List of Abbreviations

AI	Artificial Intelligence
AerChemMIP	Aerosol Chemistry Model Intercomparison Project
CMIP5	Coupled Model Intercomparison Project Phase 5
CMIP6	Coupled Model Intercomparison Project Phase 6
CMIP7	Coupled Model Intercomparison Project Phase 7
CONUS	Continental United States
CSP	Concentrating Solar Power
GeoMIP	Geoengineering Model Intercomparison Project
IPCC	Intergovernmental Panel on Climate Change
ML	Machine Learning
PACE	Plankton, Aerosol, Cloud, and ocean Ecosystem
PV	Photovoltaic
SABRE	Stratospheric Aerosol processes, Budget, and Radiative Effects
SAI	Stratospheric Aerosol Injection
ScenarioMIP	Scenario Model Intercomparison Project
SRM	Solar Radiation Modification
SSP	Shared Socioeconomic Pathways

Highlights

Renewable Energy in a Climate-Changed, Solar-Radiation-Modified World

Andrew Kumler,Ben Kravitz,Caroline Draxl,Laura Vimmerstedt,Brandon Benton,Julie K. Lundquist,Michael Martin,Holly Jean Buck,Hailong Wang,Christopher Lennard,Ling Tao

- Climate change is projected to have varying impacts on renewable energy sources.
- Solar radiation modification could also impact renewable energy generation, if implemented.
- Research on solar radiation modification impacts on renewable energy is nascent, but has critical implications.

Renewable Energy in a Climate-Changed, Solar-Radiation-Modified World

Andrew Kumler[a,b,*,1], Ben Kravitz[c,d], Caroline Draxl[a], Laura Vimmerstedt[a], Brandon Benton[a], Julie K. Lundquist[a,b,e], Michael Martin[a], Holly Jean Buck[f], Hailong Wang[d], Christopher Lennard[g] and Ling Tao[a]

[a]*National Renewable Energy Laboratory, Golden, CO 80401, USA*
[b]*Department of Atmospheric and Oceanic Sciences, University of Colorado, Boulder, CO 80303, USA*
[c]*Department of Earth and Atmospheric Sciences, Indiana University, Bloomington, IN 47405, USA*
[d]*Pacific Northwest National Laboratory, Richland, WA 99352, USA*
[e]*Johns Hopkins University, Baltimore, MD 21218, USA*
[f]*Department of Environment and Sustainability, University of Buffalo, Buffalo, NY 14260, USA*
[g]*Climate System Analysis Group, University of Cape Town, Cape Town, South Africa*

ARTICLE INFO

Keywords:
Solar radiation modification
Solar geoengineering
Stratospheric aerosol injection
Climate change
Solar energy
Wind energy
Hydropower
Bioenergy

ABSTRACT

Solar radiation modification (SRM) is a possible deliberate approach to decrease or reflect incoming solar radiation with the goal of reducing global temperatures, which have increased over the last decades due to high atmospheric greenhouse gas concentrations. Stratospheric aerosol injection, specifically, has shown potential for successfully reducing global temperatures in climate model simulations. Despite the growing literature in the areas of climate change and SRM, their combined effects on renewable energy, a climate change mitigation strategy, have not been addressed. In this review paper, we synthesize previous literature on the possible effects of climate change and SRM on renewable energy resources (i.e., wind energy, solar energy, biomass energy, and hydropower), review the status of climate change and SRM research, and explore potential effects of SRM on renewable energy. We discuss the research challenges and impacts of SRM on renewable energy and conclude by discussing the potential implications of SRM for renewables for SRM governance and policy.

word count = 8272

1. Introduction

The transition from fossil fuels to low-carbon energy sources such as renewable energy is a necessary climate mitigation strategy to avert the most pronounced effects of climate change [1]. Renewable energy, a prominent decarbonization strategy, uses resources such as sunlight, wind, biomass, and water, each of which depend on the weather and climate. Through 2022, total installed renewable energy capacity around the world grew to 3.37 TW, with wind, solar, and hydropower accounting for 95% of this capacity [2]. Asia and Europe added a combined 232 GW in 2022 alone, or roughly 10% growth year over year, while areas such as North America, South America, and Africa had a slower growth rate, between 4.8% and 7.4%. Overall, at the end of 2022, renewables accounted for 83% of all new electricity generation capacity expansion.

