On Geoengineering and Implementing an Albedo Solution with Urban Heat Islands Global Warming and Cooling Estimates

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Abstract

Solar geoengineering is vital in Global Warming (GW) as results can reverse trends and reduce the probability of a tipping point. This paper focuses on geoengineering and implementation of a surface solar geoengineering solution to global warming. Although an albedo solution is reasonably practical, work in this area appears stagnant and even implementing Urban Heat Island (UHI) cool roofs on a global level has not yet been widely adopted. This paper provides basic modeling and motivation by illustrating the potential impact for reverse forcing. We provide insights into "Earthly components" that can be utilized to increase the opportunity for reducing climate change. Modeling shows that by solar geoengineering hotspots with large heat capacities, such as UHIs, and mountain region, the effective area could be roughly 11 times smaller than nominal non-hotspot regions in influencing global warming. We find that between 0.2 and 0.5% of the Earth would require modification to resolve most of global warming. This is highly dependent on the heat capacity and irradiance of the area selected. The versatile model was also used to provide UHIs global warming and cooling estimates.

1.0 Introduction

When we consider climate change solutions, in the race against time, it is advantageous to look at the practical aspects of implementing an albedo solution. Given the slow progress reported with greenhouse gas reduction, and the continual increase in the Earth's average yearly temperature, it is important to revisit alternative albedo solutions. Unlike geoengineering solutions, GHG mitigation is highly difficult to result in reversing climate change, especially with reports on large deforestation occurring [1].

Implementation is a key focus on geoengineering an albedo surface solution. There have been a number of geoengineering solutions proposed [2-4] that are either atmospheric of surface-based. In this study, we focus on targeting surface regions and present practical engineering formulas and values.

The target areas that have the highest impacts are likely ones with:

- high solar irradiance
- large heat capacities
- low albedo
- ability to amplify nature's albedo

To clarify the last target area, we infer that cooling down certain areas may cause natural compounding albedo changes to occur, such as increases in snowfall and ice formations. We can term these as Solar Amplified Areas (SAA) relative to Nominal Land Albedo (NLA) areas (25% albedo, see Sec. 7.2).

Although the task is highly challenging, it is easier to do geoengineering of surface reflectivity compared with building cities. Often, UHIs and impermeable surfaces are haphazardly constructed in terms of solar absorption considerations. While numerous authors [4-17] have found significant warming due to UHIs, the only motivated work in this area is a result of health concerns. Therefore, albedo cool roof solutions have not received adequate attention compared to GHG efforts. This is unfortunate and makes the business of solar solution and it's financing less desirable. It is important that not just scientists understand the importance of the albedo solution. There is a lack of knowledge when it comes to the word albedo and its potential contribution. We cannot expect architects, road engineers, car designers, city planners, politicians and so forth, to do their job correctly in the green area, if these concepts are not widely understood. Therefore, a key strategy employed in this study is to demonstrate the advantages, feasibility and importance in cooling solar amplified areas made by man (and possibly nature). We provide simple geoengineering equations that can aid the designer. We need to recognize that the whole is equal to the sum of the parts in GW; mankind's resolve to greenhouse gases and albedo reductions, both need to be addressed for a realistic solution.

2. Outline of the Geoengineering the Albedo Solution

We present a brief outline to overview and clarify our modeling objectives and motivate interests.

Section 3: In this section, we identify a practical re-radiation model to help obtain accurate important values in geoengineering a global warming albedo solution. In the absence of feedback, our GW model has the form:

$$P_{Pre-Industrial} = P_\alpha + f_1 P_\alpha = \sigma T_S^4 \quad (1)$$

Here $P_{Pre\text{-}Insustrial}$ is the total warming power (in W/m^2), T_s is the Earth's average surface temperature, P_α=1361W/m²/4 x (1-α) is the short wavelength absorption and $f=\beta^4=0.618$ is a GHG re-radiation parameter, a redefined variable taken from the effective emissivity constant of the planetary system. The model is then extended so that it can be applied with climate feedback and verified using the Planck feedback parameter.

Section 4: Using the Model in Section 3, we apply it to temperature data in 1950 and 2019 to assess ΔP_{Total}, the total forcing that has occurred. This is required in order to estimate the amount of reverse forcing corrective action needed.

Section 5: In this section we first identify a key Planck-albedo parameter

$$\gamma_{\%\Delta\alpha\Delta T} \approx 1W/m^2/\Delta\%albedo/°K \quad (2)$$

The parameter converts a percent albedo %Δα change to ΔP_T, the reverse forcing from the target area where the total reverse forcing ΔP_{Rev_S} is

$$\Delta P_{Rev\_S} = -\gamma_{\%\Delta\alpha\Delta T}\ \%\Delta\alpha\ (1+f_2)\ A_F = \Delta P_T (1+f_2)\ A_F \quad (3)$$

Here f_2 is the 2019 re-radiation parameter, about 0.63 and A_F is an estimate of the anticipated GW feedback reduction.

Section 6: In this section an Albedo model is developed to use the ΔP_T goal where

$$\Delta P_T = \frac{A_T}{A_E}\frac{S_N}{4} 0.33 \mathrm{H}_{T-N}\left[(\alpha_T' - \alpha_T)\right] \quad (4)$$

The factor, H_{T-N} is the hotspot irradiance sensible heat storage potential, a function of the heat capacity, mass, temperature storage, and solar irradiance by comparison to a nominal area. Here α_T is the initial target albedo, α_T' is the modified target albedo, and 0.33 is the estimate fraction of time the target area is not covered by clouds. Then the final goal relative to fraction of Earth's area, A_E, needing modification is

- A_T / A_E, where A_T is the target area

Section 7: In this section, it all comes together by applying these models for different target areas including UHIs yielding their warming and cooling estimates.

Therefore, our task is to essentially find reasonable values for ΔP_{Total}, f_2, ΔP_{Rev_S}, H_{T-N}, $\gamma_{\%\Delta\alpha\Delta T}$, A_F ΔP_T, %Δα, in order to estimate a geoengineering GW solution by modifying the select fractional target area A_T/A_E of the Earth.

