Cost - Benefit	medium	The fishing sector will have to change anyway due to the effects of climate change, and certain management strategies could moreover increase catches and profits. However, many improvements can come with high costs (FAO 2022).
Likelihood of environmental risks	medium	Environmental risks may be associated with imperfect application of fishing strategies and management strategies (Young *et al*., 2018).
Effects on local/ indigenous communities	Beneficial	There are concerns about the potential negative impacts of fisheries management changes on small-scale and indigenous fishing communities, as well as the potential for such changes to promote consolidation and concentration of fishing rights in the hands of a few large companies. However, well implemented technological and management changes will likely be beneficial for local communities.
Ease of Reversibility	Easy	
Risk of termination shock	Low	
Suitability within current legal/ governance structures	Medium	Most of these improvements would fall under local or regional governance and legal frameworks. However, as fishing regulation is also importantly regulated through international treaties, some of these issues would potentially be more difficult to implement.
Amount of attention in	Medium	Although there is a vast literature on potential adaptation strategies of the fishing industry to the effects of climate

scientific journals and public media and currently ongoing research programs		change, the potential role of the sector in mitigating GHG emissions is very limited.

Ocean fertilization

Issue being addressed	The oceans are the largest carbon sink for atmospheric carbon, and have taken up over 30% of anthropogenic emissions. Carbon uptake occurs abiotically through processes like ocean-atmosphere interaction and weathering processes, and biotically, mainly through carbon consuming photosynthesising organisms.	
Description of the technology/ measure	Ocean fertilization schemes seek to increase the amount of available nutrients in the top layer of the ocean to stimulate the growth of phytoplankton. These organisms play a major role in the oceanic carbon cycle as they utilize CO2 when photosynthesising. By encouraging greater bioproductivity, more carbon can be sequestered by organisms in the “biological pump” when they die and sink to the ocean floor and thereby remove carbon from the carbon cycle (Smetacek et al. 2012; Williamson et al., 2012). Such fertilization can also be used to stimulate higher entropic levels, for example fish production in an area (See fish management). Moreover, the UN report on marine Geoengineering speculates that further research might be done into the potential to create albedo enhancing algal blooms, which would directly reflect incoming solar radiation (GESAMP, 2019; see also ocean albedo enhancement). Several different fertilization schemes have been suggested. Upwelling shall be discussed in more detail below, here the focus will be on the purposeful distribution of nutrients on the surface. Marine Phytoplankton need nitrogen (N), phosphorus (P), and iron (Fe) to grow, and there have been proposals to use all three of these elements as fertilization material. Most research has focussed on Fe fertilization, and this shall also be the focus of this section. Fe plays a crucial role in ocean biochemistry (Tagliabue et al 2017), and occurs naturally in the atmosphere and derives from multiple sources. Ito et al (2021) note there is still large uncertainty about such sources and its role in ocean biochemistry. Although most studies generally conceive distribution from ships, there are alternatives, like the idea to spread very fine iron-containing powder from airplanes (Emerson, 2019).	
Technological readiness	low	The technology is already proven to work locally, as natural analogues and several controversial experiments have shown that

		the addition of certain particles to the water can cause a localized algae bloom. However, whether this can be efficiently replicated artificially at a larger scale has not yet been proven. Mongin et al. (2021) for example claimed that many fertilizers would sink down before they could be utilized by phytoplankton, and their model study showed that this might reduce potential CO2 uptake by half. There are furthermore questions about the durability of carbon sequestration through the sedimentation of dead biomatter (Fuss et al. 2018). The IPCC AR6 wg3 report assigns it very low technological readiness of 1 to 2 (p116).
Scalability	Unknown	The *National Academies of Sciences* report (2022) states that they have ‘medium to high confidence that this approach will be effective and scalable’, and add that the costs to scale up the technology would be relatively low (2021). Spatially, the scaling of specific measures would be limited by the local availability of nutrients, as there are for instance only a few areas that can be said to have a major relative deficiency of iron.
Timeliness for near-future effects	Unknown	There are too many uncertainties around this measure to provide a clear answer to this.
Potential to make a difference in Northern + Arctic	unknown	It is unclear if this measure would be particularly effective in Northern and Arctic regions, but Iron fertilization could potentially be important as one of the planet's oceans three major iron deficient zones is the subarctic North Pacific (Boyd et al., 2007).
Potential to make a global difference	unknown	In their 2008 report, the Royal Society estimates that by 2100, ocean fertilization would be able to sequester up to 3.7 GtCO2 per year (Lampitt et al. 2008). The IPCC AR6 wg3 report notes that experimental results show a far lower efficiency than theoretical calculations, and ultimately estimates carbon uptake potential of 1 to 3 Gt CO2 per year. However the GESAMP report on marine geoengineering technologies states that 'degree of enhancement of the biological pump varied considerably between experiments', with findings anywhere between a 50 and 8 percent enhancement (GESAMP, 2019). It furthermore also needs to be clarified how much carbon could be released back into the atmosphere when biomass breaks down and the captured carbon is respirated back to higher oceanic layers, and if increased bioproductivity causes a greater emission of other GHGs like methane (GESAMP, 2019).
Cost - Benefit	unknown	The price per tonne of carbon sequestered is still highly uncertain, with a literature review giving the vastly differing \$2 to \$457/tCO2 (Fuss et al. 2018). The IPCC AR6 wg3 report estimates a cost of 50

		to 500 dollars per captured tonne of CO2. In terms of financing, Cooley et al. (2022) find that many ocean CDR techniques 'resonate with existing experiences of greenhouse gas mitigation and, increasingly, terrestrial CDR,' and that this allows such technologies to build on already existing financing frameworks
Likelihood of environmental risks	Medium	The oceans remain largely understudied, and tinkering with lower entropic levels could have major consequences for the entire system and might seriously impact local ecosystems (Boyd et al. 2022; IPCC IR6 Wg3, 2022). Fertilization might for example cause environmental damage by causing toxic algae blooms (Wallace et al. 2010; Bertram et al., 2010) and ocean acidification (Williamson and Turley, 2012). The NASEM report thereby attributes a medium level of environmental risk to this measure (2021).
Effects on local/ indigenous communities	Unknown	If fertilization affects local ecosystems it will also impact dependent local and indigenous communities. This could therefore have positive and negative effects, and issues of climate justice have to be taken into consideration (Batres et al. 2021). If fertilization works as it supposed to, it might for example lead to increased fish stocks (NASEM, 2022), however Wallace et al. (2010) write about the potential for ‘nutrient robbing’, or the possibility 'that fertilization of an open ocean location in international waters could reduce productivity around islands and countries not involved with the fertilization activity'. Cooley et al. (2022) find that the public stance and framing of ocean fertilization and other ocean CDR technologies is crucially important for their future implementation potential.
Ease of reversibility	unknown	Wallace et al (2010) state that even though localized experiments likely did not have permanent effects, it needs to be better understood if larger experiments would also be reversible and not have more permanent effects.
Risk of termination shock	unknown	
Suitability within current legal/ governance structures	Unknown	There are many national and regional laws that deal with water pollution. However, many early ocean fertilization experiments took place on open oceans, outside the jurisdiction of individual nation states. After the outrage this caused, several conventions tried to counter uncontrolled polluting of the oceans in this way. The most notable of these initiatives is the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (better known as the London Convention). After it was first amended in 1972, it was modified in 2008 and 2013 in order to regulate ocean

		fertilization. However, Silverman-Roati et al write ‘[t]here are currently no legally binding international treaties dealing specifically with ocean fertilization’, and ‘[i]n general, the international legal framework for ocean fertilization includes several gaps, and no comprehensive framework governs’ (2022).
Amount of attention in scientific journals and public media and currently ongoing research programs	High	Ocean Fertilization has a relatively long history, with several highly controversial experiments in the 1990s and early 2000s that gained widespread attention, most infamously perhaps when Russ George spread 100 tonnes of iron sulfate into the Pacific Ocean in 2012. In 2021, the organization geoengineeringmonitor claimed that there had been 'at least 16 open ocean fertilization experiments'. There have been large projects like the German-led LOHAFEX, and the Korean KIFES program in the Southern Ocean, as well as major institutionalized research, like at the Cambridge Center for Climate Repair, and the EU’s ongoing reviewing project OceanNETs (www.oceannets.eu/), and NASEM (2021) argued for the consideration of future mesoscale experiments. There are also many commercial companies that are exploring this measure, like Exploring Ocean Iron Solutions (https://oceaniron.org/), and the Australian Ocean Nourishment Corporation (oceannourishment.com), whose WhaleX project received some attention after being shortlisted for Elon Musk's CDR prize (Readfearn, 2021).

Seaweed and macro algae cultivation

Issue being addressed	The potential of carbon sequestration by marine based plants such as mangroves, seagrass and algae, often referred to as blue carbon, and the importance of better understanding it, has clearly been recognised (Mcleod et al. 2011). The IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (2019) concluded blue carbon can play an important role in both climate regulation and adaptation. The term algae groups together several kinds of marine photosynthetic organisms. These are often subdivided into very small microalgae like phytoplankton, and larger macroalgae like kelp and seaweed. Although there is still large uncertainty about the total amount of carbon sequestered by these marine organisms, a recent estimate by Duarte et al (2022) indicated that all macroalgae took in as much CO2 as the Amazon rainforest.

Description of the technology/ measure	There has been increased interest in the carbon capture potential of large scale algae growth (Ould and Caldwell, 2022). Several ways to enhance the growth of microalgae are covered elsewhere (see Ocean Fertilization, Upwelling, etc.), here we will focus on macroalgae. The history of macroalgae cultivation goes back very far, and is today especially developed in East Asia, where macroalgae are mainly used as food and in the cosmetics industry (Sondak et al., 2017). The produced macroalgae can either be processed, for example as biofuels (see BECCS) or biochar (see Biochar), or removed from the carbon cycle by burying it or letting it sink to the sea floor.	
Technological readiness	medium	Buschmann et al (2017) describe the production and growth of seaweed as a relatively straightforward enterprise. However, despite the long history and experiential knowledge of algal farming around the world, their large scale cultivation for carbon sequestration purposes would likely require significant alterations to be effective. Several factors like the availability of surface area, engineering issues, and market demands, complicate the expansion of the current growing practices (Duarte et al. 2017), and there remain many unexplored areas (Krause-Jensen et al. 2018). A major issue for such a project would be the durable sequestration of carbon (Ould and Caldwell, 2022). Kelp forests and other macroalgae store their carbon in their biomass, and not, like other blue carbon solutions such as mangroves, partially in the soils, and therefore risk largely decomposing and re-releasing their carbon into the oceans. Ager et al (2023) for instance found that 80 % of the macroalgal biomass studied at a fjord in Greenland stayed in that fjord, and that there is no scientific clarity on what happens to this biomass, and therefore also no certainty about carbon capture potential. Moreover, many of the macroalgal aquaculture projects aim to utilize the algae, and do not provide a carbon sink function (Troell et al. 2022). Another difficulty is highlighted by Rose and Hemery (2023) when they write that 'methods to assess the permanence of carbon in the natural life cycle of macroalgae and in products following harvest are lacking', and that it is therefore difficult to measure the carbon sequestration effect of such projects. There are many operational projects. In Iceland there is for example an experiment by Running Tide (https://www.runningtide.com/), which, with permission of the government, released buoys off the coast in order to stimulate kelp production. The Dutch non-profit organization North Sea Farmers (https://www.northseafarmers.org) recently brought great encouragement to the sector after it received €1.5m from Amazon

		for a field trial in the North Sea. NASEM (2022) estimates that $130 million would be needed in initial funding to explore the feasibility of large scale farming and the durability and environmental risks associated. However, despite large investments, and the positive associations around macroalgae as a natural measure that is sometimes even labeled ‘ocean afforestation’ (N’Yeurt et al., 2012), there are still many uncertainties, and the recent news that Exxon as the last fossil fuel company has abandoned their research into algae as biofuels (https://www.bloomberg.com/news/articles/2023-02-10/exxon-retreats-from-major-climate-effort-to-make-biofuels-from-algae) is perhaps indicative that operationalisation is perhaps not as easy as it looks. Ould and Caldwell (2022) therefore specifically warn against 'the hyperbole [around macroalgae potential] that is beginning to permeate the conversation'
Scalability	Unknown	NASEM (2022) points out that this measure would have scaling difficulties due to the large amount of required farming area. This difficulty with area requirements is echoed in Ould and Caldwell (2022), as they calculate that if carbon targets of 8 and 12 GtCO2 per year are to be met, ‘this would equate to producing, on an annual basis, between 9.75 and 14.63 Gt of farmed seaweed, which would be a 300- to 450-fold expansion of global seaweed aquaculture.’ Another issue with scaling up would be the required durability of capture. Since it could be possible that biomass would release the captured carbon again after it dies, Hasselström and Thomas (2022) suggest that '[b]lue carbon financing should be directed only to setups proven to lead to additional and permanent carbon storage.' This potential re-release of carbon, and other ecological effects are highly uncertain, and would need to be studied before this measure could be scaled up (Gao et al. 2022).
Timeliness for near-future effects	Unknown	There are still too many uncertainties to provide a clear answer to this.
Potential to make a difference in Northern + Arctic	unknown	Duarte et al (2022) emphasize the potential of the Arctic due to its 'rocky bottoms suitable for macroalgal growth' and the fact that it 'represents 34% of the global shoreline'. The potential for increased macroalgae expansion in the Arctic and Northern regions seems very high, however, the original Arctic cryophilic macroalgal species (see Bringloe et al. 2020) cannot advance further north, and will therefore face habitat loss under warming oceans (Bringloe et al. 2022). The three year long Nordic Blue Carbon project found that of the total 3.9 million tonne CO2 equivalents that were captured in the Nordic region (excluding Greenland) per year, kelp forests were responsible for 69%, or 2.7 million tonne CO2

		equivalents. They therefore conclude that apart from artificial farming, 'management measures to protect and restore blue forest habitats will have a wide range of societal and economical co-benefits, therefore making them “no-regret” mitigation options' (Frigstad et al. 2021). Much remains unknown to this point, and new discoveries, like Krause-Jensen et al’s finding of substantial kelp forests around West Greenland, at relatively extreme depths (2019), continue to advance knowledge about macroalgal importance for the region. The expansion of macroalgae in the Northern and Arctic regions could moreover occur partially naturally because of more favorable conditions, especially due to reduced ice coverage leading to greater light availability (Arrigo, and van Dijken, 2015). As Krause-Jensen et al (2014) pointedly summarize in their abstract: this ‘likely expansion of vegetated coastal habitats in the Arctic will generate new productive ecosystems, offer habitat for a number of invertebrate and vertebrate species, including provision of refugia for calcifiers from possible threats from ocean acidification, contribute to enhance CO2 sequestration and protect the shoreline from erosion.' Recent work by Wright et al (2022) found this climate driven movement could potentially have large effects on macroalgal carbon sequestration potential, for although ‘warm temperate kelp exports up to 71% more carbon per plant, it decomposes up to 155% faster’, and could therefore significantly reduce carbon sequestration potential. Filbee-Dexter et al (2020) study equally show that the carbon storage for global kelp forests reduces with rising ocean temperatures as such biomass degrades more quickly, but emphasize that this should encourage further research into the potential of colder northern regions. Lebrun et al’s overview study of the existing literature on the effect of climate change on Arctic macroalgae (2022) however indicates that there is a lack of complete understanding, and that effects can both be positive and negative. Moreover, adjusting to sea level rises might also impact carbon sequestration potential of macroalgae (Lovelock and Reef, 2020). Apart from the potential for macroalgae to grow in the Northern regions, this would however not be very likely to make a significant climate impact in the north, as the oceans and atmosphere tend to re-equilibrate their carbon level quickly, and this would largely be effective for global atmospheric carbon levels.

Potential to make a global difference	Unknown	Duarte et al (2017) note that ‘the contribution of seaweed aquaculture to climate change mitigation and adaptation will remain globally modest’.
Cost - Benefit	low	Duarte et al (2017) state that 'Because of the very low investment required to set up seaweed aquaculture farms, seaweed aquaculture is a particularly sound strategy for coastal developing nations to contribute to climate change mitigation while protecting their shoreline and marine ecosystems from some of the effects of climate change, such as ocean acidification and ocean de-oxygenation.'
Likelihood of environmental risks	low	Enhanced growth of macroalgae in Northern regions will lead to changes in ecosystems (Krause-Jensen et al. 2014), and the uptake of nutrients by their growth could impact the growth of other organisms. It is also not known what the impact of the sinking of macroalgae would have on the deep ocean (IPCC, AR6, Wg3 p1479). Gao et al (2022) emphasize therefore that the ecological impacts of blue carbon enhancement need to be assessed further if they are to be scaled up.
Effects on local/ indigenous communities	beneficial	There could be substantial co-benefits to increased macroalgal growth, both directly related to jobs in the production, maintenance and harvesting, and by providing extra food sources, directly from edible seaweed, or indirectly from increased fish catch as a result of larger spawning areas in kelp forests. Duarte et al (2017) argues that increasing the demand for seaweed and subsidizing farmers could be effective strategies to encourage further local engagement with seaweed aquaculture and provide financial benefits to cultivators.
Ease of reversibility	easy	It is likely relatively straightforward to remove seaweed farms if found undesirable, although care must be taken not to allow local ecosystems to be replaced or overwhelmed by macroalgae.
Risk of termination shock	low	
Suitability within current legal/ governance structures	High	Both Krause-Jensen et al (2022) and the Nordic Blue Carbon Project (Frigstad et al. 2021) recommend increased Nordic research and governance collaboration. Most of the potential cultivation areas are inside nations’ exclusive economic zones and can thereby be governed nationally.
Amount of attention in scientific journals and public media	High	Macroalgal stimulation has recently gained large interest from the scientific community and public at large. Importantly, also commercial parties are increasingly getting involved, and funding seems to be increasing. Apart from the already mentioned projects,

and currently ongoing research programs		there are major research projects and organizations that promote macroalgae as blue carbon solutions, like Project Drawdown (https://drawdown.org), Ocean Rainforest (https://www.oceanrainforest.com), and Kelp Blue (https://kelp.blue).

Reflective foams and bubbles on oceans

Issue being addressed	Sea water has a low albedo of around 0.1 and therefore absorbs most of the incoming solar energy. Since water covers over two thirds of the Earth's surface, changes to this albedo can potentially cause significant changes in global temperatures.	
Description of the technology/ measure	Taking inspiration from the naturally occuring whitecaps on ocean water, several scholars have raised the idea to artificially enhance ocean albedo. Such ideas roughly fall under two categories: the (often mechanical) production of microbubbles, and the chemical production of foam (Evans et al. 2010). The main study on foams is by Aziz et al. (2014), who experimented with non-toxic biodegradable additives and found that they had lifetimes beyond three months in a tank. There have been more studies on the albedo enhancement potential bubbles. Seitz's (2011) exploratory paper is often cited and suggests mechanically produced micro bubbles could provide a long lasting method of ocean albedo enhancement. A similar idea for a small floating device that injects nanobubbles in the water has more recently been suggested under the name FizzTop (see Clarke, 2022). Another often mentioned method focuses on the possible utilization of ships that already sail the oceans, mainly through a modification of their wake (Crook et al (2016). Ortega and Evans (2017) consider such deployment to be most likely because it would require far less energy to maintain a coverage as compared to other measures. Haley and Nicklas (2021) conceived of a foam or bubble-like structure that could also function as a material for floating tiles which could be released onto sea surface. They furthermore suggest these tiles could be coated with fertilizers or alkalizers to raise oceanic pH and increase oceanic carbon drawdown. However, as they mainly study releasing these in the Atlantic Gyre, an area that falls beyond the geographical scope of this study, these will not be covered further.	
Technological readiness	low	There have been a few idealized experiments with bubbles and foams in experimental tanks. The long lifetimes reported by Seitz (2011) and Aziz et al. (2014) in such tanks are, however , probably not accurate depictions of their behavior in open seas and significantly overestimate their lifetime (Crook et al. 2016). Several smaller organizations, like Reflective Earth (

		https://www.reflectiveearth.org/our-work), who have a portfolio of actions and activities, are studying ocean surface albedo modification. Apart from technical issues, there are large uncertainties around potential radiative forcing effects (Cvijanovic et al 2015) and effects on marine biochemistry. Gattuso et al. (2018) therefore label the technological readiness of ocean surface albedo enhancement as low.
Scalability	medium	This is highly uncertain as the technology does not yet exist. Some authors are very optimistic (see especially Seitz, 2011), and the potential to utilize the already large surface area covered by ocean going ships might raise high expectations. However, as Crook et al (2016) show, there have to be many adjustments to make ship's wake modification have a significant impact.
Timeliness for near-future effects	Unknown	Because the technology does not yet exist, and there are several different possible technologies to be developed, this is hard to say at this point.
Potential to make a difference in Northern + Arctic	unknown	Crook et al's (2016) model study reveals that ocean surface cooling could potentially have a large impact in the Northern regions, as they find significantly greater cooling and radiative forcing effects in the Northern Hemisphere. Cvijanovic et al (2015) however argue that surface albedo modification generates very different cooling than global TOA reduction through, for example, SAI, as the former would generate local cooling that would then diffuse to other areas, while the latter would cause a more uniform global cooling. Their model study furthermore shows that local albedo modification might to some degree restore Arctic sea ice, but that this effect would not be enough to save the ice permanently if global temperatures continued to rise. The local specificities of the Arctic would furthermore mean that the distribution of any technology would face significant difficulties (see also sea ice albedo enhancement). It is for example unclear how a bubble producing device or a chemical additive would behave in Arctic sea ice waters, and also the modification of ships' wakes might be less effective in the North as the region is less traversed (Crook et al. 2016).
Potential to make a global difference	unknown	Seitz (2011) suggest that the albedo of certain parts of the planet's oceans could be increased by as much as 0.2 if these bubbles with a radius of 1 μm could in the right concentration. He furthermore writes of ideal potential global cooling of 'a few degrees K', which would mean that relatively modest energy inputs could be enough 'to offset petawatts of CO2 induced radiative forcing.' Gabriel et al (2017) model simulation also showed that the introduction of a reflective layer on certain areas of the ocean could

		‘reduce global mean surface temperature relative to RCP6.0 by 0.6 K’, and achieve a global average forcing of −1.5 W m−2. Gattuso et al. (2018) ocean based climate solutions summary report equally estimated its potential as high. There could moreover be cooling effects from cloud interactions, as Evans (2010) noted that artificial whitecaps would increase the amount of salt aerosols in the air, and thereby encourage the formation of reflective clouds that could hopefully reduce even more radiation. However, to all these estimates it has to be added that the required technology does not exist, and Crook et al (2016) therefore also emphasize their simulation’s significant global mean radiative forcing of −0.9 Wm−2 and a 0.5°C reduction of global mean surface temperature where only a result of them enhancing 'wake albedo by 0.2 and increasing wake lifetime by ×1440'. Zhao et al (2020) modeling study moreover found that another technology Marine Cloud Brightening, could have a 40% greater forcing efficacy than ocean surface albedo modification, and that this technology could also be extra beneficial because it would reflect radiation higher up in the atmosphere, and not at the surface, which has extra benefits of reducing shortwave heating of the lower atmosphere.
Cost - Benefit	unknown	Because there is no certainty on which technology to use, there is as of now no credible costing estimate. Gattuso et al (2018) estimate a low cost efficiency in comparison with other ocean based solutions. Ortega and Evans (2017) furthermore note that energy consumption could be prohibitively high, thereby driving up costs.
Likelihood of environmental risks	High	There have been no detailed studies on the environmental effects of ocean albedo modification, but because this would impact the amount of energy available to marine life, Gattuso et al. (2018) and NASEM, (2021) warn there can be significant effects on biotic processes, which could in turn also reduce carbon drawdown. This is also highlighted in the summary by the geoengineering-skeptic platform GeoengineeringMonitor. Apart from biochemical effects on the oceans, the increased reflection of incoming solar radiation might also impact rainfall patterns, with Gabriel et al’s (2016) simulation showing 'increase in rainfall over land, most pronouncedly in the tropics'.
Effects on local/ indigenous communities	Unknown	A major effect could be that ocean albedo modification would potentially impact local ecosystems by changing the amount of available light for photosynthesis. This would thereby impact communities that rely on fishing. Given the previous protests by

		indigenous groups against sea ice albedo modification (See sea ice albedo modification), it is not unreasonable to expect similar opposition to ocean albedo modification technologies.
Ease of reversibility	unknown	The technology could likely be switched off easily. A caveat should perhaps be added to the production of foams through chemical agents, which would potentially have to be removed if found faulty.
Risk of termination shock	medium	If stopped, the regular warming rate would likely continue as before the technology was deployed. However, if applied every year, the sudden energy increase after the measure would be halted could cause a shock to local ecosystems.
Suitability within current legal/ governance structures	medium	The usage of chemicals to produce foam would likely be far more problematic than bubbles, but because the technology is in such an early stage, many uncertainties remain with regards to questions of governance.
Amount of attention in scientific journals and public media and currently ongoing research programs	medium	Although several private scholars and engineers have explored the topic, and Crook et al’s (2016) paper was part of a research project at the University of Leeds, ocean albedo modification remains a rather unexplored field that is also largely absent in popular media accounts.

