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The cost of stratospheric aerosol injection through 2100

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Abstract

This paper presents the estimated direct costs of a stratospheric aerosol injection (SAI) program through the end of this century. It displays a range of future solar geoengineering deployment scenarios that are intended to reduce anthropogenically-caused radiative forcing beginning in 2035. The scenarios reviewed herein include three commonly modeled representative concentration pathways (4.5, 6.0, and 8.5) and three possible radiative forcing targets (halving future warming, halting warming, and reversing temperatures to 2020 levels). The program relies on three successive generations of newly designed high-altitude tanker aircraft to deliver aerosols to an altitude of ~20 km. Sulfates are assumed to be the aerosol used in conjunction with the first generation tanker, supplanted by an as-yet-determined 'Aerosol 2' with the later generation aircraft. The aggregate cost over the remainder of the 21st century and the annual cost in 2100 both vary by an order of magnitude between the cheapest and the most expensive scenarios. However, the cost-per-ton of deployed aerosol varies little among scenarios and the cost-per-degree-of-warming-avoided is similarly consistent. Relative to other climate interventions and solutions, SAI remains inexpensive, but at about \$18 billion yr^{-1} per degree Celsius of warming avoided (in 2020 USD), a solar geoengineering program with substantial climate impact would lie well beyond the financial reach of individuals, small states, or other non-state potential rogue actors and would instead be the exclusive domain of large national economies or coalitions including at least one such economy.

List of Abbreviations

A2	Aerosol 2
Al_2O_3	Aluminum oxide
$CaCO_3$	Calcium carbonate
CFM	Cubic feet per minute
FOB	Freight on board
G&A	General and administrative
Gt	Gigatons
H_2SO_4	Sulfuric acid
M	Meter
Mt	Megatons
MTOW	Maximum takeoff weight
NRE	Non-recurring engineering
OEW	Operating empty weight
RCP	Representative concentration pathway
RF	Radiative forcing
S	Sulfur
SAI	Stratospheric aerosol injection
SAIL	Stratospheric aerosol injection lofter
SiC	Silicon carbide
SO_2	Sulfur dioxide
TCR	Transient climate response
Tg	Teragram
TiO_2	Titanium dioxide
USD	United States Dollars
USGS	United States Geologic Survey
W	Watt
ZrO_2	Zirconium oxide

1. Introduction

Solar geoengineering continues to be seen through the lens of its 'incredible economics' (Barrett 2008) and more specifically, its 'free driver' effect (Wagner and Weitzman 2012, Weitzman 2013). Smith and Wagner (2018) investigated the cost of the first 15 yr (2035 to 2049) of solar geoengineering in a single scenario analysis. In this paper, the timeframe is extended through the remainder of the 21st century and multiple scenarios are added to more fully explore the mature costs of solar geoengineering. The focus remains on the deployment of aerosols into the lower stratosphere at an altitude of 20 km and at latitudes of 30°N/15°N/15°S/30°S in seasonally adjusted amounts (Smith and Wagner 2018). Reliance is also made upon the conclusion that, for the reasonably foreseeable future, the lofting solution that best minimizes both technology risk and cost is a newly-designed fleet of high-altitude tanker aircraft (Smith and Wagner 2018). These parameters are used to estimate direct deployment costs from initial deployment in 2035 through 2100.

Detailed fleet plans, activity metrics, and cost inputs are used to build up annual capital and operating costs for each year through the end of the century. These take account of costs for aircraft, flight and ground crews, maintenance, insurance, fuel, and aerosol payload. Upon reaching the end of its economic useful life, the initial fleet of aircraft is assumed to be supplanted by two additional, successive fleets of improved aircraft as the century progresses. Different aerosol candidates, aerosol efficacies, and temperature sensitivities are evaluated to probe their impact on costs. Variances in each of these factors affect the cost outcomes, but in most cases, only marginally. What proves most meaningful in altering costs is the amount of aerosol deployment required, which in turn is driven by the scenario chosen. If one assumes that the world continues on a high emissions pathway and yet chooses to mitigate temperatures aggressively, annual stratospheric aerosol injection (SAI) costs by the end of the century are an order of magnitude higher than if the world diverts to a low emissions pathway and chooses modest climate intervention. Depending upon the scenario analyzed, aggregate costs for SAI through the remainder of the century can range from roughly $250 billion to nearly $2.5 trillion, with an annual budget in the year 2100 of $7 to $72 billion (all in 2020 USD). What remains remarkably constant however is the annual cost to suppress 1 °C of warming, which remains within 10% of $18 billion irrespective of the scenario chosen.

In this paper, solar geoengineering is not presented as a substitute for mitigation (Keith 2013, Keith and Irvine 2016, Keith and Dowlatabadi 1992). Indeed, SAI will not obviate the need to reach and sustain global net zero emissions in order to halt anthropogenic global warming and its effects (IPCC 2018). Instead, SAI is considered as an intervention that may buy the world time (Morton 2016) to devise and implement more comprehensive solutions.

2. Warming scenarios and deployment targets

Two important changes to the approach of Smith and Wagner (2018) are made in this paper. First, the costing timeframe is extended from 15 yr to 66 yr. Second, three scenarios for global emissions and three scenarios for radiative forcing targets are considered as opposed to a single scenario.