3.0 The Re-radiation Global Warming Model

In geoengineering, we are working with absorption and re-radiation, we define

$$P_{Total} = \sigma T_S^4 = \sigma\left(\frac{T_e}{\beta}\right)^4 \text{ and } P_\alpha = \sigma T_\alpha^4 = \sigma\left(\beta T_S\right)^4 \quad (5)$$

The definitions of $T_\alpha=T_e$, T_S and β are the emission temperature, surface temperature and β=0.887, respectively. Consider a time when there is ***no feedback issues*** causing warming trends. Then by conservation of energy, the equivalent power re-radiated from GHGs in this model is dependent on P_α with

$$P_{GHG} = P_{Total} - P_\alpha = \sigma T_S^4 - \sigma T_\alpha^4 \quad (6)$$

To be consistent with $T_\alpha=T_e$, since typically $T_\alpha \approx 255°K$ and $T_s \approx 288°K$, then in keeping with a common definition of the global beta (the proportionality between surface temperature and emission temperature) for the moment $\beta=T_\alpha/T_s=T_e/T_S$.

This allows us to write the dependence

$$P_{GHG}=\sigma T_S^4-\sigma T_\alpha^4=\frac{\sigma T_\alpha^4}{\beta^4}-\sigma T_\alpha^4=\sigma T_\alpha^4\left(\frac{1}{\beta^4}-1\right)=\sigma T_\alpha^4\left(\frac{1}{f}-1\right) \quad (7)$$

Note that when $\beta^4=1$, there are no GHG contributions. We note that f, the re-radiation parameter equals β^4 in the absence of feedback.

We can also define the blackbody re-radiated by GHGs given similarly by some fraction f_1 such that

$$P_{GHG}=f_1 P_\alpha=f_1\,\sigma T_\alpha^4 \quad (8)$$

It is important in geoengineering to view the re-radiation as part of the albedo effect. This is a key difference in how we view the total effect from short wavelength absorption by the inclusion of the re-radiation effect. Consider $f=f_1$, in this case according to Equations 7 and 8, it requires

$$P_{GHG}=\sigma T_\alpha^4\left(\frac{1}{f}-1\right)=f_1\,\sigma T_\alpha^4=f\,\sigma T_\alpha^4 \quad (9)$$

This dependence leads us to the solution of the quadratic expression

$$f^2+f-1=0 \text{ yielding } f=0.618034=\beta^4,\ \beta=\left(0.618034\right)^{1/4}=0.88664 \quad (10)$$

This is very close to the common value estimated for β and this has been obtained through energy balance in the planetary system providing a self-determining assessment. In Appendix A , we double check this model in another way by balancing energy in and out of our global system. Then in Section 4.2, we apply the model to demonstrate its capability and consistency with the Planck parameter. We note that the assumption $f=f_1$ only works if planetary energy is in balance (also see energy balance details in Appendix A) without feedbacks.

4.0 **Re-radiation Model Applied to Two Different Time Periods**

Global warming can be exemplified by looking at two different time periods. The model applied for 1950 needs to be consistent with Eq. 6 and 8. Here we will

- assume no feedback issues causing a warming trend in 1950 so that from our model

$$P_{Total\_1950}=P_\alpha+P_{GHG}=P_\alpha+f_1P_\alpha=P_\alpha\left(1+f_1\right)=1.618\,P_\alpha \quad (11)$$

where $P_\alpha=S_o\left\{0.25x(1-Albedo)\right\}$ and S_o=1361W/m^2. Although 1950 is not truly pre-industrial (see Eq. 1), we proceed under the assumption of no changes in GHG and feedback issues at this time to establish our baseline, since geoengineering a solution to earlier dates would pose even higher challenges. Under this assumption, 1+f=1.618 becomes the 1950 albedo-GHG reference value. Since its value is related to the re-radiation parameter, it is subjected to changes due to variations in our aging climate system. As a reference value, it is constrained by the energy balance in Eq. 9 and as discussed in Section 4.2.

In 2019 due to global warming trends, this model is more complex and harder to separate out terms. However, we are still able to obtain reasonable accuracy since we are fitting the model to the Earth's average temperature data with the goal in mind of finding reasonable accurate estimate of total forcing $\Delta P_{Total}=P_{Total\ 1950}-P_{Total2019}$. Therefore, we proceed similarly and results and verification will also justify its use, then

$$P_{Total\,2019}=P_{\alpha'}+P_{GHG'+Feedback}\approx P_{\alpha'}+f_2P_{\alpha'} \quad (12)$$

Here, $P_{GHG'+Feedback}$ includes the 1950 GHGs and 2019 increase with feedbacks such as water-vapor concentration, lapse rate effect and other changes including increase in snow-ice albedo variations that are hard to separate out. That is, feedbacks are related to GHG increases and albedo change. $P_{\alpha'}$ represents the 2019 point in time with its albedo due to changes in UHI absorption, cloud absorption, ice and snow melting, and so forth that can be discerned. The model does not demand rigid accountability in its application (see Sec.4.2) but reasonable estimates are helpful. We note that unlike f_1, f_2 is not a strict measure of the emissivity.

In 1950 f_1 defines the GHG re-radiation function (with no feedbacks) and is consistent with the estimates for beta. In 2019, it is more complex and according to Eq. 12, must include feedbacks. The value f_2 while close to the beta value in Eq. 10, is no longer identical as f_1 (see Equation 13). The value f_2 can also be assessed relative to f_1 as described in the next section. However, in general, between the two time periods, we will find $P_{GHG} \approx P_{GHG'+Feedback}$ (see results in Section 4.2).

4.1 Warming Imbalance in 2019

The re-radiation parameters f_1 and f_2, are connected and from Eq. 10, 11 and 12 we have

$$f_2 = f_1 + (\frac{P_{2019}}{P_{\alpha'}} - \frac{P_{1950}}{P_\alpha}) = f_1 + (\frac{P_{GHG'+F}}{P_{\alpha'}} - \frac{P_{GHG}}{P_\alpha}) = f_1 + \Delta f = \beta_1^4 + \Delta f \approx \beta_2^4 + \Delta f \tag{13}$$

In this way f_2 is a function of f_1=0.618 and the differences in the global warming residuals that is identified in Eq. 12 as Δf. The RHS of Eq. 12 (indicating that $\beta_1 \approx \beta_2$) will become apparent in application (Eq. 16 and 17) and verification.