Weather and climate phenomena will play an increasingly important role in the growth of renewable energy in the world's energy portfolio [3, 4, 5]. One phenomenon is climate change itself, which is inevitable, even if greenhouse gas emissions are rapidly reduced, because of the inertia of the climate system [6]. Other phenomena include but are not limited to increased frequency and/or intensity of extreme events such as hurricanes [7], resource droughts and fluctuations [8, 9], changes in water availability [10], and changes in crop production [11]. In short, a primary climate change mitigation strategy—implementing renewable energy—is itself vulnerable to a changing climate.

Given that renewable energy resources vary with the changing climate system, research into the possible effects of climate change on renewable energy has received considerable attention over the past decade. This attention includes investigations into the underlying meteorological resources that provide renewable energy as well as how various

andrew.kumler@nrel.gov (A. Kumler)
www.nrel.gov (A. Kumler)
ORCID(s): 0000-0002-1533-2193 (A. Kumler)

climate change scenarios might affect power production within the planning horizon of electricity generation assets. For example, over the typical 30-year lifetime of a solar project, increased cloud cover could affect the performance of a concentrating solar power (CSP) plant that primarily relies on direct radiation for its power. Additionally, while photovoltaics (PV) may experience weaker impacts from changes in cloud cover (because PV panels can use the diffuse part of the solar spectrum [12]), solar panel efficiency degrades at high temperatures. Wind patterns and climate oscillations are projected to change in a future climate, potentially impacting current and future wind farms that have lifetimes on the order of 30 years [13]. Distributions of precipitation and surface runoff are expected to alter regionally, affecting the stability of hydropower plants, many of which have produced reliable and predictable power for decades [10]. Crops used for bioenergy may realize increased production from CO_2 fertilization but will also experience the competing effects of temperature increases, water availability, soil degradation, and land-use changes [14].

If climate change is not sufficiently controlled through reductions in greenhouse gas emissions or other current mitigation measures, more direct methods of control may be applied. One of these methods, solar radiation modification (SRM), is the act of reducing incoming solar radiation to reduce Earth's surface temperature. A widely discussed approach to implement SRM is stratospheric aerosol injection (SAI), in which aerosols are injected into the stratosphere to reduce incoming solar radiation. The natural analog of SAI is powerful volcanic eruptions, such as the Mt. Pinatubo eruption in 1991 that spewed 17 megatons of SO_2 into the stratosphere, cooling global temperatures by roughly 0.5°C for 2 years [15]. Unlike a volcanic eruption, SAI would likely need to be implemented on a regular basis (e.g., annually or more frequently) to keep global temperatures consistently lower than they otherwise would be, or until significant greenhouse-gas-reducing measures have been taken and the climate has begun to stabilize (Figure 1)[16]. Researchers are unsure how long it would take after implementing SAI to distinguish the effects of SAI from natural climate variability and whether counteractions would be needed (and when). Research into how to stop the effects of SAI once implemented addresses the risks associated with the rapid rebound of incoming solar radiation [17].

SRM, and specifically SAI, has received increased attention in the literature over the past decade. Studies initially focused on modeling SAI impacts on basic climate variables and dynamics to ensure that global temperature targets were reached and that model physics were capturing anticipated changes [18]. Within the last few years, such studies have become more complex, focusing not only on important climatological metrics but also on the social and political landscape of the implementation of SAI [19]. Renewable energy, as it relates to SAI, has received some attention, with focus primarily on solar energy changes [20, 21]. Other studies have indirectly addressed precipitation and runoff [22, 23]. More work is needed to explore the potential effects of SAI on renewable resources and power production.

Both climate change and SAI could impact renewable energy generation around the world, but to the authors' knowledge, no effort has been made to review the literature on climate change and SAI as they pertains to renewable energy impacts. We review the effects of climate change on renewable energy in Section 2, including solar, wind, hydropower, and bioenergy resources, and we discuss the uncertainty in these effects and future research directions. We then review the literature on climate change and SRM that is relevant to renewable energy in Section 3, including the potential physical mechanisms of the effects, quantitative estimates of the effects if available, uncertainty, and future research directions. In Section 4, we summarize the implications that potential effects of SRM on renewable energy could have for SRM research, governance, and policy. Conclusions and future work appear in Section 5.

