# Ice Shield Strategies

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Greenland Ice as a pictorial representation of an artificial ice shield. Source: [www.mnn.com](http://www.mnn.com)

## Introduction

Climate change in the polar regions has the potential to cause a mass extinction event that is probably worse than that which ended the dinosaurs. Humanity itself is gravely threatened. The early symptoms of impending environmental catastrophe are already in stark evidence. These include: the retreat of polar summer sea ice and mountain glaciers; starvation of species dependent upon sea ice, such as polar bears, seals and penguins; the destabilisation of polar ice caps, ice tongues and glaciers; destabilisation of the jet stream and polar vortices; the increase in frequency and severity of extreme weather events; the increasing reach and warmth of the North Atlantic Current(NAC)/ Conveyor and Gulf Stream; the melting of the Arctic permafrost and consequent release of its contained or metabolised greenhouse gases; and the bubbling (ebullition) or even eruption of vast amounts of methane up through Arctic lakes, vents, seas and tundra.

All these events are related. Indeed, they all started from three unintentional climate engineering experiments that humanity commenced when we decided to burn fossil fuels, clear the bulk of global forests and swamps, and impoverish the oceans of marine life by industrial-scale fishing and pollution. What the first two of these did was to send into the atmosphere and oceans such masses of greenhouse gases that could not be sequestered safely and at a rate that the world could not safely accommodate. The early results were some global warming, ocean acidification, species loss, and weather extremes. The ongoing impoverishment of the oceans is degrading the largest and most effective carbon sink that the world possesses, thereby making almost all the other environmental problems much worse. Each of our three unintentional experiments produced a chain of deeply undesirable knock-on effects. The first two sent vast amounts of greenhouse gases into the air and sea. These initiated the early stages of runaway global warming and ocean acidification. In turn, that global warming is beginning to release potentially even larger deposits of methane into the atmosphere, where it will cause even faster global warming in positive feedback loops that exacerbate the many looming environmental catastrophes, and at the same time allow us less time and fewer resources to fix them.

This paper describes several ways by which the adaptation and deployment of a single, relatively simple technology can be made to mitigate then possibly reverse runaway global warming. The adaptation required is to use floating, buoy-mounted wind turbines to pump seawater onto sea ice, thereby creating deepening ice fields or lens/shield-shaped ice mountains around them. In seas shallower than a kilometre or so, these ice shields can be securely grounded on the seabed. They may also freeze together in rows, arrays, or onto land. Their annual accumulation of ice on top can be made to match, or exceed, that of any melting happening above and beneath. They can thus be made to cause selective glaciation in most polar and near polar regions that we choose, provided the winter there remains cold enough to generate sea ice. Careful siting and timing of these ice shields and arrays may deliver several beneficial outcomes. These include:

* Reversing the loss of polar sea ice and its beneficial albedo (reflectiveness) effect that helps cool the world.
* Sequestering the CO2 absorbed by the frigid brine as it flows over each growing ice shield.
* Preventing, slowing, or facilitating the capture of emissions of methane from melting clathrates in the polar oceans and some surrounding lakes and land masses.
* Slowing or stopping the loss of some polar and sub-polar glaciers.
* Placing ice range barriers, dams, or deep, floating ice booms in the way of the warm North Atlantic Current (NAC), ‘warm’ riverine, and Southern Ocean water that are catastrophically warming polar regions.
* Preventing the loss of polar species that depend on sea ice, such as krill, seals, penguins, cetaceans and polar bears.
* Making use of the heat island effect of the growing conical ice shields to convect the heat derived from freezing seawater via thermals high into the atmosphere, from whence it radiates out into space by long wave radiation, avoiding most of the insulating effect of atmospheric greenhouse gases.
* Stabilising the jet stream, polar vortices and ocean currents.
* Producing increased polar biomass by virtue of the nutrients that are brought to the sea surface from the depths by the pumps powered by the wind turbines operating during the warmer polar seasons. Some of this biomass moves up the food chain to become our marine catch, whilst another part sinks to become, more or less, sequestered carbon.
* Generating ice weirs across polar rivers, thereby backing up their waters until the ice formed from them insulates part of the melting Arctic tundra. Such weirs may also cause the riverine water that spills over them to freeze in extensive sheets on the sea ice, being uninsulated by any ice above, and thereby able to thicken considerably the sea and riverbank ice thereabouts.
* Economical construction of ice dams on remote Arctic rivers, from which renewable hydroelectric power might be generated or their waters made to turn south (possibly via tunnels or pumped in pipes) to irrigate crops.
* Construction of secure, accessible and economical bases for polar research and stable, long-lived platforms for drilling ice cores.
* Providing freezing brine to seal off methane vents.
* Create open, polar sea channels and polynyas for shipping and wildlife.
* Renewable electric power from offshore, ice shield-based wind farms that is transported to land via HVDC lines over flat ice ranges or undersea. The power could also be used locally to liquefy harvested methane and carbon dioxide and to pump them into vessels or along pipelines to markets, or to pump fresh river and lake water South.

## Concept Technology Overview

If seawater is pumped onto sea-ice during cold times, it spreads out and freezes, see Zhou & Flynn (2005) paper *Geoengineering Downwelling Ocean Currents: a cost assessment* https://www.see.ed.ac.uk/~shs/Hurricanes/Flynn%20downwelling.pdf. The process also serves to radiate more heat off-planet, because more heat is given off as more ice freezes quickly without the insulating effect of other ice above it. Should the discharge continue, then an iceberg or ice shield forms in a way similar to the way volcanoes form mountains, except that ninety percent of the growth in height-depth of each lens-shaped ice shield is underwater, as the base of the ice shield sinks under the increase in ice mass above it. Unlike our vanishing sea ice, these ice shields would not disappear in the warmer months, as they would have become too thick. Furthermore, with additional pumping they would tend to grow even larger, or at least regain any summertime lost mass, each cold season. Multiplied, they could thus be used to keep our polar regions safely frozen in regions where we decided it were best, leaving other parts ice-free, at least in summer.

Existing technology can be adapted to make and operate such a ‘glaciating’ system. Wind turbines mounted on moored buoys (and later surrounded by grounded ice shield arrays in ‘open-water’ polynyas) could be made to power, with renewable energy, the seawater pumps, water stream distributers, de-icing equipment, sensors, communications and other power requirements of each forming ice shield installation.

The concept would involve sending the power from Arctic-adapted commercial, offshore, floating wind turbines to sealed motors and pumps inside vertically-oriented cylindrical tubes that conduct seawater onto the forming sea-ice above. These satellite installations would be arrayed in hexagonally-close-packed, concentric rings around each moored wind turbine. The turbine would thus remain in the polynya amongst the three, adjacent installations – though it might ice over in winter. Buoyed and armoured powerlines would connect each turbine to its satellite installations which would become safely encased in deep ice. The tubes could be constructed out of non-polluting and eventually biodegradable material, such as spiral-wound plywood bonded with hot-melt lignin. Each tube would mount perhaps three to seven pumps, average five (for redundancy and power increment purposes) in a floating assembly inside the pumping tube, with each pump accessing the ocean through its own one way valve to the base of the pumping tube. A hollow, toroidal buoy made from ferro-concrete, and secured around the middle of the tube would provide the buoyancy necessary. As an ice lens formed around the tube and buoy they would gradually subside until the spar or tube reached the sediments beneath and grounded. Large perforations in the spar would ensure seawater supply to the pumps. Above the toroid, staggered horizontal slot penetrations in each tube, increasing in size with altitude, would direct the freezing seawater so that it formed a roughly circular ice lens around the tube. Each projecting tube would need to be tall enough, or else extendable, in order for its top to remain some metres above the final ice surface level after the ice lens had grounded. As the ice lens grew from the start, more power would be directed to the first pump activated. Eventually other pumps would be cut in, so that at all stages the film of seawater flowing over part, or all, of the conical ice surface remained at near-optimal depth for both flowing and freezing. Unfrozen brine at the perimeter would tend to flow into cracks in the surrounding sea-ice generated by the increasing weight and subsidence of the ice lens or else into the polynyas between the ice shields. Residual brine in the ice would tend to migrate through the ice to the sea through the pores it creates in the brackish ice shield ice. Each successive circumferential crack would eventually be frozen shut. For deeper waters, perforated extension sleeves could be added to the top of each tube some time before the ice formation reached the top of the existing satellite pumping tube. For this to be done, either the power cable running down inside the pumping tube to thee pumps could be temporarily disconnected or else the pumping assembly could be removed from the tube and replaced after the extension had been inserted.

In relatively shallow water, one mid-sized floating wind turbine might progressively power the generation of many satellite lenses in a linked ice array. Typically, pumping assemblies no longer required for maintenance pumping from some of the inner concentric circles of satellite pumping stations would be transferred to new outer locations and tubes, thereby reducing the number of pumping assemblies required. Pump maintenance, refurbishment or replacement could be conducted between extensions and transfers. Given that before such extensions and transfers a landfast ice array would typically have been formed, extensions and transfers might be conducted using ice-based heavy-lift helicopters. Refueling caches for these could be located either on ice or from moored buoys. They might even use part of the volume inside each toroidal support buoy for each wind turbine as a caching place, though it might be wise to use a biodegradable fuel.

Apart from ice generational or maintenance pumping to replace lost ice, or to perform other tasks, most of the power generated by each wind turbine (particularly that in the warmer months when ice-making is unlikely) might be sold to a mainland grid via HVDC lines laid earlier on the ice array and protected with subsequent ice. The HVDC lines to link a useful number of wind turbines would be laid only after a thick ice array had been formed. Otherwise, turbines and pumps might be idled in warm seasons or else spare pumping power might be used to perform other tasks, one of which might be bringing nutrients from the deep to fertilise Arctic marine life.

It is surmised that the pumping and seawater dissemination regime may be so varied as to cope with variations in prevailing wind, in temperature of water and atmosphere, in ice shield size, orientation and morphology, and to suit the local depth of water for grounding purposes. For instance, should a given depth of ice to ground a given array over a single cold season be required, using intermittent pumping (either to the whole ice shield surface or part thereof) in short bursts could be used to give a less extensive but deeper and more cylindrical shape to the ice lens, whereas for shallower seas, the pumping regime and proximity of secondary pumping stations might be tailored to produce an array of thinner but wider, linked ice shields. For such intermittent pumping for wide lens generation, the first pulse of water should probably be large in order that a small part of it reached the perimeter over ice considerably colder than zero degrees, whereas subsequent pulses of the series might become progressively less so that they laid down ice to the same depth but closer to the pump and over now warmer ice. The pump would then stop for a sufficient period until all the ice had formed and had cooled to well below zero. Any brine remaining on the surface would then be washed away with the next big pulse of pumped seawater. To allow the pumping to be less jerky, it may well be better to have some form of active radial or sectoral control over water flow, rather than interrupt or rapidly vary the pumping. This might be provided by a rotatable sleeve inside the pumping tube with apertures that could be matched with a portion of those in the pumping tube wall when a given fraction of the total flow was required in one or more directions. This sleeve would float upwards as the pumping assembly to which it was attached floats higher up the tube and higher outlets were required to be activated. The sleeve would tend to be rotated more slowly, or in stages, by the artificial intelligence system (AIS) as the surface to be iced over increased, thereby requiring more seawater flow in that direction. Its apertures might be variable in width, number and radial direction. Flows might be required in several radial directions at the same time, then all shifted perhaps fifteen to forty-five degrees to cover other parts of the growing ice cone. Areas not being suffused with seawater would be given time for their ice surface to cool to close to that of the ambient air. The dynamically-controlled sleeve would remain just inside of the pipe sections that closed off the tube apertures.