4.2 Results Applied to 1950 and 2019

Since the re-radiation parameter is fixed for f_1=0.618, to obtain the average T_{1950}=13.89°C (287.038°K), the only adjustable parameter left in our model is the global albedo. This requires an albedo value of 0.3008 (see Table 1) to obtain the correct value T_{1950}. This albedo number is reasonable and similar to values cited in the literature [18].

In 2019, the average temperature of the Earth is T_{2019}=14.84°C (287.99°K). Here we are not sure of the albedo value since it likely changed due to UHI increase, snow and ice melting and cloud coverage changes. The IPCC value in AR5 [19] is 0.294118 (100/340). However, this would represent a 3% change since 1950 which may be an overestimation. In this assessment, we will assume a low middle value of 1.2% change. Another reason for this choice is in a resulting analysis in Appendix A.2. Then, the f_2 parameter is adjusted to 0.6311 to obtain T_{2019}. Table 1 summarizes model results for the specified albedos and observed Earth's surface temperatures. The results yield $P_{Total\ 1950}$=384.935 W/m^2 and $P_{Total\ 2019}$=390.055 W/m^2.

Table 1 Model results

Year	T(°K)	T_α(°K)	f_1, f_2	α, α'	P_α, $P_{\alpha'}$ (W/m^2)	$P_{GHG'+feedback}$ P_{GHG} (W/m^2)	P_{Total} (W/m^2)
2019	287.991	254.83	0.63114	29.719	239.131	150.925	390.056
1950	287.041	254.51	0.6180	30.08	237.903	147.032	384.935
Δ2019-1950	**0.95**	0.328	**1.311%**	0.361 **(1.2%)**	**1.228**	3.893	**5.12**

From Table 1 we now have identified the reverse forcing at the surface needed since

$$\Delta P_{Total} = P_{2019} - P_{1950} = 5.121 W/m^2 \tag{14}$$

and

$$\Delta T_{Total} = T_{2019} - T_{1950} = 0.95°C \tag{15}$$

as modeled.

4.3 Showing Model Consistency with the Planck Parameter

To show model consistency, the forcing change, 5.121 W/m^2, resulting in a 0.95°K rise, should agree with what is expected when using the Planck feedback parameter.

In order to show model consistency, we will need some exact values for beta using the temperatures in Table 1, these are from the two different time periods (see Eq. A-3)

$$\beta_{1950} = \frac{T_\alpha}{T_S} = \frac{T_e}{T_S} = \frac{254.51}{287.04} = 0.88667 \ and \ \beta_{1950}^4 = 0.61809 \tag{16}$$

as this value is consistent with Eq. 10, and

$$\beta_{2019} = \frac{T_\alpha}{T_S} = \frac{T_e}{T_S} = \frac{254.83}{287.99} = 0.88485 \ and \ \beta^4_{2019} = 0.61304 \tag{17}$$

Although these two are very close, we use both values due to the need for high accuracy; model self-consistency is required.

From the definition of the Planck parameter and results in Table 1, we can estimated [20]

$$\lambda_o = -4\frac{\Delta R_{LWR}}{T_S} = -4\left(\frac{237.9W/m^2}{287.04°K}\right)_{1950} = -3.315W/m^2/°K \tag{18}$$

and

$$\lambda_o = -4\frac{\Delta R_{LWR}}{T_S} = -4\left(\frac{239.13W/m^2}{287.99°K}\right)_{2019} = -3.321W/m^2/°K \tag{19}$$

We note these are very close in value showing miner error and consistency with Planck parameter value, often taken as 3.3W/m^2/^{o}K. While there are only small differences between each beta and these two Planck parameters, final warming predictions using a Planck parameter method, requires values found from the model. This self-consistency helps in providing accuracy for estimating ΔT by reducing compounding error within the model. We then use the generalized form for the long wavelength estimate in Equation A-2 (and similar to Eq. 18 and 19), yielding the approximate warming change in terms of the total power and the Planck parameter method as [20]

$$\Delta T = T_{1950} - T_{2019} = -4\left\{\left(\frac{\beta^4 P_{Total}}{\lambda_o}\right)_{1950} - \left(\frac{\beta^4 P_{Total}}{\lambda_o}\right)_{2019}\right\} \tag{20}$$

Using Table 1, the temperature warming results is

$$\Delta T = -4\left(\frac{0.6181x384.935W/m^2/°K}{3.315W/m^2/°K} - \frac{0.61304x390.056W/m^2/°K}{3.3215W/m^2/°K}\right) = 0.92°K \tag{21}$$

This equation illustrates consistency of the re-radiation model with the Planck parameter showing reasonable accuracy helping to verify the model from a different perspective. The model allows for a number of helpful comparisons that are described in Appendix A.2.

5.0 Geoengineering Reverse Forcing Solution

The albedo changes and ΔP_α in Table 1, are: $\%\Delta\alpha = 1.2\%$ and 1.228W/m^2, respectively. We note that we can define a unique Planck-albedo parameter $\gamma_{\%\Delta\alpha} = \Delta P_\alpha / \%\Delta albedo$. To illustrate from Table 1

$$\gamma_{\%\Delta\alpha} = 1.023 \text{ W/m}^2/\Delta\%\text{albedo} \tag{22}$$

This parameter can also be expressed per degree (noting the 0.95^{o}K change in Table 1)

$$\gamma_{\%\Delta\alpha\Delta T} \approx 1W/m^2/\Delta\%albedo/°K \tag{23}$$

The helpful parameter [5] is featured here as a modeling tool. We term it the Planck-albedo parameter, since it relates to blackbody (P_α) absorption. A simple numeric example is given in Sec. 5.1 to illustrate how it provides helpful estimates along with the albedo-GHG factor. This interesting parameter simplifies and is not really dependent on two different time periods estimates of the global alpha changes since

$$\gamma_{\%\Delta\alpha} = \frac{(\Delta E_o)_\alpha}{\frac{\alpha_1 - \alpha_2}{\alpha_1}100} = \frac{E_o(\alpha_1 - \alpha_2)}{\frac{\alpha_1 - \alpha_2}{\alpha_1}100} = E_o\alpha_1/100 \approx 1W/m^2/\%\Delta albedo \tag{24}$$

where E_o=340 W/m^2 and when α_1 is 0.294118, the value 1.000W/m^2/Δ%albedo is obtained. We note the value 29.4118% (100/340) is given in AR5 [19].