Enhancing oceanic light availability below the photic layer

Issue being addressed	Ocean bioproductivity through photosynthesis stops beyond the photic layer as no more energy from the sun can penetrate beyond that point.	
Description of the technology/ measure	There have been some isolated speculations about a way to increase light availability at deeper levels, so as to allow more carbon sequestration in biomatter through photosynthesis. It is however very unclear how this would work. A reference to the idea can be found here: https://groups.google.com/g/CarbonDioxideRemoval/c/AXkmQwmXod0	
Technological readiness	low	This idea is apparently not being developed.
Scalability	low	
Timeliness for near-future effects	low	

Potential to make a difference in Northern + Arctic	unknown	
Potential to make a global difference	unknown	
Cost - Benefit	unknown	
Likelihood of environmental risks	medium	Like other ocean bioproductivity enhancement techniques, this idea potentially comes with significant environmental impacts. The deep sea impacts of such an intervention are potentially even more significant (Levin et al. 2023). There is moreover ample evidence that current levels of light producing are having significant effects on marine ecosystems (Maggi and Benedetti-Cecchi, 2018).
Effects on local/ indigenous communities	Unknown	
Ease of reversibility	Unknown	
Risk of termination shock	Unknown	
Suitability within current legal/ governance structures	medium	
Amount of attention in scientific journals and public media and currently ongoing research programs	low	This idea is apparently not being developed, and has only been mentioned a few times in online fora.

Promoting ocean calcifiers to sequester atmospheric carbon

Issue being addressed	The oceans are the largest carbon sink for atmospheric carbon, and have taken up over 30% of anthropogenic emissions. Carbon uptake occurs abiotically through processes like ocean-atmosphere interaction and

	weathering processes. Biotic processes play an important role in oceanic carbon uptake too, with most attention going out to carbon consuming photosynthesising organisms.	
Description of the technology/ measure	Moore et al (2023) argues that the potential role of shellfish and other calcifiers in carbon sequestration is significantly overlooked in the CDR literature. The authors suggest that calcifiers-production should be encouraged, because the production of their shells would be able to remove ‘significant amounts of CO2 … from the atmosphere with much greater permanence and less cost than any other solution can offer.’	
Technological readiness	Medium	Mussel farms are already in existence. Such farms are however not used for carbon sequestration, and it is therefore unclear if a scaling up or alteration would have the desired effects.
Scalability	medium	Moore et al (2022) and Moore et al (2023) write that it would be relatively straightforward to expand current farms to a sufficiently large scale and that ‘[a] million mussel farms would permanently remove about 4.5% of the global CO2 emissions in each year’. However, this measure is untested and only described in these two articles.
Timeliness for near-future effects	high	
Potential to make a difference in Northern + Arctic	low	Mussels grow slower at colder temperatures.
Potential to make a global difference	medium	Moore et al (2022) state that aquaculture captures ‘4.84 million tonnes of CO2 per year’, and that farms ‘designed to produce 10,000 tonnes of mussels per year would permanently remove from the atmosphere an annual total of 1,606 metric tonnes of CO2.' They therefore argue that ‘[a] million mussel farms would permanently remove about 4.5% of the global CO2 emissions in each year’. It is however hard to say how accurate such estimates are for the real world potential of this measure. Moore et al (2023) furthermore argue that this would be a permanent sequestration, in contrast to measures like afforestation which could see significant amounts of carbon re-released into the atmosphere when trees die.
Cost - Benefit	Low	Mussel farms would have the benefit of producing food, in contrast to other CDR technologies that would merely remove carbon from the atmosphere, and could thereby potentially be cheaper to run.

Likelihood of environmental risks	medium	Large scale cultivation could have an impact on local ecosystems.
Effects on local/ indigenous communities	Beneficial	Such farms could potentially provide seafood and work for local communities.
Ease of reversibility	easy	
Risk of termination shock	Low	
Suitability within current legal/ governance structures	High	
Amount of attention in scientific journals and public media and currently ongoing research programs	low	Apart from the papers cited above, there seems to be so far little attention for this measure.

Hydrological system modification - Ocean current modification

Issue being addressed	Hydrological systems play an important role in energy distribution in the climate system. For the Arctic and Northern region the clearest example of this is the habitability of the European Arctic thanks to the Gulf Stream. Furthermore, there are several access points to the Arctic ocean that play an important role in shaping local geophysical conditions.
Description of the technology/ measure	There have been several different suggestions to modify the circulation of the Arctic ocean currents and elements of the hydrological cycle. During the Cold War, there was major significant interest in the possibility of closing off (parts of) the Bering Strait, (See Borisov, 1970) to ameliorate (warm) the northern climates and make it more suitable for human habitation. Several years ago, a similar idea was proposed by the climate activist Rolf Schuttenhelm, albeit with the intent to have the intervention increase Arctic sea ice coverage (Schuttenhelm, 2008). Chatchart et al (2011) equally argued for such a plan, and suggested Fiberglass Curtains might be used to block entire passages. More recently it has been suggested to block off the North Sea with Dams

	(see NEED: Northern European Enclosure Dam, Groeskamp and Kjellsson, 2021). Apart from these ideas to block entire currents or straits, others have suggested modifying fresh water access through Northern rivers in Siberia and America to impact local climate conditions (Olcott et al. 2019, Hunt et al (2020).	
Technological readiness	low	There is currently no serious research project dedicated to any of such schemes.
Scalability	unknown	
Timeliness for near-future effects	low	
Potential to make a difference in Northern + Arctic	unknown	
Potential to make a global difference	unknown	
Cost - Benefit	high	Irrespective of which particular project is considered, construction and maintenance costs will likely be very high.
Likelihood of environmental risks	high	The effects of physically blocking or redirecting currents would likely be enormous.
Effects on local/ indigenous communities	Unknown	Although the nature of the effects would vary depending on the specific project, there will likely be major impacts on local communities.
Ease of reversibility	Low	
Risk of termination shock	High	
Suitability within current legal/ governance structures	Medium	
Amount of attention in scientific journals and public media	low	Some of these technologies gained prominence during the Cold War, but the more recent variants have not been picked up or discussed widely.

and currently ongoing research programs		

Artificial downwelling

Issue being addressed	Oceans play an important role in global heat transfer and carbon storage processes. As global temperatures and atmospheric carbon levels rise, some have suggested artificially modifying the vertical movement of water to enhance these processes.	
Description of the technology/ measure	Artificial downwelling (AD) is an idea to pump upper layer water deeper down into the ocean. This has also been suggested as a means to increase oxygen levels at deeper layers (see Oxygenating the Baltic), but in the following AD will be considered in terms of its proposed functionality of carbon transportation from upper layers to the deeper ocean. Although questions remain about the efficacy of AD for the purpose of carbon transportation to deep waters, the assumption is that it can artificially mimic a natural process in which carbon-saturated surface water can be pumped down to deeper levels where carbon levels are lower. The idea to use AD for this purpose was first suggested by Zhou and Flynn (2005), but has received relatively little further attention afterwards due to the very high associated costs and limited efficacy (GESAMP, 2019). Multiple techniques have been suggested to pump ocean water up or down (Pan et al. 2016), and small scale tests have been conducted with physical pumps (Stigebrandt et al. 2015), with at least 60 different technologies currently patented (Liu et al. 2020). However, most of these technologies are designed to oxygenate deep water, and it is unclear if these techniques could feasibly be used to increase carbon uptake in the deep ocean at scale. The GESAMP (2019) report notes that some authors have previously suggested to artificially cool areas at high latitudes to increase thermohaline circulation and enhance downwelling, but that these techniques have not since been considered.	
Technological readiness	low	As a CDR measure AD is currently not considered or developed in major research projects, and there is no clarity on how to actually downwell water at scale (GESAMP, 2019). The Swedish organization Desert Ocean writes that they want to develop AD but provide no further information (https://www.desertocean.se/technology). This lack of research stands in contrast to the relative frequency and prominence with which AD is referred to in lists of ocean based climate interventions like NASEM (2022). This can probably be explained by the linkage of AD with artificial upwelling, and

		because some of these studies include the research into AD as a measure to increase oxygen levels in the deep ocean.
Scalability	Medium	
Timeliness for near-future effects	low	
Potential to make a difference in Northern + Arctic	Low	AD has been sometimes suggested to be deployed in the Arctic through an amplification of already existing downwelling thermohaline processes (GESAMP, 2019).
Potential to make a global difference	Low	The CDR potential of AD is considered to be very low (Zhou and Flynn, 2005; Lenton and Vaughan, 2009).
Cost - Benefit	High	Zhou et al (2005) damningly conclude that: ‘[t]he estimated cost for the most favorable case is so high compared to alternatives with less uncertainty that the pursuit of this alternative for carbon sequestration is not attractive.’
Likelihood of environmental risks	medium	Although there are no specific studies on the environmental impacts of AD for CDR purposes, NASEM (2022) outlines certain risks for both AD and artificial upwelling, and Conley (2012) warns specifically of significant consequences of AD proposals in the Baltic.
Effects on local/ indigenous communities	neutral	
Ease of reversibility	Easy	
Risk of termination shock	High	
Suitability within current legal/ governance structures	medium	Webb et al (2022) note that both AD and artificial upwelling would fall under national governance and legal frameworks, as well as international conventions like the United Nations Convention on the Law of the Sea, the Convention on Biological Diversity, the Convention on the Prevention of Marine Pollution by Dumping of Waste and Other Matter, and the Protocol to that Convention.
Amount of attention in scientific journals and public media and currently	low	Although AD is being developed for other purposes, and some reviews note it as an option, as a CDR measure AD is not seriously considered after initial estimates by Zhou and Flynn (2005) judged it as infeasible (GESAMP, 2019).

ongoing research programs		

Artificial upwelling		
Issue being addressed	Oceans play an important role in global heat transfer and carbon storage processes. As global temperatures and atmospheric carbon levels rise, some have suggested artificially modifying the vertical movement of water to enhance these processes.	
Description of the technology/ measure	Artificial upwelling (AU) is an idea to increase carbon uptake of upper ocean layers by fertilizing it with pumped-up colder nutrient-rich waters from the deep, which would encourage the biological sequestration of carbon through photosynthesis (NASEM, 2022). Such fertilization occurs naturally in certain regions, and AU would thereby artificially reproduce this process. Many different upwelling technologies have been suggested (Pan et al. 2016), and several have been tested (NASEM, 2022). Apart from being used as a CDR method, AU could have several side-benefits, for example as a means to increase fish stocks (GESAMP, 2019), or hurricane mitigation (Launder, 2017).	
Technological readiness	Medium	AU has been studied for several decades in model simulations and indoor and outdoor experiments (NASEM, 2022). There have been several long running institutional research programs, like at Zhejiang University in China (See Wang and Zhang, 2023), and major national funded projects like the German GEOMAR Ocean artUp, (https://www.geomar.de/en/research/fb2/fb2-bi/research-topics/ocean-artificial-upwelling). There are also several commercial companies that explore the feasibility of AU (see for example Ocean Based Climate solutions: https://ocean-based.com/). Despite this significant interest in AU, many questions remain about the feasibility and effects of large scale deployment, as well as about the technological deployment.
Scalability	medium	It is unsure if AU would be sufficiently scalable, and, like other ocean fertilization measures, AU would likely be most effective in areas with a relative deficiency of nutrients (NASEM, 2022).
Timeliness for near-future effects	low	Due to the large uncertainties about AU, NASEM (2022) suggests that ‘model-based feasibility studies should lead the research agenda to identify optimal siting and scaling of pump networks and CDR potential.’

Potential to make a difference in Northern + Arctic	low	
Potential to make a global difference	low	Some research finds AU could have a potential positive climate effect. Oschlies et al’s (2010) model study for instance suggests that pumping deep water up could sequester 0.9 PgC per year, but note that 80% of that would be on land, not in the sea. However, most studies remain pessimistic about the ultimate CDR potential of AU. Dutreuil et al (2009) for example show that the increased amount of carbon present in the deeper waters would not lead to a decrease, but to an increased CO2 content in the atmosphere. Bauman et al (2014) write that: ‘Given the absence of positive supporting scientific evidence, we do not recommend pursuing geoengineering through artificial upwelling; our calculations indicate it is unfeasible and may amplify the warming trend it seeks to reduce.’ NASEM (2022) also summarizes that ‘The current state of knowledge … indicates that even a persistent and effective deployment of millions of functional pumps across the global ocean would not meet CDR goals for sequestration or permanence.’ Lawrence et al (2018) equally conclude that it seems unlikely that such techniques 'will contribute significantly' to emission reduction targets. Some nevertheless suggest it might be worthwhile to explore AU further, for example through natural analogues (Bach and Boyd, 2021), or because they think the technology could help study marine ecosystems (Wallace et al. 2010).
Cost - Benefit	High	The costs are likely very high, although there are large uncertainties about possible development and deployment costs (NASEM, 2022).
Likelihood of environmental risks	High	Artificial upwelling and other interventions that interfere with deep ocean layers could have major environmental effects (Levin et al. 2023), and could severely impact local ecosystems (Bauman et al. 2014; Boyd et al. 2022), and potentially lead to ocean acidification (Williamson and Turley, 2012).
Effects on local/ indigenous communities	Unknown	
Ease of reversibility	easy	
Risk of termination shock	high	Oschlies et al’s (2010), warn that a “termination shock” could occur when AU were to be abruptly halted, which would lead to rapid

		temperature rise that could be higher than if artificial upwelling would never have been done.
Suitability within current legal/ governance structures	Medium	Webb et al (2022) note that both AU and artificial downwelling would fall under national governance and legal frameworks, as well as international conventions like the United Nations Convention on the Law of the Sea, the Convention on Biological Diversity, the Convention on the Prevention of Marine Pollution by Dumping of Waste and Other Matter, and the Protocol to that Convention.
Amount of attention in scientific journals and public media and currently ongoing research programs	Medium	There has been significant scientific attention for AU, including major research projects. Apart from this institutional research, AU has been taken up by individual projects, and is often listed as one of the main Ocean based CDR techniques.

Re-oxygenating the Baltic

<table>
<tr><td>Issue being addressed</td><td colspan="2">The deep waters in the Baltic are severely deoxygenated. Although the causes of the current state are complex, this is mainly a result of increased eutrophication from sewage and agricultural runoff from surrounding lands, which leads to extreme bioproductivity (Rolff et al. 2022). Some species manage to survive in the upper water layers, but many organisms living on the seafloor are severely impacted by the hypoxia, thereby influencing the health of a wide network of ecosystems and biochemical processes. There are attempts to reduce nutrient runoff into the Baltic (see for example: https://helcom.fi/baltic-sea-action-plan/). However, some argue these will be insufficient and argue for engineering solutions to the issue.</td></tr>
<tr><td>Description of the technology/ measure</td><td colspan="2">There have been several different ideas to oxygenise the Baltic (Conley, 2009). The most discussed technique, which will be the focus here too, aims to directly increase available oxygen to the deep waters by pumping cold oxygenated water down from higher levels (Stigebrandt and Gustafsson 2007). This oxygenation can lead to changes in GHG sinks and sources. There are several potential pumping technologies that are currently being explored, but Liu et al (2020) find that a wind-powered system would probably work best in the Baltic.</td></tr>
<tr><td>Technological readiness</td><td>low</td><td>Although there remain uncertainties around downwelling techniques (Ollikainenen et al. 2016), Liu et al (2020) say they are rapidly advancing. Model and experimental studies show that it is possible to artificially increase oxygen levels in this way</td></tr>
</table>

		(Stigebrandt et al. 2015; Stigebrandt and Andersson, 2022), and the Baltic deepwater OXygenation project (BOX) conducted a field trial in the Swedish fjord Byfjord and found it had a desired effect there (Forth et al. 2015). It is however questionable if the field trial was too small to serve as a useful analogue for the scale of the entire Baltic, and many questions remain about the ultimate effects of pumping oxygen (Conley, 2012; Ollikainenen et al. 2016). Conley et al (2009) for example note that the effects of physical mixing and circulation processes are still too poorly understood.
Scalability	medium	Although the project's advocates are positive, there are questions about the potential of this technique to be effective at the scale of the Baltic beyond the small areas that have been the subject of field trials (Conley, 2012; Ollikainenen et al. 2016).
Timeliness for near-future effects	Medium	There have already been some field trials, and a pumping system should probably not be beyond current technological capabilities. However, Conley et al (2009) conclude: 'that these large-scale attempts at remediation are unlikely to substantially improve the short-term conditions in the Baltic Sea'.
Potential to make a difference in Northern + Arctic	Unknown	For ecosystems and communities around the broader Baltic region, this could potentially be of great importance. However it is unknown what kinds of climate effects this measure would have, as oxygenating hypoxic waters can lead to various changes with regards to emissions and uptake of GHG like methane and CO2.
Potential to make a global difference	Low	The effects of oxygenation would be complex, yet it seems unlikely that it would lead to significant global effects.
Cost - Benefit	unknown	Stigebrandt and Gustafsson (2007) estimate that the installment costs of some 100 wind-powered pump stations would be about 200 million Euros. This is relatively low compared to other engineering projects. However, it has to be noted that no feasible pumps exit as of yet. Ollikainenen et al (2016) cost benefit analysis of pumping in the gulf of Finland concludes that it could be net-beneficial for the coastal areas, but that it is highly doubtful that it could have a net positive effect in the open seas, even under the most optimistic scenario.
Likelihood of environmental risks	High	Conley et al (2009) and Conley (2012) highlight the many environmental risks related to such a scheme, and warn of large scale impacts on ecosystems and even of a reintroduction of toxins that rest on the ocean floor into the food system. One major issue of concern would also be cod reproduction (Conley, 2012), which is a highly complex issue already (Rak et al. 2020).

Effects on local/ indigenous communities	Beneficial	The current state of the Baltic has major consequences for local communities, and a potentially more oxygenated Baltic could prove a boom for those who rely on fishing. However, there are potentially also risks that could make the situation even worse (Conley et al. 2009).
Ease of reversibility	unknown	If the pumping would be stopped while the cause of the problem remains, it is likely that the system will revert to a low-oxygen state.
Risk of termination shock	Medium	There could be significant negative effects if the artificial mixing of water levels suddenly halted (see Artificial Upwelling and Artificial Downwelling).
Suitability within current legal/ governance structures	Medium	This could partially be done in waters that fall under States' exclusive sovereignty, however, given the probable regional and Baltic wide effects, international collaboration would likely be required.
Amount of attention in scientific journals and public media and currently ongoing research programs	medium	There has been some scientific attention for this project and it has been featured several times in popular media too.

