Supporting Information Appendix

Estimating option values of solar radiation management assuming that climate sensitivity is uncertain

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Supporting Text

Baseline Scenario. Table S1 summarizes the baseline scenario of the DNE21 model in the year 2100. Fig. S1 shows that our baseline scenario over the 21st century lies in the range between RCP6.0 and RCP8.5 both in terms of annual CO_2 emission pathways and temperature increase. The baseline CO_2 emissions, CO_2 concentration, radiative forcing, and temperature changes are derived based on a scenario for reference final energy demands (gaseous fuel, liquid fuel, solid fuel, and electricity). We exogenously assumed final energy demands over the 21st century on the basis of socio-economic scenarios regarding GDP and population as well as scenarios with regard to diffusion and selection of energy-saving technologies. The narrative of our baseline scenario in terms of GDP, population and energy-saving technologies is summarized as follows (ref. 1). The global economy (i.e., GDP per capita) continues to grow progressively until the end of the 21st century reflecting higher technological progress although its growth rate gradually declines. Population reaches its peak of around 8.6 billion in 2050 and declines to be around 7.4 billion in 2100. Attributed to high growth rates of GDP per capita, GDP continues to grow over the century, eventually exceeding US$ 300 trillion in 2100 (US$ as of 2000). With regard to energy-saving, our scenario is based on rather conservative assumptions reflecting various factors from myopic behaviors in choosing energy-saving technologies to general resistance to climate policies in a fragmented society where there are multiple objectives other than the stabilization of the climate and there are strong incentives for most countries to freeride in terms of emission reductions.

It is important to note that our assessment results (Fig. 1, 2, and 3) would change if we assume other socio-economic scenarios and their respective final energy demands. If we presume more moderate increase in the final energy demands, then the option values of SRM would decrease because the baseline temperature increase would be reduced.

Costs of SRM. As described in *Materials and Methods*, annual deployment costs for cooling the global mean temperature by 1°C ((a)US$/°C) are calculated on the basis of cost estimates per year ((b)US$/Mt-S)(Fig. 4 from ref. 3), the relationship between radiative forcing and the sulfur injection rate ((c)Mt-S/(Wm^{-2})) (The right panel of Fig. 4 from ref. 4), the relationship between temperature changes and radiative forcing in the DNE21 model ((d)(Wm^{-2})/°C) (Fig. S2). Fig. 4 of ref. 3 shows that our annual cost assumption (US$ 10 billion/Mt-S) corresponds to the high end of the uncertainty range of cost estimates for hybrid airship. Note that we set (d) to be 1.58, namely the slope of the linear approximate equation for the case of T2x = 4°C in which we assumed SRM be implemented (*Materials and Methods*).

Energy Systems Costs with and without SRM. The option value of SRM is derived based on the formula [1] in *Materials and Methods*. Figs. S3 and S4 represent how option values are calculated for the periods of 1990-2049 and 1990-2100. *Option value A* or *B* is derived from the difference between the total discounted sum of energy systems costs without SRM (green bar) and that with SRM (purple bar) (Fig. S3 for *option value A*, and Fig. S4 for *option value B*).

Rationale behind Increases in Option Values of SRM. As Table S2 shows, the dynamic model we used can precisely demonstrate CO_2 emission pathways for different temperature change targets. Fig. S5 compares the CO_2 emission pathways for 2100 temperature change targets of +2.4°C and +2.5°C relative to pre-industrial levels. The top panels are for the reference SRM costs (US$ 30 billion /°C), the middle ones for 50 times the SRM costs including side effects, and the bottom for 100 times SRM costs including side effects. The bottom right panel shows that for the +2.5°C target SRM would not be implemented and both emission pathways with and without SRM coincide.

The sharp increase in the option value of SRM from the +2.4°C to +2.5°C target would be due to the relative stringency of mitigation in the near- to mid-term, more specifically, in 2030-2040. The emission cut in 2030-2040 for +2.4°C target would be attributed to the emission increase in 2080-2100 for the high-climate-sensitivity case without SRM. This change in the timing of emission reductions from the +2.4°C to +2.5°C target is induced by cost minimization of energy systems costs over the 21st century, thereby stemming from assumptions of this study regarding energy demands and energy systems costs.

References

1. Akimoto K, et al. (2014) Assessment of the emission reduction target of halving CO_2 emissions by 2050: Macro-factors analysis and model analysis under newly developed socio-economic scenarios. *Energy Strategy Rev* 2(3-4):246–256.
2. IPCC (2014) *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer OR, et al.) (Cambridge University Press, Cambridge, UK).
3. McClellan J, Keith DW, Apt J (2012) Cost analysis of stratospheric albedo modification delivery systems. *Environ Res Lett* 7:034019.
4. Pierce JR, Weisenstein DK, Heckendorn P, Peter T, Keith DW (2010) Efficient formation of stratospheric aerosol for climate engineering by emission of condensible vapor from aircraft. *Geophys Res Lett* 37:L18805.