The albedo-GHG and the Planck-Albedo parameter may now be combined in order to provide a simple solar geoengineering solution estimate for reverse forcing

$$\Delta P_{\mathrm{Rev}\_S} = -\gamma_{\%\Delta\alpha\Delta T}\ \ \%\Delta\alpha\ (1+f_2)\ A_F = \Delta P_T\,(1+f_2)\ A_F \tag{25}$$

These variables have been defined in the outline (Section 2.0). This equation provides a fairly simple and practical way to estimate ΔP_{Rev_S}. In solar geoengineering, anticipating an allowance for the climate system to equilibrate [21] is not considered here. Furthermore, one might expect that a positive compared to negative albedo change may not have a strong hysteresis effect (as long as a tipping point has not occurred). Note that the 1+f factor accounts for one process of initial absorption change ΔP_T followed by subsequent partial re-radiation from GHGs. This value helps to clarify our goal.

The effective results

$$Effect = \frac{\Delta P_{\mathrm{Rev}\_S}}{\Delta P_{Total}} \tag{26}$$

and $\Delta P_{\mathrm{Rev}\_OLWR} = \beta^4 \Delta P_{\mathrm{Rev}\_S}$ the temperature reduction can be estimated from [20]

$$\Delta T_{\mathrm{Rev}} = -\frac{\beta^4 \Delta P_{\mathrm{Rev}\_S}}{\lambda_o} \tag{27}$$

In theory, ΔT_{Rev} is only an estimate since this equation is valid when no feedback issues result. The reason it is a reasonable value is that $\beta^4 \Delta P_{Rev\_S}$ is a good estimate OLWR (also see Eq. A-2).

5.1 Example of a Reverse Forcing Goal

In this section, we consider a goal of 1.5% geoengineering albedo change. Using Equation 25, with a decrease in water-vapor feedback anticipated, we might use a value of $A \approx 2$ [21], then

$$\Delta P_{\mathrm{Rev}\_S} = -1\mathrm{W/m^2/\%}\ \mathrm{x}\ 1.5\%\ \mathrm{x}\ (1+\mathrm{f}_2)\ \mathrm{x}\ 2 = -1.5\mathrm{W/m^2}\,x\,(1+\mathrm{f}_2)\ \mathrm{x}\ 2 = -4.9\ \mathrm{Watt/m^2} \tag{28}$$

This estimate can be compared with the re-radiation model results in Table 1 showing a forcing of 5.21 W/m^2 to obtain the relative effect of 94% from Eq. 26 for this particular geoengineering solution. From Equation 28 an estimate of the temperature cooling can be obtained with Eq. 27 [20] where $\beta^4 \Delta P_{Rev\_S} = \Delta P_{Rev\_OLWR} = -3.0 W/m^2$ is

$$\Delta T_{\mathrm{Rev}} = \frac{3.0\,W/m^2}{\lambda_o} = -0.91°K \tag{29}$$

This would indicate a significant resolution to the current warming trend. As one might suspect, a 1.5% albedo change requires a lot of modified area. Feasibility is discussed in the rest of this paper. We note a number of solar geoengineering solutions have been proposed [2-4].

6.0 Converting the Reverse Forcing Goal to Target Area

We can write the short wavelength solar absorption as

$$P = \frac{Q}{A} = \frac{S_N}{4}\sum_i \frac{A_i'}{A}(1-\alpha_i) + \frac{S_N}{4}\mathrm{H}_{T-N}\frac{A_T'}{A}(1-\alpha_T) + \frac{S_N}{4}\frac{A_C}{A}(1-\alpha_C) \tag{30}$$

Here A_i is the i^{th} effective area having an albedo α_i, $S_N = 1361 W/m^2$ and A is the surface area of the Earth and A_C is effective cloud coverage. We consider a change to a hotspot target effective area A_T with albedo α_T. In addition, because we select a particularly problematic solar absorbing target compared to a nominal area (N), it has hotspot irradiance sensible heat storage potential $H_{T\text{-}N}$, a function of the heat capacity, mass, temperature storage, and solar irradiance. Essentially this has the effect of amplifying the target area. $H_{T\text{-}N}$ is described and enumerated in Appendix B.

We note that the Earth Albedo change will only be a function of the target area variation, so from Eq. 30

$$\left(dP_T\right)_\alpha = \frac{S_N}{4}\mathrm{H}_{T-N}\frac{A_T'}{A}(-d\alpha_T) \tag{31}$$

where the subscript α indicates all other Earth albedo components are held constant.

The overall equation prior to changing the albedo is subject to the constraints

$$P = 240W/m^2 \ and \ A = \sum_i A_i' + A_T' + A_C = A_E' + A_C \ but \ A_E' = (1-\%A_C)xA_E = 0.33A_E \tag{32}$$

This indicates that because of the cloud coverage term A_C, about 67% of the actual Earth's area A'_E [23] is covered from direct sunlight. This is likely conservative as clouds do let some sunlight through. However, that means that roughly 33% of the time areas receive sun during daylight hours.

We now alter the target albedo α_T to $\alpha_T'$of a SAA so that

$$P' = \frac{Q'}{A} = \frac{S_N}{4}\sum_i \frac{0.33A_i}{A}(1-\alpha_i) + \frac{S_N}{4}\frac{0.33A_T}{A}\mathrm{H}_{T-N}(1-\alpha_T') + \frac{S_N}{4}\frac{A_C}{A}(1-\alpha_C) \tag{33}$$

Note the 0.33 factor is now added due to the percent of time the albedo change is effective. Using the example goal of the target area ΔP_T=1.5W/m^2 in Eq. 28, the change in heat absorbed is a function of the target area as indicated by Eq. 31, where

$$\Delta P_T = P - P' = \frac{S_N}{4}\frac{0.33A_T\mathrm{H}_{T-N}}{A}\left[(\alpha_T' - \alpha_T)\right] = 1.5W/m^2 \tag{34}$$

However, the same results can be obtained by changing the albedo of a nominal area; so in this case H_{T-N}=1 (see Appendix B). The equivalent change for the NLA is

$$\Delta P_{T-N} = \frac{S_N}{4}\frac{0.33A_N}{A}\left\{(\alpha_N' - \alpha_N)\right\} = 1.5W/m^2 \tag{35}$$

7.0 Geoengineering Application

Comparing the target to the nominal areas, we have

$$\frac{\Delta P_T}{\Delta P_{T-N}} \approx \frac{A_T\mathrm{H}_{T-N}\left[(\alpha_T' - \alpha_T)\right]}{A_N\left[(\alpha_N' - \alpha_N)\right]} = 1 \tag{36}$$

As an example, assume $\mathrm{H}_{T-N} \approx 9$ (see Appendix B), α_N=0.25 (see Sec. 7.2), α_T=0.12 [24], and for α_N'=α_T'=0.9, we obtain

$$\frac{A_N}{A_T} = \frac{\mathrm{H}_{T-N}\left[(\alpha_T' - \alpha_T)\right]}{\left[(\alpha_N' - \alpha_N)\right]} = \frac{9\left[(0.9-.12)\right]}{\left[(0.9-0.25)\right]} = 10.8 \tag{37}$$

This indicates that the nominal area would have to be about 11 times larger than the target area for equivalent results.