Ocean Alkalinity enhancement

Issue being addressed	The oceans are the largest carbon sink for atmospheric carbon, and have taken up over 30% of anthropogenic emissions. Carbon uptake mainly occurs directly through ocean-atmosphere interaction or through weathering processes. Due to this uptake of carbon the oceans turn more acidic overtime, and since the start of the industrial revolution oceans have become 30% more acidic. This has all sorts of effects, as it for example impacts marine biochemistry, and prevents certain organisms from successfully growing.
Description of the technology/ measure	Ocean Alkalinity Enhancement (OAE) seeks to counter the acidification of the oceans and enhance their Ph by introducing alkalinity (Renforth and Henderson, 2017). This would serve to restore the oceans to a previous state, and it could also increase the future carbon uptake potential of the ocean. Although most attention has been paid to enhanced weathering on land (NASEM, 2022), OAE is increasingly being considered as one of the main potential ocean based CDR methods. There are different potential OAE techniques, with GESAMP (2019) listing the following: Adding lime directly to

	the ocean, Adding carbonate minerals to the ocean, Accelerated weathering of limestone, Electrochemical enhancement of carbonate and silicate mineral weathering, Brine thermal decomposition of desalination reject brine, Open ocean dissolution of olivine, Coastal spreading of olivine, and Enhanced weathering of mine waste.	
Technological readiness	Low	There are research projects on OAE as a CDR method (see RETAKE: retake.cdrmare.de/), as well as some proposals for small scale experiments (see the olivine weathering experiment at the port of Rotterdam: Pokharel et al. 2023), and private companies that look at the commercial development of OAE (see: Planetary Technologies, planetarytech.com/). Many open questions still remain, for instance around issues like the durability of carbon sequestration of OAE (Hartmann et al. 2023), the stability of the added alkalinity (Moras et al., 2022), the measure's broader environmental sustainability (Foteinis et al. 2022), and potential measurement and verification techniques (GESAMP, 2019; NASEM, 2022). All proposed materials have their potential benefits and drawbacks (Bach et al. 2019). There is also no clarity about the best possible distribution methods, with ships (Burt et al. 2021; Caserini et al., 2021) and aircraft (Gentile et al. 2022) being considered. NASEM (2022) note that although some basic physical processes around the 'seawater-Co2 system and alkalinity thermodynamics are well understood', current research is largely based on modeling studies, and there is large uncertainty about the actual effect and impacts of OAE for CDR purposes. GESAMP (2019) equally concludes that ''[i]nsufficient research and testing has been done on these topics to allow informed decision-making on large-scale deployment.' The IPCC AR6 wg3 Synthesis Report (2023, p. 52) also notes that it considered OAE to be of relatively lower maturity as opposed to other CDR measures. The State of Carbon Dioxide Removal report also ascribes it a very low technological readiness level (Smith et al. 2023).
Scalability	Medium	OAE is being considered in both coastal areas and open seas, and although much depends on the durability of the achieved carbon capture and the potential unintended side effects, NASEM (2022) therefore attributes the measure a medium to high potential for scalability.' GESAMP (2019) states that logistical and practical considerations make it likely that OAE will potentially find its first applications on a local and coastal scale.
Timeliness for near-future effects	Medium	As many open questions remain about the feasibility and most promising OAE method, research programs as the one lined out in

		NASEM (2022) are needed to be able to evaluate the potential timeliness of this measure.
Potential to make a difference in Northern + Arctic	High	OAE could be deployed regionally, and would then have most pronounced alkalinity effects there (Jin and Cao, 2023). Burt et al (2021) find that such applications could potentially have an ever greater global effect than a global distribution scheme. This statement is confirmed by Wang et al (2022), as they specifically tested OAE application in the Bering Sea in their model and found it to have surprisingly high efficacy.
Potential to make a global difference	High	Model studies show OAE could have significant but variant global potential (Taylor et al., 2016; Fakhraee et al., 2022), with Feng et al. (2017) for instance finding that large- scale application could draw down as much as 800Gt CO2 from the atmosphere by 2100. NASEM (2022) estimates the potential global carbon sequestration of OAE to be over 1 Gt CO2/yr. The IPCC AR6 wg3 (2022) report and The State of Carbon Dioxide Removal report (Smith et al. 2023) both provide a very broad carbon capture potential estimate of 1 to 100 GtCO2 per year. However, to all this it has to be added that to make a significant impact, large amounts of material would have to be used (DOSI, 2022).
Cost - Benefit	Medium	Costs of OAE would be highly dependent on chosen material, strategies, goals etc,. Köhler et al (2010) for example estimate a cost of €70 to 150 per tonne of captured carbon with olivine. NASEM (2022) roughly estimates up to 150 dollars per tonne of captured CO2. The State of Carbon Dioxide Removal report and the IPCC AR6 wg3 give a figure of 40 to 260 $/tCO2 (Smith et al. 2023).
Likelihood of environmental risks	Medium	NASEM's (2022) attributes a medium level of potential environmental risks to this measure. Ferderer et al (2022) find limited effects of OAE on phytoplankton in comparison to the measure's CDR potential, but urge more research is needed. They furthermore remark that the benefits and drawbacks of OSE will be complex and plural, and that these will have to be weighed against the detrimental effects of ocean acidification. It is however generally accepted that significantly more research needs to be done to provide more clarity on this matter (GESAMP, 2019). Apart from detrimental environmental effects in the ocean, there could also be significant effects on land as a result of the mining of the materials needed (Smith et al. 2023).

Effects on local/ indigenous communities	Unknown	Both ocean acidification and OAE will have significant effects on coastal communities (Doney et al., 2020; Foteinis, 2022). Effects of OAE could have side benefits, as Pokharel et al (2023) for example suggests might be the case in relation to toxicity in the port of Rotterdam.
Ease of reversibility	Easy	The effect of OAE would overtime naturally subside.
Likelihood of termination shock	medium	Gesamp (2019) writes that 'the duration of deployment of enhanced ocean alkalinity would need to be continuous if sustained carbon dioxide removal and/or ocean acidification mitigation are required.' Jin and Cao (2023) equally find that a sudden termination of OAE would cause a rapid warming, although this warming would only be up to the expected level had it not been deployed in the first place, and not comparable to the effects of suddenly stopping SAI. They also find that such a termination would have a very substantial effect on ocean acidification, which would very rapidly start to decrease if no new alkalinity were added.
Suitability within current legal/ governance structures	Medium	Like ocean fertilization, OAE could be included to fall to a certain extent under the London Protocol, although additions would have to be made for this (DOSI, 2022).
Amount of attention in scientific journals and public media and currently ongoing research programs	Medium	There has been substantial interest in marine and land-based enhanced weathering as a CDR measure (NASEM, 2022). Some research projects and private companies are already exploring OAE, but many issues still remain open and research would have to be expanded significantly (GESAMP, 2019; NASEM, 2022). Recently, a protest in the UK against Planetary Technologies plan to add magnesium hydroxide to wastewater gained media attention (www.theguardian.com/uk-news/2023/apr/17/protesters-urge-caution-over-st-ives-climate-trial-amid-chemical-plans-for-bay-planetary-technologies).

River Liming

Issue being addressed	The pH of water is lowered when it takes up atmospheric carbon. Given that the Earth's oceans serve as a major carbon sink, there is increasing interest in the possibility to artificially increase the alkalinity of water to restore pH to previous levels, and/or increase carbon uptake potential.

Description of the technology/ measure	Like Ocean Alkalinity Enhancement, river liming seeks to increase alkalinity of water sources to increase atmospheric CO2 uptake. Because the limed rivers would ultimately flow into the ocean, this measure could thereby also be used as an extended introduction mechanism for Ocean Alkalinity Enhancement.	
Technological readiness	low	Apart from scarce earlier mentionings (Köhler et al 2010), the idea of liming rivers, or even wastewater (Cai and Jiao, 2022), by olivine has seemingly only very recently been forwarded in several presentations (Rønninget al. 2023; Sterling et al. 2023) and a thought experiment (Mu et al. 2023). Because these suggestions have been done in the form of presentations, and no peer reviewed articles have seemingly been published on the idea, details and results of the announced experiments are left out here.
Scalability	unknown	
Timeliness for near-future effects	Unknown	
Potential to make a difference in Northern + Arctic	unknown	Arctic rivers are important for the alkalinity of the Arctic ocean and its CO2 uptake (Olafsson et al. 2021), and river liming could therefore perhaps be a suitable measure if alkalinity enhancement is found to be a feasible CDR technique.
Potential to make a global difference	unknown	
Cost - Benefit	unknown	
Likelihood of environmental risks	unknown	Köhler et al (2010) states that the distribution of material and the broader environmental effects of liming should be especially thoroughly explored for rivers and coastal ecosystems.
Effects on local/ indigenous communities	Unknown	
Ease of reversibility	unknown	
Risk of termination shock	unknown	
Suitability within current legal/	High	

governance structures		
Amount of attention in scientific journals and public media and currently ongoing research programs	low	As mentioned above, the idea has likely mainly been suggested in a few recent presentations at the 2023 EGU meeting in Vienna.

Wildfire management	
Issue being addressed	Fire is important to the healthy functioning of boreal ecosystems. However, as wildfires increase, they release greater amounts of GHGs into the atmosphere, contributing to climate change. While boreal fires typically contribute 10% of global CO_2 emissions, in 2021, an extreme fire year, they accounted for 23% of global emissions (Zheng *et al*. 2023). Particulate matter in wildfire smoke (soot or black carbon, see also Black carbon mitigation) can also reduce albedo on sea ice and glaciers, enhancing ice melt (e.g., Aubry-Wake *et al*. 2022). Wildfires are projected to increase in both frequency and intensity over the coming decades (UNEP 2022). By 2050, wildfires in North American boreal forests alone could contribute close to 12 Gt CO_2, almost 3% of the remaining global CO_2 emissions to keep temperatures to below 1.5^{o}C (Phillips *et al*. 2022a).
Description of the technology/ measure	As stated, wildfires are a natural and necessary part of forest systems, and it is not desirable, let alone possible, to suppress or prevent all fires. There are however several different ways to mitigate the effect of radically changing forest fire regimes. Increased fire management through fire suppression, risk reduction, or preventative burning can help return fire regimes to historical levels (Elder *et* al. 2022; Phillips *et al*. 2022a). In a recently presented paper at the EGU 2023, Kelly et al moreover suggest that management during the first years after a fire are important too, as they found that 'similar magnitudes of carbon were emitted as CO2 in the first 4 years after the fire compared to the carbon emitted during the fire itself'. Although this will not be discussed in this section, it has also been found

	in model studies that SAI could reduce forest fire risk (see Tang et al (2023) and Stratospheric Aerosol Injection).	
Technological readiness	high	Technologies and measures are currently available, and fire management has been historically practiced by indigenous communities (Hoffman et al. 2021).
Scalability	Medium	Forest fire management would be more or less suitable in specific areas. Most fire management spending is focused on areas near human settlements, which makes the scalability of this measure limited in the vast areas of the Arctic that are unpopulated. In relation to proposals to use changes in forest management, reforestation and afforestation as climate mitigation measures (see elsewhere in this report), fire management could play an ever more important role in assuring the durability of such projects.
Timeliness for near-future effects	High	The practices are already developed and could be implemented in order to mitigate the effect of boreal forest fires in the near future.
Potential to make a difference in Northern + Arctic	High	The amount of GHG emissions from Boreal forests would be highlight dependant on the Earth's warming trajectory, as Amiro et al (2009) show that in the case of Canadian boreal forest fires GHG emissions are 'estimated to increase from about 162 Tg·year–1 of CO2 equivalent in the 1×CO2 scenario to 313 Tg·year–1 of CO2 equivalent in the 3×CO2 scenario'. However, significant emission increases and mitigation potential are to be expected. Phillips et al (2022) literature review reveals an expected increase in burned areas of '24 to 169% from 2020 to 2050 in Alaskan and 36 to 150% in Canadian boreal forests', and that this would lead to a release of 1.33 to 11.93 Gt of CO2, but that improved fire management could reduce this by '0.89 to 3.87 Gt of CO2 between 2021 and 2050.' There will however be important regional differences in the importance of wildfire management strategies, as

		Högberg et al (2021) show that '[t]he area affected by fires was around 0.5 - 0.6 % per year in Alaska, Canada and Russia, which compares with around 0.01 % in the Nordic countries, a difference by a factor 50 - 60.' Apart from the direct release of carbon due to combustion, fire management is especially important in the region to potential indirect effects. Black carbon emissions from forest fires could for example lead to decreases in albedo, and intensifying forest fires will also affect other GHG emitting processes in the region. Veraverbeke et al (2021) for instance emphasis the extra vulnerability of permafrost and peatlands under intensifying Arctic-Boreal fire regimes (see also peatland restoration and protection), whilst Ribeiro-Kumara et al (2020) highlight the complexity and potentially significant changes in soil GHG fluxes under changing boreal fire regimes.
Potential to make a global difference	Medium	By 2050, wildfires in North American boreal forests alone could contribute close to 12 Gt CO_2, almost 3% of the remaining global CO_2 emissions to keep temperatures to below 1.5°C (Phillips *et al*. 2022a). However, not all these emissions can be avoided with management practices.
Cost - Benefit	low	Phillips *et al*. (2022b) clearly states that it takes about US$12.63 to avoid one ton of CO_2 emissions from fires in Alaska in comparison to $23-26 per ton for onshore wind power and $32-41 per ton for utility-scale solar power. It seems clear that the ‘costs of avoiding carbon dioxide emissions by means of increasing investment in fire management are comparable to or lower than those of other mitigation strategies” (Phillips *et al*. 2022a). Two studies on requirements for Alaska however clearly indicate that Investments would need to increase: by a factor of four to reduce emissions from fires to historical levels (Phillips *et al*. 2022b), and ten-fold by 2100 under a high emissions scenario (Elder *et al*. 2022).

Likelihood of environmental risks	Low	Overzealous fire suppression risks creating combustible material buildup and would prevent beneficial effects of fires to ecosystems.
Effects on local/ indigenous communities	Beneficial	Many indigenous communities have historically already managed forest fires. Successful management strategies will likely create safer and more predictable circumstances, and could lead to major other benefits, most notably related to health improvements due to improved air quality.
Ease of reversibility	High	It is reversible by default
Risk of termination shock	Low	If forest fires become too managed, it might be that the removal of such practices would lead to relatively rapid shifts in fire regimes.
Suitability within current legal/ governance structures	High	Forest fire management practices can be implemented on national territories. Current governance structures should however be rebalanced from reactive fire suppression towards proactive mitigation and management measures (UNEP 2022).
Amount of attention in scientific journals and public media and currently ongoing research programs	Medium	The importance of forest fires and their increasing frequency and intensity is increasingly recognised in and outside of academia. However, Philips et al (2022a) note that '[t]hus far, limiting boreal wildfires has not been explicitly considered as a climate mitigation strategy.'

Afforestation, reforestation and forest management

Issue being addressed	Although the rate of deforestation has slowed over the last few decades, the world is still losing forest cover (FAO, 2020). Adequate management, protection, and restoration of existing forests, and the planting of unforested areas, play a crucial role in climate mitigation scenarios (IPCC AR6 WG3), and many countries now include forests in their climate mitigation targets (NDCs).The Northern and Arctic regions are essential in this endeavor since they are home to large swaths of boreal forests that make up 27% of total global forest area (FAO, 2020).

Description of the technology/ measure	Forest-based climate mitigation can occur through various means, here referred to as forest management and afforestation and reforestation. Forest management refers to the proper management of existing forests and the utilization of harvested wood products. This can be done with the aim of enhancing their carbon sink function, i.e., increasing site-level C density (e.g., intensive management, fertilization), increasing landscape-scale C stocks (e.g., sustainable forest management), or increasing off-site C in products (e.g., longer-lived wood products). Managementment practices can also aim to reduce carbon sources through: maintaining forests (e.g., preventing deforestation and land-use change), maintaining site-level C density (e.g., avoid degradation), maintain landscape-scale C stocks (e.g., suppress disturbances), and increase bioenergy and substitution (e.g., residue management) (Lemprire *et al*. 2013; Smyth *et al*. 2018). Afforestation refers to the process of planting trees on previously unforested land, while reforestation aims to replant trees in areas where forests were removed. Apart from physically planting trees, successful Afforestation and Reforestation (AR) projects need to ensure that the planted trees survive, and that the right kinds of trees are planted that would best fit within local systems (for example to optimize biodiversity or provide co-benefits to local populations). AR is an important part of all climate mitigation scenarios (see IPCC AR6 Wg3, 2022). The measure may be best suited to the tropics due fast growing rates and high carbon uptake, and limited negative geophysical effects like a lowering of albedo (Lewis et al. 2019; IPCC AR6 WG3).	
Technological readiness	High	Although the practise of planting of trees and managing forests already exists and is clearly technologically feasible (The IPCC AR6 WG3, 2022, and The State of Carbon Dioxide Removal report, 2023, assign it a TRL of 8 to 9), research is still being done into specific elements. This measure could potentially even include selecting for highest potential albedo effect (see bio-geoengineering). There is moreover still significant uncertainty about the overall climate effect of afforestation, especially in the high latitudes (Vogt et al. 2022).
Scalability	Medium	The CDR potential for a scaling up of AR and forest management is large. However, physically, it must be ensured that it does not compete with other requirements, like food and water security, and that it is not detrimental to climate goals, such as local biophysical effects (e.g., albedo reduction might outweigh the effect of carbon sequestration; Pielke et al., 2011). It must also be ensured that the planted trees are climate resilient and can resist likely increased extreme temperatures. There are very accessible sites where forests could cheaply and effectively be restored or planted at scale (IPCC AR6 WG3). Because

		a/reforestation in tropical regions comes with significant biophysical climate benefits, these regions would be especially suited for AR. However, Windisch et al (2022) note that such projects would likely clash with food production.
Timeliness for near-future effects	High	If countries realize their pledges regarding forests to the Paris Agreement, forests could become a net carbon sink by 2030 (Grassi et al. 2017), and play an increasingly important goal in GHG mitigation. One issue with AR and forest management is related to its permanence as a CDR measure. Although trees could capture large amounts of carbon effectively, ineffective strategies, forest fires, droughts, and other causes could see massive re-release of CO2 (Fuss et al 2018; Chiquier et al. 2022). Melnikova et al (2022) found that afforestation therefore could take up more carbon than another CDR method BECCS (See BEECS) in the short term (20/30 years), but that BECCS could be more effective in the long run.
Potential to make a difference in Northern + Arctic	Medium	The Vogt et al (2022) study on the role of AR in the Nordic region clearly states that 'The potential for re-/afforestation in the Nordic countries is limited compared to other European countries, as a large proportion of their land is already forested, with relatively limited areas suitable for agriculture.' They moreover conclude that both the CDR effect and the net climate effect of AR in the Nordic region remains uncertain and is still debated in scientific studies. Although many assessments of AR neglect biophysical effects and mostly focus on CDR estimates (Breil et al. 2023), Dashti et al (2023) study strongly highlighted the importance of the biophysical effects of land cover change, and note this is particularly strong in higher latitudes. In fact, whereas AR generally has an extra cooling effect on lower latitude regions, it risks reducing albedo in Northern regions and negating all climate positive effects (Bright et al. 2017; Windisch, 2022). Alongside being a CDR measure, AR and forest management improvements are also used in the Arctic and Northern regions to increase biomass production to replace fossil fuels (see BECCS). Melnikova et al (2022) study found that BECCS would likely be a more effective CDR method at high latitudes. As growing forests for both functions could lead to different ecosystem and climate effects, these aims have to be weighed against each other (Vogt et al. 2022). Due to warming temperatures, land cover changes in northern and arctic regions are already changing rapidly. This must be taken into

		consideration when planting trees on a large scale, as it might for example be a threat to previously largely open spaces or low-growth ecosystems (Halldórsson et al., 2008). This effect is for example visible in Iceland, where incentives to reforest the island have been observed to have a major impact on ground nesting birds (Pálsdóttir et al. 2022).
Potential to make a global difference	High	Estimates of total sequestration would partially depend on carbon prices, and Austin et al. 2020 suggested that 1.6 GtCO2 yr–1 could be sequestered globally through AR for an annual cost of USD130 billion if prices were at USD100 tCO2 –1. Roe et al’s (2021) literature review showed a median AR CDR rate of 475 MtCO2 yr−1 in 2050. The IPCC AR6 Wg3 (2022) gives 'medium confidence that the global technical mitigation potential of afforestation and reforestation activities by 2050 is 3.9 (0.5–10.1) GtCO2 yr–1', while Fuss et al. (2018) give a lower global estimate of 0.5–3.6 GtCO2 year-1 by 2050. With regards to forest management, Ameray *et al*. (2021) note that there is currently low understanding of ‘how forest management strategies affect the net removal of greenhouse gasses and contribute to climate change mitigation’, and Roebroek et al (2023) even show that cessation of management strategies and allowing natural forest development can have positive climate effects.
Cost - Benefit	Low	For AR, Fuss et al (2018) give a potential cost range from a very low 5 to 53 US$ per ton of CO2 removed (Fuss et al 2018), while the IPCC AR6 Wg3 (2022) estimates a cost of 0-240 USD per tonne. Costs would likely highly depend on geographical area and project. Potential costs could be reduced through payment for ecosystem schemes like REDD+, or other carbon offset schemes, which could draw in money from polluters to offset their emissions.
Likelihood of environmental risks	Low	The large-scale planting of trees can have significant beneficial environmental effects if done right, but, done incorrectly, it can be highly detrimental for local ecosystems and biodiversity (IPCC AR6 Wg3, 2022). Although these effects will likely be not as pronounced as those of other CDR measures, in the Northern regions effects on biodiversity could be significant (Vogt et al. 2022. Pálsdóttir et al (2022), for example, found a major impact of reforestation practices in Iceland on ground nesting birds, and Mooney and Lee (2022) attribute an increase of "rain-on-snow" events that poses major difficulties to local ecosystems and communities to afforestation.
Effects on local/ indigenous communities	Neutral	The large-scale planting of trees can have significant benefits, but potentially also some detrimental effects depending on the execution of the project in question (IPCC AR6 Wg3, 2022).

		Afforestation could importantly provide additional sources of income and restore soils and biodiversity. Although it is generally noted that afforestation could also compete for land and drive up food prices (Kreidenweis et al. 2016), this is likely to be minimal in the Arctic and Northern regions. In the sub-polar and Arctic, afforestation could have detrimental social effects on communities that rely on open landscapes (Vogt et al. 2022) and lead to an increase of "rain-on-snow" events, which pose major difficulties to local ecosystems and communities (Mooney and Lee 2022).
Ease of reversibility	Easy	If found to be undesirable, trees could be removed again.
Risk of termination shock	Low	It must be ensured that the planted trees are climate resistant as increasing heat extremes could increase forest fires significantly in the future (see forest fire management).
Suitability within current legal/ governance structures	High	Planting trees on national territory is unproblematic, although care must be taken this is done in a just way, and does not infringe on water and food security.
Amount of attention in scientific journals and public media and currently ongoing research programs	High	Afforestation is generally a popular and acceptable CDR method and often framed as a “natural” measure (Walller et al. 2023). With regards to this, the IPCC AR6 Wg3 notes that ‘The sometimes sole attention on afforestation and reforestation – suggesting it may solve the climate problem to large extent, in combination with the very high estimates of potentials – have led to polarization in the debate, resulting in criticism to these measures or an emphasis on nature restoration only’ (2022, p781) There are major international AR campaigns, like the One Trillion Trees project by the World Economic Forum (https://www.1t.org/) and the The Bonn Challenge (bonnchallenge.org), which aims to restore 350 million hectares by 2030. There is also significant commercial interest through measures such as REDD+ and carbon offsets, and many companies are now investing in tree planting to offset their emissions. The State of Carbon Dioxide Removal report (2023) finds that the relative number of scientific studies on AR has significantly decreased over the last years, in favor of other CDR measures like soil carbon sequestration and especially biochar.

