Frozen Arctic

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

A UArctic Rapid Response Assessment

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Key findings

- In this initial assessment, certain traditional land-based mitigation activities (such as afforestation and peatland restoration), as well as some more experimental carbon dioxide removal measures (for example, biochar), scored relatively high as potential interventions to address climate change.

- Some proposed solutions, such as hydrological cycle modification and carbon dioxide deposition in Antarctica, scored low against most criteria rendering them unsuitable for further consideration at this time.

- Generally, ocean-based measures tended to receive lower scores compared to land-based ones and exhibited higher degrees of uncertainty.

- There have only been a few suggestions on how to mitigate the melt or preserve the current extent of sea ice and ice sheets, and most of these measures come with significant uncertainties or limitations.

- Some atmospheric solar radiation management measures score very high in this assessment, particularly in terms of their potential global impact, although they also come with significant risks.

- The scores of the industry measures varied widely. Those related to methane especially showed many uncertainties.

- Significantly more research is required for most measures, particularly regarding their potential impacts on local communities.

- This preliminary, high-level analysis raises many questions that will be examined in a more comprehensive evaluation during Phase II of the Frozen Arctic project.

Introduction

The polar regions and the northern boreal zone contain elements critical to the global climate system, including the Greenland and Antarctic ice sheets, Arctic sea ice, and Arctic permafrost (McKay *et al.* 2022; see box). Although the goal of the Paris Agreement on climate change is to limit mean global temperature rise to between 1.5°C and below 2°C, the world is currently on track for an increase of approximately 2-3°C. Already the Arctic is warming at a rate four times faster than the global average (Rantanen *et al.* 2022). At this level of warming, it is highly likely that many of these vital components will be irrevocably lost.

Rapid climate change, driven mainly by human activities, is leading to significant environmental changes both in the polar regions and around the world. Global sea levels are rising as the Greenland and West Antarctic ice sheets decay. The catastrophic and irreversible loss of permafrost at somewhat higher temperature thresholds has the very real potential to release vast amounts of carbon that could dwarf all national emission reductions pledges. The boreal forest, a globally important carbon store, is advancing northwards into tundra landscapes. Replacing tundra vegetation with low-lying shrubs, bushes, and trees lowers the surface albedo (reflectivity) and does not lead to increased carbon sequestration (Zona *et al.* 2022).

The loss of carbon, especially in the form of greenhouse gas emissions from permafrost thaw, coupled with reduced albedo, creates a positive feedback loop for global warming. By 2100, financial damages stemming from sea level rise and permafrost carbon feedback are projected to reach trillions of dollars (Yumashev *et al.* 2019; Brown *et al.* 2021). Additionally, further positive feedback is anticipated from the continued loss of Arctic sea ice. As sea ice melts, less sunlight is reflected back into the atmosphere and more solar energy is absorbed by the ocean. The risk of globally significant changes in high latitude ocean circulation patterns, such as the Labrador/subpolar gyre and overturning regions of the Atlantic Meridional Overturning Circulation, is closely associated with increasing meltwater from the Greenland ice sheet.

It is now acknowledged that global ambitions to reduce greenhouse gas emissions to reach the 1.5 °C target are highly unlikely and that there is only a 50 percent chance of limiting the increase to 2°C (Meinshausen *et al.* 2022). In addition to reducing emissions, there is a critical need for an unbiased examination of potential solutions to slow down, halt, and reverse the effects of climate change in the Arctic and northern regions and prevent tipping points from occurring.

Numerous interventions to address climate change have been proposed in policy papers, by interest groups, and within the scientific literature. Nevertheless, to our

Box 1: Over 50% of climate tipping points with global repercussions are located in the Arctic

McKay *et al.* 2022 identify 16 major Global Climate Tipping Points. Nine of these are in the Arctic and northern regions (in order of the estimated global warming needed to pass their tipping point):

- Collapse of the Greenland ice sheet
- Abrupt thaw of northern permafrost
- Loss of Barents Sea ice
- Collapse of Labrador Sea current
- Collapse of northern permafrost
- Southern dieback of boreal forests
- Northern expansion of boreal forests
- Collapse of North Atlantic deep-water formation
- Collapse of the Arctic winter sea ice

Global consequences of these tipping points include:

- Amplified global warming
- Rapidly increasing sea level
- Changes in weather patterns and weather extremes
- Changes in ocean currents
- Ocean acidification, de-oxygenation
- Impact on ecosystems (fisheries, wildlife, plants)
- Impact on food production
- Impact on freshwater supply

knowledge, an overview that enables comparison of potential options for implementation in the northern and Arctic regions – the region where the majority of the tipping points are expected to occur – does not exist (Figure 1).