In assessing our goal, we have from Eq. 28

$$\Delta P_T = \frac{S_N}{4}\frac{0.33A_T\mathrm{H}_{T-N}}{A_E}\left[(\alpha_T' - \alpha_T)\right] = 1.5W/m^2 \tag{38}$$

For H_{T-N}=1, α_T'=0.9, and α_T=0.12 then

$$\Delta P_T = 340\frac{A_T}{A}\left[0.78\right]x0.33 = 1.5W/m^2 \tag{39}$$

and

$$\frac{A_T}{A} = 0.01714 = 1.714\% \, of \ Earth \tag{40}$$

For H_{T-N}=10, α_T'=0.9, and α_T=0.12 then

$$\frac{A_T}{A} = 0.1714\%\, of\ Earth \tag{41}$$

Recall that the goal for a 1.5W/m^2 corresponded to a 1.5% albedo change (see Sec. 5.1). We can check results of A_T/A=1.714% when H_{T-N}=1, yields a 1.5% albedo change using a related expression to Eq. 38. This is given by

$$\Delta\alpha\% = 0.33\frac{A_T}{A}\frac{[(\alpha_T' - \alpha_T)]}{\alpha} = 0.33(1.714\%)\frac{[(0.9-0.12)]}{0.294118} = 1.5\% \tag{42}$$

where the global albedo is taken as α=0.294118 which is indicated in AR5's energy budget figure [19].

7.1 Cooling Estimates Compared to Urban Heat Island Area

Since UHI are likely good target areas, we can compare these results to the total global urbanized area. Such estimates of urbanization unfortunately vary widely partly due to the confusing definition of what is urban. However, two studies are of interest. A Schneider study [25] on 2000 data estimated that 0.148% of the Earth was covered by UHI and the associated surrounding urban areas. Due to city growth, this extrapolates to 0.188% [5] in 2019. Similarly, a study from GRUMP [26] showing global urbanization value in 2000 of 0.783% extrapolates to 0.953% [5] of the Earth's area in 2019. These extrapolations are based on an average yearly urbanization growth rate between 1.3% to 1.6% [5]. Lastly, note that UHIs have their own hotspot amplification factors [5] that vary between 3.1 and 8.4 (see Appendix C) which are listed in Table 2 and can be applied for H_{T-N}. Therefore, compared to these 2019 estimates for urban heat island and surrounding areas, the required area changes for different H_{T-N} values (discussed in Appendix C) are summarized in Table 2.

Table 2 Cooling required areas relative to UHI areas

H_{T-N}	A_T/A (% of Earth) $\alpha_T' = 0.9$	Schneider Factor (A_T/A) /0.188% (Conservative) $\alpha_T' = 0.9$ $(\alpha_T' = 0.5)$		GRUMP Factor (A_T/A)/ 0.953 $\alpha_T' = 0.9$ $(\alpha_T' = 0.5)$	
1	1.714	9.1	(18.7)	1.8	(3.7)
3.1	0.55	2.93	(6)	0.58	(1.2)
8.4	0.2	1.06	(2.2)	0.21	(0.43)
9	0.19	1	(2.1)	0.2	(0.41)

*A_T/A represent 94% of the solution (see Sec. 5.1)

Note that an IPCC (Satterthwaite et. al. [27]) AR5 report references the Schneider et al. [25] results in urban coverage of 0.148% of the Earth.

Table 2 results are highly dependent on target albedo change and H_{T-N} which is overviewed in Appendix B. It is important to develop better estimates for both H_{T-N} and urbanization sizes than estimated here. We note that the 0.12 albedo value applies to UHI [24], which might be a good upper value when looking for hotspot targets. The albedo and two H_{T-N} values cited here have been studied in Feinberg [5]. The assessments for H_{T_N} applicable to UHIs are also provided to aid the reader in Appendix C. Results in Table 2 illustrate feasibility and the probable geoengineering challenges. A worldwide effort would provide motivation from a number of key benefits; resolving much of global warming, providing assurance against a tipping point, and local health benefits by cooling off cities. UHIs pose a number of challenges in trying to cool off their areas. The Schneider results in row 2, indicate that the potential area needed may be 3-6 times their current size. Therefore, if this was proven to be the most accurate estimate, supplementary target areas would be required to reach the 94% objective. Furthermore it is unrealistic to realize an overall UHI albedo goal of 0.9 due to their complex nature so we have also provided goals at 0.5 as well in the table.

Generally, UHIs meet a lot of the requirements for good targets having high heat capacity with large hotspot areas and massive sensible heat storage. One helpful aspect to note is that cool roof implementation also allows for more stable albedo maintenance over time compared to other areas like mountain regions. However, the complex nature of cities also makes it highly challenging.

7.2 Warming Estimates Due to Urban Heat Island Area

We can use this same model to estimate the global warming contributions due to UHIs. In this case, instead of $\alpha_T'=0.9$, we evaluate by restoring the UHIs to their original estimated albedo value of $\alpha_T'=0.25$ (pre-UHI estimate). This albedo value is based on a study by He et. al. [28] which found the land albedo varied from 0.1 to .4 having an average of 0.25. Then using the $H_{T\text{-}N}$ values in Section 7.1, we estimate the percent of the Earth needed to obtain a 94% solution and compare results to the known UHI coverage areas.