In waters deeper than very shallow ones, grounded ice shields might not produce enough ice to link up to form linked arrays for some years. As waters deepened typically further offshore, pumping stations could be located closer together and use their freezing onto earlier-constructed neighbouring ice shields as a way of securing them (beyond what could be achieved with their anchors and mooring lines) before they were able to be grounded. To maximise albedo earliest, to minimise methane emission/eruption, and to provide ice roads to the arrays, ice arrays could be grown and extended from most of the polar shoreline outwards into progressively ever deeper water.

Floating wind turbine technology is still in its rapid development phase. Recent improvements have been flexible hub structures, larger capacity turbines, variable speed turbines, gearless turbines and the use of permanent magnets. Two platform types are emerging as favourites, semi-submersibles for use in shallow water and spar buoys for use in deep water. What is proposed for generating ice shields is a combination of these that seeks to avoid the lack of standardisation and the major deficiencies of both platforms, whilst adding features believed to be useful for ice shield application. The toroidal buoy concept is reminiscent of semi-submersible construction, whereas a telescoping concept for both tower and spar provide substantial vertical dimensions up and down when deployed. This should mean that installations (minus the blades and possibly the nacelle, and with tower and spar extensions unextended) might be partly assembled in dock, then towed to any depth of ocean site without the requirement for expensive heavy-lift jack-up and dynamic positioning vessels. The combination of toroidal buoy and downwards telescoping spar is to be applied both to the floating wind turbines and to the satellite pumping units.

Delivering all the components of each standardised offshore floating wind turbine, for all water depths, by sea using a vessel equipped with a crane and heavy-lift helicopter should improve logistics considerably, even if such vessels come to be purpose-built. Each towing vessel would be made capable of towing the partly constructed elements for several floating wind turbines and/or their associated satellite pumping stations. The larger installation vessels would be capable of carrying the other components and power cables on board. A crane, large zodiac, hovercraft or helicopter, or combinations of them, should be sufficient to set the individual components in place, once the planned site had been reached.

Professor Kempton of Delaware University has recently discovered how to cut offshore wind turbine costs which we can use. The turbine blades can be attached parallel to the support shaft, and the whole structure assembled in port, prior to towing the whole structure into position. Each blade can then be winched onto its assembled attachment point in turn. He also makes use of suctioning seabed sand into large buckets on the seafloor to act as anchors, rather than having to pound in piles.

Similar installation technologies would be used for both the offshore wind turbines and the satellite pumping units. Both would be towed into place and both would use a toroidal buoy and telescoping spar for support and stability. Enclosing ice would soon take over the support and stabilisation functions for the satellite pumping stations.

For the wind turbines, the telescoping steel spar and tower assembly would be ballasted in dock. Once onsite and in place, pins are removed to allow the weight of the ballast to extend the spar to its full depth. The buoy (and possibly the spar base, though this may not be advisable) are then separately anchored, probably by using centre-weighted cables in catenary form and anchors. Such anchors may require eventual detachment if the sea ice itself is likely to move before ice shield grounding, as this could tilt the structure. Horizontal mooring lines are then attached to the toroidal buoy, should there be any fixed neighbouring mooring places available, such as those on land, landfast ice or neighbouring grounded ice shields. The hollow ferro-concrete toroid itself encloses a solid polymeric bush that secures the tower and spar, whereas the toroid is protected from sharp collision with ice or vessels by means of a thick-walled, possibly inflated, toroidal rubber buffer encircling the ferro-concrete toroidal buoy. Steel struts and rings may provide additional bracing between the buoy and the tower. The nacelle’s contents may then be attached if not already so, and the telescoping tower extended upwards. This may be done either by internal jacking or possibly by the use of a heavy-lift helicopter or ship-mounted crane. When the extension of the tower reaches its fullest extent, spring-loaded bars lock it into place. Winches or cranes, possibly temporarily mounted on the nacelle, are then used both to lift and manoeuvre each blade successively into place vertically and may rotate them so that others may be affixed. Alternatively, ship power might be sent to the turbine to rotate the blade assembly so that the other two blades might successively be attached. The installation is tested. Either then, or at a later date, the satellite pumping stations are installed, connected and the whole system is commissioned.

When the wind turbine unit to be erected is in very shallow water, methods may be used to excavate a hole in the sediments into which the extension of the spar may be inserted, thereby providing additional anchoring and stability. One such method might excavate a suitable depression using a high-powered underwater jet of pumped seawater, a suction pump, or a combination of the two.

Each satellite pumping station will typically be comprised of a vertical pumping tube, ballasted spar, possibly gratings to prevent the entry of large objects that might degrade the pumps, pump & motor assembly, toroidal buoy, anchors, stabilising weights, anchoring cables, collar, valves, sensors, AI, actuators, heating elements, comms, and power cabling elevated possibly high above ballasted buoys (so that each cable’s lost heat will not melt ways back to the ocean for pumped seawater) to connect each to its local wind turbine as well as possibly to other pumping installations.

A hollow, toroidal buoy made of ferro-concrete, similar in concept but much smaller than those used on the floating wind turbine installations, encases the pumping tube and sinks with it as the ice shield grows. The spar on this will not be locked in place when extended. When the spar it encases sinks enough to meet the ocean floor, it will tend to be forced up the pumping tube until the buoy encounters the sediments when both are likely to be crushed under the increasing weight of the grounding ice array above them. Hence, both should be made of ecologically-benign materials.

When onsite, the spar is lowered and the mooring cables and anchors attached. The sections of apron may be left attached vertically to the outside of the pumping tube, or brought in separately later, when enough thickness of sea ice has formed to allow them to be made into a circular apron and attached manually. This should ensure that they are not readily damaged by wave action.

The motors and pumps are fixed inside the pumping unit in their own cylindrical sub-assembly. This would float at sea level, rising in the pumping tube as the ice shield extended deeper into the sea. As the sub-assembly rises in the sinking pumping tube, the excess power cable might be allowed to coil up in a spring-loaded reel that is located above the sensor rack. Each pump within the sub-assembly might have its own separate pipe from the sea to the top of the sub-assembly. The pumping sub-assembly is to be designed so that it can be removed via the top of the pumping tube for reasons of tube extension, maintenance, refurbishment, re-use or recovery. Some maintenance may be performed whilst the sub-assembly is only raised just above sea level. When an additional length of pumping tube is added, an additional length of cabling might also need to be inserted. A carriage wheel form, perhaps part of the seal to prevent backflow, with ratchet attachments might be used to support the pumping assembly inside the pumping tube when the pressure of pumped water above it tried to push it deeper. In-built buoyancy of the assembly would tend to move it up the tube whenever the wind ceased and the water above leaked away.

Arranged one above the other inside the upper part of the pumping tube are lubricated short sections of tube, each of which can be explosively released to slide down the pumping tube until it cuts off and seals the apertures currently being used to disseminate the seawater and at the same time opens a new set of apertures that were previously sealed off by the newly-fallen tube section. Each new set of opened apertures is radially offset from that below it to direct the seawater flow onto a sector of the ice cone that has had time to cool to well below freezing.

The satellite pumping stations are anchored in appropriate locations in concentric rings around their central wind turbine and are connected to it. Whilst the floating wind turbines may be installed throughout each warm season, the primary satellite pumping stations are perhaps more likely to be moved into place either just before or as anchoring sea ice begins to form. Both types of installation are usually transported by ship, often ones with some modest ice breaking capability, though some maintenance and installation work might be made by ‘land’ over ice array and sea ice, once sufficient thickness had formed. Hovercraft may find a use here.

Added later, as required, are pumping tube extensions devised to keep its active seawater outlets above the ice forming around them. Each will be approximately 35-40m long, meaning that only two extensions would be required to allow an ice shield to ground securely in water a kilometre deep.

Secondary satellite pumping stations that are designed to ground each ice array once the primary ones had sunk each ice lens’ base close to the seabed would typically be moved by ice road and/or air to one or more of the local polynyas. Typically, these would be only moored to the surrounding ice, not anchored. Several trips, or one with several vehicles, might be required to move and assemble the components of each secondary pumping unit. It may also be economical to place these on standby in the places designated for their polynyas, so that most heavy transportation is done by sea.

Where ice array grounding, or wide expanses of flat ice array were required without the intrusion of many polynyas, the centre of each (or perhaps every alternate or every third) polynya could be given a vertical ‘sump’ tube, made of similar, spiral-wound, perforated plywood and possibly warmed electrically when required to keep it open so that brine from the ice forming around the tube could be given passage to the sea, thereby allowing the ice surface to build up and become level. Pumping would thus need to continue longer over the cold season until the surface was reasonably level. Of course, it may also be the case that such sumps, moulins, sinkholes or wells would be kept open naturally by the passage or ice-dissolving power of the brine.

Once a wind turbine had been operating for sufficient time in a polynya surrounded by three rings of ice shields, some of the polynyas in the second ring of polynyas can be activated or populated with new satellite pumping stations, termed secondary ones. These are the ones that ensure that the ice array can be firmly grounded because each one’s inlet pipe is protected from clogging by sediment or being crushed by virtue of the deeper ice shields surrounding it, unlike the primary pumping tubes. Sensors and actuators on the pipes of other pumping stations that are about to be clogged or crushed turn off these pumps and send a message to that effect to the pump and wind turbine artificial intelligence units (AI) and to control headquarters. These secondary ice shields commenced at these new polynya sites are controlled to grow more above sea level than the primary ice shields, so that the inverted cones of the primary ones can be firmly pressed into the seabed to secure the whole ice array, as well as to reduce under ice melting or the dissolution of methane clathrates beneath them. The waffled underside of the array also serves to direct any gas that is emitted from the seabed to the high points under the array, wherefrom it may be collected, stored temporarily, and harvested. The stored gas would typically be a mixture of methane and carbon dioxide.

The secondary satellite pumping units would replace the ice shield making function of those nearby of which the pumping tube inlets were in danger of being crushed or clogged with sediment. Thus, the whole ice array could be securely grounded, provided it was not above an unstable seabed slope or in too deep water. Ice produced by these secondary pumping stations would, over years of maintenance pumping, tend to encase in ice some, or all, of the old primary pumping stations, whilst being operated such as to leave the wind turbine sites free of thick ice.

As brine from the ice forming on top of the array from these secondary pumping stations has no ready way back to the sea, unless by way of the moulins, plastic pipes with transverse slots along their upper surface might be laid sloping in the valleys between the three adjacent ice shields surrounding each secondary pumping station. Some vertical holes are drilled in the ice, through to the sea, each is fitted with short plastic offtake pipes leading from each sloping pipe to remove the forming brine from the growing secondary ice shield. Brine from these secondary ice shields may eventually reach the polynya in which floats the wind turbine. This should help keep the buoy of the wind turbine largely free from artificially thickened ice and even some of the thicker seasonal sea ice, so that it continues to float at sea level whilst the surrounding ice shield array sinks around it until it is firmly grounded. Note, that the lowest freezing point obtainable for sodium chloride, NaCl, brine is -21.10C at 23.3wt% NaCl. As seawater is around 3.5% salt (typically somewhat less than this in Arctic surface waters because of river water inflow or the melting of brackish water from glaciers or sea ice), concentrating it by our cone-freezing process some fivefold (with 20% by volume of residual brine) should produce brine that is approximately 17% salt by weight. This very cold and dense brine might well help freeze shut the methane vents in the seabed whilst providing substantial relative density to power: local down-welling, ocean currents, distant upwelling, and carbon sequestration of CO2 captured by the icy seawater and brine flowing over the ice shield cones – the polar thermals over the ice array cones serving to suck in CO2-rich air from warmer regions during the cold and darkened, ice-forming seasons.

Should the pumping process suck up small marine life and leave it exposed on the ice shield surface, this may form a welcome cold season bounty for wildlife.

An incidental benefit of installing large offshore windfarms in the Arctic has been calculated by Professor Caldeira et al. Apparently, the energy extracted from the wind could cool the Arctic by as much as 130C. This effect would tend to make the creation of ice arrays and the re-establishment of lost Arctic sea ice progressively easier.