Supporting Tables

Table S1. Baseline scenario of the DNE21 model in the year 2100

Baseline scenario in 2100	Value	Unit
Annual fossil fuel and Industrial CO_2 emissions	84.0	$GtCO_2$/yr
CO_2 concentration	766.4	ppmv
Radiative forcing	6.4	Wm^{-2}
Temperature change relative to pre-industrial levels	4.0	°C

Table S2. Comparison between this study and ref.13 of the main text

		This study	Ref. 13 (Moreno-Cruz and Keith, 2013)
Framework		CEA (cost effectiveness analysis)	CBA (cost benefit analysis)
Time		dynamic [1990-2100]	static
		8 time points	1 time point
Stage	"act (1st stage) then learn (2nd stage)"	2 stages	2 stages
	1st stage	uncertainty in climate sensitivity	uncertainty in climate sensitivity
	2nd stage	learning of climate sensitivity	learning of climate sensitivity
Choice variables	1st stage	mitigation	mitigation
	2nd stage	mitigation, and SRM	SRM
Uncertainty	Climate senstivity	stochastic (high, moderate, low)	stochastic (high, low)
	SRM's side effects (damages)	deterministic	stochastic (climate change damage level, zero)
		treated in a sensitivity analysis	explicitly treated learning about damages
			(1st stage learning, 2nd stage learning)
SRM implementation	time	after 2050 (2nd period)	2nd period
	occasion	only in high climate sensitivity scenario	both in high and low sensitivity scenarios
	amount	up to 0.5 deg-C cooling (upper limit)	depends on cost benefit balance
Reasoning of SRM's role as an insurance		SRM is only implemented in a high climate sensitivity scenario	An upper limit for SRM side effects exists.

Supporting Figures

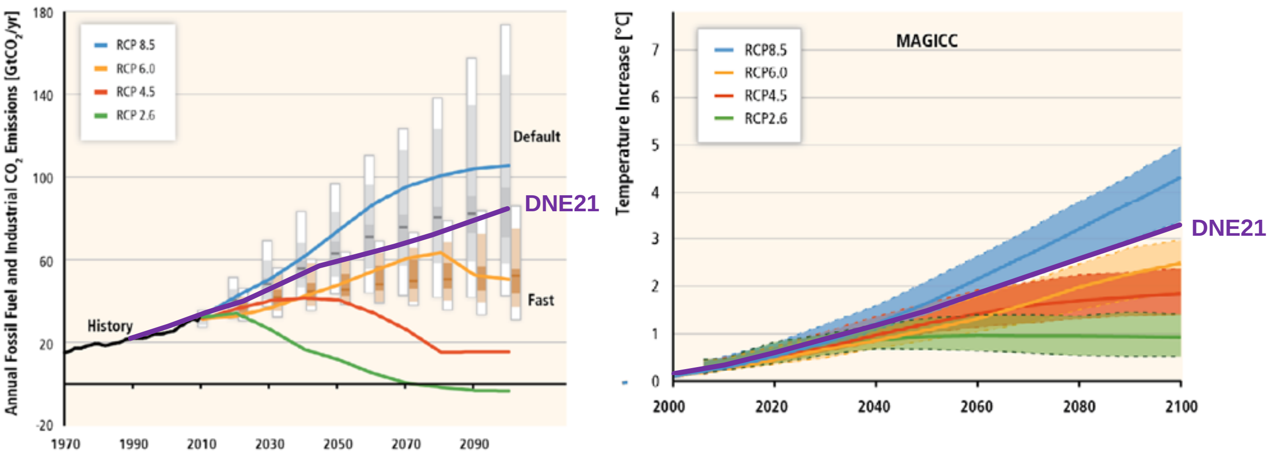

Fig. S1. Baseline CO_2 emissions and temperature increase. Source: the left panel is from Figure 6.4 of ref. 2, and the right panel is from Figure 6.12 of ref. 2. Copyright Intergovernmental Panel on Climate Change 2014, reprinted with permission of Cambridge University Press (purple lines and "DNE21" are added to original).