2. Literature review on climate change and renewable energy

2.1. Potential climate change impacts on renewable energy

Climate change will likely impact renewable energy. These impacts include changes in the meteorological variables that drive renewable energy, in exposure to extreme weather events, and in the location, magnitude, and timing of energy demand. In this section, we assess the literature that addresses the primary meteorological variables that drive solar energy, wind energy, hydropower, and bioenergy.

2.1.1. Solar energy and relevant meteorological variables

Solar energy uses the downward shortwave radiation that reaches the surface of the earth. The total downward shortwave radiation at the surface consists of both a direct normal component, which is radiation that is unaffected in its travel from the sun to the surface, and the diffuse component, or radiation that eventually reaches the surface by means of reflection and refraction. While both PV and CSP can harness the direct and diffuse components of the global horizontal irradiance, CSP is more sensitive to changes in the direct normal irradiance. Understanding future

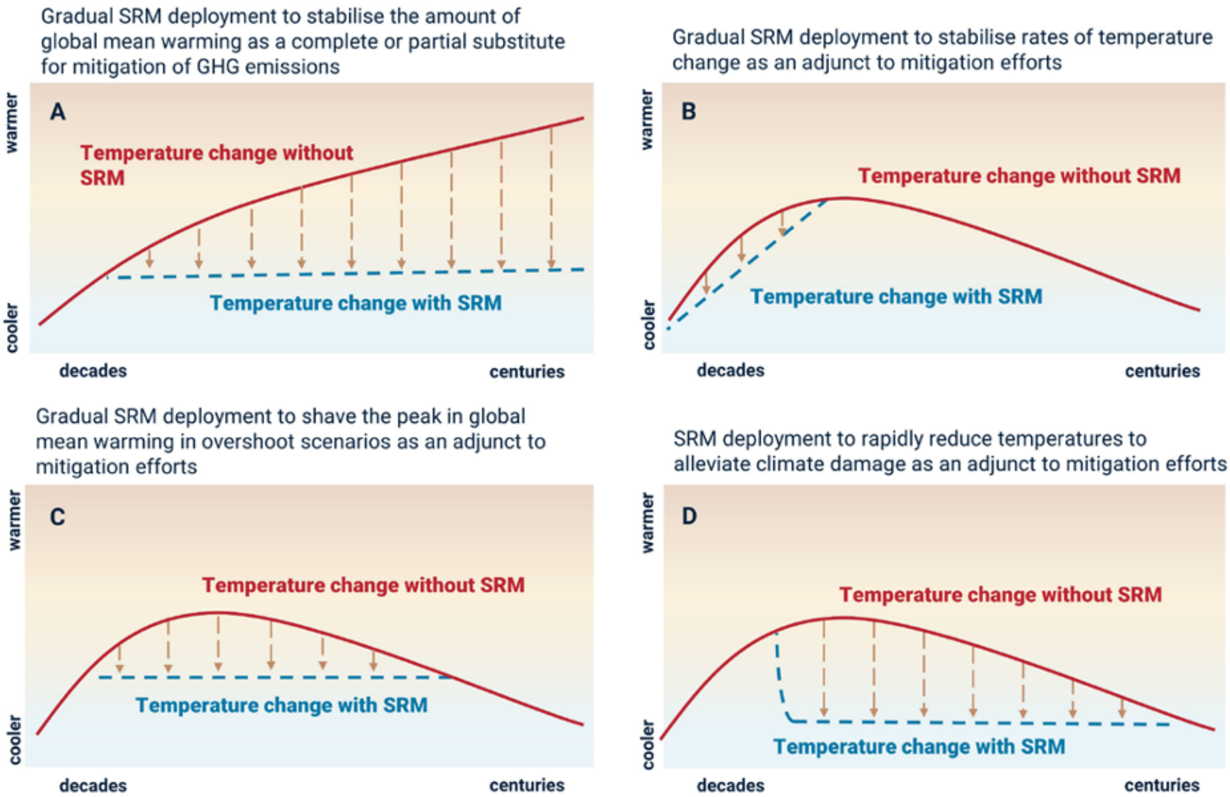

Figure 1: Examples of different SRM deployment strategies depending on the level of temperature increase from climate change and mitigation efforts to reduce temperatures. Reproduced with permission from [24].

changes in each component of the surface shortwave radiation is important if we are to understand future changes in solar energy.