## Capability Prospects

Such ice shield arrays have several prospective capabilities. These include their use as: solar reflectors, atmospheric carbon dioxide sequestration, barriers to warm water intrusion, methane emission suppressors, methane harvesting arrays, thermal bridges under pumping, weirs, bases for offshore wind farms and transport corridors, dams, shipping channel walls, research, maintenance and production bases, and providers of polar wildlife habitat. Details of these capabilities appear in Part Two of this document.

*This paper seeks support for the further development of the concept and participation to allow the funding of scientific modeling and validation, followed by pilot and sea trials. The intellectual property is offered free.*

## Proof of Concept

Preliminary tests on the viability of the ice shield concept may be performed at modest cost. A protective capsule and platform, mounted on a triangular assembly of three floating buoys, or corrugated plastic tanks for fuel on a pallet, might house a diesel-powered pump, pipework, controls and fuel tanks designed to pump seawater through a slowly-rotating nozzle (or the helical arrangement of holes or radial tubes in the central tube previously discussed) to distribute seawater so that it froze over a wide disc of sea ice, once that had formed. Sensors would monitor and relay the build-up of ice into a low iceberg, together with its overall shape and slope. Given planned variations in the design and operation of each pilot pumping facility, results would record for each the angle of inclination of the resulting conical iceberg, its changing volume, its evolving undersea profile, the energy required to produce the berg, and where improvements might be made to the design. The results would also identify some of the problems to be encountered by future wind-turbine powered designs that are designed to generate large ice shields. Such experiments should incur only modest risk, as sea ice has already been safely thickened many times by means of such pumping to provide sufficiently firm bases for Arctic drilling platforms, runways and ice roads, see http://pubs.aina.ucalgary.ca/arctic/Arctic33-1-168.pdf. In some such cases, thickening has made the ice platform ~12m thicker. Much greater thickening can be achieved.

## Arctic Strategy

Once the pilot experiments have been analyzed and computer models of its construction established, the initial detailed design of the ice shield installation can be developed and its theoretical performance characteristics and effects determined. Thereafter, each of an ice array’s prospective capabilities may in turn be tested, refined, and be provided with an individual cost-benefit analysis. Those designs with good prospects would then become subject to international vetting, staged approval, trialing and implementation.

Although most of the benefits would be public ones, there would be some with profit potential from the sale of power and methane, access, transportation and perhaps other services. However, it seems likely that a respected international body, such as the Arctic Council or UNFCCC, would co-ordinate the program, with corporations and scientific institutes being contracted to do most of the work.

Once the ice shield arrays were grounded and had reached effective height, utility companies might wish to purchase the resulting offshore/onshore wind farms to access the substantial power residual from ice shield maintenance requirements or to harvest the methane. The power plants would tend to be more reliable sources of power than are those from most wind farms because of the reliability and strength of Arctic winds and the stability and economy of their ice platforms and access routes. Pumping to benefit phytoplankton might be used mainly to remove excess power from the grid. Pumps inside especially long tubes that were buoyed vertically in some of the polynyas of each ice array might be used for this purpose, their inlet bases reaching down into the deeper and better-nutriated waters, yet not so close to the sediments that they would shortly become clogged with sediment or crushed. Similar pumps, in a pressure-reduction system, might also be of use actively to harvest dissolved, emitted or clathrate methane (perhaps by pressure reduction) from the depths at the same time as nutriating the surface waters. Gas or chemical companies might then wish to purchase these drilling-free ‘gas wells’, using cheap and sustainable local wind power to extract, process, compress and transport the gases (CH4 & CO2) by pipeline or ship.

Ice shield arrays might be so designed as to allow for high-voltage direct current (HVDC) transmission lines to be laid economically along completed, nearly level, ice highways to landfall and beyond. These lines would become encased in protective ice and might each last for several decades or even longer. Intentional gaps in the highways could employ bridges (perhaps ones made mainly from fibre-reinforced ice in formwork) or undersea HVDC power lines. Where all-season ocean passage was required through an ice shield array, it might be possible to buoy HVDC lines just off their ice walls, so that the unavoidable heat loss from the lines would help prevent sea-ice formation during the ensuing cold seasons.

## Initial Phasing

As a subset of two of the capabilities, emission suppression of methane in the Arctic Ocean, may well be regarded as being both the most urgent and important of capabilities to be developed and deployed. These are the ones that probably should strategically be addressed first. Beneficially, their deployment should inform the feasibility, cost, effects, and effectiveness of several of the other potential capabilities.

There is one location that requires only a modest number of ice shields, set in a very shallow sea, to have a substantially beneficial effect upon reducing Arctic methane emissions and increasing Arctic albedo. This is the Bering Strait which is an average of ~40m deep and is ~110km wide, less the two, small Diomede Islands and gap between them which are located near the centre of the strait. This strait separates Siberia from Alaska and is the only eastern outlet of the Arctic Ocean. Should Earth Systems modeling suggest it to be environmentally desirable, short ice shield ranges each in the form of a causeway might be constructed partially to block off the Strait, leaving open on the surface only the narrow shipping and wildlife passage between the two Diomede islands and the deeper water passages under the ice between ice lens bases.

There are three northerly currents in this strait, the shallower two of which bring relatively warm Alaskan Coastal and Bering Shelf water into the Arctic Ocean. Blocking off these, whilst allowing the deeper, colder Anadyr water in, would beneficially cool the Arctic. Ice shield barriers are ideally suited for this task, as they are porous at the bottom yet impervious at shallower depths. Such a barrier would also hinder the high albedo and methane-suppressing ice floes in the Arctic Ocean from flowing out south into the Bering Sea under the influence of strong winds. There, they melt far faster than when still in the Arctic. Hence, this could be a fast and economical way to limit the damage being done by Arctic warming until surer methods can, together with it, prevent this from evolving into global warming catastrophe.

The project would form a good test of the ice shield technology, and one from which further improvements might be derived. Some three rows of lenticular ice shields, grounded and frozen together, but with gaps for island and bridged passages, containing a total of 130 ice shields or lenses (for the triple layer) with a conical surface slope of 3-50 (until made level by secondary pumping), and each ~2.3km in diameter, might do the job. Ice shields might be securely grounded in a single cold season in any near-polar water that is less than 85m deep. The Bering Strait at this point is itself typically less than 40m deep. Each Bering Strait installation could require the power from a 2.5MW wind turbine operating at a yearly average of 40% capacity, each with an estimated cost of $1.7m/MW, giving a total cost of around $5m/floating wind turbine. Each turbine should produce the power necessary to generate multiple ice shields over time, perhaps as many as fifty, but more likely around thirty. Given the widely different power requirements over time as each ice shield is generated (the later stages typically requiring much more power), a given turbine could be powering the growth of from three to fifteen ice shields at any one time. When the wind dropped below the ideal for a given workload, the AI system (AIS) would ration what was available to the higher priorities. Batteries would store power for emergency uses that excluded pumping.

Assuming a 50 surface slope and a radius of 1.14km for each completed ice shield, this would require some 700 turbines (assuming the satellite pumping station option were not chosen that would reduce this number substantially). In 2008, Vestas’ pricing rule of thumb was ~$1.4m/MW for their wind turbines. Thus, for a bulk order of 700 2.5MW installed ice shield turbine installations in 2017, it might be reasonable to suggest a June 2014 US dollar cost of $5m/commissioned installation, or a total capital cost of ~$4.5b after the inclusion of linkages. Operational, financing and overhead costs up to 2020, when all the ice shields might have been completed, plus subsequent HVDC cabling and other works, might bring the cumulative investment to ~$6b before it might conditionally be sold to utility companies. These companies might be interested in both the electricity generation capacity and in the methane that might be captured from the submarine deposits that could be there. As well as by special pumps to liberate deep dissolved methane, this might be done using flexible polymeric covers to capture the fugitive methane rising, or what could be induced to rise perhaps by pressure reduction methods, between ice shields in open spaces called polynyas. Furthermore, collector gas pipelines, laid along the ice shield range, might be advantageous both to Russia and the USA, particularly as this might be key to harvesting and marketing otherwise fugitive methane emissions, and hence to rendering them less harmful. Power from the wind farms could be used to separate it from its CO2 component and to pump the methane to its markets, or to condense it as liquefied natural gas (LNG) for ocean transportation or for direct use by shipping – from a new form of remote service station. The same and similar service stations might also offer fast recharges for battery-powered trains, trucks, cars and shipping.

The capital cost might be substantially reduced, assuming each wind turbine would power three to many satellite pumping installations in hexagonally close-packed concentric rings. It is surmised that the average number of satellite pumping stations powered by a single wind turbine could be approximately thirty over its un-reconditioned lifetime, more with selective replacements. A single pumping sub-assembly might, with refurbishments, generate perhaps several ice shields, depending on their maximum volume and the environmental severity.

As each satellite pumping station in the shallow Bering Strait should generate a grounded ice lens over a single cold season, this porous Bering Barrier might be constructed for as little as $3b, most of which might be recouped from the subsequent conditional sale of the wind farms. And if more than three satellite ice shield installations could be grounded in a single cold season in the particularly shallow waters of the Bering Strait then the cost might be reduced still further (though fewer productive turbines would then be available for resale and power generation). In such shallow waters, the floating turbines might even be replaced by possibly cheaper ones mounted on piles hammered into the sediments (though this option is not recommended for a variety of reasons, including its adverse effect upon wildlife).

As an additional economic incentive, with the addition of a bridge spanning the ‘narrow’ shipping passage between the two islands to be left in the Bering Strait, it should be possible to use the ice shield range, or causeway, as the base for a semi-permanent East-West ice road-rail highway linking the two continents. Thus, the first industrial ice shield arrays constructed might be the ones that connect each of the two Diomede islands to its respective continent. The surface layers of ice on each ice causeway, and the ice roads leading to them, could be greatly strengthened by the addition of sawdust so that the ice formed strong, long-lasting and resistant ‘pycrete’.

With success in the Bering Strait, more ambitious ice shield projects might then follow. Now, the linked Laptev, East Siberian and Chukchi Seas contain some of the ocean seabed and vents that are most at risk of spewing out catastrophic amounts of methane emissions. These areas could partially be protected from warming by the North Atlantic Current (NAC) by a double line of ice shields, grounded in the shallow ocean (average depth ~80m), located at the edge of the continental shelf and running from Barrow Point in Alaska to the Taymir Peninsula in Russia, a sinuous distance of some 2,400km. This barrier would protect some 1.8m km2 of shallow, methane-rich sediments and vents. Note, that the depth of Arctic organic-rich sediments is typically measured in kilometres. Into this barrier, one might wish to have some narrow shipping and air-breathing wildlife channels left open, though cetaceans and pinnipeds might be expected to be able to move under the ice from polynya to polynya, as there would be undersea gaps between ice shield bases.

Should this Siberian Barrier, or a thickened one, to the intrusion of warm water into shallow, methane-clathrate-rich waters prove efficacious, then two other similar Arctic projects should be worthwhile considering. The first of these would be to erect a similar barrier to protect the sediments and sea ice in the Kara and Barents Seas from being warmed too much by the North Atlantic Current. This might be called the Barentsz Barrier. It is a more difficult area in which to form a barrier with ice shields because of its several deep, undersea canyons and because the south of the Barents Sea is typically ice free due to the NAC, or North Atlantic drift of relatively warm salty water, and to warm coastal water. However, modeling should be able to determine whether constructing ice shield ranges to connect (but possibly with gaps over canyons and for shipping and wildlife) the Taymir Peninsula to Novaya Zemlya, to Franz Joseph Land, to Svalbard (plus a short westward arm), to the North coast of Norway would be both feasible and worthwhile. Along this line, waters average approximately 200m deep, with some short stretches up to nearly 500m deep. Ice shields can probably even create an ice barrier at these depths, though the possible requirement for multi-year mooring could make it more difficult unless the more recent ice shields could be frozen onto the older ones. Creating ice shield arrays should itself make neighboring waters more easily glaciated with ice shields.