This short report presents the findings of Phase I of the Frozen Arctic Conservation project, a collaborative undertaking between the Secretariat of the University of the Arctic, GRID-Arendal, and the Arctic Centre/University of Lapland.

The goals of Phase I were:

1. To capture and effectively map out the range of possible interventions that exist or have been proposed to reverse, stabilize, or delay climate change impacts in the northern and Arctic regions for the benefit of the world;
2. To create a standardized evaluation matrix against which possible interventions could be scored;
3. To evaluate possible interventions according to an evaluation matrix in order to gain a preliminary understanding of the strengths and weaknesses of each.

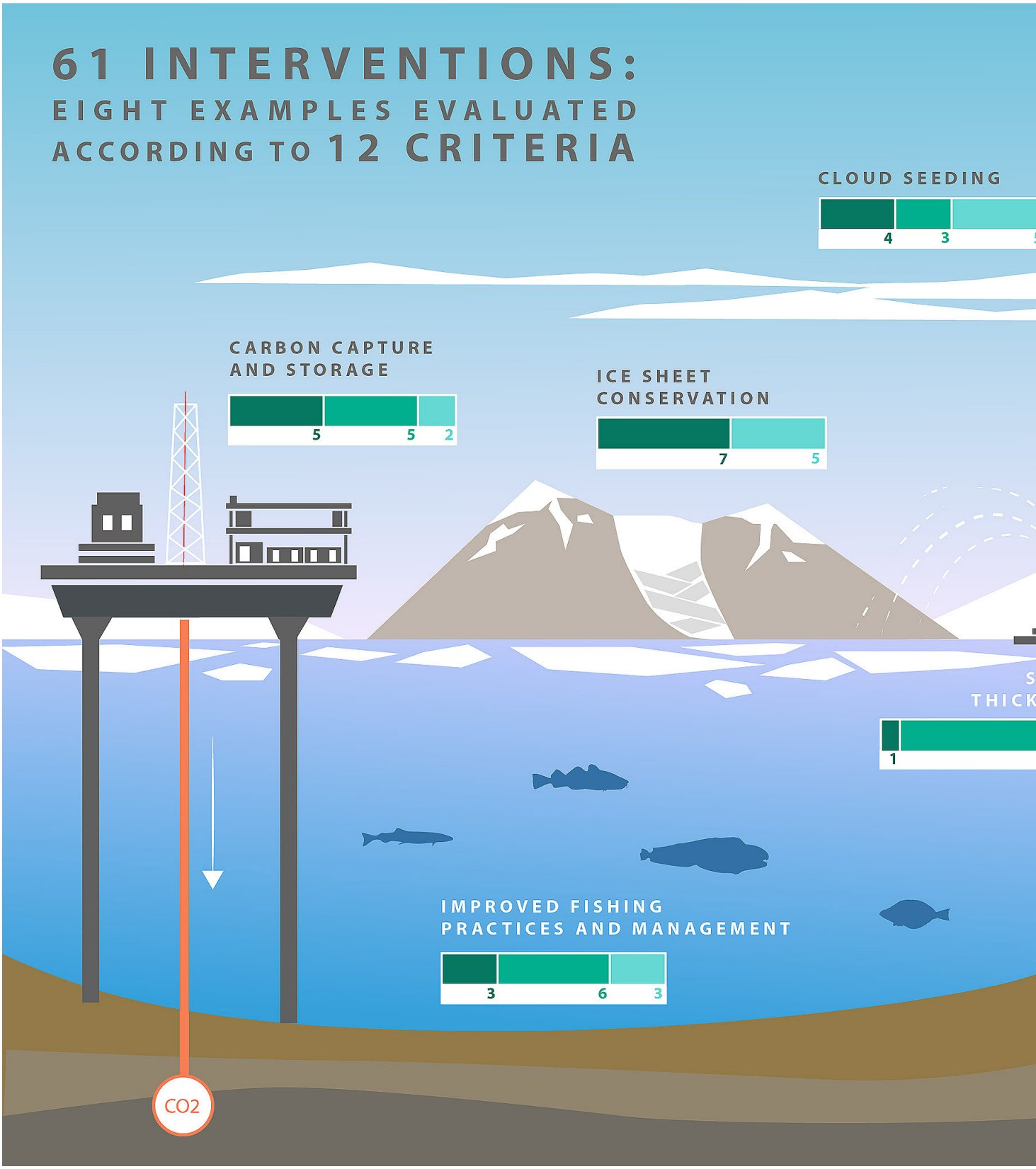
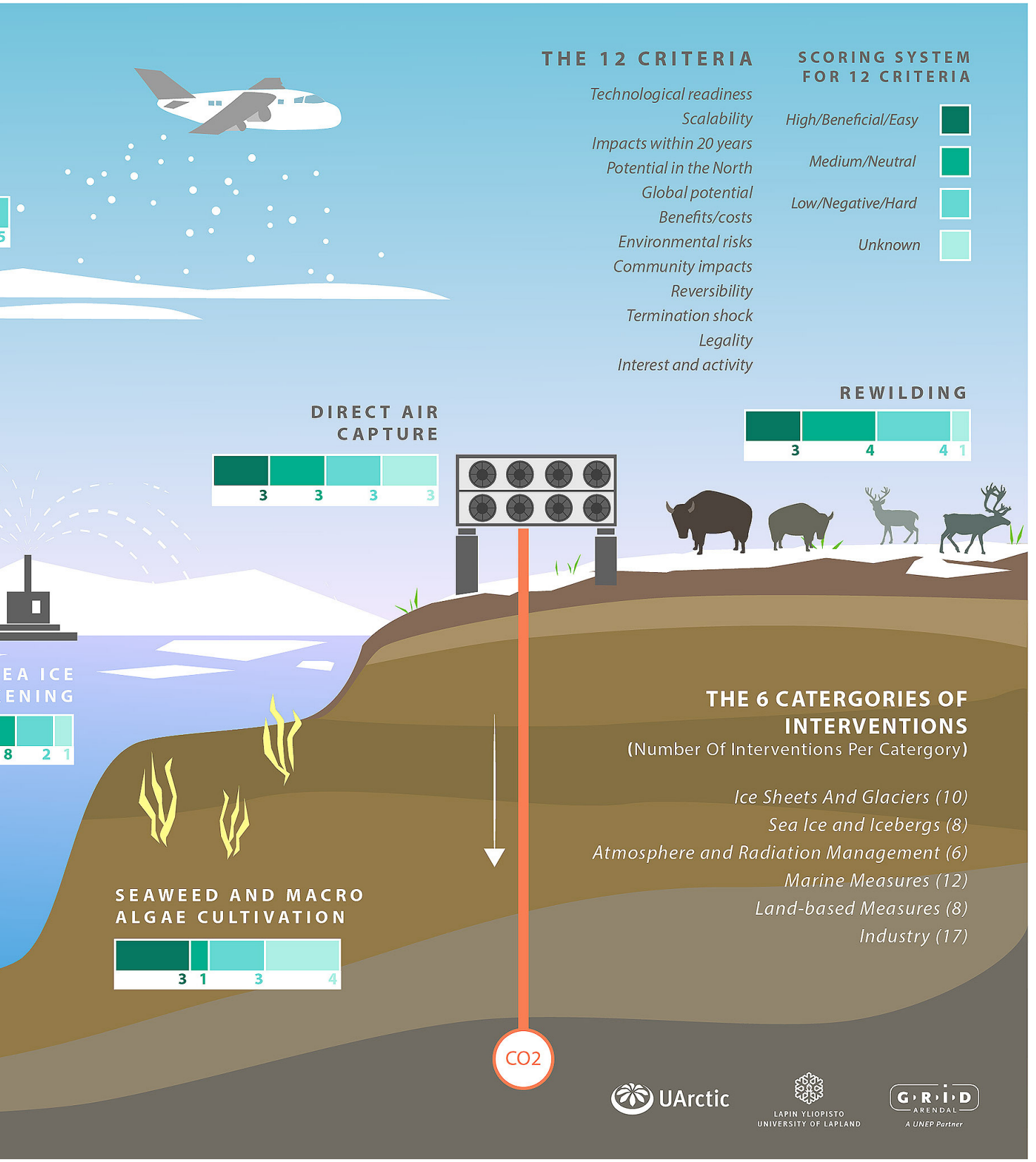