Meteorological variables such as near-surface temperature, cloud fraction, aerosols, and near-surface wind speed can also impact solar energy production, with PV and CSP having different sensitivities to these variables. PV panels become less efficient under higher temperatures and generally produce less power under cloudier conditions [12]. High aerosol concentrations can also reduce PV output. Near-surface wind speeds can act as a cooling agent for PV panels by removing excess heat, thereby increasing efficiency [25]. For CSP, higher near-surface temperatures increase efficiency, requiring less work to be done to heat liquids used to generate steam [26]. CSP is more sensitive to cloud fraction changes because CSP mirrors are more reliant on direct irradiance. Like PV, CSP is also affected by aerosol concentrations; higher concentrations in the atmospheric column make CSP plants less efficient [27]. CSP is also affected by near-surface wind speeds, which can reduce CSP efficiency by reducing temperatures or by blowing aerosols into a CSP plant [28]. Lastly, increases in extreme events can impact the spatial and temporal variability of solar energy, affecting the stability of the electrical grid [29].

Globally, the current literature shows mixed results for climate change impacts on solar energy. Modest changes to all-sky irradiance are projected through the middle to the end of the 21st century, with regional increases anticipated in central Europe; western, central, and northern Africa; and eastern Asia, and regional decreases at higher latitudes [30, 31]. Minor projected increases in direct irradiance, and thus decreased cloud fraction, are consistently shown in numerous studies, but with high regional variability [32]. Near-surface temperatures are projected to increase globally, negatively impacting PV and positively impacting CSP [33]. Wind speed near the surface is generally expected to decrease, which is connected to the decreased equator-to-pole temperature gradient [34]. Aerosols, particularly anthropogenic sources of aerosols, have decreased in China and Europe but increased in India [35]; hence, PV and CSP output is projected to decrease in India and increase in China and Europe. Because of these changes to relevant meteorological variables, occurring now and projected in the future, modest increases or decreases to solar-PV-generated energy are anticipated regionally, and increases in CSP are anticipated globally [33, 36, 14].

Changes in irradiance due to climate change in the continental United States (CONUS) are nuanced. Regionally, there are indications that irradiance will decrease in the West and increase in the East, especially in the U.S. Southeast [30, 36, 14, 37]. Changes in cloud cover, aerosol distributions, and moisture patterns are some of the primary drivers of this projected change in irradiance, though agreement varies across climate models [38]. Across CONUS, it is projected on average that irradiance due to climate change will vary within a few percent of the current climate but with a high degree of uncertainty due to higher variability at different spatial and temporal scales.

Studies focused on solar energy changes across CONUS have yielded a similar nuanced result. With an anticipated increase in irradiance, increase in near-surface temperature, and decrease in cloud fraction in the U.S. Southeast, PV and CSP resources are projected to increase. The near opposite is projected to occur in the U.S. West, where decreases are largely projected for PV and CSP resources [39, 14, 40, 38].

Cloud and aerosol physical properties are not well represented in climate models [41, 42] because of the complex and computationally expensive physical and chemical interactions that happen at various levels of the atmospheric column that modern climate models cannot completely resolve. Parameterizations help generalize these interactions but are not intended to capture all of reality, leading to more uncertainty. For example, Coupled Model Intercomparison Project Phase 5 (CMIP5) models do a poor job capturing anthropogenic aerosol emissions, which can heavily impact solar energy productivity [35]. While CMIP6 models have improved their representation of anthropogenic aerosol emissions, climate models can capture radiative effects for the wrong reasons, due to compensating errors [43]. Compensating errors can still manifest in CMIP6 models [44, 45].

Changes and uncertainty in projected solar energy and related meteorological variables are largely attributable to shortwave solar radiation at the surface. Most of the global and regional changes in surface all-sky irradiance are projected to come from changes in cloud properties, such as total cloud fraction and cloud depth [40]. Changes in natural and anthropogenic aerosols at the surface and aloft can also heavily impact surface all-sky irradiance, and thus solar energy production.

Of the uncertainty studied in the literature regarding solar energy and climate change, most studies agree there is high uncertainty around whether climate change will have a positive or negative effect on solar electricity generation efficiency, and the sign of the change can be a function of the type of climate scenario used [39, 14, 38]. While there is evidence that PV resources could decrease and CSP resources could increase globally with the most extreme climate scenarios, there are also studies showing contradictory results [37]. In general, however, climate models largely agree on the sign of change for all-sky and clear-sky irradiance in particular regions of the world—for example, Eastern Asia, most of Europe, and the U.S. Southwest [33, 30, 36]. On the contrary, climate models are less certain on cloud fraction and aerosol optical depth projections [35].