Focusing as it did on just the first 15 yr of deployment, Smith and Wagner relied upon just a single 'middle of the road' warming scenario and a conservative climate intervention objective—Representative Concentration Pathway (RCP) 6.0, with a target of cutting in half the subsequent warming from the commencement of deployment onward. However, modeling a 66 yr deployment that extends all the way to 2100 requires consideration of a much wider range of scenarios and targets, since their divergence over so long a span is quite wide. Among the four RCPs commonly considered by the IPCC, RCP 2.6 is excluded, as this relatively benign emission pathway would not reasonably call for SAI. However, RCPs 4.5, 6.0, and 8.5 are all evaluated. In addition, three radiative forcing targets are considered: a relatively conservative program that would halve the rate of warming from 2035 onward; a more assertive program that would halt temperatures at their 2035 levels; and an aggressive program that would seek to reverse temperatures to their 2020 levels by 2050 and then halt any subsequent increase. The temperature reversal target year of 2020 was selected based on prior modeling precedents (Niemeier and Timmreck 2015, Tilmes *et al* 2018b). Each target is considered in respect of each RCP, yielding a three-by-three matrix of SAI scenarios, with halving RCP 4.5 the least costly and reversing RCP 8.5 as the most. Figure 1 shows the radiative forcing assumed in each scenario.

Each of the three modeled RCPs starts in 2034 and ends in 2100 with the level of radiative forcing presented in Meinshausen *et al* (2011) particular to that RCP. However, to facilitate the implementation of an orderly industrial program that meets the long-term goals without unnecessary and inefficient year-to-year variability, the interim Meinshausen *et al* trajectories have been smoothed to entail a steady linear build up.

Table 1 summarizes key assumptions made in each of the nine scenarios. It is proposed that the initial material used is sulfur, deployed as SO_2, but that for reasons explored in section 4 below, the program diverts to an as-yet-to-be-determined second aerosol ('Aerosol 2') commencing in Year 16. Noting that the differing spatial distribution of shortwave and longwave forcing in the atmosphere as well as the nuance of instantaneous versus adjusted radiative forcing would require a climate model to properly resolve, an approximate net forcing factor is calculated here simply by netting longwave and shortwave forcing values. For sulfate efficacy, a final number is derived by netting the positive forcing due

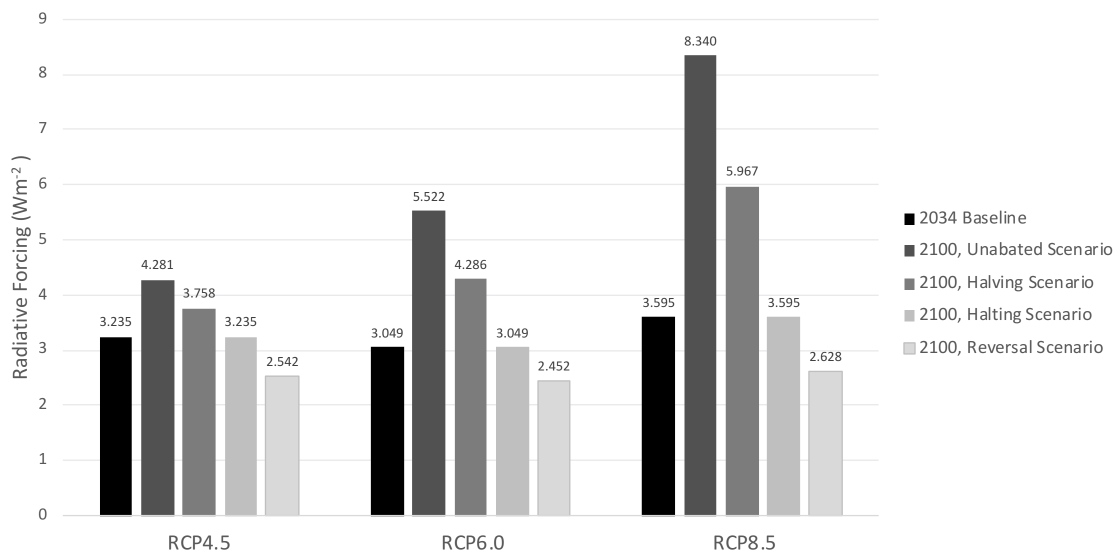

Figure 1. Comparison of radiative forcing in modeled scenarios—For each of RCPs 4.5, 6.0, and 8.5, a 2034 baseline radiative forcing is compared to four possible outcomes in 2100. Those include an unabated scenario as well as abated scenarios wherein warming subsequent to the 2034 baseline is either halved, halted, or reversed to 2020 levels.

to outgoing longwave radiation against the negative forcing due to the scattering of incoming shortwave radiation as found in Dykema *et al* (2016). This sulfate efficacy value differs from that used in Smith and Wagner (2018) (which considered only incoming radiation) and falls towards the center of the values present across recent literature (Ferraro *et al* 2012, Pope *et al* 2012, Kuebbeler *et al* 2012, Pitari *et al* 2014, Kleinschmitt *et al* 2017, Dai *et al* 2018). As sulfates sit at the low end of the net efficacy spectrum relative to other materials considered, Aerosol 2 is assumed to have a 30% net radiative efficacy advantage relative to sulfate. Temperature sensitivity is a transient climate response number in the midpoint of the range defined by the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2013).

To account for the fact that ‘any solid aerosol introduced into the stratosphere would be subject to coagulation with itself…and with natural sulfate aerosol’ (Weisenstein *et al* 2015), a decline in radiative efficacy as deployed mass increases is assumed. Working from calculations found in Niemeier and Timmreck (2015), sulfate efficacy is assumed to decline by 1% for each additional Tg added beyond the first one. This same decline curve is assumed to apply to Aerosol 2. Alternatives to many of these assumptions are explored in section 5 below.

3. Lofting platforms

Creating a fleet plan for a not-yet-extant air freight operation extending 80 yr into the future of course requires substantial speculation on matters that cannot be easily predicted. Given that, this plan is presented in order to establish a reasonable order of magnitude for costs rather than to imply specious precision. It was established in consultation with many of the world’s leading commercial aviation enterprises (Smith and Wagner 2018), and in reliance upon the author’s personal experience both as a senior executive at The Boeing Company and as the Chief Operating Officer of Atlas Air Worldwide Holdings, a global air freight operator.