Figure 1: *Comparison of selected interventions according to the 12 criteria.*


THE 12 CRITERIA
Technological readiness
Scalability
Impacts within 20 years
Potential in the North
Global potential
Benefits/costs
Environmental risks
Community impacts
Reversibility
Termination shock
Legality
Interest and activity
SCORING SYSTEM FOR 12 CRITERIA
High/Beneficial/Easy
Medium/Neutral
Low/Negative/Hard
Unknown
REWILDING
3 4 4 1
DIRECT AIR CAPTURE
3 3 3 3
EA ICE
ENING
8 2 1
SEAWEED AND MACRO ALGAE CULTIVATION
3 1 3 4
THE 6 CATERGORIES OF INTERVENTIONS
(Number Of Interventions Per Catergory)
Ice Sheets And Glaciers (10)
Sea Ice and Icebergs (8)
Atmosphere and Radiation Management (6)
Marine Measures (12)
Land-based Measures (8)
Industry (17)
CO2
UArctic
LAPIN YLIOPISTO
UNIVERSITY OF LAPLAND
GRID ARENDAL
A UNEP Partner

Limitations of this report

This report constitutes a “rapid assessment”. The project team confined itself to a desktop review of available literature (including academic, grey, opinion forums, etc.) within a span of 3 months (January to March 2023). Extensive interviews with experts or stakeholders were not conducted. The documentation of interventions and subsequent evaluations were undertaken with the information available which, for many solutions, was found to be incomplete. Our cut-off date for papers and other information was March 2023; any information available after this date has not been included. Each solution was scored by a member of the author team and then reviewed by the other team members. We, therefore, emphasize that an extensive peer review should be undertaken in phase II of this assessment.

Method

Identification of possible interventions

Our intention was to identify and document the full range of interventions that have been proposed to reverse, stabilize, or delay climate change impacts in the northern and Arctic regions. This includes back-of-the-envelope calculations and "fringe" ideas through to seriously studied and researched ideas. For this reason, we have included ideas for which there is very little documentation.

The literature review took place between January to March 2023 and included online searches of academic literature, grey literature, as well as opinion forums (e.g., active Google groups). During the conceptual stage and prior to commencing the literature review, the project team developed the following initial solution list based on their own knowledge and grouped them into three broad categories (see Table 1).

As the literature review progressed, more proposed interventions presented themselves. Ultimately, the solutions were assigned to six categories: ice sheets and glaciers, sea ice and icebergs, atmosphere and radiation, oceans and marine, land-based measures, and industry.

Table 1: *The initial list of interventions identified in the concept stage (prior to literature review).*

Ecosystem management	Geo-engineering	Industry approaches
• Re-wilding • Blue forest stimulation • Fishing practices (trophic level) • Potential increases in oceanic and coastal blue carbon with, for example, naturally retreating sea and coastal ice, seaweed farming • Boreal forest management • Peatlands and wetlands management in tundra and taiga • Northern wildfire management • Permafrost landscapes/tundra surface albedo stabilization and increases, e.g., whiter plants • Herding and land management change	• Ice sheet stabilization via seabed curtains • Pumping of water or snow making on the ice sheets • Sea ice and glacier albedo increase • Sea ice thickening to extend the ice season • Sea ice breakup in winter by icebreakers to cool the ocean • Modifying ocean density structure, e.g., pumping deep waters • Glacier insulation and ice storage • Increased snow season duration, e.g., albedo enhancement with particles • Cirrus cloud thinning in the Arctic winter • High latitude seasonal stratospheric aerosol injection • Arctic marine cloud brightening	• Direct air capture potential in cool polar conditions • Urban albedo enhancement, e.g., white roofs. • Energy production in Arctic communities • Energy sources for Arctic shipping & fishing fleets (hydrogen/ammonium) • Arctic and northern process industries – raw materials and processing

Development of evaluation criteria and scoring process

A set of criteria was developed to establish a structured and comparable approach for documenting and evaluating potential interventions. Following internal discussions, the team defined a set of 12 criteria that were deemed to be important benchmarks for evaluating solutions (see Table 2). To provide a basis for understanding the performance of each intervention, the team also devised a simple 3-point scoring system (i.e., low, medium, high; negative, neutral, beneficial), along with qualifying statements.

Each intervention was researched, documented, and evaluated by a team member. Individuals were assigned interventions according to their background and prior knowledge related to each proposed intervention. A concise narrative evaluation of each intervention was included according to the 12 criteria. This was accompanied by a brief introductory description of the proposed solution and the challenge it claims to address.

To facilitate future statistical analysis, a numerical score was also assigned to each criteria. For parameters where “high” is the desirable quality, a score of 3 was given; “medium” was scored 2; and “low” was scored 1. Conversely, when “low” is the preferred quality, it was assigned a score of 3; 2 for “medium”, and 1 for “low”. If there was no available information, “unknown” was used.