2.1.2. Wind energy and relevant meteorological variables

Possible impacts of climate change on wind resources have attracted considerable academic attention, with over 90 publications between 2005 and 2022 matching keywords "wind resources" and "climate change" as reported by Hahmann et al. [46]. Most investigations of the possible effects of climate change on wind energy focus on changes in wind speed, with a secondary possible focus on changes in air density due to temperature and humidity changes that may occur with climate change. Wind power, P, is a function of wind speed, U, air density, ρ, and wind turbine characteristics rotor area, A, and power coefficient, c_p [47]:

$$P = \frac{1}{2}\rho c_p A U^3 \quad (1)$$

Wind turbines typically experience winds between 30 m and 300 m (for the largest turbines) above the surface. Rather than steadily increasing with height above the surface, wind profiles in a region this deep can take a range of shapes. In stably stratified conditions (occurring at night over land [48] or in summertime over water [49]), a low-level jet profile often occurs, such that the fastest winds may occur within the wind turbine rotor region with decreases above or below. The complexity of the wind profile in wind turbine altitudes therefore adds uncertainty when extrapolating from a near-surface value or interpolating between a near-surface value and a value several hundred meters above the surface. Unfortunately, climate models generally predict a value of wind speed at 10 m above the surface and then winds at much higher levels, requiring an extrapolation from the surface or interpolation between distant levels that are unlikely to accommodate complicated profiles like low-level jets. This uncertainty should be considered when assessing predictions of wind speed variability from future climate simulations. In fact, Hahmann et al. [46] argue that "extrapolating wind speeds from 10 m to turbine height using a constant power law is a poor approximation in many circumstances and will often exaggerate future changes in wind resources."

Even given this uncertainty, most investigations of climate change impacts on wind speed and wind power production find only subtle decreases of wind speed, which many authors consider will be small compared to anticipated growth in installed capacity and expansions of technical capacity [50, 46] or constrained to summertime periods when solar energy can compensate for decreases in wind [51]. The changes found by Pryor et al. [52] are considered small in comparison with current interannual variability, where impacts are "generally <5% of the current mean energy density."

Given the current large wind energy deployment in Europe, many studies focus on European wind resources. Most of these studies find a small increase in the annually averaged wind resource in northern Europe accompanied by a small decrease in southern Europe [53, 54, 55, 56, 50]. Wind speeds are projected to increase over much of the continent of Africa in the near term and mid-century, with some regional variability in this general signal [31].

In North America, similar regional variability may occur. In the southern Great Plains, an area experiencing wide wind energy deployment, Pryor et al. [52] find likely increases in wind energy resources but regional decreases over much of western North America.

In fact, in studies that consider multiple members of climate model ensembles, ensemble members often disagree on even the sign of future wind speed and wind power changes [13, 52]. This disagreement is more widespread for ensembles relying on more finely resolved simulations [50, 51].

Given this small anticipated impact of climate change on wind resources, the details of possible changes may be relevant for practitioners in specific regions.

Estimates of climate change impacts on wind resources are vulnerable to uncertainties deriving from several sources beyond the uncertainty in climate scenario projects. As discussed above, a significant source of uncertainty in estimating the impacts of climate change on wind resource assessment is the extrapolation of wind speed from 10 m to wind turbine hub heights because wind shear coefficients vary considerably over the course of a day [57], discussed in detail in [46]. Uncertainty in temporal variability is also critical, given the strong diurnal cycle in winds and the fact that climate model output is generally limited to monthly means. Climate models are also at coarse spatial variability (on the order of 30 km, except for higher-resolution products from the Coordinated Regional Climate Downscaling Experiment). Karnauskas et al. [13] quantify the impact of each of these sources of uncertainty, concluding that there may be a bias introduced in estimates of wind resource using coarse spatial and temporal data and in extrapolating, but that this bias should be consistent globally.

Further, few estimates of climate change impacts consider the effect of wind farm wakes and the variability of those wakes, which vary considerably with atmospheric stability [58].