For $H_{T\text{-}N}=3.1$, $\alpha_T'=0.25$, and $\alpha_T=0.12$ then

$$\Delta P_T = \frac{1361W/m^2}{4}\frac{0.33A_T 3.1}{A_E}\left[(.25-.12)\right] = 1.5W/m^2 \tag{43}$$

and

$$\frac{A_T}{A} = 3.3\% \tag{44}$$

of the Earth. Similarly for $H_{T\text{-}N}=8.4$, $\alpha_T'=0.25$, and $\alpha_T=0.12$ then

$$\frac{A_T}{A} = 1.2\ \% \, of\ Earth \tag{45}$$

Table 3 summarized the warming trend results

Table 3 UHI Warming estimates

$H_{T\text{-}N}$	A_T/A (% of Earth)	Schneider Factor (A_T/A) /0.188% (Conservative)	GRUMP Factor (A_T/A)/ 0.953	GW% 1/Schneider Factor / 0.94*	GW% 1/GRUMP Factor / 0.94*
3.1	3.3	17.6	3.5	6.1	31
8.4	1.2	6.4	1.26	16.9	85.4

*A_T/A GW represent 94% of the solution (see Sec. 5.1), and are adjusted to 100% in Column 5 & 6

Results in Column 5 and 6 are reasonably comparable to Feinberg 2020 [5]. The model shows that between 6.1% and 85% of global warming could be due to UHIs and their coverage. We note these large variations are due to the difficulty in estimating $H_{T\text{-}N}$ and knowledge of UHI area coverages, as shown in the differences found between Schneider and the GRUMP studies. However, the model provides a reasonable way to make estimates which can be further refined once better values are known.

Furthermore, we note the cooling potential in Table 2 is about a factor of 3 to 6 times compared to the warming shown in Table 3. For example in Table 2 and 3, the area full warming to cooling ratio 17.6/2.93 yields an effective potential factor of 6 for $\alpha'_T=0.9$, and a factor of 2.9 (17.6/6) for $\alpha'_T=0.5$. As stated above, obtaining the full cooling potential ($\alpha'_T=0.9$) for UHIs and their impermeable surfaces is likely unobtainable due to the complex nature of cities therefore the value $\alpha'_T=0.5$ is a better guide.

7.3 Some Hotspot Target Areas

There are many hotspots that provide likely target areas. Deserts would be highly difficult to maintain any albedo change. However, mountains, UHI cool roofs in cities, and impermeable surface such as roads might be logical target areas. Some interesting known hotspots include

- Flaming Mountains, China
- Bangkok, Thailand (planet's hottest city)

- Death Valley California
- Titat Zvi, Israel
- Badlands of Australia
- Urban Heat Islands & all Impermeable surfaces
- Oceans [2]

We note that mountain areas in cool regions should not be excluded; natural compounding albedo effects may occur from increases in snow-fall and ice formations. Albedo changes could be performed in summer months and then in winter months compounding effects assessed.

As a summary, Equations 25 and 35 can be combined to provide a resulting solar geoengineering equation for reverse forcing obtained in this study where

$$\Delta P_{\mathrm{Rev}\_S} = -\gamma_{\%\Delta\alpha\Delta T}\ \%\Delta\alpha\ (1+f)\ A_R = \left\{ \frac{S_N}{4} 0.33\mathrm{H}_{T-N} \frac{A_T}{A} \left[(\alpha_T' - \alpha_T) \right] \right\} (1+f)\ A_R \tag{46}$$

with suggested values $H_{T-N}=6$, $\alpha_T'=0.9$, $\alpha_T=.12$, $\Delta P_{Rev\_S}=4.8W/m^2$, and f=0.63.

8. Conclusions

The albedo solution is vital in mitigating global warming. Today, technology has numerous advances that include improvements in materials, drone capability, artificial intelligence, which could be helpful in geoengineering surfaces. Mankind has addressed many technological challenges successfully. It is not illogical to consider a global albedo solution while time permits prior to a potential tipping point.

In this paper we have provided a number of important estimates that include:

- A target albedo goal of $-4.8W/m^2$ ($\Delta P_{Rev\_LWR}=-2.97W/m^2$)
- The target area required to resolve 94% of global warming is about 0.2% to 0.5% (Table 2) of the Earth, if proper hotspots are cooled with highly reflective surfaces. This is likely on the order of UHIs coverage today
- The cooling potential of UHIs is about a factor of 3 time higher than their warming contribution if highly reflective surfaces can be realized
- Likely target areas may include problematic hotspots such as UHIs, mountains regions and possibly ocean areas [2]
- Selecting proper hotspots can reduce the required target area by an estimated factor of 11
- Changing the albedo has 1.6 benefit factor due to GHG re-radiation
- UHIs likely contribute significantly to global warming
- Solutions are highly dependent on H_{T-N}.

Finally we suggest:

- Tasking agencies worldwide, such as NASA, to work full time on solar geoengineering, which at this late time should be our highest priority,
- Worldwide albedo guidelines for both UHIs and impermeable surfaces similar to on-going CO_2 efforts
- Worldwide guidelines for future albedo design considerations of cities,
- Changing impermeable surfaces of roads, sidewalks, driveways, parking lots, industrial areas such as airports, distribution centers, and roof tops to reflective surfaces. We note that their cooling potential can be much larger compared to their warming contribution, and a full review should be performed. Furthermore, such surfaces create hydro-hotspots [29] which may contribute to higher values of H_{T-N}. A hydro-hotspot is a hot surface that creates moisture in the presence of precipitations. Such surfaces create excess moisture in the atmosphere promoting a local greenhouse effect.
- Manufacturing cars to be more reflective including reducing their internal solar heating. Although, worldwide solar cool vehicles (e.g., silver or white) will likely not contribute significantly to global warming mitigation, recommending them could. It will help raise badly needed albedo awareness similar to electric automobiles that help improve CO_2 emissions. It could increase interest in similar projects thereby

promoting other related changes by city planners and architects for cool roofs, reflective building designs, and road engineers for pavement color changes and so forth.

Appendix A: Re-radiation Model's Energy Balance

Although f_1 has been uniquely defined in Eq. 10, this should also result from balancing the energy in and out of the global system.