<table>
<tr><th colspan="3">Reindeer herding</th></tr>
<tr><td>Issue being addressed</td><td colspan="2">In many Arctic and Northern regions, domesticated or semi-domesticated reindeer (*rangifer tarandus*) are the only large herbivores (Uboni et al. 2016). Reindeer play a crucial role in these ecosystems and in the livelihoods and traditions of multiple local and indigenous populations.
In light of the major impact of climate change in the Arctic, the capacity of large herbivores to mitigate some of these effects is being explored. Herbivores can have different climate positive effects as they can reduce shrubification and slow ecosystem responses to climate change (Olofsson and Post 2018; Happonen et al., 2021), modify summer and winter surface albedo (te Beest et al. 2016), trample winter snow to thicken permafrost (Beer et al. 2020; Windirsch et al. 2022), and increase biomass and soil carbon sequestration (Ylänne et al., 2018; Ylänne et al. 2021; see also soil management).</td></tr>
<tr><td>Description of the technology/ measure</td><td colspan="2">The Arctic contains around 1.8 million reindeer on some 1.8 million km2 (Forbes et al. 2006), and the effect of wild caribou and domesticated reindeer have been found to be practically similar (Bernes et al. 2015). This makes the management of reindeer a potentially impactful measure alongside major rewilding efforts with multiple species as is done in the pleistocene park experiment (see re-wilding). Marin et al (2020) however clearly show that the case of failing reindeer policies in the northern Norwegian region of Finnmark exemplify the need for management strategies that are sustainable and not (primarily) focussed on productivity.
The main currently ongoing research project on reindeer management and presence in the Arctic is the multinational and multidisciplinary EU-funded CHARTER project (charter-arctic.org/), which, amongst other goals, seeks to provide clear policy advise on the potential of reindeer management in the region to mitigate some of the effects of climate change. CHARTER even uses the term ‘biogeoengineering’ for the large-scale management of reindeer grazing (see CHARTER Deliverable 5.2; N.B. this definition of biogeoengineering differs from how it is used elsewhere in this report). The project is still ongoing, and was severely hampered by the break in relations with Russia mandated by the EU due to the Ukraine war. So it has not yet released clear findings on potential scale and feasibility or form of potential management proposals.</td></tr>
<tr><td>Technological readiness</td><td>high</td><td>Reindeer herding has long since been practiced by indigenous Arctic communities, and implementation of novel herding strategies can likely be done without the development of novel technologies.</td></tr>
</table>

Scalability	high	Physically, alternative reindeer herding strategies could potentially be implemented across the 1.8 million km2 where reindeer are currently living. But there could be significant clashes with other forms of land use such as forestry (Horstkotte et al. 2022; see also afforestation and forest management). In the CHARTER working paper 1, Eronen et al (2020) also clearly state that: 'Almost every new land-use project has detrimental impacts on reindeer herding.’ There might however also be cases of positive feedback between reindeer herding and other forms of land management, as Tarvainen et al (2022) for example find that peatland restoration might be combined with the usage of those lands for reindeer herding (see also peatland restoration).
Timeliness for near-future effects	high	CHARTER is not yet completed, and follow up research is likely needed. However, it seems likely that the relatively flexible nature of herding management could quickly be shifted to a more optimal strategy. In any case, the project description clearly notes that it aims to provide ‘policy-relevant, testable and locally applicable results for the next generation, out to the year 2050’.
Potential to make a difference in Northern + Arctic	Unknown	Although most studies seem to indicate climate positive effects of reindeer herding, some note detrimental effects, for example on permafrost stability and surface albedo (See for a clear literature review the CHARTER scientific background document). It is furthermore still unknown if reindeer management strategies can make a significant and durable impact on the region, especially in light of the rapidly increasing temperatures.
Potential to make a global difference	Low	If reindeer herding turns out to be able to help to preserve Northern permafrost this can also have significant global effects. This is planned to be simulated using Earth System Models in Charter. However, the dominant effects of this measure will remain largely regional.
Cost - Benefit	Unknown	Costs would depend on the extent of the proposed shifts in current practice. Reindeer herding requires significant amounts of land, and can therefore conflict with commercial interests related to logging, infrastructure, mining, renewable energy generation, or afforestation. If this measure is considered mostly for its potential climate positive effect, there will have to be a cost-benefit analysis against other measures.

Likelihood of environmental risks	Low	Modifying reindeer territories will lead to different ecological and environmental effects (Stark et al 2023). It has to be ensured that such modifications are sustainable under near-future climate conditions in a warming region. However, given the very known practice of reindeer herding, it is unlikely to come with significant risks.
Effects on local/ indigenous communities	Beneficial	Reindeer herding is of high cultural and historical significance for Sámi Indigenous peoples. Reindeer husbandry provides employment and income through meat production, tourism and handicraft production. However, as stated above, reindeer herding can also conflict with several other economic activities, and interests will have to be weighed.
Ease of reversibility	easy	If found to be undesirable, reindeer could easily be removed again from the concerned areas. Shrubs would regrow in a decade.
Risk of termination shock	low	
Suitability within current legal/ governance structures	high	Indigenous reindeer herding is protected under international legal norms in Norway, Sweden, Finland and Russia, the four nations that make up Sápmi (Kirchner and Fresse 2016). See for example the Reindeer Husbandry Act (848/1990) from the Ministry of Agriculture and Forestry, Finland.
Amount of attention in scientific journals and public media and currently ongoing research programs	medium	Although reindeer herding has not been picked up by global media like Pleistocene Park has, there is major regional interest in the topic. There is also significant academic interest in the topic, both from social- and natural scientists, with CHARTER being the central research project.

Rewilding

Issue being addressed	Large areas of the Northern and Arctic regions consist of permafrost, almost permanently frozen soil. As global temperatures rise, these permafrost areas are thawing at an ever faster rate. This thawing leads to massive amounts of GHGs being released into the atmosphere, either as CO2 or CH4 in generally dry or wet areas. Because methane is a very potent GHG, the thawing of the

	permafrost is considered a major tipping point in the climatic system. Permafrost preservation is of the utmost importance because Arctic terrestrial regions alone hold up to 1500 Pg C (Schuur et al. 2015), and although there is large uncertainty about the total amount of emissions from permafrost (Miner et al. 2022), especially when it comes to nonlinear abrupt thawing (Turetsky et al. 2020), significant amounts of carbon release is to be expected as the Northern regions warm.	
Description of the technology/ measure	Natural climate solutions like conservation or restoration can significantly contribute to climate change mitigation efforts (Griscom et al. 2017). One such category of natural climate solutions is re-wilding. The concept is contested, with some scientists even suggesting doing away with the term altogether and replacing it with restoration (Hayward et al. 2019), but is generally used to refer to large scale projects to (re)introduce larger herbivores and predators to ecosystems. Several Re-wilding schemes in the Northern and Arctic region investigate whether it might be feasible and desirable to recreate elements of the environment as it existed during the Pleistocene, so-called Pleistocene re-wilding (Donlan et al. 2006), to preserve parts of the permafrost. The main re-wilding project in the region is Pleistocene Park, which is located close to the Arctic ocean in the far north of Russia's Sakha Republic (https://pleistocenepark.ru/). The Park is run by father and son Sergei and Nikita Zimov, and attempts to show the possibility to preserve permafrost, or slow its thaw, by Pleistocene re-wilding in an area that is mostly covered by boreal forest. Controlled experiments and observations at the Park have shown that the introduction of large animals has multiple beneficial climate effects, as it reduces soil temperatures leading to increased winter permafrost thickening, increases bio-productivity and encourages carbon storage, and increases albedo through shrub reduction (Zimov, 2005; Fischer et al. 2022). Although it has to be noted that there are still debates on the ultimate effects of re-wilding in terms of ecosystem services in the region, for example with regards to side effects of the removal of shrubs by herbivores, which have also been found to be detrimental to permafrost stability (Nauta et al. 2015).	
Technological readiness	medium	Pleistocene park already exists, but it only consists of 2,000 hectares and contains a limited number of large herbivores of different species. To be truly effective, the Park would require huge amounts of land and animals. Current Arctic biodiversity levels and ecosystems differ greatly from those in the Pleistocene, particularly when it comes to the presence of megafauna (Olafson and Post, 2018), and Pleistocene re-wilding strategies therefore seek to use various kinds of large herbivores to recreate parts of the previously existent grasslands that extended across vast swaths of the north that are currently covered by taiga forests.

		Because many of the larger herbivores would have trouble removing already existing boreal forests, an idea is to bring back the mammoth from extinction, or at least create a modified cold-resistant elephant, and introduce it to the Park. The elephant/mammoth would be a key species because it would be able to bring down trees and could thereby gradually expand the grasslands, a task that is now still being performed by large ex-military vehicles. Although there is still uncertainty when this introduction would take place, the geneticist team at Harvard who are working on it say a first hairy elephant could be born within the next few years (Dutchen, 2021).
Scalability	Low	The most serious obstacles for a project like Pleistocene Park are its scalability and potential to make a meaningful difference at the required timeframe (Macias-Fauria et al. 2020). Given the huge area that would need to be re-wilded, the reproduction rate of animals is a serious issue, especially for the mega-fauna that would be crucial to the success of the re-wilding due to their ability to remove trees. It is furthermore also not certain that the ecosystem would remain viable in the contemporary and future climate, as conditions are vastly different from how they were during the Pleistocene.
Timeliness for near-future effects	Low	There are large uncertainties over the rate of permafrost melt, and the potential to see sudden massive melt. Given the slow reproduction rate and potential obstacles, it is questionable if rewilding efforts could significantly impact methane release from permafrost in the coming decades.
Potential to make a difference in Northern + Arctic	High	Both experimental research at Pleistocene Park (Fischer et al. 2022; Windirsch et al. 2022) and model studies (Lucas and Enos, 2019) confirm that the approach could be effective, although the efficacy of rewilding remains largely unknown. In any case, the large-scale implementation of such schemes would also impact the region in other ways, as rewilding will have significant side effects (see below).
Potential to make a global difference	Medium	Permafrost can potentially release massive amounts of GHGs, but it is unsure how much rewilding can credibly be prevented by rewilding.
Cost - Benefit	Low	Although the project could bring in significant financing through carbon credits (Macias-Fauria et al. 2020), initial costs of such a project would likely be higher than in some other schemes, especially compared to SAI technologies. It is possible that rewilding could become a source of food, or could have other benefits to biodiversity or to local ecosystems that might reduce

		costs further. A carbon price of 5$/ton would make an investment in this kind of re-wilding repay over 100 years (Macias-Fauria et al. 2020).
Risk of environmental risks	Medium	It is not certain that the newly rewilded ecosystem would remain viable in the contemporary and future climate, as conditions are vastly different from how they were during the Pleistocene. The region is already becoming increasingly vulnerable to wildfires, and it has to be studied how this would affect it. Moreover, mass-scale rewilding would cause radical changes in ecosystems, which will have widespread consequences (Rubenstein et al. 2006). However, as these are all “natural” interventions, such risks are potentially less objectionable than those caused by artificial measures.
Effects on local/ indigenous communities	Unknown	There has been little attention to possible effects on local and indigenous communities. Pleistocene rewilding strategies would seek to be, what Fraanje and Garnett (2022) call *land sparing*, meaning that it would seek to have as little human presence as possible. Certain side benefits could occur, as has been postulated in the case of rewilding in Finland (Koninx, 2019).
Ease of reversibility	Medium	Probably massive rewilding would need to be highly managed for a long time until herds become self-sustaining and can expand. There have however been many examples throughout history where human introduction in ecosystems has led to runaway consequences.
Risk of termination shock	Low	
Suitability within current legal/ governance structures	High	It is likely that nation states could implement such measures on their own territory.
Amount of attention in scientific journals and public media and currently ongoing research programs	High	The mammoth-cloning-plan has, unsurprisingly, generated quite some public media interest and has led to several documentaries and a whole swath of newspaper coverage and articles. The de-extinction has also led to criticism from an ethical standpoint (Sandler, 2014). But in general, a main advantage for the reputation of Pleistocene re-wilding as practiced at Pleistocene Park is that it uses natural, low-tech measures that would likely be less objectionable than more technological and invasive technologies. At the Park there has been serious research on the effect of herbivores on permafrost. However, it is unsure what the

		effects of Russia’s invasion of Ukraine will have on the long term feasibility of this project.

Conservation and restoration of peatlands and wetlands in taiga and tundra

Issue being addressed	Wetlands and peatlands play important roles in global carbon cycles. Wetlands are areas that are seasonally covered by water. Globally mangroves are often the main topic of focus when it comes to wetlands (IPCC AR6 WG3, 2022, 7.4.2.8). In the Arctic and Northern regions, peatlands are important wetland elements, and will be the focus of what follows. Such peatlands are very carbon rich and store carbon in biomass below and above ground and in soil carbon. Although they only make up 3% of the Earth’s surface, peatlands store up to 21% of terrestrial carbon, and damaged peatlands contribute close to 5% of anthropogenic CO2 emissions (Leifeld et al., 2019). Peatland drainage between 1850 and 2015 has globally already released 80 Gt CO2-eq, and this figure may climb to 250 Gt CO2-eq by 2100 (Leifeld et al. 2019). Compared to the global state of such areas, Arctic and Northern wetlands and peatlands remain relatively intact (UNEP, 2021), and only around 2% of boreal peatlands are currently converted into croplands (Leifeld and Menichetti, 2018). However, increasing attention is being paid to the importance of restoring destroyed areas, which make up 78% of total global peatlands, and preserving endangered ones, especially in light of the effects of climate change on such ecosystems. The Resilience and Management of Arctic Wetlands notes (CAFF, 2021) therefore highlight the need for increased wetlands resilience to protect against future damage.	
Description of the technology/ measure	When it comes to enhancing or mitigating climate effects of wetlands and peatlands, this can be separated into the protection of existing-, and restoration of damaged or disappeared areas. Protecting and restoration can be done in multiple ways and is case dependent in the required approach, although most would be related to water provision (rewetting). The IPCC AR6 wg3 (2022) report likens peatland restoration to deforestation in that its conservation can be done by controlling the drivers such as 'commercial and subsistence agriculture, mining, urban expansion', or management or governance improvement.	
Technological readiness	High	The technologies and methods to protect and restore wetlands and peatlands already exist, and the IPCC Ar6 wg3 assigns it a TRL of 8/9.

Scalability	Medium	In its spatial extent, this measure is necessarily limited by definition, and could be even smaller due to the effects of climate change like sea level rise and temperature increases, which limit previously occupied territory. However, Roe et al (2019) show that the carbon mitigation potential of protection and restoration is the highest of all suggested natural land based measures.
Timeliness for near-future effects	High	The UNEP report on peatlands (2021) reads that 'Peatlands can be part of an effective climate change mitigation strategy', and that they 'could help countries meet Nationally Determined Contributions to global climate action.' Goldstein et al (2020) consider Peatlands and marshes to be 'irrecoverable carbon' ecosystems that would not be able to recover 'on timescales relevant to avoiding dangerous climate impacts', and these measures are therefore most urgent to prevent near future effects.
Potential to make a difference in Northern + Arctic	Medium	Boreal and subarctic peatlands make up 78% of total global peatlands. These areas remain largely intact, and are less vulnerable than peatland areas in other areas such as the tropics (Goldstein et al. 2020). Protection and preservation would therefore be especially important (Strack et al. 2022). However, the IPCC AR6 wg3 notes that restoration would still be important, as it would bring significant ecological and socio-economical side-benefits. The report furthermore clarifies that global warming is the biggest threat to northern peatlands as almost half of all stocks north of 23° latitude cover permafrost, the thaw of which also endangers the peatlands on top. However, large uncertainties about the future development of this process makes it difficult to estimate the magnitude of potential emissions.
Potential to make a global difference	Medium	The UNEP report on peatlands (2021) writes that 'Peatlands can be part of an effective [global] climate change mitigation strategy'. IPCC ar6 wg3 states even clearer that 'Restoration and rewetting of almost all drained peatlands is needed by 2050 to meet 1.5°C–2°C pathways (2022, p785). There are however significant differences in carbon mitigation potential estimates, for example around increased releases of methane and permanence in light of increased droughts and fires (Günther et al. 2020). More research is therefore direly needed (Monteverde et al. 2022). Strack et al (2022) note that their literature review showed that all peatland solutions could have a global potential of 1.1 to 2.6 Gt CO2e year−1 in 2030. Leifeld and Menichetti (2018) find that peatland restoration could globally reduce the emissions of 1.91 Gt CO2-eq, and note that this would require far less land nitrogen than

		an equivalent effect from an increase in carbon sequestration in agricultural soils (See carbon capture in soils). The IPCC Ar6 wg3 provides a slightly lower median estimate for restoration of 0.79 GtCO2-eq yr–1, and gives medium confidence that Peatland protection can mitigate 0.86 GtCO2-eq yr–1.
Cost - Benefit	medium	The IPCC Ar6 wg3 notes that there is insufficient data on the cost of peatland restoration to give an accurate estimate. However, the UNEP (2021) report gives a rather extensive cost-benefit analysis. The cost of peatland restoration can be very high, as a global effort to rewet '40% of drained peatlands by 2050' would mean a rise in investments from 'US$19 billion annually to US$31 billion by 2030, to US$39 billion by 2040, and then in excess of US$46 billion by 2050.' Yet, they also note that peatlands provide numerous benefits, including economical, and that the price for restoration will only rise in the future. There will be significant difference between costs of individual projects, with Roe et al. (2021) noting that 0.2 GtCO2-eq yr–1 could already be mitigated for up to USD100 tCO2 –1.
Likelihood of environmental risks	Low	IPCC Ar6 wg3 note that there is a risk of reversal of peatland restoration under increased warming and forest fires. However, there is general agreement that protection and restoration of wetlands and peatlands will provide many ecological benefits (IPCC AR6 wg3, 2022).
Effects on local/ indigenous communities	Beneficial	CAFF (2021) highlights the specific importance of wetlands for indigenous peoples in Northern regions. Apart from positive ecological and environmental effects, protection and restoration of wetlands and peatlands can, according to the IPCC AR6 wg3 report, lead to improvements in local economies and likelihood. Such measures could however be in competition with other means of subsistence. Martino et al (2022) also notes that there could be different preferences in extent of restoration strategies, with some sections of society preferring "less wild" states of natural restoration.
Ease of reversibility	Medium	As noted above, it has to be made sure that protected or restored ecosystems are viable in light of changes brought about by climate change.
Risk of termination shock	Low	
Suitability within current legal/	High	UNEP (2021) and Monteverde et al (2022) both note that there needs to be more coordination between government levels and

governance structures		international governance initiatives when it comes to peatland preservation. Seifollahi-Aghmiuni et al (2019) literature review equally highlights key gaps in wetland management plans. Apart from highlighting similar policy inconsistencies in wetland management efforts, CAFF (2021) specifically also urges for improvements in ecosystem service rapportation to international organizations, as this could encourage protection and restoration projects.
Amount of attention in scientific journals and public media and currently ongoing research programs	High	There is increasing interest in the protection and restoration of wetlands and peatlands. Apart from numerous researcher projects at various institutes, the Arctic Council's Resilience and Management of Arctic Wetlands project (sei.org/projects-and-tools/projects/resilience-and-management-of-arctic-wetlands/ and https://caff.is/wetland), in collaboration with the Stockholm Environment Institute, is the main example in the Arctic and Northern regions.

Agricultural soil management

Issue being addressed	Terrestrial carbon can be stored in biomass above or below the ground, and in soils themselves. Soil organic matter can form differently, and have different amounts of plant and microbial components depending on the availability of water (Cotrufo and Lavallee, 2022). The large amounts of the Earth that have been brought under cultivation over the past 12.000 years have significantly degraded soil carbon levels, and have released some 110 billion metric tons of carbon (Sanderman et al. 2017). Soil security and health is increasingly being recognised as essential for planetary health (Kopittke et al (2022).
Description of the technology/ measure	Agricultural soil management, as considered here, seeks to increase soil carbon content, and thereby reduce atmospheric carbon levels. There are various different methods to do so, like shifts in fertilization practices, soil tillage practices, and crop management practices, with specific strategies depending on local conditions and desired outcomes (Lessmann et al. 2022). There are therefore many links to other land management practises (see for example afforestation, and peatland restoration), as well as albedo enhancing strategies like the use of cover crops to influence albedo (Lugato et al. 2020; see bio-geoengineering) and sometimes biochar application is also considered under this category (see biochar). Amelung et al (2020) note that such soil management can be especially effective in cropland soils 'with large yield gaps and/or large historic soil organic carbon losses'.

Technological readiness	High	Straightforward soil management practices are already very well developed, and the IPCC Ar6 wg3 therefore assigns a TRL of 8/9 to Soil carbon sequestration in croplands and grasslands. Paustian et al (2019) however notes that some to-be-developed technologies might be even more effective.
Scalability	Medium	IPCC Ar6 wg3 notes that 'Regionally, soil carbon management in croplands and grasslands is feasible anywhere, but effectiveness can be limited in very dry regions, and for grasslands it is greatest in areas where degradation has occurred (e.g., by overgrazing) and soil organic carbon is depleted.'
Timeliness for near-future effects	High	IPCC Ar6 wg3 has medium to high confidence that this measure could deliver 0.6–9.3 (GtCO2 yr–1). Paustian et al (2019) literature review states that 'There is a strong scientific basis for managing agricultural soils to act as a significant carbon (C) sink over the next several decades.' Beyond this, more novel technologies might enhance effectiveness even further.
Potential to make a difference in Northern + Arctic	Low	Because the extent of cropland is limited in the Northern and Arctic region, the effects will likely be less there than in other areas of the globe. However, many foresee a northward expansion of agriculture under warming climate conditions (Unc et al (2021); Meyfroidt, 2021; Bradley and Stein, 2022; Angers et al. 2022). Unc et al (2021) notes that although this might provide food for 0.25 to 1 billion people, it also risks releasing up to 76% of vegetation and soil carbon there by 2100. This would make soil carbon management practices more relevant for the region. However, much more research would be needed, as at present, there are already large uncertainties around general soil carbon losses in the Arctic due to climate warming (Wieder et al. 2019).
Potential to make a global difference	Medium	The IPCC Ar6 wg3 gives a broad range for the global potential of Soil carbon sequestration in croplands and grasslands of 0.6 to 9.3 (GtCO2 yr–1). Fuss et al. (2018) carbon mitigation overview study estimates 0.4 to 0.8 Gt C yr−1. Lessmann et al (2022) gives an optimal global potential of 0.44 to 0.68 Gt C yr−1, but cautions that this figure is more realistically 0.28 to 0.43 Gt C yr−1. Beyond this, Paustian et al (2019) literature review notes that the developments of newer technologies might almost double expected carbon mitigation potential in a couple of decades. Guenet et al. (2021) caution that this should be done without increasing fertilizer inputs, as related N2O emissions might offset carbon mitigation gains. Related to this, Leifeld and Menichetti

		(2018) show that peatland restoration would have a similar sequestration potential, but would require far less land and 3.4 times less nitrogen.
Cost - Benefit	Low	The IPCC Ar6 wg3 estimates a cost of negative 45 to plus 100 (USD tCO2–1), depending on the local specificities and potential economic side benefits. Tang et al (2016) give estimates in the range of 3 to 130 USD tCO2–1.
Likelihood of environmental risks	Low	The IPCC AR6 (2022) notes that this measure could in some cases reduce production, but that it might also have numerous beneficial environmental side effects.
Effects on local/ indigenous communities	Beneficial	The IPCC AR6 (2022) notes that this measure could in some cases reduce production, which could be negative for local populations. Although there is also significant evidence that sustainable land management leads to numerous beneficial side effects (Branca et al. 2013). Vendig et al (2023) for example found that the use of cover crops might be especially promising as it both increased soil carbon levels and increased crop yields. Richards et al (2019) moreover find that 'synergies between adaptation and mitigation exist in many cases', and that this can be particularly beneficial in developing countries.
Ease of reversibility	easy	
Risk of termination shock	low	
Suitability within current legal/ governance structures	High	Unc et al (2021) write that there are significant differences between countries. As ‘Finland, Sweden, and Denmark support agricultural intensification through the development of resilient farming systems and food value chains that consider changing dietary preferences and impact of land use and land use changes on biogeochemical cycles’, while ‘in the Canadian prairies and Mongolia, legislation favors the northward areal expansion of commercial agriculture, even in the absence of explicit policies or strong local population pressures.’
Amount of attention in scientific journals and public media and currently ongoing research programs	High	Apart from broad scientific interest, there is increasing attention for soil management by the public and politicians. This is partially due to large international programs like the UNFCC’ *4p1000 initiative* (https://4p1000.org/), and popular grassroots campaigns like the one started by the popular figure Sadguru (https://consciousplanet.org).