2.1.3. Hydropower and relevant meteorological variables

Hydropower is the largest contributor to the total renewable energy portfolio across the globe. Most of the current installed hydropower capacity is based on rivers, which can be dammed, and is reliant on a stored reservoir, or run-of-river, where the river is allowed to flow more freely. Given its reliance on rivers, hydropower can potentially be impacted by climate change impacts to rivers and the physical systems that influence rivers, like changes in precipitation (timing, duration, type), flooding, glacial dynamics, runoff, drought, and sediment load of rivers (soil erosion).

Climate change impacts on the physical systems that hydropower relies on have received considerable attention in the literature. In the Intergovernmental Panel on Climate Change's (IPCC's) most recent assessment report, they state with high confidence that projected changes to water systems will increase energy production globally, but with other potential consequences and regional variability [1, 59]. Increases in hydropower are mainly attributable to increased runoff from snow and glacial melt and changing precipitation regimes. Precipitation regimes are projected to change, with precipitation coming in shorter, more intense events [1, 60]. Snow is anticipated to start falling more as rain, accelerating snowmelt and winter/spring runoff, potentially decreasing overall snowpack and summer runoff [61, 62]. Glacial melt will continue, potentially increasing river flow and thus hydropower, but with the potential of increased flooding, soil erosion, sediment load on facilities, and, ultimately, shifting seasonal patterns of generation [1, 59, 60]. These projected changes are likely to accelerate hydropower generation in the next few decades, but changes late in the 21st century are more uncertain once/if the global cryosphere driving hydropower is largely depleted.

More regionally, climate change impacts on water systems in CONUS are projected to impact hydropower generation as well. This includes many of the same anticipated changes in global relevant meteorological variables, such as precipitation patterns and intensity, river flooding, and snow and glacial melt [1, 60]. Impacts are not uniform, with shifts in the seasonality of snowmelt and precipitation increasing the likelihood of higher hydropower generation in the late winter/early spring and decreased generation in the summer [59]. Craig et al. [39] conducted a review of potential climate change impacts on hydropower potential in the United States, finding that annual hydropower generation potential is projected to generally increase across CONUS during the winter and decrease in the summer, shifting the seasonality of demand and generation. Kao et al. [63] further confirmed these results for federal hydropower, where annual hydropower generation is projected to increase by 4% by midcentury due to a 9% increase in streamflow. This same study also emphasizes that a projected increase in extremes from both flooding and drought, along with increased disparities between seasonal supply and demand, will likely make management of hydropower generation facilities more difficult.

Uncertainty from hydropower analyses and projections comes from a variety of sources. Kao et al. [63], Rastogi et al. [64], Zhou et al. [65] used a similar multi-model framework that consisted of multiple global climate models, downscaling strategies, hydrologic and hydropower models, and reference meteorological observations. They show that uncertainty can come from all aspects of the multi-model framework, but that the choice of global climate model and hydrology model leads to the greatest variance in outcome. The choice in reference meteorological observations also cannot be ignored, confirming that better observations of watersheds are needed to help reduce uncertainty around current and future river flow and hydropower generation.

2.1.4. Bioenergy and relevant meteorological variables

The anticipated changes in biomass production for bioenergy production and relevant meteorological variables are tightly tied to many Earth and human systems, such as food processing, waste management, and agricultural systems, that can produce biomass for bioenergy in the form of wastes (fats, oils, and greases; animal and human wastes), agricultural and forest residues, and energy crops. Carbon, nitrogen, and the water cycle play critical roles in the development of various crops, where a surplus in carbon can help crops become more productive, but a deficiency in nitrogen or water can limit growth in others. Therefore, examples of climate change impacts on agriculture include potential changes to the carbon, nitrogen, and water cycles in addition to changes in direct and diffuse radiation. Crops need water to grow, and as such, the water cycle, driven by changes in precipitation, evaporation, and runoff, determine water availability around the world. Human systems such as dietary preferences, consumer products demands, planting and harvesting practices, geopolitics, and land-use management also have profound implications for how and what crops are ultimately grown and which wastes are generated. While it is difficult to disentangle these systems, a plethora of research has investigated how biomass production and agriculture are projected to change throughout the 21st century.