A.1 Balancing P_{out} and P_{in} in 1950

To balance the energy in 1950, we start with Eq. 11. In equilibrium the radiation that leaves must balance P_α, from the energy absorbed, so that

$$\begin{aligned} Energy_{Out} &= (1-f_1)P_\alpha + (1-f_1)P_{Total} = (1-f_1)P_\alpha + (1-f_1)\{P_\alpha + f_1 P_\alpha\} \\ &= 2P_\alpha - f_1 P_\alpha - f_1^2 P_\alpha = Energy_{In} = P_\alpha \end{aligned} \quad \text{(A-1)}$$

This is consistent, so that in 1950 Eq. A-1 requires the same quadratic solution as Eq. 10. It is also apparent that

$$P_\alpha = f_1 P_{Total\_1950} = \beta_1^4 P_{Total\_1950} \quad \text{(A-2)}$$

since

$$P_\alpha = f_1(P_\alpha + f_1 P_\alpha) \;\; or \;\; 1 = f_1(1+f_1) \quad \text{(A-3)}$$

The RHS of Eq. A-3 is Eq. 10. This illustrates f_1 from another perspective as the fractional amount of total radiation in equilibrium. As a final check, the application in Section 4.2, Table 1, illustrate that f_1 provides reasonable results.

A.2 Comparisons Using the Albedo-GHG Factor

We can look at an important ratio, the power created by the albedo effect compared to GHGs in 1950. The initial radiation is P_α, and then according to Eq. 11 and Table 1, the energy is increased by P_{GHG} due to re-radiation fP_α that yields the ratio

$$\left\{\frac{P_\alpha + P_{GHG}}{P_{GHG}} = \frac{P_\alpha + f_1 P_\alpha}{f_1 P_\alpha} = \frac{1+f_1}{f_1} = \frac{1.62}{0.62} = 2.62\right\}_{1950} \quad \text{also note that} \quad \left\{\frac{1+f_2}{f_2} = 2.58\right\}_{2019} \quad \text{(A-4)}$$

We note the ratio is reduced in 2019 due to the addition ΔP_{GHG} and feedbacks. If f could eventually approach a catastrophic value of unity, this ratio reduces to a minimum of 2.

In this engineering view, a change in albedo forcing compared with a change in GHGs can be described. The variation in the energy due to an average albedo change and its re-radiation is

$$\Delta P_{\bar{\alpha}} = \Delta P_{\alpha'} + f_2 \Delta P_{\alpha'} = 1.631\, \Delta P_{\alpha'} \quad \text{(A-5)}$$

The average change in GHGs can be written in terms of *Δf*

$$\Delta P_{\overline{GHG'}} = \Delta f\, P_{GHG'} = 1.311\%\left(f_2\, P_{\alpha'}\right) = 0.827\% P_{\alpha'} \quad \text{(A-6)}$$

This resulting ratio from Table 1 is

$$\frac{\Delta P_{\bar{\alpha}}}{\Delta P_{\overline{GHG'}}} = \frac{\Delta P_{\alpha'}}{\Delta f}\frac{(1+f_2)}{P_{\alpha'}\, f_2} = \frac{1.228 W/m^2}{0.0131}\frac{1.631}{239.1 W/m^2\; 0.631} = 1.01 \quad \text{(A-7)}$$

Note that this ratio is of course dependent on the 2019 albedo 1.2% change, selected here to obtain unity for illustrative purposes. The ratio, $\Delta P_{\alpha'}/\Delta f$, is an interesting aspect of climate change. In 2019, if we have knowledge of values, we can compare the dominant aspect of the warming trend. It also provides us with a measure of solar reversibility

$$\Delta P_{\alpha'} \geq \Delta f \, \frac{P_{\alpha'} f_2}{(1+f_2)} 1.02 \approx 1.21 W/m^2 \tag{A-8}$$

This ratio is dependent on the change in the albedo compared with a GHG change. It may be helpful in assessing negative CO2 emissions vs an albedo reduction. Although, it is perhaps not the best way to assess geoengineering estimates. True values of Δα and Δf are not easily obtained in 2019. However, it avoids CO_2 doubling estimates, which are also difficult to evaluate. Furthermore, in some instances, a local change in ΔP_α can create excess increase in GHGs. This has been a concern with cool roofs in the winter which might require additional anthropogenic energy. This might be a good way to estimate by Eq. A-8, whether such a change is beneficial by comparison.

It is important to simplify further to provide a more productive approach. In reverse solar geoengineering a global warming solution, it is helpful to have simple reliable values. In this view, the 1.6 albedo-GHG factor (which is reasonably accurate) is an important engineering number. Another important engineering value is described by a Planck-albedo parameter found in Section 5.

Appendix B: Estimating the Potential for Hotspot irradiance Sensible Heat Storage $H_{T\text{-}N}$

A candidate hotspot irradiance sensible heat storage potential $H_{T\text{-}N}$ was described in Section 6. Here we provide a preliminary suggested model to clarify and enumerate this factor. It is likely that more rigorous models can be developed. Such solutions are outside the scope of this paper.

We consider a ratio for a target (T) area relative to a nominal (N) area defined in Sec. 6. Consider a target area with sensible heat storage q due to a mass *m*, having specific heat capacity *Cp* experiencing a day-night *ΔT* change in time τ, then the suggested potential for sensible hotspot heat storage $H_{T\text{-}N}$ has the form

$$H_{T-N} = \frac{q_T}{q_N} x \frac{I_T}{I_N} = \frac{m_T C_{PT} \Delta T_T}{m_N C_{PN} \Delta T_N} x \frac{I_T}{I_N} \approx \frac{\tau_T C_{PT} \Delta T_T}{\tau_N C_{PN} \Delta T_N} x \frac{I_T}{I_N} \tag{B-1}$$

Here we provide the option of using temperature change in time τ in place of mass. For example, the time to 63% change in ΔT might be useful (similar to a time constant). We also consider that the irradiance (I) term is needed since not all solar absorption energy is stored.