It may even prove feasible to construct tethered, floating ice shield ranges over the canyons, provided they could be sufficiently constrained by perhaps giant, looping cables or meshes set in later ice. These ranges over canyons would only need to be made and maintained deep enough to fend off the warmer surface water currents, winds, waves and floes, whilst possibly leaving any deeper, colder currents unimpeded. However, should the growth of each ice shield be enabled to continue for years, there appears to be little reason why most could not eventually become securely grounded. Constructing the section of ice shield barrier to insulate the Kara Sea from the NAC would be the easiest part of the task. Following this, ice shield barrier construction might best proceed from the northeast to the southwest, as each new construction would then tend to make the construction of the next one easier as more warm NAC water is repelled, making ice shield construction thereafter the easier. Moreover, done this way, the ice-free passage from Murmansk to the Atlantic might be preserved without any special provision being made for it.

Similar modeling and calculations might be made regarding the erection of an ice shield range at the edge of the continental shelf between Mackenzie Bay and Prince Patrick Island in Canada. This is typically less than 400m deep. Alternatively, other ice shield ranges might be made linking the islands (whilst missing out on protecting some of the methane-rich sediments) and thereby reducing the number of required ice shield installations. This would hinder the westward flow of water amongst those islands by acting as a partial plug, rather than being the initial barrier itself to NAC water. Such barriers and constrictions may well be sufficient to turn the bulk of warm North Atlantic Current water back into the North Sea, thereby helping to save the Arctic ice, stabilizing the polar vortex, and helping to prevent catastrophic emissions of Arctic methane. Ice shield extensions might even be considered to Ellesmere Island or Greenland.

Development of ice shield arrays behind these barriers, whilst providing channels in the arrays for shipping and wildlife, may then also be considered. The pattern of such arrays might best be one that left some spaces or channels in each array, as this would provide shipping and wildlife access, whilst encouraging sea ice formation and allowing additional ice shield growth, should that be so desired. Unusually deep areas might be avoided, unless it were decided that floating ice shields which moved under wind, wave and current, but were constrained by corralling ice shield ranges, shoals and land, would be desirable additions thereto. Anchoring is probably not a viable option here. Corralled areas might eventually be entirely covered in a single ice shield array that would prevent normal wave action from breaking it up.

Once the remaining open and seasonally frozen parts of the Arctic Ocean had been porously corralled, consideration could be given to whether floating ice shields in open water there might also net-benefit global climate, wildlife, scientific endeavour, and industry.

Ice shield arrays might even be grown in the non-polar regions of Hudson Bay and in some parts north of the Kuril and Aleutian island chains which could act as corral walls. These arrays would probably be grown last of all in the northern hemisphere, after ice shield arrays had been established progressively southwards from the Arctic regions, thereby making the growth faster and their ice mass more durable.

One region where it could be advantageous to generate ice shields that might float free during the warm season is in the higher latitudes of the Southern Ocean. This is so for three reasons. First, the strong circumpolar winds that blow there, together with the Southern Antarctic Circumpolar Current (SACC), would both tend to keep the new ice shields/icebergs productively in the Antarctic and from forming navigational hazards elsewhere. Second, there is relatively little seaborne traffic or marine installations there that would be adversely affected. Third, as the area covered by winter Antarctic sea ice has been expanding, if only for an uncertain number of years (it may already have started to recede), there is a window of opportunity to thicken part of the sea ice there such that it may last for some useful decades before requiring refurbishment. In turn, this would tend to stabilize the ice tongues there, to help cool the world as a result of the increased oceanic albedo, and to delay sea-level rise that would otherwise be caused by the on-going disintegration and melting of the unstable West Antarctic ice cap and that of other regions. However, research should be undertaken to try and have such an increase in sea ice provide net benefit, rather than net harm, to marine species’ breeding and foraging. Modeling would also need to establish the regions and latitudes where the increase in thickness of ungrounded ice shield ice through pumping seawater onto the ice during the colder seasons would offset or exceed that of its thinning by melting and abrasion during the warmer seasons. Given the protective and nucleating effects of an array of ice shields, it might even be that such a cryogenic area could, for a while at least, increase its extent and/or its seasonal duration by as much as 30% more than was reached in the Antarctic winter of 2010. Furthermore, should deep, pumped Southern Ocean seawater be close to its freezing point, it may be convenient to continue pumping it over or around each roughly circular ice shield, rather than installing separate piping, as this would tend to disperse its bottom nutrients more effectively to surface waters whilst not melting too much of the ice shield. This variant would tend to produce unusually well-nutriated icebergs, to the probable benefit of marine life.

## Cost Benefit Analysis

Taking the Laptev to Alaska barrier as being a representative investment, the principal benefit would be that the methane-clathrates in the shallow sediments behind the barrier would no longer be warmed by the NAC (though they still might be warmed and stratified somewhat by riverine flows and the atmosphere in the warmer seasons), so that this NAC factor neither caused nor exacerbated catastrophic methane emissions.

Secondary, but possibly substantial, benefits might well result from: increased Arctic albedo leading to global cooling; convective heat removal; some beneficial effect on stabilising the jet stream and polar vortices; excess renewable power generation carried by undersea HVDC lines from ice shield installations to land; stabilisation of some Arctic glaciers; stable and permanent drilling and production platforms; secure access for controlled, drill-free submarine methane extraction and piping; additional fish stocks; air strips; research station bases; and reclaimed wildlife habitat.

Modelling would need to determine what effects there might be to or from: partially constraining Arctic riverine water to the corralled area; sea conditions; wind conditions; ice floes and their movement; snow cover; global climatic changes; Arctic and sub-Arctic life, including that of migratory species and vegetational changes; shipping; the NAC and Great Conveyor Belt, particularly assessing where the redirected NAC heat and cold briny currents would thence end up and their effects in those places. Here it should be noted that, whilst warm surface currents would be constrained by the ice shield range barriers, cold or particularly salty deeper water might tend to find its way through the undersea gaps between the ice shields. Thus, the global ocean current driver of dense, Arctic, cold and briny water would tend to be maintained.

# Part Two – Individual Capabilities and Installation Design

### Capability One: Thermal Bridge

What ice shield pumping does, is to create a thermal bridge between the ocean water under the ice and the below-freezing atmosphere. The thermal air convection effect would extend the bridge to the tropopause. This is so, because the heat liberated by the freezing of the seawater on each ice shield surface warms the air and this is then convected upwards in rising air columns or thermals. These carry the released latent heat of fusion into the upper atmosphere where it is above most insulating greenhouse gases. With therefore little interference, the heat radiates directly into outer space via long wave radiation. In Bonnelle’s phrase, a *thermal shortcut* is formed linking the seawater under the otherwise insulating ice and insulating atmosphere, to the tropopause. The process is akin to the action of a heat pipe, where differential heating and cooling is applied between two zones, either actively by pumping, as in this case, or passively as in the millions of heat pipes, or thermosiphons that de Richter notes are used to keep frozen the permafrost under some Arctic pipelines, roads, railways and other infrastructure.

Each growing ice shield would act as a conical heat island, where the heat released by the freezing water would flow centripetally (centre-seeking) as a relatively ‘warm’ air current up the gently inclined, conical ice shield to produce a strong cylindrical updraft, or thermal, of relatively warm air from its pinnacle. This might be lofted as high as the tropopause (the boundary between the troposphere and stratosphere), even when strong winds are present. From high in the troposphere there is little insulating greenhouse gas or cloud above the top of the thermal to prevent its contained heat from radiating directly into space, thereby efficiently cooling the world by taking heat from the ocean under the ice almost directly to the tropopause, and with little heat loss on the way because of the substantial diameter, integrity and velocity of each thermal. The heat would tend not to be radiated back to the Earth’s surface because of the reflecting clouds and insulating greenhouse gases below. Thermals produced from almost the entire surface of what might be an ice array extending for hundreds or thousands of kilometres would tend to combine to produce an even more efficient global radiator or heat removal system. As this effect would tend to suck much more air polewards in the cold two thirds of the year, modelling is required to determine the effects on weather systems and climate closer to the Equator. It is surmised that these will largely be net beneficial, but where, when and how is to be determined. It may be that cell movement, or more cells, or more powerful, Polar, Ferrel and Hadley Cells would form – or else the effect would just re-establish those that formed under previous, more stable and beneficial, climatic conditions, or else prevent the possibly adverse reduction of the number of such cells. The movement, or the expansion & contraction, of Hadley cells has major effects upon latitudinal precipitation.

Such thermals might well become strong (and hence increasingly effective as global radiators) as they are, in a sense, the inverse of the powerful katabatic winds that can flow at speeds up to 220km/hr down, admittedly much steeper and often longer, frozen slopes. Whilst katabatic winds are driven by gravity and the increasing density of air as it contacts a long, downwards sloping stretch of much colder surface, thermals generated by pumping water to freeze in thin layers over horizontal formations of ice cones, even with as little inclination per three-kilometre wide cone of 30, that might stretch in arrays for as much as hundreds or thousands of kilometres laterally, are powered by buoyancy or the decreasing density of air as it warms to as much as 300C above that of the air surrounding each formation.

It is also conceivable that very large ice arrays might generate their own strong surface winds, somewhat analogous, if less in intensity, to those produced by bombing major cities or forests with incendiaries or nuclear bombs - the firestorm or Dresden Effect. Thus, even in the occasional absence of strong, natural Arctic winds, the offshore wind turbine farms might still produce substantial amounts of winter power by this effect.

Should the lateral winds generated by very large ice shield arrays be estimated to be too strong for Arctic-adapted wind turbine operations, then the size and location of each array, and hence their combined effect, could probably be kept well within operational levels for such turbines by careful spacing of the arrays. It will also be important to model what effects region-sized thermals would have upon the stability of the polar vortex, amongst other possible effects.

### Capability Two: Solar Reflector

Ice shield arrays would increase the albedo (solar reflectivity) of the Arctic in five ways. Their brilliant white would reflect much more sunlight than does the dark-blue ocean. The light-green concentrations of phytoplankton produced in surface waters as a result of the ice shield pumps bringing deep, highly-nutriated water to the surface in summer would have a similar, if lesser, effect. The extra DMS compound indirectly produced by the extra phytoplankton would serve to increase and brighten reflective marine clouds. The additional moisture in the air might induce greater snowfall, though it might also detract from long-wave radiation. And finally, because of maintenance pumping, the ice and snow surface would tend to remain a brilliant white, no longer being dulled by now-buried black carbon deposits.

### Capability Three: Physical Barrier

In waters up to perhaps 900m deep, though typically much less, the creation of grounded ice shield ranges can act as a physical barrier to the lateral movement of water. As much of the Arctic Ocean is shallow, this means that areas in danger of being heated by warm currents might be virtually sealed off from them. This is particularly the case with warm, less-dense water currents, as these tend to travel near the surface, whilst colder, saltier and denser currents tend to travel at depth. Moreover, because of the way they are constructed and tend to melt more from below, ice shield barriers, both before and after they are grounded, provide greater resistance to surface water lateral movement than they offer to deeper water movement.

The creation of such grounded ice shield ranges might even be able to prevent the collapse of ice shelves and glaciers, such as the Thwaites in Antarctica, thereby stabilizing the Western Antarctic ice sheet and thus preventing the sea level rise of ~4 metres to be caused by such a collapse. A ‘warm’ ocean current is currently undermining and melting the Thwaites ice tongue and shelf, and its intruding water, together with meltwater from the upper surface, is helping to lubricate the base of the glacier itself. However, the water just ‘offshore’ there is only ~600m deep and has transverse ridges to help grounded ice shield ranges provide strong resistance to further glacial collapse. Similarly, might some of the Greenland Ice Sheet (GIS) and other Antarctic glaciers be protected, particularly those with valleys that deepen as they go further inland.