The narrative descriptions and assigned scores were reviewed by at least one other person in the team. The evaluation results are presented in Table 3.

Table 2: *Criteria and scoring system for evaluating interventions.*

Criteria	Description	Scoring levels	Score	Scoring statement
Technological Readiness Level	Technological Readiness Levels (TRL) as defined by Horizon Europe to measure or indicate the maturity of a given technology (hereafter referred to as solutions)	Low	1	Defined as a technology with TRL of between 1-3: TRL 1 – basic principles observed TRL 2 – technology concept formulated TRL 3 – experimental proof of concept
		Medium	2	Defined as a technology with TRL of between 4-6: TRL 4 – technology validated in lab TRL 5 – technology validated in relevant environment (industrially-relevant environment in the case of key enabling technologies) TRL 6 – technology demonstrated in relevant environment (industrially-relevant environment in the case of key enabling technologies)
		High	3	Defined as a technology with TRL of between 7-9: TRL 7 – system prototype demonstration in operational environment TRL 8 – system complete and qualified TRL 9 – actual system proven in operational environment (competitive manufacturing, in the case of key enabling technologies, or in space)
Scalability	Ability to replicate the same approach in terms of the space available, and the efficiency of scalability	Low	1	Physically unable to scale; sub-linear/logarithmic efficiency of scalability
		Medium	2	Physically somewhat able to scale; linear efficiency
		High	3	High ability to scale physically; exponential efficiencies
Timeliness for near-future effects.	Ability to get the solution in place in time to make a significant difference within the coming 20 years	Low	1	Implemented too late to make a significant difference
		Medium	2	Implemented in time to make some difference, although questionable
		High	3	Implemented in time to make a significant difference
Potential to make a difference in Arctic and northern regions given enough time	Would the effects of this solution benefit the Arctic/northern regions specifically, and are there specific benefits to deploying this solution in the Arctic/northern regions vs elsewhere?	Low	1	No noticeable extra positive effect beyond the global average; technology is unsuited to the Arctic
		Medium	2	Statistically detectable impacts in the Arctic above the global average; no difference to deploying the solution here or elsewhere
		High	3	Very detectable impacts in the Arctic above the global average; technology ideally/preferably located here

Table 2: *Criteria and scoring system for evaluating interventions (continued).*

Criteria	Description	Scoring levels	Score	Scoring statement
Potential to make a global difference given enough time	Potential for the technology to make a difference globally, i.e., beyond the Arctic/ northern regions	Low	1	Insignificant to be detected at a global scale
		Medium	2	Statistically detectable impacts
		High	3	Major impacts detected
Cost to Benefit Comparison	Cost comparison to other similar technologies in relation to the benefit derived	Low	3	Low cost of investment vs. cost of damages avoided (e.g., a few %) and/or inexpensive in comparison to other measures which have similar impact
		Medium	2	Significant costs of investment needed but these still much cheaper than cost of damages avoided (e.g., 30%)
		High	1	Comparable to damage
Likelihood of environmental risks	The likelihood of side effects on the environment as a result of the deployment of a solution	Low	3	Very limited effects which are site-specific to the solution deployment location only
		Medium	2	More widespread and possibly regional impacts going beyond the immediate solution deployment location
		High	1	Major, serious risks with a high disaster risk potential; multiple and cascading risks
Effects on Indigenous/local communities	The actual effect of installing solutions and long-term impact of solutions on communities, from a livelihood, social and health-related perspective.	Negative	1	Serious detrimental effects
		Neutral	2	Unnoticeable/negligeable positive or negative effects
		Beneficial	3	Significant benefits to communities
Ease of reversibility	The ability to reverse back to the original present state prior to solution deployment (once a solution is stopped).	Low (hard)	1	Impossible or very difficult to reverse
		Medium	2	Possible with significant investment
		High (easy)	3	Easily reversible naturally
Likelihood of termination shock	The level of damage that could be expected if the solution were to be stopped abruptly	Low	3	Low/insignificant termination shock or damage
		Medium	2	Medium/relatively significant termination shock or damage
		High	1	High/very significant termination shock or damage