As a numeric example, first consider a 90% irradiance target area (compared to the equator) with nominal mid-latitudes (45°) roughly 70%, compared to say the Arctic and Antarctic Circles at 40% [29]. Then the irradiance ratio is

$$\frac{I\%_T}{I\%_N} = \frac{90\%_T}{70\%_N} = 1.3 \tag{B-2}$$

For the sensible heat numeric portion, consider a rocky area as the target (such as Flaming Mountains). This can be compared with a nominal vegetative land area. As a rule of thumb, most rocks have a density of 2.65 g/cm^3, about 50% difference compared to a nominal soil area of 1.33 g/cm^3 [32]. The heat capacity of rocks compared with vegetated land is 2000 to 830J/Kg/°K [32]. Then ΔT is estimated from tables for a day-night cycle [33]. The estimate is

$$\frac{q_T}{q_N} = \frac{m_T C_{PT} \Delta T_T}{m_N C_{PN} \Delta T_N} = \frac{\rho_T C_{PT} \Delta T_T}{\rho_N C_{PN} \Delta T_N} = \left(\frac{2.65}{1.33}\right)_\rho \left(\frac{2000}{830}\right)_{C_p} \left(\frac{(10°C)}{(6.9°C)}\right) = 2x2.4x1.45 = 6.96 \tag{B-3}$$

Then including irradiance

$$H_{T-N} \approx 9 \tag{B-4}$$

Appendix C: UHI Amplification Factors

An analysis of UHI amplification effects which can be applied to $H_{T\text{-}N}$ was originally provided in Feinberg [5] and this work is added here to aid the reader.

C.1: UHI Area Amplification Factor

To estimate the UHI amplification effects, it is logical to first look at UHI footprint (FP) studies as they provide some measurement information. Zhang et al. [34] found the ecological FP of urban land cover extends beyond the perimeter of urban areas, and the FP of urban climates on vegetation phenology was 2.4 times the size of the actual urban land cover. A more recent study by Zhou et al. [35], looked at day-night cycles using temperature difference measurements in China. This study found UHI effect decayed exponentially toward rural areas for the majority of the 32 Chinese cities. Their comprehensive study spanned from 2003 to 2012. Zhou et al. describes China as an ideal area to study as it has experienced the most rapid urbanization in the world during the decade evaluated. Findings state that the FP of UHI effect, including urban areas, was 2.3 and 3.9 times that of urban size for the day and nights, respectively. We note that the average day-night amplification footprint coverage factor is 3.1.

The UHI Amplification Factor (AF) is highly complex, making it difficult to assess from first principles as it would be some function of

$$AF_{UHI\ for\ 2019} = f\left(\overline{Build}_{Area}\ x\ \overline{Build}_{C_P}\ x\ \overline{R}_{wind}\ x\ \overline{LossE}_{vtr}\ x\ \overline{Hy}\ x\ \overline{S}_{canyon}\right) \quad \text{(C-1)}$$

were

$\overline{Build}_{Area}$ =Average building solar area
$\overline{Build}_{C_P}$ = Average building heat capacity
$\overline{R}_{wind}$ = Average city wind resistance
$\overline{LossE}_{vtr}$ = Average loss of evapotranspiration to natural cooling & loss of wetland
$\overline{Hy}$ = Average humidity effect due to hydro-hotspot
$\overline{S}_{canyon}$ = Average solar canyon effect

To provide some estimate of this factor, we note that Zhou et al. [35] found the FP physical area (km^2), correlated tightly and positively with actual urban size having a correlation coefficients higher than 79%. This correlation can be used to provide an initial estimate of this complex factor. Therefore, as a model assumption, it seems reasonable to use area ratios for this estimate.

$$AF_{UHI\ for\ 2019} = \frac{\sum\left(UHI\,Area\right)_{2019}}{\sum\left(UHI\,Area\right)_{1950}} \quad \text{(C-2)}$$

Area estimates have been obtained in the Feinberg [5] yielding the following results for the Schneider et al. [24] and the GRUMP [26] extrapolated area results:

$$AF_{UHI\ for\ 2019} = \frac{\left(Urban\ Size\right)_{2019}}{\left(Urban\ Size\right)_{1950}} \approx \begin{cases} \left(\dfrac{[0.188]_{2019}}{[0.059]_{1950}}\right)_{\text{Schneider}} = 3.19 \\ \left(\dfrac{[0.952]_{2019}}{[0.316]_{1950}}\right)_{GRUMP} = 3.0 \end{cases} \quad \text{(C-3)}$$

Between the two studies, the UHI area amplification factor average is 3.1. Coincidently, this factor is the same observed in the Zhou et al. [35] study for the average footprint. This factor may seem high. However, it is likely conservative as other effects would be difficult to assess: increases in global drought due to loss of wet-lands, deforestation effects due to urbanization, and drought related fires. It could also be important to factor in changes of other impermeable surfaces since 1950, such as highways, parking lots, event centers, and so forth.

The area amplification value of 3.1 is then considered as one of our model assumptions.

C.2: Alternate Method Using the UHI's Dome Extent

An alternate approach to check the estimate of Equation C-3, is to look at the UHI's dome extent. Fan et al. [36] using an energy balance model to obtain the maximum horizontal extent of a UHI heat dome in numerous urban areas found the nighttime extent of 1.5 to 3.5 times the diameter of the city's urban area (2.5 average) and the daytime value of 2.0 to 3.3 (2.65 average).

Applying this energy method (instead of the area ratio factor in Eq. C-3), yields a diameter in 2019 compared to that of 1950 with an increase of 1.8. This method implies a factor of 2.5 x 1.8=4.5 higher in the night and 2.65 x 1.8=4.8 in the day in 1950 with an average 4.65. This increase occurs 62.5% of the time according to Fan et al., where their steady state occurred about 4 hours after sunrise and 5 hours after sunset yielding an effective UHI amplification factor of 2.9. We note this amplification factor is in good agreement with Equation C-3. Fan et al. [36] assessed the heat flux over the urban area extent to its neighboring rural area where the air is transported from the urban heat dome flow. Therefore the heat dome extends in a similar manner as observed in the footprint studies. If we use the dome concept, we can make an assumption that the actual surface area for the heat flux is increased by the surface area of the dome. We actually do not know the true diameter of the dome, but it is larger than the assessment by Fan et al. Using the dome extend due to Fan et al. [35] applied to the area of diameter D, the amplification factor should be correlated to the ratios of the dome surface areas:

$$AF_{UHI\ for\ 2019} = \left(\frac{D_{2019}}{D_{1950}}\right)^2 = 2.9^2 = 8.4 \tag{C-4}$$

Thus, this equation is a second value for H_{T-N}, where it is reasonable to use the ratios of the dome's surface area for an alternate approach in estimating the effective UHI amplification factor [5]. We will have two values, 3.1 and 8.4 to work with that provides an upper and lower bounds for effective amplification area.

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