Stabilizing permafrost by covering it		
Issue being addressed	Large areas of the Northern and Arctic regions consist of permafrost, almost permanently frozen soil. As global temperatures rise, these permafrost areas are thawing at an ever faster rate. This thawing leads to massive amounts of GHGs being released into the atmosphere, as carbon stored in the permafrost is converted into methane by bacteria. Because methane is a very potent GHG, the thanwing of the permafrost is considered a major tipping point in the climatic system. Permafrost preservation is of the utmost importance because Arctic terrestrial regions alone hold up to 1500 Pg C (Schuur et al. 2015), and although there is large uncertainty about the total amount of emissions from permafrost (Miner et al. 2022), especially when it comes to nonlinear abrupt thawing (Turetsky et al. 2020), significant amounts of carbon release is to be expected as the Northern regions warm.	
Description of the technology/ measure	There have been several isolated suggestions to mitigate permafrost thaw or influence the thaw processes in the active layer by physically covering the surface with materials (see for example https://groups.google.com/g/geoengineering/c/u2b9Xb5B0C8/m/aXQia-nNDbcJ) in a similar way to how glaciers might be preserved (see Glacier Insulation, and Passive Radiative Cooling). Although different materials have been suggested, these have not been worked out further, and are likely to be a very costly, and impractical solution.	
Technological readiness	Unknown	Glacier insulation is an existing technology although it is not sure if this could be directly applicable to permafrost.
Scalability	Low	This measure would require massive areas to be effective.
Timeliness for near-future effects	Low	Even if shown to be effective, the required surface area, materials, and costs make it unlikely to be deployed timely.
Potential to make a difference in Northern + Arctic	Low	This measure would require massive areas to be effective.
Potential to make a global difference	Low	This measure would require massive areas to be effective.
Cost - Benefit	High	Abermann et al (2022) already show that even for the most visited glaciers, a coverage scheme is most likely too expensive. It seems therefore unfeasible to expand this over large swaths of the north to protect permafrost.

Likelihood of environmental risks	High	The environmental consequences of large-scale operationalisation are likely enormous, as these materials would prevent sunlight from reaching the surface and thereby impact bioproductivity in the active layer. Moreover, these materials would degrade and release particles into the ecosystems.
Effects on local/ indigenous communities	negative	The implementation of such a measure on scale would likely massively impact local communities, and would especially disturb indigenous reindeer herding practices.
Ease of reversibility	Hard	The material could perhaps be physically removed, albeit likely at great costs.
Risk of termination shock	Low	
Suitability within current legal/ governance structures	High	It is likely that nation states could implement such measures on their own territory.
Amount of attention in scientific journals and public media and currently ongoing research programs	low	This idea has only been hinted at but not seriously explored.

Enhancing permafrost refreezing with air pipes

Issue being addressed	Large areas of the Northern and Arctic regions consist of permafrost, almost permanently frozen soil. As global temperatures rise, these permafrost areas are thawing at an ever faster rate. This thawing leads to massive amounts of GHGs being released into the atmosphere, as carbon stored in the permafrost is converted into methane by bacteria. Because methane is a very potent GHG, the thanwing of the permafrost is considered a major tipping point in the climatic system. Permafrost preservation is of the utmost importance because Arctic terrestrial regions alone hold up to 1500 Pg C (Schuur et al. 2015), and although there is large uncertainty about the total amount of emissions from permafrost (Miner et al. 2022), especially when it comes to nonlinear abrupt thawing (Turetsky et al. 2020), significant amounts of carbon release is to be expected as the Northern regions warm.

Description of the technology/ measure	Thermosyphon technologies that passively cool soils if the air temperature is colder than surface temperatures have been used on a smaller scale to stabilize permafrost that supports infrastructure (Xu and Goering, 2008). The largest example of thermosyphon usage is the Trans Alaska Pipeline which uses such systems along its 1300 km track. There have been some isolated online suggestions to use such a technology on a larger scale to stabilize Northern permafrost. Similarly, there has been a suggestion to use passive air cooling with large ceramic half-pipes built into the permafrost (https://klinkmansolar.com/kfrozen.htm).	
Technological readiness	low	Thermosyphon technologies are already in use, and combining them with renewable energy systems might make their cooling far more efficient (Wagner et al. 2021; Zueter and Sasmito, 2023). However, these have been only used to preserve the human built environment, and it is unclear how this would work on a larger scale.
Scalability	Low	This measure would require massive areas to be effective.
Timeliness for near-future effects	Low	
Potential to make a difference in Northern + Arctic	Low	This measure would require massive areas to be effective.
Potential to make a global difference	Low	
Cost - Benefit	High	Installing and maintaining such systems would likely come at significant cost.
Likelihood of environmental risks	unknown	
Effects on local/ indigenous communities	Unknown	
Ease of reversibility	hard	The systems could perhaps be physically removed, albeit likely at great costs.
Risk of termination shock	low	

Suitability within current legal/ governance structures	High	It is likely that nation states could implement such measures on their own territory.
Amount of attention in scientific journals and public media and currently ongoing research programs	low	Passive cooling systems for permafrost have only been hinted at, and not seriously explored.

Radiative covering and building technologies/ Passive daytime radiative cooling

Issue being addressed	An increase in GHGs in the atmosphere leads to a greater amount of outgoing infrared radiation from the earth being retained. There are several ideas to reduce the resulting warming by modifying surface radiation processes.	
Description of the technology/ measure	Passive daytime radiative cooling (PDRC) promises to provide energy free cooling through thermally-emissive surfaces that reflect incoming solar radiation whilst simultaneously enhancing longwave heat transfer to space through the infrared window of the atmosphere (8–13 µm) (Yin et al, 2020). The technology is relatively novel, and has seen rapid growth over the last couple of years (Khan, 2022). Several different variants exist that all have slightly different properties, but generally share a layered structure which allows for its shortwave reflective and longwave emissive properties, whilst not letting heat through. Some of PDRC advocates have described it as a ‘third, less intrusive geoengineering approach’ (Zevenhoven and Fält, 2018). Probably PDRC should however not be grouped under the category geoengineering (see for differing categorisations of geoengineering: Heyward, 2013; or Pereira, 2016).	
Technological readiness	medium	These materials are currently being developed in material and laboratory tests.
Scalability	Low	Such materials are likely to be most effective in the built environment, which would make them less applicable to the Arctic (see also urban albedo enhancement).

Timeliness for near-future effects	High	Many of these new materials are already in use, whilst new ones are being developed.
Potential to make a difference in Northern + Arctic	Low	Although PDRC is held up as a great promise for urban areas in temperate or desert environments, its potential for northern and Arctic regions could be limited (Yin et al. 2020). Combined with the lack of built environment to apply PDRC on, there would be serious issues with overcooling in winter, although Khan et al (2022) suggest this might be compensated for by installing switchable coatings. Li et al (2022) suggest that this technology might be used to prevent ice from melting, and it might in the future be feasible that it could be used on particularly valuable glaciers (see glacier covering), however, these would be equally limited in scalability and therefore global impactfulness.
Potential to make a global difference	Low	
Cost - Benefit	High	
Likelihood of environmental risks	Medium	
Effects on local/ indigenous communities	Neutral	
Ease of reversibility	Hard	
Risk of termination shock	Low	
Suitability within current legal/ governance structures	High	It is likely that nation states could implement such measures on their own territory.
Amount of attention in scientific journals and public media and currently ongoing research programs	Medium	There seems to be an increase in scientific papers and commercial applications that is mainly centered in China.

Bio-geoengineering (increasing crop albedo)		
Issue being addressed	Surface albedo has a significant impact on global climate (Zhang et al. 2022). Plants play an important role in this. Matthews et al (2003) for example estimate that the spread of agriculture has led to a global cooling of around 0.17°C, as agricultural crops tend to have a higher albedo than wild vegetation (Monteith and Unsworth, 1990).	
Description of the technology/ measure	The term Bio-geoengineering is used in several different ways related to the modification of living organisms (see for instance its usage by Peacock, 2015, and Reindeer management elsewhere in this report). Bio-geoengineering has for example been linked to the idea to increase the capabilities of peatlands to absorb carbon (Freeman et al. 2012), and to the aim to increase precipitation (Branch and Wulfmeyer, 2019). However, here it refers to the idea to increase land surface albedo by growing higher-albedo plants, for example: the selection for broader leaves in trees (Ridgwell et al 2009). To achieve this, the planting of already existing variants of a species or close relatives could already suffice, although gene editing might also be an option (Ridgewell et al., 2009). The topic has many links to other forms of surface albedo management (see Land Management and reindeer herding). Bio-geoengineering could be especially important when considering biofuels because the large-scale usage of forest harvesting (Bright et al. 2011) or cultivation of specific crops (Cai et al. 2016; Abraha et al. 2021) can have significant albedo effects.	
Technological readiness	Medium	Crops have always been selected for specific purposes in agriculture, and Bio-geoengineering could be seen as adding one more trait to a list of desired qualities. Ridgewell et al. (2009) say that opposed to other SRM measures, the infrastructure is already in place and relatively easily operationable. However, there have not been enough focussed studies into the topic to give clarity on the potential readiness of Bio-geoengineering, which would in any case be highly case dependent. Because the climate effect of plants can be highly complex and multiple and would have to be carefully analyzed so as not to have detrimental side-effects. As is the case for agriculture as a whole, it is also clearly required that such schemes be viable under a warming climate and increasingly high temperature extremes (Batissi and Naylor, 2009). Although Ridgewell et al (2009) and Singarayer and Davies-Barnard, 2012 stress that such practices need not negatively affect food yields, Genesio et al. (2020)

		describe an experiment with an albedo enhancing soy bean variant that would however reduce overall yields.
Scalability	Medium	A large part of the global land surface area is taken up for agricultural purposes, which has a huge climate impact, so already slight modifications of surface albedo could potentially be very impactful (Liu et al. 2022). However, there are high uncertainties around the feasibility of Bio-geoengineering and its fit within global agricultural systems.
Timeliness for near-future effects	Medium	Sometimes different varieties of the same crop species exist, which could allow for a speedy implementation by just switching variants.
Potential to make a difference in Northern + Arctic	low	As stated above, Bio-geoengineering can have significant regional effects. Sieber et al (2022) field trial and satellite observation study found significant radiative forcing reduction potential for different kinds of agricultural crops in Northern Europe. Model studies found the effects of their global application were most pronounced in the Northern regions. Ridgewell et al. (2009) and Singarayer et al. (2009) show that cooling in their studies was most pronounced in Northern hemisphere Eurasia and America, and that large-scale implementation could even slightly delay Arctic sea-ice retreat. Irvine et al (2011) model study equally shows cropland geoengineering led to slight increases in sea ice thickness and recovery, and in snow depth. However, it is not clear if the northern and Arctic regions are best suited for the application of Bio-geoengineering. Smoliak et al (2022) for example find that the highest potential for surface-based albedo interventions is clearly in the tropics and subtropics. Because of the prominence of forestry in the northern regions, this would partially hang together with findings from forestry management (see Forest management and Land management). Moreover, since Northern and Arctic regions are mostly covered by snow during winter season, any kind of land mitigation strategies should be carefully investigated as they might interfere with the effect of winter albedo (Bright et al. 2015).
Potential to make a global difference	medium	Although the global potential for albedo surface management is significant Smoliak et al (2022), and can be important for climate mitigation strategies (Zhang et al. 2022), it is generally accepted that effects would be mostly regional. In the estimates of Lenton and Vaughan (2009) the global forcing potential when applied to all the world's grasslands would be -0.51 W m^{-2}, and Irvine et al (2011) model study shows a maximum global cooling of 0.23°C.

		The local effects could however be significant, as Genesio et al. (2020) described their experimental results that the introduction of a soybean mutant reduced local radiative forcing by −4.1 W/m-2. Liu et al (2022) also found that the potential impact of surface albedo management on the Canadian prairies could be significant, and in CO2 equivalent terms 'comparable to that due to soil carbon sequestration.' Smoliak et al (2022) therefore urge that it should be explored where surface albedo could achieve cost-effective climate positive effects, and disagree with the simple dismissal of the measure because it is too expensive and inefficient on a global scale. This is confirmed by case studies, like Carrer et al (2018) who found that strategically planted cover crops, which increase albedo of dark soil, 'may mitigate up to 7% of the human-induced GHG agricultural emissions per year'. Vendig et al (2023) moreover found that the use of cover crops might be especially promising as it both increased soil carbon levels and increased crop yields.
Cost - Benefit	low	Ridgwell et al (2009) claim that Bio-geoengineering would be relatively low cost in comparison to other measures. This is echoed by Singarayer and Davies-Barnard (2012) and Nogués and Azcón-Bieto (2013), who even suggest it might therefore be appealing to developing countries, and could even bring economic opportunities. However, costs would likely be highly crop and region dependent.
Likelihood of environmental risks	Medium	Although this would depend per species, it seems likely that major changes in biota could have environmental impacts - as does farming. Ridgewell et al (2009) study for example suggests potential effects of global precipitation patterns by large-scale deployment. Ridgewell et al (2009) and Smoliak et al (2022) however note that associated risk would be minor in comparison to other SRM measures.
Effects on local/ indigenous communities	Neutral	Agriculture is not a common occupation in indigenous Arctic communities. Nogués and Azcón-Bieto (2013) suggest cheap options might be appealing to developing countries, and could even bring economic opportunities. However this is largely unstudied, and since bio-geoengineering would involve changes in land and plant coverage, it is likely to have at least some effects on surrounding communities and ecosystems.
Ease of reversibility	Easy	Farmers change crops fairly often in some regions (e.g. China), but much slower in others (e.g. parts of Africa).
Risk of termination shock	low	Ridgewell et al (2009) claim that bio-geoengineering does not hold the risk of termination shock that other SRM measures do.

Suitability within current legal/ governance structures	High	Smoliak et al (2022) note that bio-geoengineering is not as controversial as other SRM and relatively low risk. Implementation would therefore likely not be subject to strict restrictions, and mainly need to conform to regular national regulations.
Amount of attention in scientific journals and public media and currently ongoing research programs	medium	Biogeoengeering is mentioned in reports and the subject of some studies, although it is not as broadly covered as other albedo modification schemes (NASEM, 2015; Smoliak et al. 2022). Zhang et al. (2022) however note that their literature review showed that research into surface albedo increased since 2008 and that '[r]ecently, increasing attention has been dedicated to human-induced albedo variances', and Liu et al (2022) equally note that they observe a recent increase in attention for the importance of surface albedo changes by land management practices.

<table>
<tr><th colspan="3">Built-environment albedo enhancement (white roofs etc.)</th></tr>
<tr><td>Issue being addressed</td><td colspan="2">An increase in GHGs in the atmosphere leads to a greater amount of outgoing infrared radiation from the earth being retained. There are several SRM ideas that seek to compensate for this by reflecting more radiation back to space.</td></tr>
<tr><td>Description of the technology/ measure</td><td colspan="2">The built environment takes up an ever greater portion of the earth's surface. This mostly unused surface area could be coated in albedo enhancing paints or material which would allow them to reflect incoming sunlight.</td></tr>
<tr><td>Technological readiness</td><td>High</td><td>In many warm regions of the world it has been a longstanding custom to paint buildings white. Although certain paints or new to develop coatings might be extra efficient (See passive radiative cooling) the technology basically already exists.</td></tr>
<tr><td>Scalability</td><td>low</td><td>There have been several major experiments to increase albedo over land, most infamously the attempt by Eduardo Gold, who received $200,000 to paint a mountain white in the Peruvian Andes. However, this specific measure is limited to the built environment. This means there is only a limited surface area. Moreover, although the technology already exists NASEM (2015) points to the large costs related to painting and maintenance.</td></tr>
</table>

Timeliness for near-future effects	high	
Potential to make a difference in Northern + Arctic	low	If all urban areas would be modified, Irivine et al (2011) found that this could lead to a 13% increase in minimum sea-ice cover. Generally though, this measure is mainly considered as effective when applied at a local scale (IPCC AR6 wg 1, 2021, chapter 4), and holds particular potential to reduce the urban heat island effect (Jacobson and Ten Hoeve, 2011). However, this would mainly be so in densely populated low latitude areas, and would be ineffective in the Arctic (Smoliak et al 2022). Moreover, since the northern regions face very cold winters, such measures might lead to increased heating requirements, and such measures should therefore be carefully considered in the North (Bright et al. 2015).
Potential to make a global difference	medium	There is general agreement that this measure would be ineffective as a measure to counter the effects of climate change on a global scale (NASEM, 2015; Lawrence et al. 2018; IPCC AR6 wg 1, 2021, chapter 4). The IPCC 2021 AR6 wg 1 report gives a global mean forcing effect of less than 0.5 W m–2 (chapter 4), and some studies see even a global net warming effect of the painting of urban roofs (Jacobson and Ten Hoeve, 2011).
Cost - Benefit	High	The costs to paint and maintain a white coat of urban areas is considered to be very high, and relatively very expensive when considering the potential effect (NASEM, 2015).
Likelihood of environmental risks	Low	Lawrence et al. (2018) note in their literature review that this measure might be very invasive and lead to many regional side effects.
Effects on local/ indigenous communities	Beneficial	Summer temperature extremes are increasingly problematic in urban areas, and this measure might thereby significantly help local communities.
Ease of reversibility	easy	NASEM (2015) considers this measure to be of 'low overall risk, and ‘easily reversible', although

		the painting over of white surfaces would require another major investment.
Risk of termination shock	low	Although all SRM measures will lead to warming once it is halted, paints and similar reflective surfaces are likely to be effective for a long time, and will therefore not hold the risk of causing an abrupt warming.
Suitability within current legal/ governance structures	High	It is likely that nation states could implement such measures on their own territory.
Amount of attention in scientific journals and public media and currently ongoing research programs	medium	There is a general lack of discussion of this measure as a major climate action (Lawrence et al. 2018), although there seems to be quite some interest in it from local urban planners.

Arctic Methane capture and usage

Issue being addressed	Methane is a highly potent greenhouse gas and its reduction is given ever greater priority in international emission reduction policies (see for example https://www.globalmethanepledge.org/). Given the increasing, and potentially catastrophic rate of methane release from the thawing Arctic and Northern permafrost, these regions are crucial in this endeavor. Apart from the methane release from microbial activity in thawing permafrost on land, methane also escapes in the form of hydrates which have been formed under sediments beneath the sea.
Description of the technology/ measure	There are several ways to counter the increase of atmospheric methane such as: emission reductions strategies, increases of biological sinks (see several measures in this report), degradation of atmospheric methane (see photocatalytic methane destruction and destruction through iron salt aerosols), and methane flaring (See Methane Flaring). Some have however suggested it might be possible to capture methane or methane hydrates and transform it into useful materials (one specific methane capture technique through porous polymer networks is discussed separately (see Zeolites).

	The capture part poses a first difficulty. Salter (2011) suggested it might be possible to physically cover certain areas in the Arctic to capture the hydrates escaping from permafrost sediments. Amongst several other techniques, this idea was also echoed in Lockley (2012) and Stolaroff et al., (2012). Another proposed method would inject CO2 into hydrate sediments, thereby potentially storing CO2, and allowing methane to be utilized (Babu et al., 2014 see also Carbon Capture and Storage), with Brewer et al. (2014) even conducting a small scale field trial. GESAMP (2019) however notes that 'given the limited information currently available, it is too early to have clarity about the options that may be available for methane capture.' A second issue relates to the transformation of the captured methane into useful products like hydrogen or methanol (Reddy et al. 2013). Although recently several advances make future operationalisation more likely, it is currently still far off from being implemented at a large scale (Cho et al. 2021).	
Technological readiness	low	As GESAMP (2019) notes, there is little scholarship on the feasibility of methane capture from thawing Arctic permafrost. Moreover, there are significant concerns about the effect of some of the capture techniques, with Zhang and Zhai (2015) for example warning of massive methane leakage from hydrate capture technologies. The utilization of the captured methane also remains complicated, despite reports of recent progress in methane transformation technologies (Cho et al. 2021).
Scalability	Low	It might be that certain measures could be able to capture methane or hydrates from concentrated sources, although given the huge surface area and logistical difficulties, Stolaroff et al. (2012) write that '[f]ew of the known mitigation measures appear applicable to large-scale aqueous sources.'
Timeliness for near-future effects	Unknown	
Potential to make a difference in Northern + Arctic	unknown	Given the increased international attention for methane mitigation, methane release from Arctic permafrost could play a significant role. However, it is unclear how, and how much methane could feasibly be captured.
Potential to make a global difference	unknown	
Cost - Benefit	unknown	Given the logistical difficulties and large surface area, significant costs are likely. If methane is transformed into useful materials, this will drive down costs.

Likelihood of environmental risks	unknown	GESAMP (2019) notes that there is insufficient information to judge this. But depending on the used techniques and materials, there could be environmental effects. For example from the degradation of material used to cover some areas as suggested in Salter (2011).
Effects on local/ indigenous communities	Unknown	There might be local benefits in terms of income or employment related to the production of materials from captured methane.
Ease of reversibility	Unknown	
Risk of termination shock	unknown	
Suitability within current legal/ governance structures	High	It is likely that nation states could implement such measures on their own territory.
Amount of attention in scientific journals and public media and currently ongoing research programs	Medium	There is some renewed attention for methane capture in light of the recent global push for methane mitigation. This could also influence the debate on methane transformation in the Arctic context. In a popular article for Arctic Today, Yee (2020) for example writes that Rwanda is already using methane as energy, and asks: ‘Can we harness the Arctic’s methane for energy?’ However, to date, there have not been many detailed studies on the specific functioning of such technologies in the Arctic.