Table 2: *Criteria and scoring system for evaluating interventions (continued).*

Criteria	Description	Scoring levels	Score	Scoring statement
Suitability within current legal/ governance structures	The extent to which solutions are adapted to, can fit within, and are supported by existing governance including laws and policies	Low	1	Illegal/banned or legal regime not suited to deployment
		Medium	2	To a certain degree fitting within existing structures but some changes to policy would be needed to deploy at scale
		High	3	Currently legal to deploy and/or governance structures in place to facilitate it and/or financial incentives to develop it
Amount of attention within the academic community, public media, and industry	The level of attention that solutions are receiving from the academic community, public media, and industry	Low	1	Very fringe attention from individuals and/ or abandoned ideas; low media attention; no commercial interest
		Medium	2	Some attention within the scientific community, including published research and funding programmes; some media attention; attention from a few companies
		High	3	Lots of scientific papers with large amounts of funding and ongoing research groups; significant media attention including "hype"; many companies looking at commercialization options

Results

Table 3 provides a summary of the results of the analysis undertaken by the project team. In total, 61 possible interventions were identified, documented, and evaluated according to the criteria. The full compendium is available at DOI: 10.5281/zenodo.8408608.

Table 3: *Evaluation of interventions according to 12 criteria.*

ID	Category	Title	Technological readiness	Scalability	Timeliness for near-future effects	Potential to make a difference in Northern + Arctic	Potential to make a global difference
1	Ice sheets and glaciers	Stabilizing glaciers by cloud seeding	High	Low	Medium	Medium	Low
2	Ice sheets and glaciers	Increasing glacier thickness by local artificial snow production	Medium	Low	High	Low	Low
3	Ice sheets and glaciers	Glacier albedo increase	Medium	Low	Medium	Low	Low
4	Ice sheets and glaciers	Glacier insulation with fabrics	High	Low	High	Low	Low
5	Ice sheets and glaciers	Artificial glaciers	High	Low	High	Low	Low
6	Ice sheets and glaciers	Ice sheet stabilization via seabed curtains	Low	Medium	Medium	Unknown/ High	High
7	Ice sheets and glaciers	Ice sheet stabilization via buttressing	Low	Low	Low	Low	High
8	Ice sheets and glaciers	Ice sheet stabilization by draining water or bed freezing	Low	Low	Low	Low	Low
9	Ice sheets and glaciers	Pumping of water on ice sheets	Low	Low	Low	Low	Low
10	Ice sheets and glaciers	Increasing humidity around glaciers and ice sheets	Low	Low	Low	Low	Low

Cost – Benefit	Likelihood of environmental risks	Effects on local/ indigenous communities	Ease of reversibility	Risk of termination shock	Suitability within current legal/ governance structures	Amount of attention in scientific journals, and public media, and currently ongoing research programs
High	Low	Neutral	Easy	Low	High	Low
High	Low	Beneficial	Medium	Low	High	Medium
High	Medium	Unknown	Easy	Low	Medium	Medium
High	Low	Beneficial	Easy	Low	High	High
Medium	Low	Positive	Easy	Low	High	High
Low	Unknown	Unknown	Medium	Medium	Medium	Medium
High	High	Neutral	Hard	High	Low	Low
High	Medium	Neutral	Easy	Low	Medium	Low
High	High	Neutral	Hard	Low	Medium	Low
Unknown	Low	Neutral	Easy	Low	High	Low

Table 3: *Evaluation of interventions according to 12 criteria (continued).*

ID	Category	Title	Technological readiness	Scalability	Timeliness for near-future effects	Potential to make a difference in Northern + Arctic	Potential to make a global difference
11	Sea ice and icebergs	Iceberg management	Low	Low	Low	Low	Low
12	Sea ice and icebergs	Modular iceberg creation by submersibles	Low	Low	Low	Low	Low
13	Sea ice and icebergs	Sea ice thickening	Low	Medium	Medium	High	Low
14	Sea ice and icebergs	Sea ice albedo Modification	Low	Medium	Medium	Unknown	Unknown
15	Sea ice and icebergs	Sea ice breakup in winter	Low	Low	Low	High	Unknown
16	Sea ice and icebergs	Pykrete usage	Medium	Medium	Medium	Low	Low
17	Sea ice and icebergs	Sea ice growth management	Low	Low	Low	Low	Low
18	Sea ice and icebergs	Ice shields and “volcanoes”	Low	Low	Low	Low	Low
19	Atmosphere and radiation management	Snowfall enhancement	High	Low	Low	Low	Low
20	Atmosphere and radiation management	Arctic winter high latitude seasonal stratospheric aerosol injection	Low	Medium	High	High	High
21	Atmosphere and radiation management	Cirrus cloud thinning	Low	Unknown	Unknown	High	Unknown
22	Atmosphere and radiation management	Mixed phase regime cloud thinning over the polar oceans during winter	Low	Unknown	Unknown	Unknown	Unknown
23	Atmosphere and radiation management	Arctic marine cloud brightening	Low	Medium	High	High	High