Unmoored, unanchored, floating and still-growing ice shield arrays might be expected to run aground offshore of the Thwaites and other glaciers, ice shelves and tongues, thereby providing barriers to both melting and fast glacial movement.

As wave action and swells over 3m high can penetrate up to hundreds of kilometres into an ice pack or sea ice of normal thickness, cracking it up along the wave direction, the barrier to these waves caused by massive ice shield array ranges would itself tend to retain sea ice integrity for longer duration each year. It would also prevent the ice breaking up so readily into smaller pieces that melt faster due to their increased surface area, abrasion and frictional heating.

### Capability Four: Emission Control and Capture

Ice shield range barriers and arrays could be constructed to protect the shallow, methane-rich sediments of the Arctic Ocean from submarine warming and the consequential melting of their methane clathrates and the release of the methane trapped beneath them. In particular, the grounded arrays might be used to suppress Subsea Methane Eruption Centres (torches) where the NAC (Gulf Stream) is causing them to appear in increasing numbers and extent in the Laptev and East Siberian Seas.

The ice shield arrays, and frigid brine flows from them, could also be used to form cold caps or icy plugs for methane vents, and also by the underside conformation of the arrays, to regulate and direct the residual outflows of methane to zones within the arrays where they might be harvested, or selectively released by reducing the local pressure on methane clathrates by pumping, or released by warming them with pumped-down warmer surface water, then captured, compressed and piped south. There is enough methane in Arctic and other sediments to replace the energy from all high-carbon, coal-fired power plants and high-polluting unconventional oil and gas resources until sustainable sources can, in turn, replace most of them. In short, the Arctic methane can be used as a low-carbon transition fuel (particularly when used in efficient fuel cells rather than in less-efficient combustion), as well as a temporary source feedstock for food/fodder, chemicals and polymers for an over-populated world.

When hexagonally close-packed, and with the direction of their growth controlled once they reached their intended dimensions, there would form open areas at the juncture of any three ice shields. In polar regions, such openings in the ice cover of the ocean are termed polynyas. In our case, each polynya would typically be in the shape of an equilateral triangle with its sides bowed inwards. Polynyas are vital to much air-breathing polar marine life, including seals, walruses, cetaceans, polar bears, penguins and migratory birds. Without special provision, polynyas serving as aggregation points for bubbles of methane ascending vertically from the seabed, or following the sloping underside of a lenticular ice shield, might possibly become suffocating wildlife death traps, even though methane is lighter than air. Such can be avoided by the designs by which we harvest the emitting methane. One such set of designs follows.

To collect the methane being emitted from the sediments and vents directly below the polynya, all that might be required is a thin membrane fixed to the ocean floor in the form of a shallow, inverted funnel. For strength and simplicity of construction, the membrane might be made of transparent or black PET film of circular form, possibly with a weighted, springy rim of brine-filled PET piping and a tube leading to an off-take gas pipe at the surface. Such funneling at depth would tend to restrict the metabolisation of the methane on its way up. Furthermore, just prior to the three intersecting ice shields reaching their fullest extent, a triangular boom with weighted hanging skirt would be floated just at the edges of the forming polynya and overlapping each ice shield. The boom might be made from PET piping, to which was fixed a semi-flexible skirt of the same material. The ice growing from each ice shield would eventually enclose the boom, allowing the methane to collect just outside the skirt. Drillholes made in the ice should allow this gas and that from the funnel to be tapped, compressed, and pumped away by pipeline, leaving the polynya largely methane-free and accessible to drones, divers, birds, polar bears and marine life. Where methane was only emitted very slowly from the sediments immediately below the polynya, either the funnel alone or the boom and skirt as well might be omitted. Presumably, seals would soon learn not to breathe the collected under-ice and in-funnel methane, just as they now avoid breathing the methane/CO2 bubbles collected under the ice.

Where the provision of polynyas for wildlife is not required, but methane capture is, the simpler strategy of ensuring that each three adjacent ice shields overlap fully may be sufficient to create an ice cavern, void or vent from which the gas may be harvested. Where polymeric covers are used for these (often avoidable) they should probably be black or opaque so as not to attract wildlife from underneath. New seawater-forming ice from one or more of each of the three adjacent pumping stations may eventually meet where the shrinking polynya finally disappears, unless care is taken to avoid this. Once sufficient ice forms over a polynya, an inverted tetragonal, subglacial cavern is formed, into which methane bubbling up from clathrates and ocean sediments below can accumulate. Provided there are no cracks in the ice above the cavern (or a membrane cover is in place), and the ice is thick enough to form a strong barrier, the methane will become pressurized, forcing the ocean surface beneath it to become lower, thereby pressurizing the gas even more. Taps could be made into this cavern to extract the gas, or possibly better, buoyed vertical pipes with elevated valves and gas pressure & flow-rate sensors could be placed in the polynya before it freezes over. Once a strong cavern has been formed, the valve may be closed and harvesting can commence. The caverns so formed may become quite large, thereby performing a useful storage system function between extractions, or when market demand or off-take capacity is low. A single such irregular tetragonal cavern, with horizontal sides each 500m long and a height of 30m, would hold just over a million cubic metres of modestly pressurized gas (probably a mixture of methane and CO2). However, because of the chance of cracks or holes developing in its icy container, it might be wise to keep such interim storage containers relatively small and at pressures below three atmospheres. The gas-holding capacity per cubic metre of a cavern and its underlying water would increase with both pressure increase and reduced temperature. It would suddenly increase much more, once the hydrate-gas phase boundary had been passed in freezing conditions at approximately 17atm pressure (either that below ~170m depth or pressurized by the water below this depth) due to the formation of clathrate. Methane clathrate is lighter than water at 0.95gm/cm3. Methane stored as clathrate in such caverns would store a far greater concentration of readily off-takeable methane than as a gas. Note, regular offtake and separation of the CO2 component may be required in order that the seawater is not rendered too acidic for marine life. The same may be required of lightly pressurized methane in order not to lose too much of it to methanotrophs.

The excess renewable power generated by the ice shield wind turbines could be used to capture, separate, compress, and transport by pipeline (or ship) Arctic methane and CO2. Should the Arctic winds temporarily fail, then it should be possible to send power from other sources back along the same, or parallel, HVDC lines in order to maintain the compression/separation processes and pumping flow of the gases (CH4 & CO2), both of which might best be transported in their supercritical or liquefied phases.

In the early stages of ice shield deployment, some preference might be given to plugging the hot spots, rift zones and vents that were then releasing methane fastest, provided they were in relatively shallow water. However, care would need to be taken that the wind turbine itself, or nearby vessels or humans, did not spark a conflagration. Moreover, fire (probably from lightning or internal sources) is the single greatest risk to wind turbines.

The process of forming each ice shield may have another benefit: it could make ice plugs or caps form in and over the vents and depressions in the seabed where methane was issuing or might issue forth. The cause of this plugging would be the frigid brine streaming off the edge of each growing ice shield. Typically, this would be well below the freezing point of seawater and considerably denser than it due to its coldness and high salinity. As each ice shield grew, its expanding ring of down-welling frigid brine would tend to cover and freeze much of the seabed surface beneath. The accumulation of these large amounts of frigid, salty and dense water would, also beneficially, tend to reinvigorate the ocean current system.

Now, the lowest freezing point obtainable for NaCl brine is -21.10C when the water is at its maximum 23.3wt% NaCl. The average winter Arctic temperature is -340C, but if we hope to freeze shut most of the methane vents then perhaps the average seasonal temperatures of Barrow in Alaska are more appropriate to use. Subject to later warming, these are: autumn -80C, winter -250C, and spring -180C. Hence, if ice shield growth is made to happen over these three seasons, the average temperature of the brine is likely to be around -170C and its salt content 20wt%. If we assume that, the loose salt crystals carried by the rivulets of brine as they cascade over the edge of each ice shield partly offset the warming and diluting effect of the seawater, when the brine comes in contact with the seabed, the brine might be around -120C with a salinity of perhaps 15wt% and a density of approximately 1.12g/cc. This should be sufficient to allow it to enter many methane vents and displace or freeze the fresher water in their cores, sides and bases. Brine warmed and diluted in the vents would tend to be displaced by new, colder and denser brine, thus enlarging and cooling the icy plugs still further.

The ice formed on the top of the ice shields will, until aged, have approximately the salinity as new-formed sea ice, or nilas, that is around 1.5% NaCl – or a little less than half the salinity of seawater ~3.5%. Although the salt content would tend to reduce over time because of the migration through the ice of brine concentrations and salt, in deep ice shields this freshening of the shield ice could probably not be expected to be great, except over a long time.

Benthic organisms are used to frigid streams of brine descending as sea ice forms and wends its way to the depths by way of valleys and depressions in the seabed. Most probably find a way to move out of such killing zones to higher ground. The same should occur with ice shield formation, only perhaps now more so and for an extended period. It is even possible that much of the surface sediments will become frozen and no longer emit methane, at least whilst pumping in winter continues at scale.

### Capability Five: Weir

An ice shield installation on either side of the mouth of a north-flowing Arctic river, or a string of such structures across the wider estuaries of such rivers, might well be able to freeze together to form a weir designed to hold back some, or all, of the issuing riverine water for a while. Once the weir had formed, the river flow (even under some of its own ice) could back up, rise in level and break through sufficiently well for a portion of its water to cascade over the weir onto the still-frozen sea ice beyond. As fresh water freezes at a higher temperature than does seawater, provided the flow was not sufficiently strong initially to melt the underlying sea ice, the freezing fresh water would tend to increase the area of thickened ice many times over. Furthermore, the surface of the area-increased fresh water behind the weir might also tend to freeze. This would have the effect of encasing the newly-submerged, low-lying land in a coat of ice, thereby possibly increasing its albedo and tending to lock in most of the otherwise outgassing methane, NOx and CO2 beneath it. Thus, both shallow ocean, littoral, and nearby low tundra could be frozen over by such applications. The area frozen over by such river mouth, inter-island (particularly Canadian), or shallow ocean installations might come to cover many tens of thousands of square kilometres.

### Capability Six: Hydroelectric and Diversionary Dams

Tall ice shields might be created in river valleys, thereby providing economical and non-polluting dams in Arctic and sub-Arctic regions from which hydroelectricity might be generated. However, unless the ice dams were thick and frozen onto the permafrost, they might not be as stable as traditional dams. Hence, care would need to be taken regarding the safety of inhabited areas, infrastructure and wildlife in the lower levels downstream. Ensuring that each ice shield froze solidly onto the local permafrost might be as easy as installing passive heat siphons akin to those used to keep Arctic infrastructure frozen. It may be necessary to hold back the flow until sufficient water could flow downstream not to be quickly frozen, thereby shutting off continuous flow. Such dams might be useful in providing power to the grid when Arctic winds failed to deliver enough power to it.

Similar or the same dams might be constructed to help divert a portion of some north-running rivers south, to where their water could be used for irrigation and industry. This would also serve to diminish their undesirable warming and stratification effects on the Arctic seas.

In spring and summer, Arctic wind farm power could be directed in part to pump water from the Arctic rivers south for irrigation, industry, and to remediate the lakes, rivers and aquifers there, whereas in autumn and winter that part could be directed towards ice array and AMOC maintenance or ice shield proliferation pumping.

### Capability Seven: Wind Farm Power Plant

As has already been noted, ice shield installations can become major producers of renewable energy, once their shields have become sufficiently well-grounded. Their construction and operation allow them to operate as grounded, off-shore power plants in waters less than about 900m in depth, though they are more readily constructed in shallower waters where a single cold season or three is enough to ground them. Their ability to be linked together in ranges and plateaus linked to land, and the flatness of their topography, makes laying HVDC power lines on them relatively easy. The lines are then readily protected by pumping seawater over them to encase them in protective ice. Should the power lines generate heat, it may be necessary to support them by transverse strips of tape or polymeric meshes frozen into unmelted ice nearby. Thermosiphons may also be useful here. Access to the power lines and supporting infrastructure by maintenance crews becomes relatively easy by air, land or sea.