Methane flaring (not industrial)

Issue being addressed	Methane is a highly potent greenhouse gas and its reduction is given ever greater priority in international emission reduction policies (see for example https://www.globalmethanepledge.org/). Given the increasing, and potentially catastrophic rate of methane release from the thawing Arctic and Northern permafrost, these regions are crucial in this endeavor. Apart from the methane release from microbial activity in thawing permafrost on land, methane also escapes in the form of hydrates which have been formed under sediments beneath the sea.
Description of the technology/ measure	Apart from proposals to destroy atmospheric methane (see methane destruction measures), or capturing it (see methane capture measures), some have suggested it could be possible to prevent methane from researching the atmosphere or flaring it. Sellers (2011) noted that it could be

	possible to cover a certain subsea area and, instead of trying to capture the hydrates, flaring them, thereby turning the methane into relatively less potent GHG CO2. Lockley (2012) also writes about ‘Small, inexpensive spark devices can ignite combustible methane/air mixtures at source’. Paul Klinkman equally writes about 'Compact wind-powered sparking devices with small batteries' to flare methane at source (klinkmansolar.com/kfrozen.htm). Alternatively, Stolaroff et al. (2012) and Lockley (2012) suggested ideas to disturb the methane bubbles while they traveled through the water column, thereby making it less likely for them to reach the surface and enter into the atmosphere.	
Technological readiness	low	There has not been major scientific interest in the idea, as major difficulties arise from non-point source emissions mitigation (Johannisson, and Hiete, 2020). Small scale experiments with capturing and flaring methane using recycled parachutes is done by the company Frost Methane (https://www.frostmethane.com/, see Catalog of Research Funding Needs to Advance Methane Removal (2023) at methaneaction.org). Methane flaring development is also part of the US Reducing Emissions of Methane Every Day of the Year (REMEDY) program (arpa-e.energy.gov/news-and-media/press-releases/us-department-energy-awards-35-million-technologies-reduce-methane). Ming et al (2022) however argue that such ideas remain speculative without concrete details.
Scalability	Low	It might be that certain measures could be able to capture methane or hydrates from concentrated sources, although given the huge surface area and logistical difficulties, Stolaroff et al. (2012) write that 'Few of the known mitigation measures appear applicable to large-scale aqueous sources.'
Timeliness for near-future effects	Unknown	
Potential to make a difference in Northern + Arctic	unknown	
Potential to make a global difference	unknown	
Cost - Benefit	unknown	

Likelihood of environmental risks	unknown	
Effects on local/ indigenous communities	Unknown	
Ease of reversibility	Unknown	
Risk of termination shock	low	
Suitability within current legal/ governance structures	High	It is likely that nation states could implement such measures on their own territory.
Amount of attention in scientific journals and public media and currently ongoing research programs	low	Apart from a few studies, there has been relatively little attention for this measure.

Atmospheric Methane destruction: Tropospheric iron salt aerosol injection

Issue being addressed	Methane is a highly potent greenhouse gas and its reduction is given ever greater priority in international emission reduction policies (see for example https://www.globalmethanepledge.org/). Given the increasing, and potentially catastrophic rate of methane release from the thawing Arctic and Northern permafrost, these regions are crucial in this endeavor. Apart from the methane release from microbial activity in thawing permafrost on land, methane also escapes in the form of hydrates which have been formed under sediments beneath the sea.
Description of the technology/ measure	There are various methods to remove atmospheric methane (Jackson et al 2021). Tropospheric Iron Salt Aerosol injection (ISAI) has recently received significant attention as a potential methane mitigation technique. It would mimic a naturally occurring methane degrading process by injecting iron salts in the troposphere (Oeste et al., 2017). In reaction with sunlight, these iron salts would irradiate and form chlorine radicals, which would then allow

	methane to be degraded into CO2. Alongside this methane destruction capability, ISAI is said to have other climate cooling effects as it might break down tropospheric ozone, and, if released over oceans, it might brighten clouds brightening (see Marine cloud Brightening) and the iron particles might fertilize the ocean (see Ocean Fertilization). Potentially, the aerosols could be distributed by ships.	
Technological readiness	low	The technology was patented in 2002, but only really highlighted to the broader scientific community in a 2017 paper by Oeste et al. and is at a very initial stage. Apart from institutional research (see: https://www.sparkclimate.org/methane-removal/grantees), there is significant private interest in the technology, with the MIT review finding at least 3 commercial companies experimenting with the technology (Temple, 2023). A main next step would be small-scale outdoor testing to provide clarity on the feasibility of this technology, with Blue Dot Change for example planning the experimental release such aerosols from already sailing ocean going ships (https://www.bluedotchange.com/, see also Temple, 2023). Many scientific uncertainties still remain (Nisbet- Jones et al. 2021), and as not many studies have been published by scholars who have not been directly or indirectly involved in the research projects it is hard to evaluate the claims made in some of the papers.
Scalability	High	This measure can likely be easily scaled up and deployed anywhere around the planet.
Timeliness for near-future effects	Unknown	Although some grand claims exist around ISAI (see for example Oeste et al. 2017), and Ming et al (2021) claim it could be deployed relatively straightforwardly through modification of combustion fuels of the shipping industry, or major fossil fuel power plants, there are still many uncertainties about the actual feasibility of this measure.
Potential to make a difference in Northern + Arctic	unknown	Sun et al (2022) show early methane mitigation strategies are key to preserving Arctic summer sea ice. However, it is hard to evaluate the potential of this measure.
Potential to make a global difference	unknown	Given the potential impact of methane mitigation, the potential impact of this measure could be major. However, the current scientific status of the technology does not yet allow substantiated evaluations on the potential.
Cost - Benefit	Low	Ming et al. 2021 give a cost of ~$1/tCO2, which would make it by far the cheapest measure for CDR.

Likelihood of environmental risks	Unknown	The technology is until now not explored, and possible effects unknown (Nisbet- Jones et al. 2021), with some scholars explicitly warning against it (see Temple, 2023). Ming et al. (2021) claim some of these fears, like the potential negative effect of iron fertilization on algae blooms, do not apply to ISAI because of the smaller amount of used aerosols in comparison to artificial fertilization proposals (see Artificial Fertilization), and Sturtz et al (2022) equally found that a hypothetical outdoor test would remain within safe levels.
Effects on local/ indigenous communities	unknown	
Ease of reversibility	unknown	
Risk of termination shock	unknown	
Suitability within current legal/ governance structures	Unknown	Nisbet- Jones et al (2021) warn that measures like these could become relevant over the coming years, and that political, governance, and ethical issues need to be taken into consideration. No governance focus studies on ISAI exist as of yet, but, depending on the magnitude of the potential listed effects, it is possible that deployment might be relevant to multiple governance regimes, for example related to marine pollution and SRM governance.
Amount of attention in scientific journals and public media and currently ongoing research programs	medium	Attention for methane action has been increasing (see for example advocacy group Methane Action methaneaction.org and O'Grady, 2021), especially in the wake of the Global Methane Pledge (https://www.globalmethanepledge.org/). Of the many suggested methane mitigation measures, ISAI is increasingly often found. However, the scope of scientific research is as of yet very limited, and commercial companies are relatively prominent in the research into it (Temple, 2023).

Biochar	
Issue being addressed	The concentration of GHGs in the atmosphere will have to be stabilized or lowered to mitigate or even reverse current global warming. To achieve this, current GHG emissions need to be reduced. Such mitigation strategies will however take time to deploy, and some emission sources will be difficult to mitigate. Moreover, since current atmospheric levels are already having a

	major warming effect, negative emission or Carbon Dioxide Removal (CDR) measures that reduce the amount of GHGs in the atmosphere are an active topic of research.	
Description of the technology/ measure	The most widely studied carbon storage technique is the large-scale application of biochar (Smith et al. 2023). Biochar is produced when biomass is pyrolysed - a thermal process in which oxygen for combustion is lacking. Although carbon is released during pyrolysis, this could potentially be captured, and the remaining carbon is then stabilized and can be removed from the atmospheric carbon cycle (Woolf et al., 2010). Generally, biochar is envisioned to be used as a soil amendment, which allows carbon to be stored while benefiting soil fertility, or even to restore soil quality of degradation or polluted areas (Oliveira et al. 2017). Yet, it could also be used in production processes or stored underground.	
Technological readiness	high	Biochar has been used throughout history, mostly in tropical areas. Although the technology therefore already exists, and can be considered amongst the most technological ready amongst CDR measures (Möllersten and Naqvi, 2022), much new research is currently being done on the properties of specific production processes and materials. An extensive literature review by Elkhlifi et al (2023) stressed the need to develop economically viable production methods, and encouraged further research into specific production and application procedures.
Scalability	Medium	Although the measure seems promising, uncertainties remain about the extent of the scalability of biochar (Smith et al. 2023). Chiquier et al (2022) comparative study of carbon removal technologies suggest biochar is relatively inefficient at sequestration, and risks decreasing in efficiency due to the decay overtime. Furthermore, if biochar is produced on regular agricultural land it can take up valuable space that would otherwise be used for food or energy purposes.
Timeliness for near-future effects	High	The technology already exists and will likely play some role in mitigating carbon emissions, but uncertainties remain about total effectiveness.
Potential to make a difference in Northern + Arctic	Low	Although biochar has historically been mainly used in tropical areas, Lévesque et al. (2021) literature review shows certain specifically produced sorts are also beneficial to temperate areas. Since biochar application can have a multitude of other beneficial soil effects besides carbon sequestration, it might be beneficial to polluted areas in the Arctic. Studies by Karppinen et al. (2017) and Zahed et al (2021) for example suggest biochar could be used to remediate soils that have been contaminated by hydrocarbons, especially if specific kinds of biochar production techniques are

		used. Tregubova et al (2021) experimental study equally showed that biochar has a capacity to restore soils that were polluted by long term emissions of the nickel industry in the Kola peninsula.
Potential to make a global difference	Medium	Both the State of Carbon Dioxide Removal report and the IPCC AR6 wg3 report estimate a potential global carbon capture potential between 0.3 and 6.6 GtCO2/yr (Smith et al. 2023; IPCC, 2022). Although biochar will likely play an increasing role in global mitigation strategies, uncertainties however remain about the possible scale of mitigation, as uncertainties remain, for example around the potential warming effect of low-albedo biochar to soils (Meyer et al. 2012).
Cost - Benefit	Medium	The cost of biochar application would be highly case dependent (Möllersten and Naqvi, 2022). The State of Carbon Dioxide Removal report estimates potential costs of 10 to 345 $/tCO2 (Smith et al. 2023). alongside the highly spread costing estimate, durability of sequestration should also be taken into consideration, with Chiquier et al’s (2022) comparative CDR study finding that biochar is relatively inefficient at sequestration, and risks decreasing in efficiency due to the decay overtime.
Risk of termination shock	Medium	As mentioned above, many studies indicate possible beneficial effects of biochar application for polluted areas. There might however be negative environmental effects of the production process, and unsustainable material harvesting (Smith et al. 2023; IPCC AR6, wg3 2022). Given the already occurring increase of natural and anthropogenic black carbon in the Arctic (Stubbins et al. 2015), large-scale application of biochar in the region should likely be further studied.
Effects on local/ indigenous communities	Beneficial	The IPCC AR6 wg3 report (2022) warns that poorly implemented biochar production and distribution risks causing adverse effects for local communities and ecosystems. However, biochar could also be greatly beneficial due to positive side effects on soil fertility and potential to mitigate certain toxins and increase drought resistance (Smith et al. 2023). A 2019 study by Keske et al specifically showed that in the case of a majority indigenous inhabited remote area in Labrador, Canada, the practically free by-products of wood logging could be utilized for biochar production. The subsequent usage on the area's marginal soils could for some produce form an economic benefit and might improve food security. The authors furthermore argue that from an environmental justice standpoint, it could even be argued that the government should forward the high initial investments to create a biochar industry for a region that has been historically exploited.

Ease of reversibility	Medium	The biochar would decay overtime.
likelihood of termination shock (what would happen if technology were to be abruptly stopped	low	
Suitability within current legal/ governance structures	High	This would fall under national legislation.
Amount of attention in scientific journals and public media and currently ongoing research programs	High	Although public attention seems limited, and popular media references more limited as opposed to more spectacular geoengineering ideas, biochar is by far the most studied CDR ideas. There are many research projects, roughly 40% of all studies on CDR methods being biochar related, and around 50% of all CDR studies published in 2021 studying biochor (Smith et al. 2023).

Bio-energy with carbon storage **BECCS**

Issue being addressed	The concentration of GHGs in the atmosphere will have to be stabilized or lowered to mitigate or even reverse current global warming. To achieve this, current GHG emissions need to be reduced. Such mitigation strategies will however take time to deploy, and some emission sources will be difficult to mitigate. Moreover, since current atmospheric levels are already having a major warming effect, negative emission or Carbon Dioxide Removal (CDR) measures that reduce the amount of GHGs in the atmosphere are an active topic of research.
Description of the technology/ measure	Bio-Energy with Carbon Storage (BECCS), offers a nature-based way in which to remove CO2 from the atmosphere by consuming biomaterial and removing the remaining carbon residues from the carbon cycle. The biomass can be turned into energy through various ways, such as burning it, gasification, or fermentation (Pires 2019). The CO2 released from consumption of the biomass would preferably be captured to a large degree if the net positive effects of the biomass capture would not be negated. This could be done through similar methods already in use for Carbon Capture and Storage by the fossil fuel industry (Azar et al. 2006).

Technological readiness	Medium	The use of biomass for energy is already quite developed, and a 2022 study by Almena et al reported six operational BECCS facilities worldwide.The State of Carbon Dioxide Removal report gives it a potential readiness level of 5-6 (Smith et al. 2023). However, several key issues remain around the capture and storage of the carbon released when biomass is consumed (See carbon capture and storage), the sustainability of the sourcing of materials and its scalability, and the overall net effects of the entire BECCS process continue to pose serious issues. As with biochar application (see Biochar) there is also great variability between the sustainability and ultimate climate effect of individual BECCS projects (Fajardy and Dowell, 2017).
Scalability	medium	Although BECCS play an important part in all negative emission scenarios that aim to keep temperature rises within an acceptable level, serious concerns remain around the potential and effect of its scalability (Ekardt and von Bredow, 2012; Vaughan and Gough, 2016; Mander et al. 2017). A main downside to BECCS is that it would use large volumes of biomass, and would therefore need space and nutrients that could otherwise be used to produce resources, food, or provide other ecosystem services (RoyalSociety 2018). This large-scale deployment of BECCS and the required amounts of land could also have significant negative climate effects (Newbold et al. 2015) and might affect albedo (See bio-geoengineering), especially at high-latitudes (Fuss et al., 2018). Williamson (2016) also warns that biomass might not be as efficient at capturing CO2 at scale for use in BECCS and that the response of plants to future climate change needs to be taken into consideration. The production sites might furthermore be far removed from the places of energy generation, and might therefore come with significant extra transportation costs. These are now estimated to be around 100 to 200/tCO2 (Fuss et al. 2018). Fridahl and Lehtveer (2018) moreover find important socio-political constraints to BECCS deployment, and highlight the need for further research into factors such as social acceptance or policy development. Chiquier et al (2022) notes that while ‘BECCS delivers immediate and permanent CDR’, ‘its CO2 removal efficiency can be significantly impacted by any initial carbon debt associated with (direct and indirect) land use change, and thereby significantly delayed’.
Timeliness for near-future effects	High	There are already several operational plants, but captured amounts remain minimal, and questions about scalability remain (Smith et al. 2023).

Potential to make a difference in Northern + Arctic	medium	Although the CDR potential of BECCS in the Arctic and Northern regions is uncertain, higher latitude areas can provide specific kinds of biomatter, like remains from the logging industry or microalgal cultivation. Vogt et al (2022) study on the potential of afforestation in the Nordic region conclude that BECCS 'has a very high CDR potential due to already existing large point sources of biogenic CO2 (from forest industry and bioenergy production).'
Potential to make a global difference	medium	There is significant uncertainty about the potential of BECCS (Anderson and Peters, 2016; Hanssen et al. 2020), with the IPCC AR6 wg3 (2022) following the estimates of the State of Carbon Dioxide Removal report of a carbon capture potential of 0.5 to 11 GtCO2/yr (Smith et al. 2023). There are many variables that would decide the effectiveness of BECCS, with Vaughan et al's (2018) model study for instance showing poor governance can significantly reduce the CO2 capture potential.
Cost - Benefit	medium	The State of Carbon Dioxide Removal report estimates potential costs of 15 to 400 $/tCO2 (Smith et al. 2023). Yet, as with biochar application (See biochar), significant uncertainties remain about the costs of BECCS deployment as there are major differences between individual projects, and much research is still needed into costs, and designing strategies that could pay for BECCS (Honegger et al. 2021). Möllersten and Naqvi reported in an overview study (2022) that estimated costs of BECCS deployment in the Nordic region would be around 60-135 USD/tCO2.
Likelihood of environmental risks	medium	The environmental effects of large scale BECCS deployment could be significant as unsustainable and large scale biomass harvesting could cause competition for land and water and reduce biodiversity and soil fertility (Smith et al. 2023 IPCC AR6,wg3 2022). Crucially, specific parts of the BECCS chain could be more or less sustainable, and it has to be made sure that the process as a whole has positive effects (Fajardy and Dowell, 2017; Briones-Hidrovo et al. 2022). Briones-Hidrovo et al. (2022) for example note that the use of residual forest biomass had a positive climate impact, but also had significant impact on land and water. The use of contaminated biomass could moreover incur pollution risks (Smith et al. 2023), and Deng et al (2017) point to significant risks of leakage if captured carbon needs to be transported.
Effects on local/ indigenous communities	Unknown	BECCS could have positive and negative effects on local communities.Small scale bioenergy development could provide extra local income (Almena et al. 2022). And a sound growth process could improve crop growth and health, enhance biodiversity, soil health, and water quality (Smith et al. 2023).

		However, as large-scale BECCS deployment would require significant amounts of land and water Günther and Ekardt (2022) point out that it can have significant detrimental impacts for communities, and even violate their basic human rights like the rights to food, water, and a healthy environment. The IPCC AR6 (2022) report therefore warns that poorly implemented biomass growth for BECCS could have significant negative effects on ‘local livelihoods and on the rights of Indigenous Peoples, especially if implemented at large scales and where land tenure is insecure (high confidence).'
Ease of reversibility	medium	
Risk of termination shock	low	
Suitability within current legal/ governance structures	High	BECCS systems are already operational and will mostly continue to fall under national legislations. Günther and Ekardt (2022) study on the legal aspect of large scale BEECS deployment however find that it could have significant impacts on basic human rights of surrounding communities, for example the right to water and food’.
Amount of attention in scientific journals and public media and currently ongoing research programs	High	BECCS is one of the main currently considered CDR measures and plays important roles in almost all negative emission strategies. There are many research projects, and several operational plants in existence.

Direct air carbon capture and storage **DACCS**	
Issue being addressed	The concentration of GHGs in the atmosphere will have to be stabilized or lowered to mitigate or even reverse current global warming. To achieve this, current GHG emissions need to be reduced. Such mitigation strategies will however take time to deploy, and some emission sources will be difficult to mitigate. Moreover, since current atmospheric levels are already having a major warming effect, negative emission or Carbon Dioxide Removal (CDR) measures that reduce the amount of GHGs in the atmosphere are an active topic of research.

Description of the technology/ measure	Direct air carbon capture and storage (DACCS) aims to reduce the amount of carbon dioxide in the atmosphere by taking it directly out of the air, and removing it from the carbon cycle. Because the concentration of carbon dioxide in the air is relatively low, this involves huge ventilators that suck in large amounts of air (NASEM, 2019). The carbon could then be removed from the passing air by sorbents. There are two main sorbent ideas currently being explored: absorption and adsorption, with the former dissolving the CO2 into it, and the latter adhering it to a substance (Gambhir and Tavoni, 2019). In both cases, the sorbent will release the CO2 again after energy is applied, allowing for the material to be reused (Gambhir and Tavoni 2019). These systems therefore require significant amounts of energy, and they therefore should be coupled to renewable sources so as not to end up with net negative emissions. The potential of cold areas like the northern and arctic regions is likely to be great for DACCS, as cold climates can provide significant benefits for the efficiency of certain technologies, and especially improve the recovery process after capturing the carbon from the air (Wilson, 2022). Song et al (2022) furthermore note that specific DACCS processes can be especially beneficial in cold areas if co-benefits like water production are taken into consideration. The captured CO2 thereafter needs to be disposed of (see also Carbon Capture and Storage). There are several ways to do this. The company Carbfix (https://carbfix.com/) for instance injects the captured carbon in superheated liquid form into basalt rock formation at a depth of 400m to 800m, with which it reacts, thereby stabilizing the carbon. However, there are significant uncertainties about the large-scale feasibility of such injections (Sovacool et al (2022), and this kind of a solution is not available everywhere. An alternative method would be injecting the carbon underseas, or in depleted gas fields. A good example of this is the recently launched Danish project *Greensand*, which intends to store large amounts of CO2 under the North Sea (projectgreensand.com/). Apart from risks related to earthquakes (Kazemifar 2022), storage underground requires monitoring to see if there are no leaks (Godin et al 2021). Such projects could furthermore run into social acceptance issues of local populations (Cox et al 2020, Sovacool et al 2022). Although there are therefore enough sedentary basins or basalt rocks to store far more carbon than humanity has ever emitted (Sovacool et al. 2022), alternatively the carbon could be turned into resources or materials (Godin et al 2021), although that brings questions about related climate effects and possible costs.	
Technological readiness	Medium	There has been a lot of hype around DACCS, and commercial companies like ClimeWorks, Carbfix, Carbon Engineering, and Global Thermostat have been featured broadly. Many issues however still need to be resolved. The State of Carbon Dioxide

		Removal report therefore gives it a readiness level of 6 (Smith et al. 2023).
Scalability	Medium	NASEM (2019) claims that DACCS offer one of the few technologies that could potentially ' be scaled up to remove very large amounts of carbon.' And the State of Carbon Dioxide Removal report estimating potential capture of 5 to 40 GtCO2/yr (Smith et al. 2023). However, given the very limited state of current DACCS systems, there would have to be a significant scaling up of activities (Powis et al. 2023). The issue of scalability is key, as Realmonte et al (2019) show in their model study that assuming DACCS to be scalable, and finding out they aren't, would lead to an overshoot of up to 0.8°C. One requirement for scaling would be a suitable financial system that would enable investment and deployment at scale (McCormick, 2022). Another issue related to the high energy demand of DACCS. This means that scaling up could lead to energy competition (Smith et al. 2023), with Hanna et al (2021) suggesting that they could consume 14% of global electricity by 2075. Potentially DACCS could be built everywhere (Strefler et al 2021), with the provision that they have access to renewable energy (IPCC, AR6, wg3 12.3.1.1) Specific DACCS technologies would be more efficient in certain areas like colder regions.
Timeliness for near-future effects	Low	DACCS currently only removed 1% of total novel CDR technology removal of 2.1 million tonnes (see Smith et al. 2023). Given that 0.96 billion tonnes of extra carbon dioxide would be required to keep global warming below two degrees above pre-industrial levels, DACCS would need to be improved and scaled up very quickly to make a significant difference.
Potential to make a difference in Northern + Arctic	High	Although the DACCS would reduce global atmospheric CO2 levels, specific DACCS systems are especially efficient in colder climates (Wilson, 2022), making the construction of DACCS in Northern and Arctic regions attractive (see also Antarctic air capture).
Potential to make a global difference	High	Fuss et all (2018) estimated that DACCS could potentially increase its potential uptake from 0.5 to 5 GtCO2 per year by 2050 to 40 GtCO2 year by the end of the century, this is a figure that is also given in the recent State of Carbon Dioxide Removal report (Smith et al. 2023), and the IPCC AR6 wg3 (2022).
Cost - Benefit	medium	Because the technology is currently rapidly developed, the costs of DACCS could drop over the coming years, potentially greatly impacting the potential for this technology to be scaled up and used at scale (McQueen et al. 2021). Keith et al (2018) giving levelized

		costs of 94 to 232 USD per ton of CO2 from their pilot plant study. In 2018 Fuss et all estimated that costs per tonne CO2 would drop from 600-1000 to 100-300 dollars, and the State of Carbon Dioxide Removal report repeated this amount in 2023 (Smith et al. 2023). Möllersten and Naqvi’s review of CDR technologies (2022) notes a potential cost reduction from 100-1500 USD/t CO2 to 150-230 USD/tCO2. However the spread of estimates is significant (Sovacool et al. 2022). A major boost for the industry was the launch of a $3.5 billion US Government program in 2022 that included a $180 per ton tax credit and could significantly push down prices.
Likelihood of environmental risks	Low	The environmental risks of DACCS are likely to be relatively low in comparison to other CDR methods, although Gambhir and Tavoni (2019) note that some uncertainties around this remain with regards to large scale deployment.
Effects on local/ indigenous communities	neutral	Günther and Ekardt (2022) note that although DACCS are less land intensive than BECCS, they could nevertheless impact human rights negatively, especially the right to energy due to their high energy demand.
Ease of reversibility	easy	
Risk of termination shock	low	
Suitability within current legal/ governance structures	High	Such systems are already operational and fall under national legislations.
Amount of attention in scientific journals and public media and currently ongoing research programs	High	DACCS are widely discussed and covered in both academia and in popular discourse, with companies like Carbfix and Climeworks being frequently covered. Major political interest in DACCS has also started to materialize, especially in the US (Scott-Buechler et al. 2023), as is also testified by the 2022 US government $3.5 billion program.