Cost – Benefit	Likelihood of environmental risks	Effects on local/ indigenous communities	Ease of reversibility	Risk of termination shock	Suitability within current legal/ governance structures	Amount of attention in scientific journals, and public media, and currently ongoing research programs
High	Medium	Neutral	Easy	Low	High	Low
High	Medium	Neutral	Easy	Low	Medium	Low
Medium	Medium	Unknown	Medium	Medium	Medium	Medium
Low	Medium	Unknown	Medium	Low	Medium	High
High	High	Negative	Hard	Low	Medium	Low
Low	Medium	Neutral	Medium	Low	Medium	Low
Low	Medium	Unknown	Easy	Low	Medium	Low
Medium	Medium	Unknown	Medium	Medium	Medium	Low
High	Low	Neutral	Easy	Low	High	Medium
Low	Medium	Unknown	Easy	High	Low	High
Low	Unknown	Unknown	Easy	High	Medium	Medium
Unknown	Unknown	Unknown	Unknown	Unknown	Medium	Low
Low	Medium	Unknown	Easy	High	Medium	High

Table 3: *Evaluation of interventions according to 12 criteria (continued).*

ID	Category	Title	Technological readiness	Scalability	Timeliness for near-future effects	Potential to make a difference in Northern + Arctic	Potential to make a global difference
24	Atmosphere and radiation management	Space-based solar radiation management	Low	Medium	Low	High	High
25	Marine measures	Improved fishing practices and management	High	Medium	Medium	Low	Low
26	Marine measures	Ocean fertilization	Low	Unknown	Unknown	Unknown	Unknown
27	Marine measures	Seaweed and macro-algae cultivation	Medium	Unknown	Unknown	Unknown	Unknown
28	Marine measures	Reflective foams and bubbles on oceans	Low	Medium	Unknown	Unknown	Unknown
29	Marine measures	Enhancing oceanic light availability below the photic layer	Low	Low	Low	Unknown	Unknown
30	Marine measures	Promoting ocean calcifiers to sequester atmospheric carbon	Medium	Medium	High	Low	Medium
31	Marine measures	Hydrological system modification – ocean current modification	Low	Unknown	Low	Unknown	Unknown
32	Marine measures	Artificial downwelling	Low	Medium	Low	Low	Low
33	Marine measures	Artificial upwelling	Medium	Medium	Low	Low	Low
34	Marine measures	Re-oxygenating the Baltic	Low	Medium	Medium	Unknown	Low
35	Marine measures	Ocean alkalinity enhancement	Low	Medium	Medium	High	High
36	Marine measures	River liming	Low	Unknown	Unknown	Unknown	Unknown

Cost – Benefit	Likelihood of environmental risks	Effects on local/ indigenous communities	Ease of reversibility	Risk of termination shock	Suitability within current legal/ governance structures	Amount of attention in scientific journals, and public media, and currently ongoing research programs
High	Low	Unknown	Unknown	High	Unknown	Medium
Medium	Medium	Beneficial	Easy	Low	Medium	Medium
Unknown	Medium	Unknown	Unknown	Unknown	Unknown	High
Low	Low	Beneficial	Easy	Low	High	High
Unknown	High	Unknown	Unknown	Medium	Medium	Medium
Unknown	Medium	Unknown	Unknown	Unknown	Medium	Low
Low	Medium	Beneficial	Easy	Low	High	Low
High	High	Unknown	Low	High	Medium	Low
High	Medium	Neutral	Easy	High	Medium	Low
High	High	Unknown	Easy	High	Medium	Medium
Unknown	High	Beneficial	Unknown	Medium	Medium	Medium
Medium	Medium	Unknown	Easy	Medium	Medium	Medium
Unknown	Unknown	Unknown	Unknown	Unknown	High	Low