If SAI proceeds at all, the first-generation aircraft will be succeeded by improved designs. Engine technology, drag reduction, and lighter weight materials will likely advance in the coming decades as they have in the prior ones, with successive generations of aircraft leapfrogging their predecessors every couple of decades, delivering economic performance that improves at a rate of roughly 1% per year or 15%–20% per aircraft generation (a design objective common in the industry). The scenario assumes that aircraft will continue to be the preferred aerosol lofting method from now until the end of the century, while noting that better, cheaper, and perhaps radically different lofting technologies may become available hereafter which would prompt a reformulated scenario.

The primary challenge in the aircraft development program contemplated herein is building a plane capable of lofting large payloads to a high altitude. Twenty kilometers is near the upper limit of altitudes achievable by traditional fixed wing aircraft and the few jets that reach this height carry very modest payloads. At the latitudes contemplated herein,

Table 1. Injection regime.

Common Assumptions		
Commencement Date	Jan 1 2035	
Sulfate sensitivity	−0.62	Wm^{-2} per Tg-S yr^{-1}
Aerosol 2 sensitivity	−0.89	Wm^{-2} per Tg yr^{-1}
RF efficacy decline	1%	for each additional Tg-S yr^{-1}
Temperature sensitivity	0.7	°C per Wm^{-2}
SO_2/S mass ratio	2	
Aerosol 2/S mass ratio	3	

deployment at 20 km is considered to be effective for SAI (Pierce *et al* 2010) but for aircraft design, this altitude assumption is critical. If 15 km were to prove sufficient for effective deployment, existing or modified jets would suit. On the other hand, if in furtherance of the logic illustrated in Tilmes *et al* (2018a) and Krishnamohan *et al* (2019), a deployment altitude of 25 km were ultimately required, fixed-wing, self-propelled, air-breathing aircraft would likely no longer serve and one would be compelled to consider alternative lofting systems such as guns, rockets, or balloons with lofting costs an order of magnitude higher (Smith and Wagner 2018).

Building on previous work considering platform alternatives (Mcclellan *et al* 2012), Smith and Wagner presented specifications for a first-generation stratospheric aerosol injection lofter (SAIL) aircraft with four engines, an operating empty weight (OEW) of 50 metric tons, and a maximum payload of 25 tons (Smith and Wagner 2018). The refined lofter design presented here is referred to as SAIL-1. This is a smaller aircraft with six engines, an OEW of 38.2 tons, and a payload of 15.7 tons (Bingaman *et al* 2020). While SAIL-1 will require roughly 60% more cycles to loft the same mass as SAIL, it climbs and descends much more rapidly and cruises for a mere 10 min, cutting cycle time in half. Therefore, both fleet size and overall costs are reasonably consistent with those previously presented for the same scenario but vary substantially herein based upon the scenario chosen.

SAIL-1 will likely be developed in an uncertain political environment where the public acceptance of SAI cannot be assured. Confronting a material likelihood that the plane will never fly or may have its mandate revoked early and abruptly, the financial plan for SAIL-1 minimizes developmental cost at the expense of higher operating cost. The certification path will assure merely that the aircraft is safe and airworthy, but little money will be spent to optimize weight, fuel performance, or maintenance cost as would be done with a commercial airliner. This approach will shorten both the production run of the SAIL-1 aircraft program and the useful economic life of each aircraft (20 yr).

If, however, SAIL-1 proves the desirability and efficacy of SAI, then its successor SAIL-2 will merit a much larger developmental budget ($10 billion versus less than $2.5 billion). The new budget assumes that the SAIL-2 will have newly developed engines and a much more efficient airframe design. SAIL-2 is planned to enter into service in year 16 of the SAI program (2050), after which no additional SAIL-1s will be delivered, though each Generation 1 aircraft will continue flying to the end of its 20 yr economic useful life. SAIL-2 is 35% larger in OEW (51.6 tons) and payload (21.2 tons), and will have four substantially more powerful engines, enabling it to burn 20% less fuel. Cycle time however will grow to 2 h due to a change in aerosol payload (see below). SAIL-2 will be the backbone of the deployment fleet through 2070, when SAIL-3 will enter into service, capping the production of SAIL-2 aircraft and commencing their phase out after a 30 yr useful economic life.

SAIL-3 has a developmental budget equal to that of SAIL-2. It entails no OEW increase, but augments payload by a further 20% (25.4 tons) and improves fuel burn. Cycle time grows commensurate with the increased payload. By 2100, the SAI fleet will consist entirely of SAIL-3 s, with the last of the SAIL-2 s having reached the end of their economic useful lives a year earlier. Table 2 summarizes key aircraft assumptions for all three generation of SAI lofters.

Beyond aircraft design and specifications, there are several important lofting system operational and cost assumptions made in this paper. With modest changes, these assumptions mirror the scenario devised in Smith and Wagner (2018). The Smith and Wagner (2018) scenario entails a 7 yr ramp-up commencing in 2028 to design and certify the first-generation deployment aircraft, with the last two years of that interval also used to establish and organize the 'airline' necessary to fly them. An initial fleet of fewer than 10 aircraft would commence deployment in Year 1 (2035), ramping up by Year 15 (2049) to a fleet ranging from two dozen to several hundred, depending on the scenario chosen. The aircraft would operate initially from one quartet and ultimately from several quartets of bases arrayed at latitudes of 30°N/15°N/15°S/30°S (Macmartin *et al*

Table 2. Key aircraft assumptions.