CO2 “snow” deposition in Antarctica, cryogenic CO2 capture

Issue being addressed	The concentration of GHGs in the atmosphere will have to be stabilized or lowered to mitigate or even reverse current global warming. To achieve this,

	current GHG emissions need to be reduced. Such mitigation strategies will however take time to deploy, and some emission sources will be difficult to mitigate. Moreover, since current atmospheric levels are already having a major warming effect, negative emission or Carbon Dioxide Removal (CDR) measures that reduce the amount of GHGs in the atmosphere are an active topic of research.	
Description of the technology/ measure	Inspired by the discovery of CO2 ice caps on Mars, Agee et al (2013) suggested it might be possible to artificially create similarly cold conditions in the already frigid temperatures of Antarctica that would allow CO2 to “snow” out of the air. They envision a ‘depositional plant’, where air would be introduced into a refrigerated chamber, which would cool the air to -140 degrees C and freeze the carbon dioxide, while remaining the other components like oxygen and nitrogen in a gaseous state. This frozen CO2 would then be deposited into a dry ice underground landfill for storage. Apart from making use of the much colder Antarctic air, which significantly reduces energy requirements for cooling, the colder air also is largely devoid of moisture (Perskin et al. 2022).	
Technological readiness	low	Agee and Orton (2016) conducted some small scale experiments, von Tippel (2018) and Boetcher et al (2020) looked at energy and scaling issues, Andrea Orton conducted modeling on the climatic effects of this measure as doctoral research (2020), and a more recent study by Perskin et al (2022) explored the topic further and compared it to other precompression methods for direct carbon capture. However, the idea seems not to have been picked up broadly, and remains in a very theoretical stage. In a 2012 article by the New Scientist (Marshall, 2012), Tim Kruger furthermore highlights issues with storage, as the solidified CO2 would either have to be kept frozen, or stored in highly pressure resistant tanks.
Scalability	Low	Agee et al (2013) claims that this technology could be scaled up to remove 1 GtC equivalent of 4 Gt CO2 from the air annually. Perskin et al (2022) equally state it might be scaled up rapidly. However, given the technical difficulties related to the project and the suggested location, and the unproven nature of the idea, this is highly uncertain. A main issue would also be power for the project, as the envisioned 1 GT/ year plant would require 16 1200 MW wind farms, and would therefore run into similar obstacles as those outlined for the idea to pump water on ice sheets (See pumping water on ice sheet). Although von Tippel (2018) estimates energy requirements of 112 to 420 GW to remove 1 billion tonnes of CO2 for a similar system, which he considers comparable to those of other CDR methods.

Timeliness for near-future effects	Low	There have been small-scale experiments, but development would likely take a long time. After that, construction would be a major undertaking given the remoteness and climate of Antarctica or the Arctic.
Potential to make a difference in Northern + Arctic	unknown	If found to work, this could be of major importance for the Northern and Arctic regions.
Potential to make a global difference	unknown	It is unsure if the technology would work, and if it could make a difference.
Cost - Benefit	High	The cost of constructing and maintaining the facility would likely be very high. Moreover, the energy requirements would be significant, so it is questionable whether this would be the most feasible and competitive CDR method.
Likelihood of environmental risks	High	Because this project would be built in the especially environmentally sensitive context of Antarctica, special care would have to be taken to prevent serious risks. However, there appear to be several potential risks, especially those to safe and durable storage of captured CO2.
Effects on local/ indigenous communities	Unknown	
Ease of reversibility	Hard	Because the frozen CO2 would have to be stored permanently, there would probably be some difficulties with reversing this scheme fully.
Risk of termination shock	High	Given the storage issues, the solidified CO2 would either have to be kept frozen, or stored in highly pressure resistant tanks, lest it escapes again into the atmosphere, likely leading to a quick spike in CO2 levels and subsequent greenhouse effect amplification.
Suitability within current legal/ governance structures	Low	There have been no studies on this topic, but similarly to ideas to stabilize Antarctic ice sheets (See undersea curtain), or the pumping of water on top of it (See pumping water on ice sheet), this measure would have to fit into the framework of the Antarctic treaty.
Amount of attention in scientific journals and public media and currently	low	Apart from a small community around the original developers of the idea, and a couple of separate references (see for example McQueen et al. 2021; Betts, 2022), the plan has not received significant attention.

ongoing research programs		

Direct ocean capture		
Issue being addressed	The majority of the inorganic carbon on Earth is stored in the oceans. There is a natural carbon exchange between the ocean and the land.	
Description of the technology/ measure	Direct Ocean Capture (DOC) is a method that seeks to remove inorganic carbon directly from seawater. This can be done through various electrochemical means (see NASEM, 2022 and Jayarathnaa et al. 2022). The captured carbon can then be stored or utilized, and the decarbonised water could be returned to the ocean where it would be able to take up more carbon. Because such carbon extraction would require large volumes of water throughput, there have been suggestions to combine it with a system that uses tidal or wave energy, desalination systems, or more experimental Ocean Thermal Energy Conversion.	
Technological readiness	low	GESAMP (2019) describes DOC as conceptually ‘one of the simplest [marine] CDR techniques’, However, it has not been applied at scale, and significant questions about potential feasibility and scalability remain. There are several suggested electrochemical DOC techniques, some of which are already in use at a smaller scale for different purposes (see NASEM, 2022). One often mentioned technology, that is also featured in GESAMP (2019), combines electrodialysis with a bipolar membrane. There have been laboratory and prototype and model studies on this technique (see mainly: Eisaman et al., 2012; de Lannoy et al. 2017; Eisaman et al., 2018; Digdaya et al. 2020), although it is not the only one. Kim et al (2023) for example recently announced they found a far cheaper method for DOC without the use of expensive membranes. In the US, ARPA is funding a project on DOC and supports programs at California Institute of Technology, the University of North Dakota, and MIT (arpa-e.energy.gov/technologies/exploratory-topics/direct-ocean-capture). DOC is also developed by commercial companies Heimdal (https://www.heimdalccu.com/), which has built a pilot plant in Hawaii and aims to build larger ones in the following phase, and Captura (capturacorp.com), who built a first pilot plant in 2022 and aim to have a next one ready in 2023.

Scalability	medium	Although proponents of DOC often highlight that the technique would be far easier scalable than air capture technologies because of the large area the oceans offer and the greater concentration of carbon in seawater as opposed to air, many questions remain. NASEM (2022) gives a medium to high confidence for potential scalability of DOC, with the caveat that energy requirements may limit scaling. GESAMP (2019) note that due to the energy requirements, the potential area for DOC could be limited. It has been suggested to combine DOC with tidal or wave energy, desalination systems, or experimental Ocean Thermal Energy Conversion. This last method generates power through temperature differences in the ocean, and is itself also still in a developmental stage (See GESAMP, 2019). If coupled with Ocean thermal energy conversion, deployment would be most efficient in tropical areas, as thermal energy generation works best there.
Timeliness for near-future effects	Unknown	
Potential to make a difference in Northern + Arctic	Unknown	
Potential to make a global difference	low	NASEM (2022) estimate that electrochemical DOC technologies might sequester 0.1 to 1.0 Gt CO2 per year.
Cost - Benefit	medium	Costs remain very uncertain, and will be to a large degree dependent on the means of energy generation. At the moment costs are relatively high compared to other carbon capture methods, but could come down significantly in the future (Digdaya et al. 2020). Eisaman et al (2018) cost assessment found that even when combined with a desalination plant, this lowest cost assessment would likely cost $604 per tCO2, with a lowest estimate of $373. Heimdal notes that their first Hawaian version has a cost of 475$ per tonne of CO2, and that they hope to drive this down to $200 in their next version. Kim et al. (2023) recently claim to have developed an improved system that could operate at $50–$100 per ton CO2. NASEM (2022) notes that hydrogen might be a by-product of electrochemical direct ocean capture, and could offer substantial side benefits and thereby reduce costs.

Likelihood of environmental risks	high	GESAMP (2019) note that ‘clearly the manipulation of large volumes of sea- water in this way could have a deleterious effect on oceanic biota.’
Effects on local/ indigenous communities	Unknown	
Ease of reversibility	easy	
Risk of termination shock	low	
Suitability within current legal/ governance structures	high	Webb et al (2021) explored the governance issues around electrochemical direct ocean capture methods through alkalinity addition (see Ocean Alkalinity Enhancement), but there seem to be no direct studies on governance of direct ocean capture as described here.
Amount of attention in scientific journals and public media and currently ongoing research programs	medium	Although DOC features in major reports like NASEM (2022) and GESAMP (2019) it is one of the lesser explored ocean CDR technologies, and is studied by several organizations and institutions, it remains one of the lesser known and understood CDR techniques.

Enhanced Weathering (on Land)

Issue being addressed	The concentration of GHGs in the atmosphere will have to be stabilized or lowered to mitigate or even reverse current global warming. To achieve this, current GHG emissions need to be reduced. Such mitigation strategies will however take time to deploy, and some emission sources will be difficult to mitigate. Moreover, since current atmospheric levels are already having a major warming effect, negative emission or Carbon Dioxide Removal (CDR) measures that reduce the amount of GHGs in the atmosphere are an active topic of research.
Description of the technology/ measure	Enhanced weathering (EW) is a measure that seeks to enhance and speed up the process of rock weathering in which CO2 reacts with minerals (Schuiling and Krijgsman 2006) that naturally occurs and already consumes 1.1 Gt CO2 per year (Ciais et al., 2014). EW would seek to encourage this by grinding up silicate rocks to increase their surface area. Calcium and magnesium rich rocks like olivine or basalt would be most feasible (Beerling

	et al. 2018). The used rocks could either be mined for the purpose or be rest products of the mining industry. Alternatively, other waste sources could also be used (Renforth 2019), with incinerator ash, fly ash, or steelmaking slag all being considered for use towards similar purposes (Möllersten and Naqvi, 2022). Here the application of such rocks on land will be considered, although it has also been suggested to add them to seawater (see Ocean Alkalinity Enhancement). Apart from direct chemical carbon sequestration, EW could also sequester carbon indirectly by providing nutrients for plants which could then take up CO2 through photosynthesis (Fuss et al. 2018; Vicca et al. 2022).	
Technological readiness	medium	The IPCC AR6 wg 3 report (2022, p1267) gives EW a technological readiness level of 3 to 4, as there have been laboratory and field tests, but no scaled up proofs yet. Apart from effects at scale, research needs to be done on co benefits and side effects, and potential production and distribution methods (Beerling et al. 2018; IPCC AR6 wg3). Amann et al's (2018) field experiments for example highlighted large uncertainties, and the importance of water flow on EW efficacy, an observation that is seconded by Buckingham et al (2022). Fawzy et al (2020) are more optimistic and claim 'enhanced weathering can be practically deployed at the moment.' The website of the Leverhulme Centre for Climate Change Mitigation is equally optimistic (sheffield.ac.uk/lc3m/research/faqs), as they write that 'Arable farms already apply crushed rock in the form of limestone to reduce the acidity of their soils that results from farming practices, including the use of fertilizers', and that the availability of 'infrastructure such as roads and machinery needed to undertake this approach at scale … make it straightforward to adopt.'
Scalability	Medium	There are large discrepancies between estimates, and much depends on rock type used, size of ground particles and application strategy, as large amounts of rocks would be required for a scaling up. It is generally estimated that for every sequestered ton of CO2 2 to 3 tonnes of silicate would be needed, and given the high demand for and price of minerals, this could make scaling difficult (Möllersten and Naqvi, 2022). Moreover, the large volume to be grinded would lead to power demands that might reduce net carbon positive effect by up to 30%, although Beerling et al. (2020) note that efficiency and renewable energy use might reduce this significantly. If applied on agricultural land, no extra land would need to be converted to CDR purposes. Bach et al (2019) therefore write that 'in contrast to many other NETs, [EW is] generally not competing

		with other Sustainable Development Goals like global food and water security but [is] potentially even beneficial for them'.
Timeliness for near-future effects	Unknown	
Potential to make a difference in Northern + Arctic	unknown	Although most research on EW seems to be done in regions outside of the Arctic, in a recent study Dietzen and Rosing (2023) argued that naturally produced Greenlandic glacial rock flour could provide a significant EW method that requires little extra energy input. The authors estimate that the distribution of 50 tons ha−1 of such material on sandy soils with high acidity could over the course of three years lead to a CO2 uptake of 728 kg CO2 ha−1.
Potential to make a global difference	Medium	The IPCC AR6 follows Fuss et al (2018) in estimating a global CDR potential of 2–4 GtCO2 per year. Beerling et al (2020) already predict China, India, the USA and Brazil would be able to capture 0.5 to 2 Gt of CO2 per year. However, this is highly variable between studies, and would be largely dependent on rock type. te Pas et al (2023) for instance found that olivine or wollastonite could capture 0.43–2.30 or 0.45–1.78 t CO2 ha−1 globally, respectively. Whereas Buckingham et al (2022) calculated that five years of annual basalt application on UK cropland would only compensate for 3% of UK agricultural emissions. Taylor et al (2016) equally gives a very broad estimate that EW 'could lower atmospheric CO2 by 30–300 ppm by 2100'.
Cost - Benefit	Medium	Costs of scaled up deployment are still somewhat unknown, and would likely be highly dependent on materials, technique, and location. Beerling et al (2020) estimate USD 54–220 tCO2 –1, while Fuss et al (2018) gave a price range of USD 50–200 tCO2 –1, which is also the figure given by IPCC AR6 wg3 (2022).
Likelihood of environmental risks	Medium	Although the effects of EW on microbial levels needs to be explored further and depends on the minerals used (Bach et al. 2019), the measure seems to have relatively low environmental risks in comparison to other CDR. On the one hand, the effects of mining all the rocks required for large-scale application might be detrimental for the environment (IPCC AR6 wg3), and waste material is being used instead of mined rock, special care has to be taken not to use polluted material (Fuss et al. 2018). On the other hand, the pH adjustment from EW and related nutrientification might be beneficial to plants (Beerling et al. 2018), Fawzy et al (2020) review furthermore find numerous soil benefits being mentioned in the literature.

Effects on local/ indigenous communities	Beneficial	The mining of rocks could have impacts on local communities, and distribution could affect air quality (Edwards et al. 2017; Strefler et al. 2018). However, Beerling (2017) also notes it might provide additional benefits, like food security, and Bach et al (2019) state that 'in contrast to many other NETs, [EW is] generally not competing with other Sustainable Development Goals like global food and water security but are potentially even beneficial for them'.
Ease of reversibility	easy	
Risk of termination shock	low	
Suitability within current legal/ governance structures	High	Lawford-Smith and Currie (2017) discuss the ethics of EW.
Amount of attention in scientific journals and public media and currently ongoing research programs	Medium	Although not the primary CDR method, EW has been increasingly focussed on. Field trials have been conducted in several countries like the Netherlands, Belgium, and Canada. Several institutional programs exist, like the Leverhulme Centre for Climate Change Mitigation at the University of Sheffield (www.sheffield.ac.uk/lc3m/). There is also commercial exploration, with Microsoft recently announcing they paid the company UNDO to apply 25.000 tons of grounded basalt to cropland (Velev, 2023).

Black Carbon Reduction

Issue being addressed	Black Carbon (BC), also known as soot, is produced through the incomplete combustion of fossil fuels and biomaterials. Apart from its negative health impacts, BC also has significant climate effects as it generally has a lower albedo than its surroundings, and thereby increases the amount of radiation that is absorbed, both when BC is present in the atmosphere, and when it is deposited on land (Stjern et al. 2017). Due to the large albedo differences, the effects of BC are especially significant on areas that are normally covered in snow or ice (Hadley and Kirchstetter, 2012; Sand et al. 2016; Kang et al. 2020).
Description of the technology/ measure	The importance of reducing BC emissions from natural sources like forest fires is discussed elsewhere (see forest fire management). BC emission reductions from anthropogenic sources can be achieved in multiple ways. In high mountain regions much attention goes out to technological improvements, like the replacement of biofuel systems with cleaner burning

	alternatives. In the Arctic, legal and governance approaches like the banning of certain fuels for shipping vessels have been important (Messner, 2020). Which measure would be most effective, would highly depend on the region. Makarovaa et al (2021) for instance found that road transport was the most important anthropogenic BC source in Murmansk, and that a combination of measures together could reduce soot emissions by 65.5%. Stohl et al. (2013) found that one of the main sources of BC in the Arctic is flaring, while Virkanrt et al (2021) note that in the case of Greenland BC emission comes from multiple sources, and is increasing due to tourism, forest fires, and ship traffic.	
Technological readiness	High	Given the large scope of possible mitigation strategies, there is no clear answer for this, although most techniques are already readily available. There is also a need for increased BC emission data and observation to design adequate policies. Kang et al (2020) for instance note large discrepancies between studies on BC concentrations, depending on measurement methods and models used. Moreover, it is not clear how effective BC mitigation would be as a measure to cool global and Arctic temperatures because of many indirect effects of such mitigation (Kühn et al. 2020) and if mitigation strategies would not end up with a net heating effect, for example due to the reduction of sulfate particle emission, which have until now had a cooling effect on temperatures (Takemure and Suzuki, 2019; von Salzen et al. 2022).
Scalability	medium	Depending on the strategy and BC source, scalability would be more or less easy. Although local Arctic mitigation is shown to have significant potential (Aakre et al. 2017; Kühn et al. 2020), most of BC in the region is emitted outside of the region (Browse et al. 2013; Khan and Kulovesi, 2018), and would therefore require international collaboration. Rypdal et al (2009) argue that the most effective BC mitigation strategies would focus on Asia, as such reductions would be relatively cheaper to make and most BC emissions originate on the continent.
Timeliness for near-future effects	High	Some of the technologies would need to be developed further, but most mitigation strategies would be relatively quick to deploy if the adequate policies were taken. BC mitigation would moreover be able to achieve effects on a relatively short timescale (Kühn et al. 2020).
Potential to make a difference in Northern + Arctic	Medium	Given the increased albedo reducing effect of BC on snowy and icy surfaces, the reduction of such particles would be of prime importance for the region.There are however still significant uncertainties when ‘quantifying the role of BC in cryospheric melting' (Kang et al. 2020). Apart from the previously mentioned

		net warming effects that could come with changes in anthropogenic emissions, the role of BC on ice melt could in some contexts be relatively insignificant compared to other albedo reducing particles like dust or organic matter. Kaspari et al (2020) for example find that at present the effect of dust far outweighs that of BC when it comes to albedo effects on the North American South Cascade Glacier. There are already numerous actions by states to take carbon seriously, for example through the Arctic-Council “Enhanced Black Carbon and Methane Emissions Reductions: An Arctic Council Framework for Action”. Local mitigation strategies could also play an important role in this, with Makarovaa et al (2021) study on BC reduction in Murmansk showing a mix of policies could reduce BC emissions there by 65.5%. Aakre et al (2017) write that major BC reductions in the Arctic can be made by specific groups of Arctic countries, and that Russia is of crucial importance for the Arctic region. Kühn et al (2020) equally argue that Arctic states can by themselves already significantly reduce regional BC concentrations. Much attention in the Arctic has gone to shipping regulation, as 5 to 25% of air pollution in the region is shipping-related (Aliabadi et al. 2015), and Comer et al (2017) note that ‘[r]oughly two-thirds of the BC emissions (e.g.193 tons) made in 2015 over the Arctic could be attributed to ships.’ Browse et al (2013) however highlight that shipping regulations in isolation might be only effective locally, like in Greenland, where 10 to 15% of BC is attributable to shipping, but that major reductions would have to come through international regulations as most of the BC in the Arctic is emitted outside of the region. This international focus is also advocated by Khan and Kulovesi (2018), who equally argue for ‘global engagement’.
Potential to make a global difference	Low	According to a literature review by Kang et al (2020) the globally averaged direct and indirect radiative forcing effects of BC are estimated to be up to 1.2 W m−2 and second only to those of CO2. However due to the complexity of the indirect temperature effects of BC such as cloud formation, the effectiveness of mitigation efforts would be complicated to assess, especially as compared to the mitigation of other aerosols like methane (Smith et al. 2020). The ultimate net effects of mitigation would therefore likely be far smaller than could be assumed when only direct effects were taken into consideration (Kühn et al. 2020). Mitigation of BC would likely also impact the atmospheric presence of other aerosols (IPCC AR6 W3), like sulfate, which have had a net cooling effect on the climate (Takemure and Suzuki, 2019; von Salzen et al. 2022). Harmsen et

		al (2020) even find 'the effect of BC mitigation on global mean temperature is found to be modest at best (with a maximum short-term GMT decrease of 0.02 °C in 2030) and could even lead to warming (with a maximum increase of 0.05 °C in case of a health-focused strategy, where all aerosols are strongly reduced).'
Cost - Benefit	Unknown	This would depend highly on the chosen measure. Furthermore, different measures would be paid for by different groups. Legislation of shipping fuels would for example likely incur costs for commercial companies, whereas the alteration of combustion systems in public facilities would require public expenses.
Likelihood of environmental risks	Low	BC reduction would likely also entail reduction of other pollutants (IPCC AR6 Wg3). This is generally beneficial, although the removal of certain other chemical particles like sulfite might ultimately also have a net warming effect, and thereby could be detrimental to the environment (von Salzen et al. 2022).
Effects on local/ indigenous communities	Beneficial	Apart from the climate effects of BC mitigation, a reduction of such particles in the air would also lead to significant health benefits (Shindell et al. 2012; Messner, 2020; IPCC AR6 Wg3). Harmsen et al (2020) even write that stringent action could potentially avoid/ have avoided as many as 4 to 12 million deaths between 2015 and 2030. Kühn et al (2020) argue that a successful BC mitigation in ‘all Arctic Council member and observer states could reduce the annual global number of premature deaths by 329 000 by the year 2030, which amounts to 9 % of the total global premature deaths due to particulate matter.'
Ease of reversibility	easy	
Risk of termination shock	low	
Suitability within current legal/ governance structures	high	There are several attempts to include such measures into Arctic and Northern governance, especially around shipping fuel, like the Arctic-Council’s adaptation in 2015 of the “Enhanced Black Carbon and Methane Emissions Reductions: An Arctic Council Framework for Action”. Kühn et al (2020) note that they believe the probability that such reductions will be implemented is relatively high, as institutions like the Arctic Council have already done a lot of work on it, and member states have an active interest in its success.
Amount of attention in scientific journals and public media	Medium	There is significant interest into BC mitigation, especially when it comes to fuel legislation of shipping and the effects of forest fires. There have also been major global strategies from UNEP, and specific Arctic focussed projects like the EU funded Arctic Black

and currently ongoing research programs		Carbon impacting on Climate and Air Pollution (ABC-iCAP) project (abc-icap.amap.no), and the Arctic-Council “Enhanced Black Carbon and Methane Emissions Reductions: An Arctic Council Framework for Action” (Ginzburg, 2018).