Table 3: *Evaluation of interventions according to 12 criteria (continued).*

ID	Category	Title	Technological readiness	Scalability	Timeliness for near-future effects	Potential to make a difference in Northern + Arctic	Potential to make a global difference
37	Land-based measures	Wildfire management	High	Medium	High	High	Medium
38	Land-based measures	Afforestation, reforestation, and forest management	High	Medium	High	Medium	High
39	Land-based measures	Reindeer herding	High	High	High	Unknown	Low
40	Land-based measures	Rewilding	Medium	Low	Low	High	Medium
41	Land- based measures	Conservation and restoration of peatlands and wetlands in taiga and tundra	High	Medium	High	Medium	Medium
42	Land-based measures	Agricultural soil management	High	Medium	High	Low	Medium
43	Land based measures	Stabilizing permafrost by covering it	Unknown	Low	Low	Low	Low
44	Land-based measures	Enhancing permafrost refreezing with air pipes	Low	Low	Low	Low	Low
45	Industry	Radiative covering and building technologies/ passive daytime radiative cooling	Medium	Low	High	Low	Low
46	Industry	Bio-geoengineering (to increase crop albedo)	Medium	Medium	Medium	Low	Medium
47	Industry	Built-environment albedo enhancement (white roofs, etc.)	High	Low	High	Low	Medium
48	Industry	Arctic methane capture and usage	Low	Low	Unknown	Unknown	Unknown

Cost – Benefit	Likelihood of environmental risks	Effects on local/ indigenous communities	Ease of reversibility	Risk of termination shock	Suitability within current legal/ governance structures	Amount of attention in scientific journals, and public media, and currently ongoing research programs
Low	Low	Beneficial	High	Low	High	Medium
Low	Low	Neutral	Easy	Low	High	High
Unknown	Low	Beneficial	Easy	Low	High	Medium
Low	Medium	Unknown	Medium	Low	High	High
Medium	Low	Beneficial	Medium	Low	High	High
Low	Low	Beneficial	Easy	Low	High	High
High	High	Negative	Hard	Low	High	Low
High	Unknown	Unknown	Hard	Low	High	Low
High	Medium	Neutral	Hard	Low	High	Medium
Low	Medium	Neutral	Easy	Low	High	Medium
High	Low	Beneficial	Easy	Low	High	Medium
Unknown	Unknown	Unknown	Unknown	Unknown	High	Medium

Table 3: *Evaluation of interventions according to 12 criteria (continued).*

ID	Category	Title	Technological readiness	Scalability	Timeliness for near-future effects	Potential to make a difference in Northern + Arctic	Potential to make a global difference
49	Industry	Methane flaring (not industrial)	Low	Low	Unknown	Unknown	Unknown
50	Industry	Atmospheric methane destruction: tropospheric iron salt aerosol injection	Low	High	Unknown	Unknown	Unknown
51	Industry	Biochar	High	Medium	High	Low	Medium
52	Industry	Bio-energy with carbon storage (BECCS)	Medium	Medium	High	Medium	Medium
53	Industry	Direct air carbon capture and storage (DACCS)	Medium	Medium	Low	High	High
54	Industry	CO_2 "snow" deposition in Antarctica, cryogenic CO_2 capture	Low	Low	Low	Unknown	Unknown
55	Industry	Direct ocean capture	Low	Medium	Unknown	Unknown	Low
56	Industry	Enhanced weathering (on land)	Medium	Medium	Unknown	Unknown	Medium
57	Industry	Black carbon reduction	High	Medium	High	Medium	Low
58	Industry	Carbon capture and storage	Medium	Medium	High	Medium	Medium
59	Industry	Atmospheric methane removal: solar chimney and photocatalytic semiconductor technology	Low	Unknown	Unknown	Low	Unknown
60	Industry	Atmospheric methane capture by zeolites	Low	Medium	Unknown	Low	Unknown
61	Industry	Polar chimneys	Low	Low	Low	Low	Low

Cost – Benefit	Likelihood of environmental risks	Effects on local/ indigenous communities	Ease of reversibility	Risk of termination shock	Suitability within current legal/ governance structures	Amount of attention in scientific journals, and public media, and currently ongoing research programs
Unknown	Unknown	Unknown	Unknown	Low	High	Low
Low	Unknown	Unknown	Unknown	Unknown	Unknown	Medium
Medium	Medium	Beneficial	Medium	Low	High	High
Medium	Medium	Unknown	Medium	Low	High	High
Medium	Low	Neutral	Easy	Low	High	High
High	High	Unknown	Hard	High	Low	Low
Medium	High	Unknown	Easy	Low	High	Medium
Medium	Medium	Beneficial	Easy	Low	High	Medium
Unknown	Low	Beneficial	Easy	Low	High	Medium
Low	Low	Beneficial	Medium	Easy	High	High
Unknown	Unknown	Unknown	Easy	Low	High	Medium
Low	Low	Beneficial	Easy	Low	High	Medium
Unknown	Unknown	Beneficial	Unknown	Low	High	Low

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A full reference list for each intervention can by found in the compendium. DOI: 10.5281/zenodo.8408608.

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