Weights in metric tons	SAIL-1	SAIL-2	SAIL-3
Maximum Takeoff Weight	59.2	81.1	83.7
Operating Empty Weight	38.2	51.6	51.6
Fuel capacity (in deployment mode)	5.4	8.3	6.7
Payload capacity	15.7	21.2	25.4
Engines per aircraft	6	4	4
Cycle time (block hours)	0.7	1.5	1.8
Cycles per day	6.0	5.0	4.0
Daily utilization (on operational days)	4.2	7.5	7.2
Operational days per year	330	330	330
Flight hour/block hour ratio	75%	90%	90%
Useful economic life (years)	20	30	30

2017, Richter *et al* 2017, Tilmes *et al* 2017, Dai *et al* 2018) so as to allow latitudinal and seasonal variations in deployment mass. Smith and Wagner concluded that pre-start costs of less than $4 billion would be sufficient to launch such an operation; that costs per lofted ton of sulfate aerosols would be in the range of $1500; and that annual operating costs in the first 15 yr would average $2.3 billion (all figures in 2018 USD).

As the deployment fleet grows, so too will the number of bases from which it operates. The expansion of the deployment bases represents one of several assumptions made to increase resiliency and limit the probability that operational factors would lead to an unplanned program discontinuation and therefore 'termination shock' (Jones *et al* 2013). While as a matter of distributional efficiency the entire planet could be geoengineered from just one quarter of bases, prudence would call for additional and redundant quartets as soon as the fleet count warrants. To further bolster resiliency, each aircraft is expected to be out of service for 35 d per year for planned maintenance, leading to a total fleet that is larger than the available fleet on any given day. Aircraft utilization is capped at roughly 10 block hours per day, though this could be exceeded in unusual circumstances such as following a service interruption due to strikes, fires, floods, earthquakes, or local political disturbances. Each base would be provisioned with a substantial inventory of spare parts, which would grow with each aircraft added to the fleet. Aircraft can of course be redeployed to other bases in the event that their home base were to become inoperative. Each base is also assumed to have one 'hot spare' available at all times to provide substitutes for unplanned maintenance or accidents. Flight crews are planned with similarly robust and flexible numbers. In combination, these measures would provide for high operational reliability and limit the prospect of unplanned, long-term program discontinuations. However, they of course would not (and should not) prevent a shut-down mandated as a deliberate decision by the deploying entity (or demanded by others), and therefore do not address all the circumstances that could lead to a sudden termination.

Table 3 summarizes the total fleet size and annual deployment activity for selected program years and selected scenarios.

This deployment plan assumes that SAI is undertaken by a single, rational, and legitimate global monopolist deployer operating on a not-for-profit basis and backed by substantial guarantees from one or more economically powerful governments. While alternative scenarios are certainly possible and arguably equally likely, they would suffer diminished economies of scale and therefore be more expensive. Introducing a profit motive or competing deployers using the same aircraft design to achieve the same radiative forcing targets would increase costs marginally. Assuming competing aircraft programs (i.e. Boeing vs. Airbus) among coordinated actors would likely increase costs more substantially. Assuming uncoordinated SAI programs by multiple actors with competing and potentially conflicting climate goals would likely increase costs substantially as well. This paper does not delve into the likelihood or desirability of the assumed 'benign global monopolist' beyond noting that from a cost standpoint at minimum, it represents the best-case scenario.

4. Aerosol candidates

Given their long and continuing history of natural deployment via volcanoes, sulfates appear to be the best understood and least risky aerosol with which to commence deployment (Crutzen 2006; National Research Council 2015). It is therefore assumed that sulfates are the aerosol used in the first deployment phase. However, due to their negative environmental impacts, it seems prudent to assume that as the second generation of deployment aircraft enters into service in year 16, a second aerosol supplants sulfates. While deployed sulfates may create modest airborne public health impacts (Effiong and Neitzel 2016),

Table 3. Fleet size & deployment activity.

RCP 4.5 Target: Halving

Program Year	Calendar Year	Fleet Count: SAIL-1	SAIL-2	SAIL-3	Total	Annual Sorties	Deployed mass (Tg): Tg SO_2 Deployed	Tg A2 Deployed	Total Deployed
1	2035	3	0	0	3	2296	0.0	0.0	0.0
6	2040	13	0	0	13	13 778	0.2	0.0	0.2
16	2050	25	3	0	28	36 226	0.5	0.0	0.6
26	2060	12	28	0	40	49 956	0.3	0.7	1.0
36	2070	0	50	3	53	63 844	0.0	1.4	1.4
46	2080	0	47	23	70	77 870	0.0	1.7	1.7
56	2090	0	22	60	82	86 974	0.0	2.1	2.1
66	2100	0	0	86	86	97 992	0.0	2.5	2.5

RCP 6.0 Target: Halting

Program Year	Calendar Year	Fleet Count: SAIL-1	SAIL-2	SAIL-3	Total	Annual Sorties	Deployed mass (Tg): Tg SO_2 Deployed	Tg A2 Deployed	Total Deployed
1	2035	7	0	0	7	10 854	0.2	0.0	0.2
6	2040	39	0	0	39	65 124	1.0	0.0	1.0
16	2050	90	7	0	97	171 231	2.5	0.2	2.7
26	2060	51	98	0	149	242 065	1.5	3.2	4.6
36	2070	0	194	7	201	307 811	0.0	6.6	6.6
46	2080	0	187	77	264	380 696	0.0	8.5	8.5
56	2090	0	96	230	326	432 959	0.0	10.4	10.4
66	2100	0	0	380	380	486 350	0.0	12.4	12.4