Once established, their marketability as wind farms and semi-permanent ice roads, onto which HVDC powerlines and gas pipelines can be laid, should make them an attractive funding and investment option.

### Capability Eight: Shipping Channels

Under current global warming, the Arctic Ocean will develop valuable shipping routes. Even with the increased Arctic glaciation that hopefully results from these ice shield techniques, selected routes may still be able to be maintained ice free for much or all of the year. This should be possible by the careful placement of shipping and wildlife channels between and through ice shield ranges and arrays, possibly aided by residual flows of funnelled and channelled warm water from the south, emitted HVDC cable heat, periodic ice-breaking, or the pumping of ‘warmed’ brine from the depths using ice shield wind turbine power.

### Capability Nine: Wildlife Habitat

We are progressively losing polar wildlife habitat because of the retreat of sea ice, on which so many species depend. These species include phytoplankton, krill, penguins, pinnipeds (seals), cetaceans (whales) and polar bears. Reversing global warming by means of increasing global albedo and keeping warm water away from polar regions will help. However, possibly the best way to use ice shields to provide additional habitat for these species is to construct open or closed arrays of grounded ice shields. These might populate the areas enclosed by ice shield ranges constructed for power generation. The open spaces amongst the arrays would provide access for air-breathing marine species. Sea ice and snow would tend to cover the narrower spaces; and the ice shields might provide over-wintering habitat for algae and krill, undersea, sea surface and land transit routes, and convenient rest and feeding areas called polynyas.

### Capability Ten: Access, Research, Maintenance & Production Bases

The grounded and nearly level ice shields would provide stable, long-term platforms for drilling operations, though drilling for fossil fuels in the vulnerable Arctic should be discouraged. With some grading, the elevated flat surfaces would be useful as ice roads, causeways or aircraft runways. The nearly level plateaus of linked ice shields that reached to the land would provide near-all-weather ‘land’ access for vehicles. Should it be desirable, the ice roads, or even railway lines, might be transformed into covered bridges or ice tunnels whose passages were safe from weather extremes, wind, ocean waves, snowfall and wildlife. This might be done economically by encasing parallel, seawater-filled PET tubes in ice. Inflated transverse PET arches, linking the tubes, would support bulging, inflated and externally-textured PET membranes onto which seawater was sprayed to freeze, thereby forming thick tunnel walls and roof. For long tunnels, either ventilation or the use of electric vehicles could be employed.

Pipelines and power lines could be buried in ice running along the plateaus. Such pipelines might be constructed economically by unrolling flat, PET+glass fibre tubes from tractor-borne reels along the ice roads, inflating them, then spraying them with seawater that freezes, forming a polymer-lined ice pipe of almost any wall thickness required, thereby to conduct pressurized and well-insulated gases over long distances.

Some of the ice shield installations could also be designed to include laboratories, storage facilities, utilities, pumps, power, communications and accommodation.

The ability of the larger wind turbine installations or satellite pumping stations to act as self-powered, all-weather bases and observatories should also prove advantageous. Indeed, the larger ice shield installations having accommodation, that are to be spaced amongst the regular arrays of unstaffed ones, might prove to be ideal platforms for the East Siberian Arctic Shelf (ESAS) observatory network, as well as for other Arctic research studies.

### Capability Eleven: Sequestering Atmospheric Carbon Dioxide

Generating thick ice shield arrays over much of the polar waters and nearby seas would produce vast quantities of frigid, residual brine. Despite the dampening effect of the increased salinity, such brine, being at temperatures well below zero Celsius, would tend to absorb a significant, or perhaps even a substantial, part of the CO2 content, together with a lesser amount of the oxygen, from the turbulent air flowing over the thin sheets of seawater-brine flowing for up to kilometres over the conical ice shields. The effect would be magnified because the thermals generated in the atmosphere by the heat released by the freezing seawater would convect large volumes of that air directly to the tropopause, thereby sucking in CO2-rich air from the lower latitudes. As it seems possible for the ice shield generation process to thicken sea ice by tens of metres every cold season, the amount of CO2 sequestered safely for hundreds of years in the abyssal depths by this process in just northern hemisphere waters could exceed 15GtC each year for a few decades. Such ice thickening operations in the Southern Ocean might perform a similar service over perhaps an even longer time period.

## Proof-of-Concept Experimentation

The small-scale pilot pumping experiments to be conducted would be designed to increase the 8-12m ice-thickenings previously achieved by substantial factors. Each experiment might be performed using a diesel-powered pump, housed and protected on a rigid triangle of hollow, cylindrical or spherical, steel, wood or polymer buoys. After the experiment, each installation would desirably be retrieved, so it might be best if the experiment were to be conducted in a sand-banked inlet or in waters that could otherwise be closed off until each ice hill had melted, thereby freeing the equipment. This could take long. Regrettably, such corralled experiments might do little to test the effects on ice shields of ocean currents and waves. Each experiment would be intended to run until its fuel tank on the buoy assembly was exhausted, thereby reducing the likelihood of pollution. With refueling, each experiment might continue for some years, provided its inlet and outlet pipes were not blocked. Other ice structures might also be formed from the pumped seawater.

Parallel experiments at the same general site and time should be able to provide data regarding the optimization of: pump type; pumping rate; pumping velocity; nozzle height above ice, inclination and speed of nozzle rotation (if nozzle there be) ; nozzle shape and flow cross-section; development of ice cone inclination; radial and mass growth rate; wind effects; tilt and remediation methods; insulation and de-icing effects; radial ice salinity gradient; submarine, radial and surface profile development; brine and temperature effects; wildlife effects (if any); stressing and cracking phenomena; encrustation and fouling; mooring stresses; equipment performance; and warm current/warm season melting effects, amongst others.

Should greater control be required over the seawater issuing from the tube, then an adjustable lozenge might be located at the exit to produce a variably umbrella or wedge-shaped sheet of water flowing down onto the forming ice cone. Both direction and flow rate could be adjusted by moving or re-orientating the lozenge. Alternatively, and assuming such ice shields would not become unbalanced, helically-arranged apertures in satellite vertical pumping pipes might distribute the seawater radially as is required, but without the expense of active directional control. A second alternative would be to use a ruff made from separable sheets of plywood to adjustably direct the flow and thin the radial seawater flows using radial separators of rounded wooden rods. A third alternative being to use a rotatable sleeve within a slotted-aperture vertical outlet pipe to dynamically direct the flow. Note, that at times of power failure, the level of seawater in the outlet pipe should probably be allowed to recede to lessen the chance of freeze-over. Warming elements or flows or salt introduction might be required to recover from such an event.

Pipe subsidence under increasing ice shield mass might be accommodated with flexible piping or with simple upward pipe and power line extensions, the pumps and sealed motors remaining inside and floating on the seawater surface of the slowly submerging pumping pipe or tube. Such satellite pipes might be of biodegradable plywood, spiral wound and adhesively bonded with hot-melt lignin, preferably under compression.

## Linking

Each satellite pumping installation would be connected to its wind turbine power source by buoyed or floating power lines. Those installations in outer concentric circles surrounding a wind turbine would be connected by possibly split and extension power lines laid on the ice shields and possibly protected with further ice accumulation. It may be advisable to have the insulating material of each power line linking a wind turbine to its satellite pumping installations strengthened with a high-tensile strength, braided polymer fibre, such as Zylon. Such cable-cum-power lines could be looped and buried in later ice to anchor new-forming but still ‘loose’ ice shields and to improve ice array integrity.

## Ice Shield Distortion

Whilst the fierce Arctic winds could be a problem for the even distribution over time of seawater that freezes over each growing cone, there are mitigating effects. First, as the water is not to be sprayed high, but instead will gush out of the orifices in each tube that are very close to the ice surface, there will be little chance for momentum to be transferred from the wind to the seawater stream. Second, any surface water that is pushed downwind would tend to begin freezing there, thereby decreasing the inclination of the forming ice cone and possibly causing later water to be pushed uphill or sideways, thereby offsetting the tendency for it to be pushed preferentially downwind. Third, although strong wind would cause an otherwise nearly perfectly even cone (or lens) of ice to form a distorted cone, similar distortions would tend to occur in all such cones resulting from similar winds. Hence, roughly hexagonal close-packing would still occur to make an integral ice array incorporating polynyas, some of which would have a non-submerging wind turbine floating in them, but that each circular lens would become elongated and its peak would be offset from the centroid. Fourth, should prevailing winds cause each ice shield to tilt because of excess ice accumulation on the downwind side before it froze onto its downwind neighbor (thereby arresting any further tilt), vertical extension tubes added periodically to compensate for ice shield subsidence could be made curved or angled to offset further tilting by preferentially directing the gushing seawater upwind. Alternatively, seawater might be directed dynamically to compensate for the prevailing wind.

## Mobility

To prevent evolving ice shields from becoming moving navigational hazards, they should perhaps be initially moored or anchored in shallow enough water that just one cold season of about eight months would allow enough ice to be accumulated so that the growing ice shield became grounded, or else that it became frozen onto some immovable structure. Should the ice shield be allowed to melt, the facility might become free floating or anchored again, provided that its buoy was still intact. Note, in the diagram below, the stabilizing spar (concept added later) extending into the sediment or having been pushed inside the pumping tube again is not shown. Furthermore, using the satellite pumping station concept, the wind turbine would be separated from the pumping units that it powers, and would remain floating in its own polynya. Also, no L-shaped horizontal pumping tunnel or water inlet would be required as those pumping units growing the ice that grounded each lens-shaped ice shield would be at the shallower depths unaffected by sediment.

In Antarctic waters, whilst some ice arrays should be able to be grown so that they freeze onto existing ice shelves and tongues until they can ground themselves and thence serve to slow down glacial movement, melting and breakup, others might be grown as free-floating arrays. These could be made to form initial, bonded threesomes in sea ice during a single cold season. They would be grown typically deeper each cold season until one or more became temporarily secured in autumnal sea ice, whereupon the number of their component ice shields might be increased progressively on the periphery, thereby increasing the area covered by the ice array. To ensure that these additional ice shields were well-bonded to their parent ice array in the rough Antarctic seas, it may be advisable to attach mooring lines for each new satellite pumping station so that it nestles at the V-intersection of two existing peripheral ice shields in the array. Such arrays would tend to remain in the circumpolar current and winds, endlessly circling unless beached or broken up by unusually wild weather. The polynyas and open water areas they create should allow most marine life to flourish. Whilst the mobile ice arrays remained, they should have net beneficial effects upon global cooling, polar glaciation, and methane suppression. They might possibly increase primary ocean productivity, though they would tend to increase the difficulties of navigation there.

# Ice Shield Design

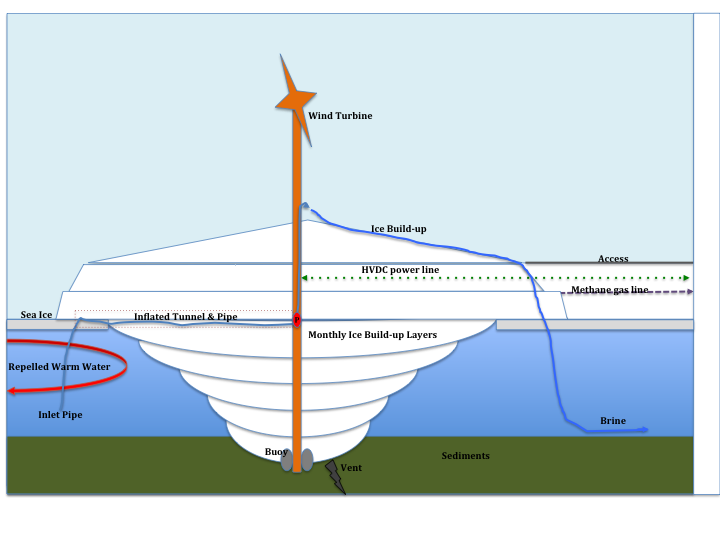


Fig. 2 A horizontally-compressed view of an eight month build-up of an ice shield, now grounded on the seabed.