Carbon capture and storage	
Issue being addressed	Both emission reductions and CDR measures that actively reduce carbon dioxide are essential to reduce the amount of GHGs in the atmosphere and mitigate the effects of climate change. However, some carbon emissions, especially in the industrial and energy sectors, will be difficult to fully decarbonise.
Description of the technology/ measure	Carbon Capture and Storage (CCS) refers to a scope of technologies that seek to capture point source carbon emissions and remove them from the carbon cycle (Metz et al. 2005). The capture and storage of carbon from biomass and the atmosphere is considered elsewhere in this report (see BECCS and DACCS respectively), and the focus here will be on capturing emissions from industrial and power sections. These technologies do not fall under the category of CDR as they do not directly reduce current atmospheric carbon levels, but rather seek to mitigate current carbon emissions as much as possible. There are several different carbon capture methods that can be roughly grouped together into pre-combustion, post-combustion, oxyfuel combustion, and High-temperature solids-looping processes (Möllersten and Naqvi, 2022). There are several options to store the captured carbon. Some suggest ocean storage (See GESAMP, 2019) at mid or deep levels (Marchetti, 1977) or on the seabed (Goldthorpe, 2017), but most studies and project consider geological reservoirs like saline aquifers, storage under seabeds, or in depleted fossil fuel sites (Holloway, 2007), and the injection of liquified CO2 into silicate rock formations (See also DACCS). Alternatively the captured carbon could also be utilized or turned into other materials. IPCC AR6 Wg3 report notes that such carbon capture and utilization (CCU) ‘has been envisioned as part of the ‘circular economy’ but conflicting expectations on CCU and its association or not with CCS leads to different and contested framings.’ The International Energy Agency (IEA) Energy Technology Perspectives 2023 report argues that such CCU could help CCS development and have some short term mitigating effects, however, Bui et al (2018) clearly state that 'The magnitude of the role that CCU might play in climate change mitigation is likely to be very small, relative to that played by CCS.' The focus of this review will therefore also be on CCS.

<table>
<tr><td></td><td colspan="2">All elements of CCS are currently already in use in some form (Kearns et al. 2021), however many issues remain with its’ large scale implementation and potential effect. Möllersten and Naqvi (2022) furthermore write that most of the 26 commercial CCS projects were related to enhanced oil recovery, which uses captured CO2 to increase oil production and can therefore not be considered as a climate positive measure. Bui et al also (2018) note that reducing industrial emissions is difficult, and give the example for the cement sector: 'even if the energy required to operate the process was entirely zero carbon, this would only reduce the CO2 intensity by 40%.' IPCC AR6 W3, also remark that 'As a general rule it is not possible to capture all the CO2 emissions from an industrial plant. To achieve zero or negative emissions, CCS would need to be combined with some use of sustainably sourced biofuel or feedstock, or the remaining emissions would need to be offset by carbon dioxide removal (CDR) elsewhere.'

Nevertheless, CCS is essential to almost all IAMs that keep temperature rises below 2 degrees (Bui et al 2018), and is also an essential part in CDR measures like DACCS and BECCS. The International Energy Agency (IEA) also clearly states in their Net Zero by 2050 report (2021) it considers CCS to belong to one of the three technological sectors in which lie the 'biggest innovation opportunities’.</td></tr>
<tr><td>Technological readiness</td><td>Medium</td><td>Technological development of carbon capture capability is happening, but at a relatively low rate, although Kearns et al (2021) note that 'All elements of the carbon capture and storage value chain are mature and have been in commercial operation for decades.'

The IPCC AR6 WR3 however write of ‘Low readiness in several supply chain components’, and particularly highlights the need to develop an infrastructure and logistical networks (2022).

Bui et al (2018) observed 'great progress … in the area of CO2 storage' in the years leading up to their study, however, although there is theoretically more than enough capacity in the Earth’s basalt and underground storage areas (Metz et al. 2005; Sovacool et al 2022), questions remain especially about feasibility, performance and safety of storage. Apart from risks related to earthquakes (Kazemifar 2022), storage underground requires monitoring to see if there are no leaks (Godin et al 2021). Such projects could furthermore run into social acceptance issues of local populations (Cox et al 2020, Sovacool et al 2022). There are several large-scale storage projects, like the Danish project *Greensand*, which intends to store large amounts of CO2 under the North Sea (projectgreensand.com/).</td></tr>
</table>

Scalability	Medium	Kearns et al (2021) describe significant economies of scale that could benefit larger projects, at concentrated sources, with better infrastructure, with costs that could be reduced even further as the technology matures. However, the IPCC AR6 Wg3 write that ‘A key challenge with all CCS strategies, however, is building a gathering and transport network for CO2, especially from dispersed existing sites; hence most pilot projects are built near EOR/geological storage sites’. The scaling of CCS could therefore be physically limited.
Timeliness for near-future effects	High	There is widespread agreement in studies that CCS deployment has not proceeded as quickly as hoped. In 2009 Haszeldine already argued for the urgency for a rapid deployment of CCS in an influential Science article. However, in 2018 Bui et al noted that 'It is evident that, despite substantial public and private effort to commercialize and deploy CCS technology, progress is lagging behind what is commonly considered to be required to meet climate targets. This is echoed by Fawzy et al in 2020 when they state that the development of CCS at the time of writing was far below the scenario of IEA, and Chen et al (2022) who wrote that ‘the actual scale of CCUS is still far behind our expectations’ and therefore foresee the global "Golden Age" for the technology only from 2040 to 2060. Grant et al (2022) provide an even more sobering picture about future potential by claiming that some models are wrong in assuming ‘abundant and globally accessible CO2 storage’, and that they therefore could ‘substantially overestimate the role of CCS in low-carbon scenarios.'
Potential to make a difference in Northern + Arctic	Medium	Bankes (2012) writes that CCS projects in the Arctic region will likely mostly be centered around highly concentrated emitters like fossil fuel industry or mining, and would also need to be close to storage sites. Given the relatively limited population density, CCS potential in the Northern regions would be less in absolute numbers than in more densely inhabited regions. Although improved infrastructure might enable storage in further locations, as Lefvert et al (2022) note might be the case for Sweden, which could store captured CO2 in Norwegian deposits. Some also foresee that CCS could allow the Arctic fossil fuel reserves to be turned into non-GHG emitting hydrogen (Dvoynikov et al. 2021). Moreover, given the importance of emission reductions in the Arctic (See black carbon reduction) and the existence of highly polluting industries related to oil and gas extraction, CCS could nevertheless play an important role.

Potential to make a global difference	Medium	If found to be feasible, CCS could reduce some emissions significantly, and it plays an important role in most mitigation scenarios (See for example IPCC AR6 W3). However, CCS is not a CDR measure by itself, and it would not change the level of already emitted carbon in the atmosphere unless combined with other elements (see for example BECCS or DACCS). Grant et al (2022) also caution that 'models which assume abundant and globally accessible CO2 storage may substantially overestimate the role of CCS in low-carbon scenarios.'
Cost - Benefit	Low	Although capture costs and efficacy from a point source will be far lower than direct air capture (see DACCS), cost estimates vary substantially (Leeson et al. 2017; Vinca et al. 2018; Kearns et al. (2021), and would depend highly on location and storage methods. Kearns et al (2021) give a price range of less than \$20/t CO2 to over \$120/t CO2', and foresee that costs will drop significantly with time. IPCC AR6 W3 (2022) adds that 'Because CCS always adds cost, policy instruments are required for it to be widely deployed.'
Likelihood of environmental risks	Low	There might be risks related to the storage component of CCS (Fawzy et al. 2020). GESAMP (2019) and Levin et al (2023) highlight significant risks to marine ecosystems of marine storage, and leakage from storage on land could potentially pose serious dangers to local communities and ecosystems (Ma et al. 2020). Boot-Handford et al (2014) however argue that storage appears increasingly safe, and that natural examples show potential impact of leakages in geological storage is limited. IPCC AR6 W3 (2022) also warned that CCS would cause "considerable increases in some resources and chemicals, most notably water.' They furthermore write that the utilization of CCS would add some further difficulties to the environmental evaluation of CCS, and would require careful analysis over the entire lifecycle.
Effects on local/ indigenous communities	Beneficial	Faulty storage could potentially be dangerous for local communities. According to Bui et al (2018) CCS could also 'create a significant number of jobs.'
Ease of reversibility	easy	
Risk of termination shock	Medium	Issues around storage will have to be solved. It is unlikely that stored carbon can feasibly be removed again once in place.
Suitability within current legal/ governance structures	High	Bui et al (2018) note that 'the private sector can likely deliver CCS without any change to existing regulation.' Yet, adequate policy implementation could substantially increase CCS development

		(Kearns et al. 2021), and might even be required for CCS to be widely deployed (IPCC AR6 W3). Storage on national territories would be subject to national law, but some storage projects could directly, or indirectly through risk if faulty, also fall under the legislation of other states or international law. In case of the Arctic, Bankes (2012) notes there might be some hurdles for large scale CCS regulation.
Amount of attention in scientific journals and public media and currently ongoing research programs	High	CCS is part of almost all climate mitigation scenarios, and there is growing commercial-driven interest in CCS. There are already many CCS projects (see for a list of all European projects for example zeroemissionsplatform.eu/about-ccs-ccu/css-ccu-projects/). On the public perception of CCS IPCC AR6 W3 (2022) notes: 'Many people are unfamiliar with carbon capture and storage (CCS), so have not formed firm opinions. Some firmly reject CCS; some are concerned that CCS may avoid making greenhouse gas (GHG) emission reductions.'

Atmospheric Methane removal: Solar Chimney and Photocatalytic semiconductor technology

Issue being addressed	Methane is a highly potent greenhouse gas and its reduction is given ever greater priority in international emission reduction policies (see for example https://www.globalmethanepledge.org/). There are several suggested ways to remove atmospheric methane (see Nisbet Jones et al. 2021; and Ming et al. 2022; see in this report also iron salt aerosols and zeolites). One of the main issues with methane removal is that atmospheric methane concentrations are very low. This means that very large volumes of air, and related energy demands, are required, making the use of ventilators like those used for DACCS (see direct air capture) more complicated (Nisbet-Jones et al. 2021).
Description of the technology/ measure	De Richter et al (2017) first suggested that it might be possible to combine photocatalytic reactors, which would degrade methane into water vapor and CO2, with a solar updraft tower that uses large volumes of air that are passively moved inside it by incoming solar radiation to power generators. De Richter et al (2016 & 2017) suggest multiple solar chimney power plants with photocatalytic reactors (SCPP-PCR) could potentially produce renewable energy and process large enough amounts of air to significantly reduce methane levels.

Technological readiness	low	Solar chimneys have been in use for a long time in warmer regions of the world. The first ideas to combine the passive system with power generation were proposed in the 70s (Zhou et al. 2010; Kasaeian et al. 2017). Multiple small pilot plants have since been built. The largest of these was already constructed in Spain in the 1980s. Recently, interest in the technology seems to have been growing, with multiple studies exploring different elements of its design and effectiveness (See for example Ming et al. 2021; or Xiong et al. 2023). However, apart from the pilot plants, the technology has not yet been operationalised or commercialized, and questions remain about ultimate feasibility to scale. The other part of this technology is the photocatalytic methane removal systems. These are already in use in various forms (Wang et al. 2022). With growing interest in methane removal technologies, the development of such photocatalytic technologies is also advancing (Li et al., 2019). However, scaling up is a major issue of concern to all methane mitigation technologies, given the large amounts of air required (Lackner, 2020; Jackson, 2021). Although new studies are exploring crucial issues (see for example Ming et al. 2021 and Huang et al. 2021), studies will have to provide experimental data and show how effective and scalable such a system can be. Cobo et al's (2023) review assigns photocatalytic methane degradation in general a low technological readiness level of 3 to 4.
Scalability	unknown	Scaling up is a major issue of concern to all methane mitigation technologies, given the large amounts of air required (Lackner, 2020; Jackson, 2021). Huang et al (2021) already showed that size of the towers would significantly influence the system’s efficiency. Nisbet-Jones et al (2021) note that the use of solar towers for energy generation seemed to be best feasible through especially large structures, but that it is not sure if this holds true for methane removal too. Because solar towers depend on solar radiation to function, it is likely that physically scaling across the globe will not see similar efficiency rates, and greatest efficiency will be achievable in parts of the globe with the greatest amount of sun hours.
Timeliness for near-future effects	Unknown	

Potential to make a difference in Northern + Arctic	Low	Given this technology’s dependency on sunlight, it is likely the Arctic is not the most promising for such structures. Although variants to a chimney system have been proposed for the Polar regions (see Polar Chimney).
Potential to make a global difference	unknown	It is not yet clear how effective such systems would be. Some studies extrapolate very high potential capture rates, with De Richter et al (2017) claiming that 2 out of 3 CH4 molecules would be removed from the airflow, and Huang et al (2021) calculating that a large tower combined with an effective photocatalyst could remove up to 42.5%.
Cost - Benefit	unknown	Apart from the construction and maintenance costs of the towers, these devices would not require energy input and could potentially be relatively cheap measures for methane removal.
Likelihood of environmental risks	unknown	
Effects on local/ indigenous communities	Unknown	Apart from methane removal and energy generation, solar towers have in other studies also been explored in their capacity to provide other utilities like water production (Zuo et al. 2020; Wu et al., 2020) or to counter local air pollution (Liu et al. 2021). If such co-benefits could be realized, this could be very beneficial to local communities.
Ease of reversibility	Easy	
Risk of termination shock	Low	
Suitability within current legal/ governance structures	High	This will likely fall under national or regional legislation comparable to the construction of other kinds of power plants.
Amount of attention in scientific journals and public media and currently ongoing research programs	Medium	Although the importance of methane mitigation is increasingly recognised, this particular measure has not been widely picked up other than in some academic studies. Interest in solar towers seems particularly great amongst specific groups, especially in China, but has not really captured mainstream attention yet.

<table>
<tr><td colspan="3">Atmospheric methane capture by zeolites</td></tr>
<tr><td>Issue being addressed</td><td colspan="2">Methane is a highly potent greenhouse gas and its reduction is given ever greater priority in international emission reduction policies (see for example https://www.globalmethanepledge.org/). There are many different materials that have been suggested and explored to capture methane (Alonso et al. 2017).</td></tr>
<tr><td>Description of the technology/ measure</td><td colspan="2">Zeolites are porous minerals that can capture methane (Jackson, 2019). Many studies focus on zeolites’ capacity to transform methane into more useful methanol (Tomkins et al. 2017; Ravi et al. 2019; Mahyuddin et al. 2019), and into syngas (Hambali et al. 2022), and there is also significantly scholarly attention for the CO2 capture potential of zeolites (see for instance Findley and Sholl, 2021; Tao et al. 2023; and DACCS), with the company Removr currently building a large scale carbon capture device using zeolites (https://www.removr.no/).
Yet, the transformation of methane into “less harmful” CO2 can already provide major climate benefits (Jackson, 2019; Brenneis et al. 2021). As a material, zeolite is very inexpensive and often found in clay, and therefore, as almost all popular science references highlight, currently used to make cat litter. The methane capture potential of zeolites can be further enhanced if treated with very small quantities of metals like copper (Brenneis et al. 2021). Methane capture through copper treated zeolites would work especially well when the gas is present in larger quantities, but can also function in small concentrations under relatively low temperatures (Brenneis et al. 2021).</td></tr>
<tr><td>Technological readiness</td><td>low</td><td>Cobo et al's (2023) review assigns methane oxidation in general a very low technological readiness level.
Nisbet Jones et al (2021) write that zeolite-using devices are already in widespread use, for example by oxygen concentrators in use in hospitals. According to the authors, this makes it more likely that zeolite-based methane capture could be more easily scaled up than other more experimental technologies. However, given the relative novelty around the usage of zeolites for methane capture, many questions remain open. Moreover, not all zeolite structures are useful, as Kim et al (2013) showed after screening over 87,000 zeolite structures for their capture potential.
Due to the urgency given to methane mitigation, there seems to be great potential for future developments, with an MIT team working on the idea receiving a $2 million development grant from the U.S. Department of Energy (news.mit.edu/2022/dirt-cheap-solution-common-clay-materials-may-help-curb-methane-emissions).</td></tr>
</table>

Scalability	medium	Scaling up is a major issue of concern to all methane capture technologies given the low methane concentrations and therefore large amounts of air required (Lackner, 2020; Jackson, 2021). Zeolites too would be much more effective close to sources of concentrated emissions. This could limit the effective scalability. However, due to the low costs and energy requirements, zeolites application could also be relatively easily scalable, with economies of scale potentially probably down costs further. Moreover, the chemical process releases heat, and air with above 0.5 percent concentration of methane would provide more energy than was required to start the process (Brenneis et al. 2021). This means such devices could be used to generate energy when deployed near very concentrated sources. Some zeolites can capture methane at room temperature, and because the goal would be to transform CH4 into CO2, and the transformed methane could be released after its transformation into carbon dioxide, there would be no need for the construction and maintenance of compression, purification, storage or related infrastructure (Ming et al 2022). This could mean that potential application could be done at many and diverse sites, rather than other capture techniques relying on storage (see DACCS, BECCS, and CCS).
Timeliness for near-future effects	Unknown	Methane mitigation holds the promise of providing major climate benefits in a short timespan (IPCC AR6 Wg3, 2022; Sawyer et al. 2022). Nisbet Jones et al. 2021 write that the already widespread use of similar techniques in other areas, they believe they ‘could likely be readily upscaled in a way that a more experimental technology could not, which is a significant advantage when dealing with the immediate need for decarbonization’. However, in a short comment in Nature Sustainability Klaus Lackner (2020) also notes that the short lifetime of tropospheric methane in comparison to CO2 requires methane destruction measures to treat significant amounts of air to make a meaningful difference.
Potential to make a difference in Northern + Arctic	Low	There have been no studies on the potential role of zeolites for Arctic methane. Physically, zeolite-based methane capture devices would ideally be placed close to point source emissions. Because this method to capture methane would not need storage facilities and related infrastructure, some of the objections against DACCS and BECCS

		sites for remote regions of the Arctic do not apply to zeolite capture facilities.
Potential to make a global difference	unknown	Rapid methane mitigation is given increasing international priority. However, the potential of methane capture is not included in the IPCC AR6 WG3 mitigation scenarios because their role 'has not been quantified' yet (2022, p348), and the report also writes that a ‘scarcity of literature on these methods prevents assessment’ (p. 1261). It is therefore difficult to estimate the potential global effect of methane capture.
Cost - Benefit	low	Brenneis et al. (2021) write about potential costs below $15–50/ton of CO2 equivalents. Ming et al (2022) report a target cost of a $100 per ton−1 of CO2-eq, but note that costs could be reduced if air capture plants could combine a CO2 and CH4 capture function. Given the low material cost and energy requirements, zeolites are likely to be relatively cheap in comparison to other methane capture technologies. The chemical process also releases heat, and air with above 0.5 percent concentration of methane would provide more energy than was required to start the process (Brenneis et al. 2021). This means such devices could be used to generate energy when deployed near very concentrated sources.
Likelihood of environmental risks	low	
Effects on local/ indigenous communities	Beneficial	If applied at sufficiently concentrated sources, the energy production of the process might provide side-benefits to local communities.
Ease of reversibility	Easy	
Risk of termination shock	Low	
Suitability within current legal/ governance structures	High	
Amount of attention in scientific journals and public media and currently	medium	This measure is relatively new, but is gaining increasing attention and is mentioned in several methane mitigation reports. It has featured in several popular and popular science articles (see for example news.mit.edu/2022/dirt-cheap-solution-common-clay-materials-may-help-curb-methane-emissions or weforum.org/agenda/2022/01/solution-clay-curb-methane-

ongoing research programs		emissions/#:~:text=They%20used%20zeolite%20clays%2C%20a,even%20at%20extremely%20low%20concentrations).

Polar chimneys

Issue being addressed	Some have suggested modifying incoming and outgoing radiation budgets in the Arctic to mitigate the warming in the region.	
Description of the technology/ measure	Bonenelle and de Richter (2010) and Ming et al (2014) describe a polar chimney built on the Arctic coasts allinging mountains, like Alaska or Norway. The system consists of a large tower leaning against the relief that sucks in cold polar air, coupled with a heat exchanger at the bottom that reacts with the relatively warm waters of the gulf stream. In two heat exchange processes this system would generate energy, whilst also helping sea ice formation and cooling down seawater. Moreover, in Ming et al (2014) description, an addition would encourage snowfall and thereby 'increase polar albedo'.	
Technological readiness	low	This has only been referred to in a few isolated studies.
Scalability	low	
Timeliness for near-future effects	low	
Potential to make a difference in Northern + Arctic	low	It is specifically thought out to be built in the Arctic.
Potential to make a global difference	Low	
Cost - Benefit	unknown	
Likelihood of environmental risks	unknown	
Effects on local/ indigenous communities	Beneficial	If this technology could indeed generate electricity this would be beneficial to local communities.

Ease of reversibility	unknown	
Likelihood of termination shock	low	
Suitability within current legal/ governance structures	High	
Amount of attention in scientific journals and public media and currently ongoing research programs	low	This has only been referred to in a few isolated studies.

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