RCP 8.5 Target: Reversing

Program Year	Calendar Year	Fleet Count: SAIL-1	SAIL-2	SAIL-3	Total	Annual Sorties	Deployed mass (Tg): Tg SO_2 Deployed	Tg A2 Deployed	Total Deployed
1	2035	22	0	0	22	39 503	0.6	0.0	0.6
6	2040	127	0	0	127	239 386	3.7	0.0	3.7
16	2050	319	12	0	331	633 048	9.6	0.4	10.0
26	2060	192	239	0	431	752 871	5.8	8.1	13.9
36	2070	0	520	13	533	852 174	0.0	18.1	18.1
46	2080	0	508	153	661	1008 983	0.0	22.2	22.2
56	2090	0	281	507	788	1103 830	0.0	26.2	26.2
66	2100	0	0	920	920	1198 328	0.0	30.5	30.5

the negative environmental impacts of stratospheric heating (Heckendorn *et al* 2009) and ozone destruction (Crutzen 2006, National Research Council 2015) are of substantially greater concern. Increased concentrations of sulfates in the stratosphere would absorb both incoming shortwave and outgoing longwave radiation, thereby heating the stratosphere and (depending upon the injection altitudes and latitudes ultimately chosen) potentially impacting the phases of the quasi-biennial oscillation (Aquila *et al* 2014), tropospheric winds (Garfinkel and Hartmann 2011), high latitude seasonal temperature cycles (Jiang *et al* 2019), and precipitation (Simpson *et al* 2019). They also would interfere with the recovery of the stratospheric ozone layer, and at large quantities, actually reverse it (Tilmes *et al* 2008). Consequently, before building to potentially problematic levels of deployed sulfates, it is assumed that the program introduces a second-phase aerosol (Aerosol 2) which supplants sulfates as the first generation aircraft are retired.

It is unnecessary for costing purposes and beyond the scope of this paper to speculate as to what substance may be chosen as Aerosol 2. The radiative efficacy by mass (and therefore the required deployed masses to achieve a given radiative forcing) of all the top aerosol contenders vary within a reasonably narrow band, as illustrated in table 4. So long as very costly materials such as diamond powder are avoided, the cost of the aerosols also remains a small fraction of overall costs and is therefore also not a major driver of aggregate costs. For cost purposes, Aerosol 2 is assumed to have a net radiative forcing efficacy 30%

better than sulfates, placing it in the middle of the range presented in table 4. Aerosol 2 is also assumed to have a cost per ton of $1000, once again placing it in a middle range between the cheap aerosols (sulfate and calcite) and the more costly group (including silicon carbide and titanium oxide). Section 5 below presents cost sensitivity information for the yet more expensive candidates (zirconium oxide and diamond powder) as well as the cheaper option of staying with sulfates. Nonetheless, it seems reasonable to assume that as a nascent SAI program unfolds, alternative aerosols with fewer environmental side effects will be explored and that one of those may be chosen as a successor aerosol.

An optimal particle size is also sourced from Dykema *et al* (2016). For costing purposes, a simplifying assumption is made that all deployed particles are of monodisperse distribution at these optimal sizes and are therefore ideal scattering agents, noting that this would in fact be difficult to achieve. These particle sizes pertain to annual deployed masses of between one and three teragrams. This is annually averaged and zonally averaged data for 15°S to 15°N with equinox solar illumination and fixed emissivity.

SAIL-1 derives a marginal cost benefit from the fact that the SO_2 payload it would loft and vent would, after several weeks in the stratosphere, evolve into H_2SO_4 (Kravitz *et al* 2009) with a mass roughly 50% larger than that of the SO_2 precursor. Neither Aerosol 2 nor any of the other candidates listed in table 4 benefit from a similar mass inflation after deployment, meaning SAIL-02/03 will no longer enjoy this 'three-for-the-price-of-two' cost benefit. The even greater 'three-for-one' cost benefit assumed in Smith and Wagner to derive from the on-board combustion process sourced from Smith *et al* (2018)[3] was not found to be practicable on the SAIL-1 design due to increased hardware weights and cruise time requirements and is not assumed herein.

All prospective second-phase aerosols included in table 4 are reflected at current costs, most of which are sourced from the US Geological Survey. In a few cases, the quantities called for by the SAI scenarios reflected here would constitute enormous increases in (if not multiples of) the current global demand. How these commodity costs might change in the context of emerging SAI demand is not considered here. Nonetheless, at current prices, certain of these commodities (sulfate, calcite, and aluminum oxide) are dirt cheap. Zirconium oxide on the other hand has a price roughly 10 times that of these cheaper alternatives, which would more than double the annual costs in the year 2100 irrespective of the scenario chosen. At the far end of the spectrum, diamond powder costs are 2400 times those of sulfur, which would balloon year 2100 program costs into the trillions and require far more industrial diamond than is currently produced in the world (U.S. Geological Survey 2019). While the relatively low cost of SAI will likely mean that aerosols will be chosen for refractive and environmental impacts rather than cost, there are clearly exceptions and economics may indeed preclude certain aerosols.

5. Cost factors

Key aircraft cost factors presented in table 5 are generally consistent with (and in many cases identical to) those presented in Smith and Wagner (2018), at least in the early years.

Aircraft costs are modeled as if the operating entity leases the aircraft from an external lessor, which does not materially change long term costs but smooths the cash flow requirements. The monthly lease rate is derived from the aircraft purchase price via a lease rate factor which is a convention common in the aircraft leasing community. As noted previously, developmental costs for SAIL-2 and 3 are roughly four times those of SAIL-1 in constant dollar terms. Nonetheless, given the larger production runs of the latter aircraft, the developmental costs on a per-plane basis roughly double for SAIL-2 but return to their original value for SAIL-3. The fact that the latter two versions have a 50% longer economic useful life than SAIL-1 also helps to ameliorate their higher developmental costs on an amortized annual basis. Fuel burn is expected to improve materially with each new generation of aircraft, while real fuel costs are modeled to remain constant. Nonetheless, presented below are alternative scenarios wherein fuel costs double or even quintuple as the century progresses, due either to fuel scarcity or carbon taxes.