The concept is to use the power generated by a wind turbine mounted upon a special buoy to pump seawater onto sea ice, possibly from satellite installations. As it flows away from the pumping tube, ice forms leaving the remaining flowing water saltier. Gradually, a gently sloping cone of ice forms around the tube and a lens of ice grows below it. The increasing weight of the ice lens presses it deeper into the water. Some of the remaining brine from the flow runs through developing cracks in the sea ice, back into the depths of the sea where it helps drive critically useful ocean currents. The rest will tend to freeze, as it is no longer insulated from the freezing temperatures above the ice. The leading edges of the growing ice shield will tend to melt somewhat faster than the rest, being exposed to warmer and shallower water. These factors result in the generation of a thick ice shield that wraps around the pumping tube. Melting will cause the toroidal buoy on each tube support to be fully exposed at some distance beneath the shield. Each ice shield may grow to be as thick as a kilometre, only ten percent of which is above sea level. Ice shields become securely grounded once their lower portions are pressed firmly against the sea floor by the weight of ice above sea level.

Once completed, and except for maintenance pumping, most of the generated power from ice shield installations can be applied to other purposes. Frozen together to form nearly-level expanses, ice shield arrays or ranges can become sustainable, semi-permanent polar highways for vehicles, powerlines, pipelines and wildlife. Ice formation from maintenance pumping in colder seasons, when the sea ice has reformed, replaces any ice lost through melting, calving and abrasion.

Varying the pumping regime, for instance by using short pulses of pumped seawater interspersed with intervals long enough for most of the output water to freeze close to the outlet and the resulting ice to cool well below freezing level would allow ice shields in the form of deep but narrow cylinders to form that grounded quickly into the seabed sediments. Varying the pumping regime could result in dynamically-stable, grounded mushroom-shaped ice shields. A wide, linked array of shallow ice shields that provide rapid albedo increase over a large area might be securely grounded when interspersed with deep cylindrical pillars, triangles or wider circles of pillars of ice. Other composite ice shapes might also be similarly generated for other purposes – not unlike some of the 3D printing processes now being developed, but on a vaster scale.

Arctic conditions are particularly harsh, but are not that different from those experienced by existing North Sea wind turbines in winter. However, unmanned ice-shield wind-turbine installations in the Arctic are individually probably less mission-critical than are those in the North Sea and they may not have the complication of marine power line maintenance to the shore. Hence, most of the maintenance and repair of installations used to generate ice shields, albedo, thermals and biomass can probably be left mainly to the summertime.

Given the corrosiveness of brine, together with the effects of extreme cold, marine organisms and ice, pumping elements in contact with the brine may need to be made of highly resistant materials, such as titanium, ceramics, polymers and/or carbon fibre. Plywood satellite pumping tubes and aprons do not need to be so resistantly structured as they are essentially single-use and largely biodegradable. Both remote and artificial intelligence (AI) control of the ice shield infrastructure should be possible.

Wind turbines come in many capabilities, sizes and heights. Large current ones deliver 8MW of power or more and have blades that, at their lowest sweep, are still 45m off the ground. It is surmised that only average capacity wind turbines of approximately 2.5MW power output will be required for most ice shield purposes, provided their initial supporting column could be sufficiently above the ~30m diameter, supporting toroidal buoy and final surrounding ice. Alternatively, a shorter initial column could be designed to be extendable by the insertion of additional segments (each operation being only performed in a warm season) or by telescoping using internal jacks. In either case, for extra column strength, cable guys would secure the upper part of the turbine support column to projections extending from the outer rim of the hollow, reinforced concrete (ferro-concrete) toroidal buoy, in a way akin to some tall radio masts. Should the guys be liable to heavy ice encrustation (unlikely as they should not come into significant contact with freezing water), provision might be made for them to be heated temporarily should it become necessary to shed the ice.

Each initial satellite pumping tube might be approximately 50m long, or perhaps 70m long with its submarine stabilizing spar extended. Without vertical tube extensions, such a configuration could ground itself securely in water up to perhaps 40m deep. With extensions, it might be grounded in water up to 900m deep, particularly if it did not require anchoring or mooring whilst it grew, apart from that given by freezing onto stable objects. The actual maximum height-depth of an ice lens is really only constrained by the increasing amount of energy required to pump seawater up increasing height.

For a notional circular ice lens (comprising the shape of two reflected cones fused together at their bases) 1,000m in height-depth and having an angle of inclination of 40, floating in seawater, and assuming that 10% of its volume floats above sea level, then the elevation of its peak is approximately 232m above sea level when its pointed base just touches the seabed. When the substantial additional ice volume has been generated by the secondary pumping tubes to more nearly level the upper surface of the ice array of which our ice shield forms a part, the whole array should be securely bedded into the somewhat compressible and displaceable, typically exceptionally deep (up to ~20km) sediments of the Arctic Ocean seabed. This extra weight above water should be sufficient to secure the array against the forces of wave, wind, current, moving pack ice, and even of moving floating ice arrays – provided the maintenance pumping is continued to offset any melting. Note, that for angles of inclination less than 40 the diameter of each ice shield might be measured in many kilometres (the theoretical diameter of the above ice shield is ~14.3km, assuming that the flow down the ice cone could flow that unlikely distance before it froze). The effective diameter would tend to be governed by how far radially down the gentle, conical slope the pumped and increasingly saline water could flow before it froze or else made its way as icy brine or salt back to the ocean through the ice. This distance would be governed largely by the pumping rate, spread and direction, the slope, the wind, the temperature and thermal conductivity of the underlying ice surface, the surface conformation, and the air temperature.

Now, for a 40 inclination lens shape, the height above sea level of the ice cone peak is some 23% of its total height-depth, whereas for an ice disc it is only some 10% above. However, for such a notionally lens shaped ice shield, the seawater-to-brine flowing over the conical surface would tend to reach the seawater lapping over the shield-depressed sea ice well before it reached the notional circumference of the lens. This effect would change the shape of the lens to one with pared-off edges, less diameter than otherwise, and greater depth than otherwise (assuming that the pumping regime was constantly changing to minimize waste). As it grew, the initial ice lens would come to resemble a lengthening and slowly thickening vertical cylinder, or better a truncated and inverted cone, having slightly conical ends and a top wider than its base.

Whilst a kilometre thick ice array would be enormous and would take a long time to grow using the pumping and freezing systems outlined, there appears to be no theoretical reason why wind-powered pumps could not lift seawater economically as high as 250m. It is surmised that ice array conformations this high above sea level could be grounded in the approximately 60% of the Arctic Ocean that are less than a kilometre deep. The maximum depth of the Arctic Ocean is 5,450m. The area suitable for grounding ice arrays could be expanded by some 30% by the inclusion of some of the shallower northern seas just outside of the Arctic Ocean and again by some of the shallower waters close to Antarctica.

Deeper Arctic waters might be given floating ice shield arrays, sometimes fused together, and interspersed frequently and regularly with polynyas and with shipping/wildlife channel access, including to Arctic ports and the global oceans.

Stability for floating ice arrays might be achieved by freezing them onto landfast ice, grounded ice arrays or land, or else they might be allowed to drift or possibly to freeze together and maybe beach when wind and current allowed their coalescence against fixed objects or by them growing into each other in giant corrals, such as might be formed by island chains and the often shallow intervening waters of the Aleutian and Kuril chains, or by Hudson Bay.

For floating wind turbines that use satellite pumping tubes, no provision for submersibility is required, as each of these would remain floating on the seawater surface of its generated polynya, secured from wave and unlimited lateral movement by the eventual surrounding ice shield array. Spring-loaded mooring lines secured to the three neighboring ice shields could be used to keep each floating wind turbine in the centre of its polynya after any securing sea ice melts in summer, assuming that the turbine’s anchors alone might not be sufficient. These mooring lines might most easily be placed after sufficient autumnal sea ice and ‘pumped’ ice had formed.

The maximum rate at which water freezes whilst flowing over an ice shield surface at an optimal depth and velocity during a single, nine month cold season may help determine the maximum depth in which ice shields can use integral sea ice as their temporary securing medium. Thus, the colder the location and the longer the cold season lasts, the deeper is the grounding possible in one cold season. However, thicker and larger ice shields could be constructed where other anchoring, mooring, attaching, directing or corralling means can be used.

Should twenty centimetres depth per day (or less than a centimetre per hour if the water is properly distributed over its cone) over nine months be the effective average freezing rate at a given location, then (ignoring undersea melting) 54m is the height of the ice shield generated, and ~50m the water depth in which grounding will occur that year. Forty centimetres per day, or else two years’ growth, would allow ~104m deep grounding in a single cold season. Ready ways to increase this depth might include: spraying the water high into the cold air so that it cooled faster (undesirable as it makes weaker ice and takes more energy); using fresher water from the sea surface that freezes at a higher temperature; using deeper colder water; using a strong undersea support column; using floating piles frozen into the sea ice or driven into the sediments to increase the effective grounding thickness of the ice shield; or tethering a floating ice shield to one that had already grounded, or having it freeze onto land or landfast ice. As previously noted, varying the pumping regime can also improve the depth growth rate of an ice shield.

For reasons of economy, perhaps only one or two standard sizes of wind turbine might be considered, the larger version possibly being better designed to permit location in deeper water. For early uses, a single size of turbine should be made standard.

The ice encased satellite pumping stations, particularly the secondary ones, might be best to establish as drilling platforms, gas processing operations, and for storage, workshops, laboratories and accommodation. These would also be good places to establish infrastructure nodes such as ice roads, pipelines, and airstrips. Building bases in or around the satellite facilities would avoid the discomfort of wind turbine noise and vibration, though pumping would still generate some, if much less. The freezing water might be used to construct much of the above facilities a short distance from the satellite pumping unit itself. It could be done in a way analogous to 3-D printing, though on a much vaster scale. Robots might be programmed, or else remotely controlled, to direct part of the freezing water from the pumps into or onto formwork where it was required to make the required (possibly fibre-reinforced and then insulated inside) ice structures. Note, many of the ice structures might be made in dome or half-tube form (as in giant igloos) by directing freezing seawater onto inflatable and re-usable polymer forms. Power for the activities would come from the electrical link (probably ~600v power as this is what wind turbines tend to generate) to the nearby wind turbine or to batteries charged by it.

Now, a 2.5MW wind turbine is capable of producing enough power for a 60% efficient pump, to pump seawater some ten metres above sea level at the rate of six cubic metres per second, when at full capacity. However, as winds are inconstant and there will be power losses elsewhere, an average 1MW pumping delivery is used here in the calculations. In a nine months cold season this 1MW would generate an ice shield of volume of 0.14km3, less any undersea and subsequent warm season losses. Call it 0.12km3 per year to allow for residual brine loss, snow & ice accumulation and melting. Provided the water could be frozen fast enough, such a rate might enable a single ice shield to ground itself in water that was less than ~85m deep before the encasing sea ice melted, thereby threatening the mooring system. This might translate to three satellite ice shields being grounded in water that is <65m deep or many more in water less deep. Subsequent years of ice accumulation would tend to secure the ice shield even more firmly. However, as the ice shield grew above the size it would reach in the first year, its volumetric growth rate would decline progressively because the seawater would need to be lifted progressively higher than a few metres (depending on the possibly complex shape of the ice shield). Note, for satellite operations the average height above sea level to which the seawater would need to be lifted might be as low as 2m to create a 70m thick (at its centroid and zero at the circumference), 40 inclination ice lens, though to create a level and well-grounded ice array would require much infill ice. If warm season pumping for algal nutriation purposes was not required, the system might be shut down or else used to generate power for other purposes.