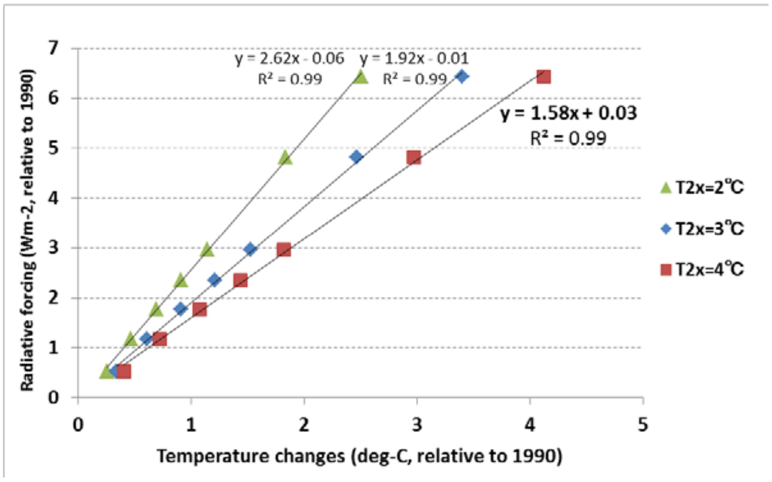

Fig. S2. Relationship between temperature changes and radiative forcing in the DNE21 model for different levels of climate sensitivity: T2x=2°C, 3°C, and 4°C.

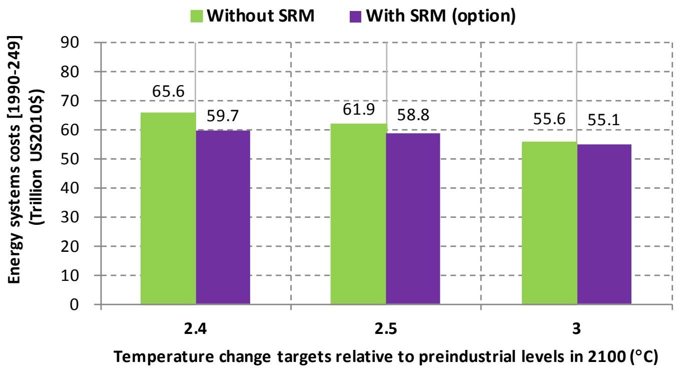

Fig. S3. Relationship between temperature change targets and total discounted sum of energy systems costs in 1990-2049 (Discount rate: 5%/year).

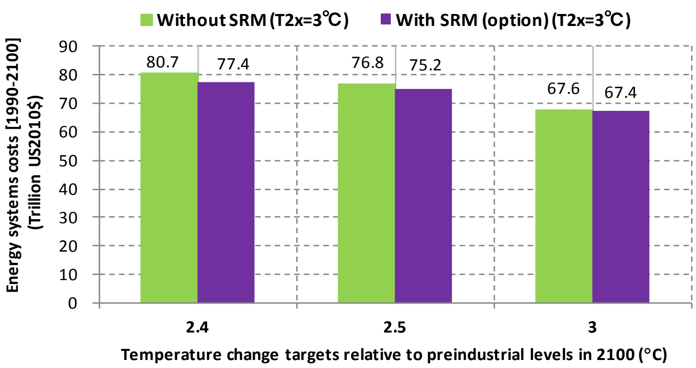

Fig. S4. Relationship between temperature change targets and total discounted sum of energy systems costs in 1990-2100 for T2x = 3°C (Discount rate: 5%/year).