SAIL-1 has a manned cockpit, as under the current regulatory regime, certifying a remotely piloted large aircraft would likely add substantially to the development cost. However, it is assumed that by the time SAIL-2 is developed, the combination of greater regulatory experience with unmanned aerial vehicles and a larger developmental budget will permit SAIL-2 and its successor to be remotely piloted. Nonetheless, the economic modeling still assumes a fully dedicated crew member on the ground for each aircraft as well as a payload operator monitoring several aircraft simultaneously. Consequently, crew costs per block hour for SAIL-2/-3 are half the SAIL-1 levels.

Table 6 summarizes SAI program costs in 2020 dollars for the nine relevant scenarios—halving, halting, and reversing global temperatures to 2020 levels under each of RCP 4.5, 6.0, and 8.5. Each of these nine scenarios is evaluated via four key cost metrics.

[3]No relation to the author of this paper

Table 4. Aerosol Efficacy Comparisons.

Material	Polymorph	Description	SW RF[a]	LW RF[b]	Net Forcing	Δ in Deployed Mass vs H_2SO_4	Delivered Cost per Mt	Optimum Radius (μm)
H_2SO_4	70% wt	Sulfate	−0.89	0.26	−0.63		$250	0.300
TiO_2	Rutile	Titanium Oxide	−0.95	0.26	−0.69	−8.7%	$2800	0.130
TiO_2	Anatase	Titanium Oxide	−0.88	0.12	−0.76	−17.1%	$2800	0.145
SiC		Silicon Carbide	−1.20	0.07	−1.13	−44.2%	$2000	0.150
Carbon	Diamond	Synthetic Diamond	−1.10	0.01	−1.09	−42.2%	$600 000	0.150
ZrO_2		Zirconium Oxide	−0.88	0.04	−0.84	−25.0%	$4200	0.170
Al_2O_3		Aluminum Oxide	−0.99	0.09	−0.90	−30.0%	$400	0.215
$CaCO_3$	Calcite	Calcium Carbonate	−0.88	0.06	−0.82	−23.2%	$350	0.275
Aerosol 2			–	–	−0.90	−30.0%	$1000	

[a]Shortwave radiative forcing (Wm^{-2}) at top of atmosphere. [b]Longwave radiative forcing (Wm^{-2}) at tropopause. SW and LW values are from Dykema *et al* (2016). Optimal radii are calculated assuming deployed masses of 1–3 Tg. Delivered costs are from personal communications with the USGS.

Table 5. Aircraft costs.

Dollar amounts in 2020 USD	SAIL-1	SAIL-2	SAIL-3
Marginal build cost per aircraft	$75 000 000	$112 500 000	$112 500 000
Airframe NRE[a] & certification	$2000 000 000	$6000 000 000	$6000 000 000
Engine NRE[a] & certification	$350 000 000	$4000 000 000	$4000 000 000
Production run[b]	90	194	380
NRE amortization per aircraft[b]	$26 111 111	$51 546 392	$26 315 789
Total cost per aircraft[b]	$101 111 111	$164 046 392	$138 815 789
Monthly lease rate factor	0.8%	0.8%	0.8%
Monthly lease rate[b]	$808 889	$1312 371	$1110 526
Developmental period (years)	7	7	7

[a]NRE is non-recurring engineering. [b]Values are for RCP 6.0 and Halting Target.

Table 6. Cost impact of scenario choices.

(All in 2020 USD)							
Aggregate Cost 2035–2100 (Trillion)				Annual Cost in 2100 (Billion)			
RCP	Halving	Halting	Reversing	RCP	Halving	Halting	Reversing
4.5	0.25	0.43	0.83	4.5	7.0	12.8	20.9
6.0	0.50	0.96	1.31	6.0	15.1	29.8	37.1
8.5	0.92	1.84	2.45	8.5	28.4	58.7	71.7
Cost Per Deployed Ton				Cost per −1 °C Impact in 2100 (Billion)			
RCP	Halving	Halting	Reversing	RCP	Halving	Halting	Reversing
4.5	2987	2592	2279	4.5	19.0	17.5	17.2
6.0	2530	2369	2264	6.0	17.4	17.2	17.2
8.5	2376	2294	2223	8.5	17.1	17.7	17.9

Table 7. Sensitivity table.

	Aggregate cost through 2100 (Trillions USD)	% Δ	Annual cost in 2100 (Billions USD)	% Δ	Average cost per deployed ton thru 2100 (USD)	% Δ	Cost per −1 °C achieved in 2100 (Billions USD)	% Δ
Base Case (RCP 6.0; Halting)	$1.0		$29.8		$2369		$17.2	
Sulfur/Aerosol 2 Efficacy of 150%	$0.7	−32%	$19.9	−33%	$2449	3%	$11.5	−33%
Sulfur/Aerosol 2 Efficacy of 50%	$1.9	100%	$61.2	105%	$2290	−3%	$35.3	105%
Temperature sensitivity of 150%	$0.7	−32%	$19.9	−33%	$2449	3%	$11.5	−33%
Temperature sensitivity of 50%	$1.9	100%	$61.2	105%	$2290	−3%	$35.3	105%
Aircraft Cost * 200%	$1.1	20%	$35.1	18%	$2832	20%	$20.3	18%
Fuel cost * 200%	$1.1	16%	$34.7	16%	$2744	16%	$20.0	16%
Fuel cost * 1000%	$1.6	63%	$49.2	65%	$3869	63%	$28.4	65%
All other ops cost * 150%	$1.1	14%	$33.6	13%	$2699	14%	$19.4	13%
All other ops cost * 50%	$0.8	−14%	$26.0	−13%	$2039	−14%	$15.0	−13%
Continue with sulfur	$0.7	−30%	$19.6	−34%	$1717	−27%	$11.3	−34%
Aerosol 2 cost = zirconium oxide	$2.2	133%	$74.2	149%	$5194	119%	$42.9	149%
Aerosol 2 cost = diamond powder	$175.4	18 242%	$6139.3	20 499%	$513 899	21 595%	$3547.1	20 499%

All other ops costs = total costs less aircraft, fuel, and payload costs, per block hour.