Installations located in deep water might take several years before they grew thick enough to become grounded. They might thus tend to require interim mooring or corralling by other means. This might be done by freezing them onto nearby land or previously grounded ice shields, or else situating them such that the prevailing currents and winds would force them against restraining obstacles. They might also be corralled in deeper waters by ice shield construction in surrounding shallower waters. The open spaces within an array could be useful for wildlife, navigation, and possibly for methane capture.

Purpose-designed vessels will probably be needed efficiently to fit the components of the two types of installation (wind turbine and satellite pumping station) together on-site at sea. This is because whole installations are likely to be too unwieldy and unstable to tow there in assembled form. Whilst an ordinary tugboat or other vessel might tow a string of ferro-concrete buoys or collapsed turbine-tower-spar and satellite pumping units to the general area, the other installation components will be more easily transported as deck cargo or in-hold. The stern of one type of purpose-designed vessel might have a dock into which a single buoy for either type of installation could be secured, with one or more cranes alongside to manipulate the components for assembly.

The order of attachment to the wind turbine & buoy could be: release the spar; anchors and cable weights; attach nacelle, generator, gearing and equipment; sensors, controls and communications; jack up the telescoping tower/supporting column; guy lines; then attach the turbine blades and power lines. Excepting possibly the anchor laying and mooring of each toroidal buoy, these functions would not be easily performed in either rough seas or high winds.

The superstructure of each installation is to be supported on a hollow, reinforced concrete buoy, shaped something like a doughnut, lifebuoy or toroid. This toroid is designed to encase the top of a downward and stabilizing spar extension to the installation’s column. Each buoy is designed to resist being crushed by ordinary sea ice. Each might be constructed economically on a submersible mold that is floating in a dock. The dock or harbourside facility may house many such molds, so that mass production, or even fully automated techniques, can be used. Note, for satellite pumping installations, construction would be much simpler, see separate diagram.

The molds for the buoys of both the wind turbine and satellite pumping unit are shaped like the lower fifth of a toroid, but with an even-diameter inner neck to accommodate and secure the inserts. Above the mold is suspended an inflated, afterwards spirally-wound reinforcement, polymeric, toroidal-shaped bladder that is held in place by straps and wires attached to a surrounding, toroidal mesh of steel reinforcing bars, each of which may typically be pre-formed into circle. The bladder acts as an integrated mold and is not removed. Its outer layer may be textured on the outside to increase wet concrete adhesion. Fibres in the concrete help it to resist cracking. The steel mesh skeleton and bladder of the forming buoy is then lowered onto a bed of fresh, semi-liquid concrete lying in the mold. This has been vibrated to remove air pockets. In a process called shotcreting, concrete is then sprayed onto the remaining open part of the pressurized bladder and steel skeleton until the buoy shape and the desired wall thicknesses in each part are obtained. The pressurized in-situ bladder helps prevent subsequent water intrusion. When the setting concrete of the buoy is steam cured from possibly both inside out and externally and the resulting internal condensed water is removed if found necessary, the semi-submersible mold is detached from the buoy by reducing the water level in the dock or by raising the buoy. This is done to allow painting or other forms of concrete surface treatment, should they be thought necessary.

On-location, some four pre-laid, drag-embedded anchors laid typically at right angles would initially anchor each buoy. Centre-weighted cables would provide the necessary tensioning. Any such anchoring system could not be expected to restrain a pumping unit buoy that was encased in massive free-floating ice. This is so because once even a modest ice lens had formed, the tension placed on the anchoring system due to wind, wave and current would tend to break it loose, unless the ice structure itself were already grounded or otherwise attached. An ungrounded ice shield not encased in sea ice, and that was itself not attached to the land or immovable ice, would tend to be a hazard like unto an iceberg and would move until beached.

### Base Construction

The outline of base construction has already been given. Such an installation could become like Norway’s Svalbard facility for seed preservation or Sweden’s IceHotel. Successively higher, linked habitats could be constructed as the ice shield grew upwards from its top surface. When the planned full height was reached, a final habitat level might be constructed with direct access to the nearly-flat surface of the ice cone or array with triple-glazed windows to the outside. This topmost habitat could easily be over 30m in diameter just by using inflated and triple-insulated roofing material. Linked and similar radiating domes at the end of short, split-tube corridors might be used for diverse purposes. Spare power from the wind turbines might even permit artificially-lighted hydroponic horticulture and waste recycling to occur there. Each completed ice shield would be able to include landing strips in different directions, longer ones if it formed part of an array. Power storage systems would ensure that air-conditioning, communications and other vital services did not fail when the winds did.

## Ice Shield Creation and Characteristics

The main constraints on the eventual mass of the ice shield are two: the height above sea level to which the seawater can economically be pumped; and the depth of water in which it is to be located. Also of relevance is the distance and gradient down which the pump’s flow of seawater would flow as less salty water from it froze out, leaving the increasingly cold and briny residuum to flow somewhat further.

The mass of each ice shield would be typically composed mainly of nutriated seawater, depleted of some of its salts by the freezing process, salt accretions, snow, and marine organisms drawn from probably the middle depths. As this mass partly melted (probably mainly from below) in warm times or by non-freezing waters, nutrients from it should help generate Arctic biomass, possibly far more than did the original, nutrient-depleted brackish sea ice and freshwater snow. Furthermore, in warm times and when the power was not required for other purposes, pumping energy might be used to bring nutriated water to the sea surface for fine dissemination and consequent uptake of its nutrients by phytoplankton, thereby increasing both Arctic biomass and ocean albedo. This effect would be akin to that of an upwelling.

The shape of each ice shield would tend to be that of a lens, convex on both sides, though other shapes are possible. A thick, grounded ice shield, with much of its mass above sea level, might be expected to last several decades, perhaps even much longer, after equipment decommissioning – unless it were refurbished or replaced, whereupon its life could be indefinitely prolonged. Of course, in summertime the outer edges of each ice shield array could be expected to melt and break off under the influence of storms, abrasion and warm currents (much less so the ice edges of each protected polynya). However, under maintenance pumping, edges would be reformed and possibly extended outwards the following winter, or else frozen onto neighboring arrays, landfast ice or land.

It is surmised that, with good management, the angle of slope on the surface of the cone might be able to be kept to as low as 2-50 (four has been used in the examples), though higher inclinations and lesser ice shield radii might be achievable via customized pumping when more columnar ice structures are required. Directing the flow of pumped seawater outwards should be able to prevent ice build-up that is too much above the rest of the nearby ice shield surface.

After being towed into place and anchored, operators would wait for a sufficiently thick sheet of sea ice to form around the satellite pumping buoy. When this was thick enough, previously described mechanisms would send shallow floods of pumped seawater radially outwards in one or more directions, flattened to increase their exposure to the freezing atmosphere. As this lens-shaped ice shield grew, its base would slowly submerge as its mass increased, keeping only around ten percent of the forming ice lens above water. As the weight and perimeter of the ice shield increased, the sea ice around it would both bend and crack. The cracks would tend to let any brine that had reached the perimeter flow through them. Soon however, these cracks would tend to freeze shut again, letting the seawater/brine flow ever further outwards. Eventually, the base of the ice lens would tend to ground upon the ocean bed, making its own, possibly deep, impression in the possibly very deep sediments. Any rock strata in the vicinity would tend to anchor it even more firmly than did its weight in its sedimentary depression. Care would need to be taken that such new stresses did not set off submarine ‘landslides’ and tsunami.

Once the ice shield had grounded, if its pinnacle were built-up to some metres above sea level, the ice shield could be easily 2-3km or more in diameter, the diameter depending in part upon how far seawater could flow down the gently sloping conical ice surface of the ice shield before it froze. The closer in temperature the air is to the freezing point of the seawater, the further the water would tend to flow over the ice shield surface, and vice versa.

## Ice Shield Placement

The placement of such installations would not necessarily be restricted to the extensive shallow waters inside and just outside the Arctic Ocean. Provided a new installation had its forming ice shield frozen solid onto that of an existing one or land, thereby mooring it before the warmer season began, there seems to be no reason why arrays of such installations might not extend progressively further offshore and into sub-polar regions, basically wherever sea ice formed in winter.

Thus, there seems to be no physical reason why these human-made ice sheets, shields and arrays might not cover most of the Arctic Ocean (14m square kilometres, which includes Hudson Bay), though some 4m km2 of this is typically already frozen by sea ice for most of the year. However, deeper glaciation with ice shield arrays would help to prevent its sea ice from melting under warm currents and Arctic amplification. It should also reduce methane emissions there. Selected passages and open areas in the polar oceans would be maintained for wildlife, shipping and other activities. Ice array glaciation might be beneficial for the areas of the Southern Ocean (having an area of 20.33m km2 of which all is seasonal ice). The Bering Sea (2.292km2, enclosed by the Aleutian Island chain), and the Sea of Okhotsk (1.583km2, enclosed by the Kuril Island chain) might also be so glaciated with an acceptably low chance of iceberg escape, given our need for substantial global cooling until the climate is restored to something like its pre-industrial state. The Norwegian Sea (1.383km2 is not regarded as suitable for glaciation because of its warming by the Gulf Stream that might become even greater as warm waters are turned back from the Arctic by deep ice arrays. The Southern Ocean contains relatively little area that is suited to grounding ice arrays. However, its circumpolar winds and currents should permit a much greater area to be covered in moving, floating arrays. Totaling these areas, it would appear that something less than 38m km2 of ocean might be amenable to semi-permanent glaciation or ice thickening by wind turbine powered ice shields.

## Cost to Refreeze the Arctic Ocean

Until designs have been tested and refined, the expected cost of glaciating a given area of ocean can only be very roughly approximated. As such, the following estimates should not be taken as anything more than early ballpark ones and hence subject to substantial revisions as more is learned and as production costs move down the Experience Curve.

To estimate the number of wind turbines and satellite pumping units that might be required **to glaciate the bulk of the Arctic Ocean,** it was assumed that each wind turbine might power perhaps three satellite pumping stations at any one time, each at different stages of growth, as forming the last stage requires the most power. Over its un-refurbished lifetime, a typical 2.5WM turbine might generate perhaps 50 ice shields in its array. An estimation for the Arctic might run thus: a single wind turbine that powered the formation of 50 ice shields, each of radius 1.25km, over a 20 year period, and maintained them thereafter for its lifetime, could glaciate 50x3.142x1.25x1.25x1.05 = ~258km2 of ice array, the 1.05 factor representing the combination of the area of the channels, open areas, enclosed polynyas and the lesser area glaciated by the secondary pumping units. Hence, the number of turbines required to glaciate the whole Arctic Ocean would be approximately 14m/258= ~54,000. At mass production prices, the deployed cost of these might be around 54,000x$5m = $270b or $14b/yr for the 20 years it might take to deploy them all. Adding the capital costs of satellite pumping stations and infrastructure might bring this to around a **capital cost of $25b/yr**. This seems eminently achievable, given the alternative. Should some, or all, of the wind farms be later purchased conditionally, perhaps by energy companies from the developers who had removed the initial risk, then much, all, or well in excess of this capital amount in real terms should be recoverable. Operating costs, revenues and public net benefits would be additional to this, but as these are even less certain they are not estimated here.

## Conclusion

Should constructively-critical expert review, followed by preliminary Earth Systems and engineering modelling, confirm that some of the capabilities of ice shields claimed here may be valuable tools in the fight to save the polar regions and the planet, or may otherwise be wise investments, then responsible agencies will not hesitate to provide early and sufficient funding to develop, test and deploy them – following UN approval and cover, and being always subject to international scientific monitoring and policing.