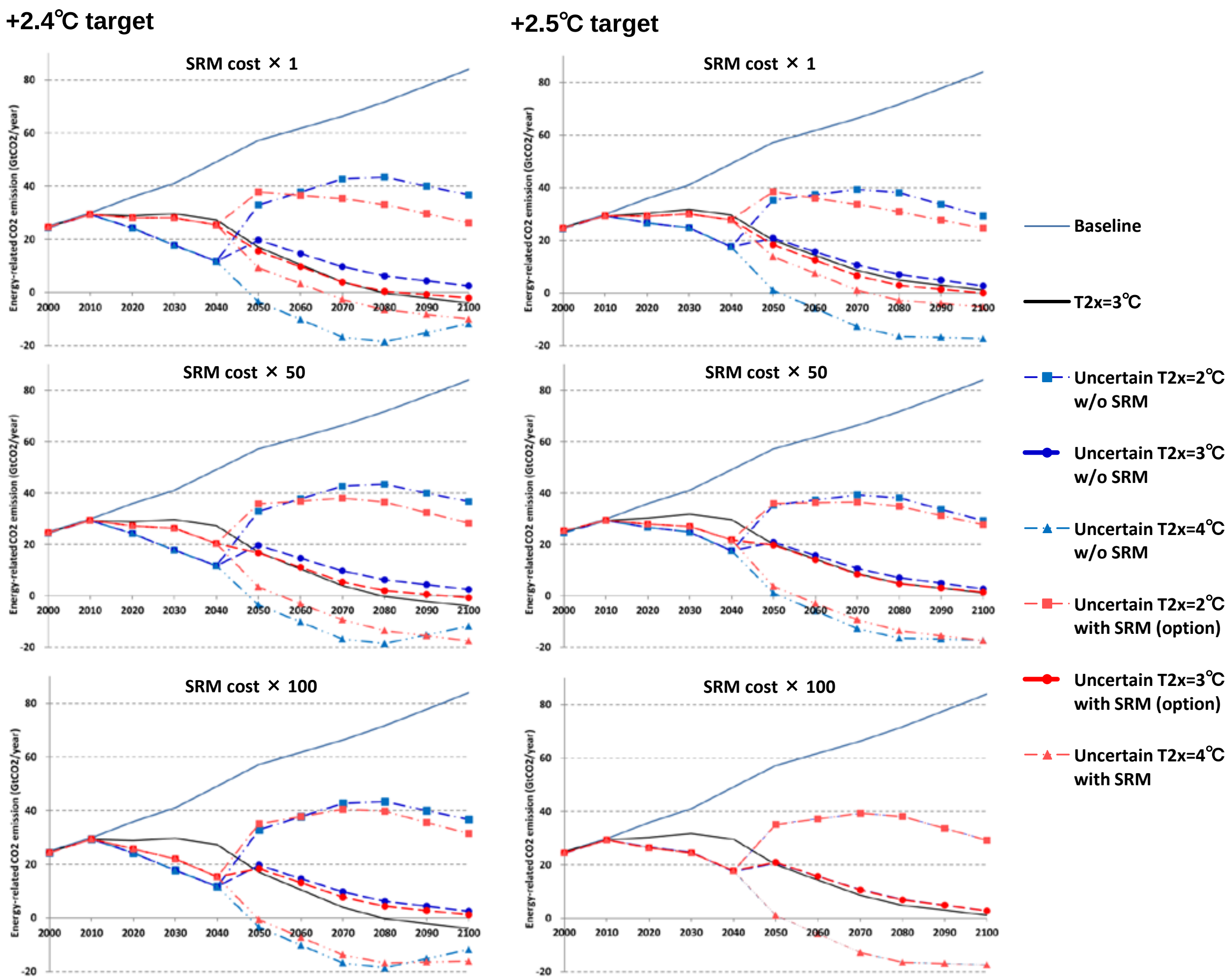

Fig. S5. Effects of SRM options on CO_2 emission pathways for +2.4°C and +2.5°C targets relative to pre-industrial levels in 2100.

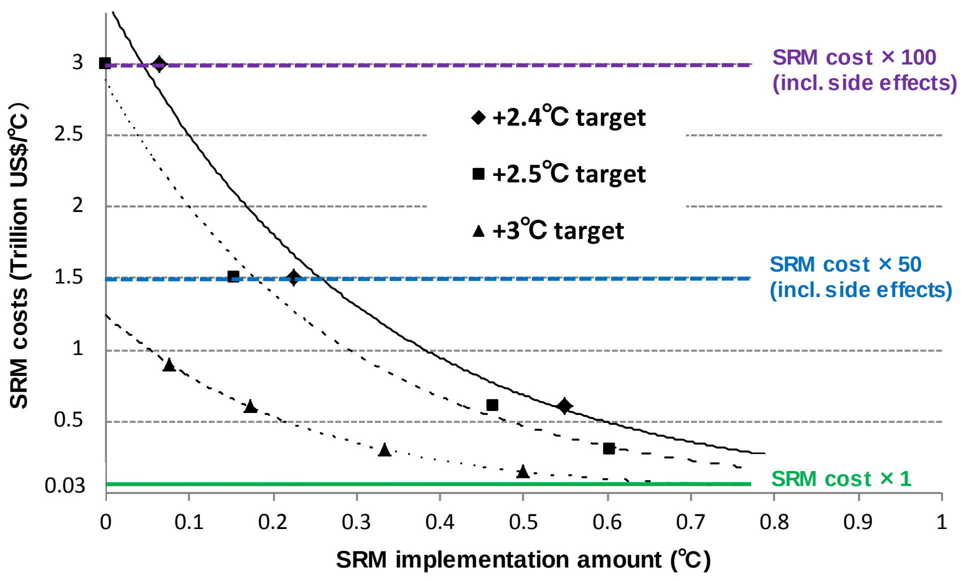

Fig. S6. Global demand curves of SRM in 2100 by temperature change targets (climate sensitivity is T2x=4°C).