Table 8. Financial comparisons.

(billion 2020 USD)			
Name	2020 Net Worth[a]	Country	2019 Military Expenditures[b]
Jeff Bezos	$156	US	$732
Bill Gates	$111	China	$261
Bernard Arnault	$108	India	$71
Mark Zuckerberg	$87	Russia	$65
Warren Buffett	$77	Saudi Arabia	$62
Larry Ellison	$68	France	$50
Amancio Ortega	$67	Germany	$49
Steve Ballmer	$67	UK	$49
Larry Page	$65	Japan	$48
Sergey Brin	$63	South Korea	$44
		Brazil	$27
		Italy	$27
		Australia	$26
		Canada	$22
		Israel	$21
		Turkey	$20
		Spain	$17
		Iran	$13
		Netherlands	$12
		Poland	$12

[a]Forbes, as of June 10, 2020, 2020. [b]Stockholm International Peace Research Institute (SIPRI), 2020.

Aggregate costs reflect all pre-start, capital, and operational costs for an SAI program that commences deployment in 2035 and continues through 2100. It ranges from hundreds of billions to the low trillions, with the cheapest scenario (RCP 4.5, halving) costing roughly one-tenth that of the most expensive (RCP 8.5, reversing). A similar ~10X span is observed in the annual deployment cost in 2100, which ranges from $7 billion in the cheapest scenario to $72 billion in the dearest. On the other hand, weighted average costs-per-deployed-ton are rather consistent ranging between $2200 and $3000, with modest economies of scale emerging in the larger deployment programs. Also, quite consistent across scenarios is the annual cost-per-degree (Celsius) of warming avoided, which is within 10% of $18 billion in all cases.

Sensitivities in respect of certain key assumptions are displayed in table 7. Throughout the table, the scenario used for evaluation is the one in the middle of the three-by-three matrix, which is RCP 6.0 with a target of halting warming. The sensitivities for sulfur efficacy, Aerosol 2 efficacy, and temperature are evaluated by varying the baseline assumptions for those factors up and down by 50%. Each of these substantially changes the mass of aerosol to be deployed and therefore the overall costs, while affecting only marginally the unit costs (cost-per-ton). In all cases, 50% higher sensitivity would reduce program costs by a third, whereas 50% lower sensitivity would double them. The model is fairly insensitive to changes in the aviation-related costs factors. Given the long history of program cost overruns related to new aircraft, it would be easy to envision circumstances doubling aircraft acquisition costs, but this would only increase aggregate program costs by ~20%. A doubling of fuel costs would have even less impact—roughly 15%. Even a quintupling of fuel costs would only increase program costs by about 65%. An increase or decrease of 50% in all other aviation-related cost factors (maintenance, flight and ground crews, insurance, navigation charges, etc) would also toggle aggregate costs by less than 15%. Aerosol choices can have more substantial impacts. A decision to continue with sulfur rather than changing to Aerosol 2 would reduce aggregate costs by about a third. Nominating zirconium oxide as Aerosol 2 more than quadruples the cost of the successor aerosol and increases aggregate costs by 150%. Still, relative to the order-of-magnitude cost impacts that different scenario choices can have, all the sensitivities displayed in table 7 are small. The sole exception is the prospect of nominating diamond powder as Aerosol 2, which would explode program costs by well in excess of two orders of magnitude. However, the sensitivity analysis reinforces a central theme in SAI economics, which is that so long as ruinously profligate choices are avoided, SAI remains so cheap that costs are unlikely to be the driving factor in decision making.

To provide context for the scale of SAI costs, the ~$30 billion annual budget called for in the middling scenario (RCP 6.0, halting) in 2100 is roughly equal to the amount spent today on pet food in the United States (Euromonitor International 2017). Nonetheless, this is more than ten times the average annual budget during the first 15 yr presented in Smith and Wagner. Late century annual costs of perhaps $30 or even $72 billion are tiny relative to a world economy currently producing GDP in the range of $90 trillion but as shown in table 8 would quickly exhaust the fortunes of the world's wealthiest individuals and would more than consume all but the largest of national military budgets.

However, comparing late century SAI annual budgets to current-day personal fortunes and military budgets is perhaps misleading because of the assumption that an SAI program would be small at the outset and ramp into effectiveness over time. A more comprehensible cost metric for the purpose of understanding whether a unilateral or rogue actor could afford to implement an SAI program is the cost per degree of warming avoided. The unilateral actor paradigm that should be of serious concern to the world is not that a rogue implements a solar geoengineering program so small that its climate impact can hardly be distinguished from the data noise, but rather that an unauthorized actor might materially tamper with global average surface temperatures. Such an actor would not reasonably risk international condemnation and potential military attack to change temperatures by a few hundredths of a degree. Rather, such an actor should be assumed to intend a discernable change—on the order of a degree or more. Therefore, the fact that a degree of cooling would require an annual expenditure on the order of $18 billion means once again that funding such a program would quickly wipe out the individual fortunes and fully consume the annual military budgets of all but 15 countries. SAI on a scale that would substantially affect the world's climate is affordable only by the world's largest economies.

The costs explored here are direct deployment costs only and do not include costs for adjacent and simultaneous functions such as monitoring or governance that may reasonably be considered essential costs of an SAI endeavor. These non-deployment program costs could equal or exceed the deployment costs, at least in the early years of such an SAI program (Reynolds *et al* 2016). However, if such costs doubled or even tripled overall program budget, the aggregate costs would still sit in the same qualitative range—easily affordable for the world, but beyond the reach of most individual actors. Moreover, this analysis also excludes any indirect costs for damages that might accrue either from SAI or from climate change itself. Those could be orders of magnitude larger than the aggregate program budget.

6. Conclusion

Relative to mitigation, adaptation, or negative emissions technologies, climate intervention in the form of SAI remains extraordinarily inexpensive (Ackerman and Stanton 2007). Seductive though this characteristic may seem, this is an apples to oranges comparison, since SAI is a mere palliative intended to ameliorate some symptoms, while doing nothing to cure the underlying disease (Crutzen 2006; Keith 2013). SAI is not a substitute for mitigation. Net global emissions must still be brought to zero as rapidly as possible. Nonetheless, if global demand for climactic morphine becomes acute, SAI may play a critical role in the triage toolkit.

The pre-start costs for SAI also remain low—on the order of a few billion dollars. If this remains an aircraft-based program, the technology appears to be quite straightforward, with no major breakthroughs needed. However, cheap and simple should not be conflated with small. SAI deployment would entail a massive industrial undertaking, with scores—and soon hundreds—of planes deploying millions of tons of material into the stratosphere every day for decades from many bases around the globe. If any of the RCPs modeled here prove accurate, greenhouse gas concentrations will continue to grow substantially through at least the remainder of the century, potentially calling for an SAI program that would start small but grow quickly in both magnitude and cost. In addition to the unaddressed indirect costs previously noted, there may also be as yet unknown environmental costs resulting from deploying teragrams of aerosols continuously into a part of the atmosphere where they may be rare or utterly alien. Direct deployment expenditures, therefore, may prove to be only one of several costs associated with SAI.

Nonetheless, returning our focus to the narrow lens of deployment costs, SAI continues to appear remarkably inexpensive, even if we extend our gaze out to the end of this century. The economics remain 'incredible' even if tens of billions in annual late-century annual costs no longer seems quite 'free'. Instead, the annual costs of a mature SAI program exceed the financial capability of individuals, small states, or other potential non-state rogue actors and situate such a program squarely within the funding framework of large national economies.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

Appendix 1. Operations Cost Build Up (in 2020 USD)

Cost Item	SAIL-1	SAIL-2	SAIL-3	Units	SAIL-1 Calculation Basis	SAIL-2/3 Change
Capital costs						
Aircraft capitaI cost	808 889	1312 371	1110 526	per aircraft per month	Total aircraft cost of $100M for RCP 6.0 Halting; 0.8% monthly lease factor	Revised aircraft costs
Initial spares purchase	2000 000	2000 000	2000 000	per aircraft	Premium over typical narrowbody cost given unusual airframe; balance sheet item only	No change required
Spares carrying cost %	20%	20%	20%	% per year	Typical industry cost; both depreciation and replacement costs	No change required
Inventory carrying cost	400 000	400 000	400 000	peraircraftper year	Annual Income Statement impact for spares	No change required
Flight operations						
Crew	1400	700	700	per block hour	9 crews/aircraft; narrowbody pay scale; crew utiI of 275 block hours/month; Includes travel and remote accommodation; times 140% to account for payload operator	Cut by 50% assuming unmanned cockpits
Initial crew training	800 000	800 000	800 000	per aircraft	Typical industry cost; upfront cost per aircraft; recurring training cost in crew cost numbers	No change required
Navigation charges	400	400	400	per block hour	Typical industry cost	No change required
Maintenance						
Airframe(heavy)	42 986	58 031	58 031	per aircraft per month	3 yr, 8 yr, 10 yr and 12 yr checks	Grossed up for OEW* increases
Engines	4305	4305	4305	per aircraft cycle	Average of industry CFM or Rolls Royce large engine full restoration cost per cycle plus $280 per cycle for life limited parts; 6 engines; Full restoration costs $3.5 M	Down to 4 engines, but bigger engines; same total maintenance cost
Landing gears	4167	4167	4167	per aircraft per month	Typical narrowbody industry cost; 10 yr overhaul interval	No change required

(Continued)

Appendix 1. (Continued)

Cost Item	SAIL-1	SAIL-2	SAIL-3	Units	SAIL-1 Calculation Basis	SAIL-2/3 Change
Aux Power Unit	20	20	20	per block hour	Typical industry cost	No change required
Line maintenance	800	800	800	per block hour	Average industry cost for narrowbody plus a premium for unique parts; modeled hourly despite some cyclic drivers	No change required
Specialized Equipment	250	250	250	per block hour	Maintenance of specialized aerosol storage,combustion,and dispersal equipment	No change required
Ground Operations						
Landing fees	1065	1458	1504	per cycle	$0.009 per kg of MTOW **typical industry cost x 2 for specialized facilities	Ratable to revised MTOW**
Ground handing	2000	2000	2000	per cycle	Tow, pushback etc.; premium atop typical narrowbody costs to reflect low utilization airports	No change required
Cargo handing	0.05	0.05	0.05	per kg	Typical industry loading cost; applied to departures only (no offload on landing)	No change required
Insurance	41 042	65 476	56 498	per aircraft per month	0.5% of acquisition cost (typically 0.25%, added 0.25% for non-typical operation)	Ratable to revised aircraft values
Fuel usage	2775	2775	2775	gal per aircraft block hour	Average for 737 and 757, tripled given 6 engines	Fewer/bigger engines. Same burn
Fuel price	2.00	2.00	2.00	per gallon	Projected long-term cost per gallon	No change
Overhead	250 000	250 000	250 000	per aircraft per month	Dispatch, crew scheduling, flight planning, Flight Ops and Tech Ops administration, other G&A	No change required
Payload cost	0.25	1.00	1.00	per kg	Sulfur based on 2019 USGS# data: $120/Mt fob cost,plus estimate of $130 for trans. cost	Vendor data $220/Mt + $130 trans

*OEW: Operating empty weight
**MTOW: Maximum take off weight
#USGS: US Geological Survey

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