Most studies agree that a global increase in biomass growth, or primary production, is projected to occur, primarily driven by the CO_2 fertilization effect [14, 66, 67, 68, 69]. While crops have different sensitivities to increased CO_2 levels, on average, biomass is anticipated to increase [67]. Regionally, these changes are nuanced, but the current scientific consensus is that biomass production will grow at higher latitudes and decline at lower latitudes [66, 70]. Various crops are anticipated to benefit from warmer temperatures in higher latitudes, where historically these same crops may not have been viable. In turn, crops at lower latitudes will see increased heat stress from warmer temperatures. At midlatitudes, changes are more uncertain and dependent on other factors, such as precipitation changes, soil quality, nutrient leaching, and extreme events [66, 67, 71, 72].

Across the United States, biomass production is projected to increase, despite general uncertainties around midlatitude changes. Studies are consistent with respect to the CO_2 fertilization effect increasing biomass production, but not necessarily for all crops, especially when accounting for other processes such as the nitrogen cycle and water quality [14, 66, 67, 68, 71, 73]. Additionally, these increases in production could come at the cost of increased deforestation, higher water stress, and nutrient leaching [73]. On the other hand, global agricultural productivity has largely increased since the mid-20th century, thanks in part to technological advancement and improved farming practices, but more recently, climate change has slowed this progress [74]. Overall, while biomass production is projected to rise in the United States, negative impacts on other Earth and human systems may counter this increase at particular times and places and may challenge the productive use of biomass resources for bioenergy.

Bioenergy uncertainty is likely the largest out of the renewable resources discussed here, as it is highly sensitive to human systems and to climate. This concept was explored by Groundstroem and Juhola [72] using a systems thinking and causal loop diagram approach to understand how the wood pellet industry and its subsystems are all linked, and thus how they impact each other. It is immediately apparent that climate change impacts on bioenergy and biomass can have many competing and cascading effects, all of which have their own sensitivities. The CO_2 fertilization effect will increase production for many crops, but numerous studies have limited or incomplete crop and land surface models. The projected sign of change could be affected by, for example, nitrogen limitation. While research in recent years has started to use more robust crop and climate models, uncertainty has not necessarily been reduced [68].

It should be noted that while we focus on climate change impacts on bioenergy-related variables, research has also been performed on how bioenergy could impact the climate [75, 76]. Additionally, biomass for bioenergy has applications beyond agriculture, but the details of these areas of research are beyond our scope.

Effects of climate change on hydropower and solar, wind, and biomass resources are potentially significant to renewable energy production, with varying uncertainties and variability across climate scenarios and geographies. Having considered the literature on these effects, we now examine the literature on the effects of solar radiation modification on renewable energy.

3. Literature review on climate change and solar radiation modification relevant to renewable energy

Just as climate change is anticipated to impact renewable energy, SRM is likely to affect renewable energy if implemented. Projecting the effects of SRM adds uncertainty and complexity beyond climate change considerations. Here, we discuss research relevant to SRM and renewable energy, but we also touch upon the uncertainty in the science and future research directions.

3.1. Potential solar radiation modification impacts on renewable energy

3.1.1. Solar energy and relevant meteorological variables

The primary purpose of SRM is to affect the total energy balance of the Earth by reducing incoming solar irradiance. However, SRM would affect the quality of light, not just the quantity. A 2% reduction in insolation, approximately equivalent to the forcing required to offset a doubling of CO_2 [77], could reduce downwelling direct irradiance by more than 20% and increase diffuse irradiance by approximately a factor of 3 [78]; similar results were seen after the 1991 eruption of Mt. Pinatubo [79]. There would be numerous climate effects as a result of these changes, notably on terrestrial ecosystems and carbon uptake [80]. In terms of solar power generation, CSP plants depend on direct radiation, so SAI would reduce the amount of power these plants could generate [81]; Smith et al. [20] found that global cooling by 1°C would reduce CSP generation by 5.9% on average over land. However, solar PV cells can use both direct and diffuse light, so impacts on solar generation from this source would be much smaller [20]. There may also be regional effects that cause shifts in cloud cover [82], affecting solar generation; this is presently difficult to quantify.

Solar energy is affected by more than just solar irradiance, as described in Section 2.1.1. SRM would also affect precipitation, wind, and near-surface temperatures, among other factors that contribute to solar energy efficiency. On average, the projected changes from SAI would offset those of climate change for a wide variety of variables [83], but regional departures from average behavior are likely. Preliminary studies [21] suggest a decrease in total generated solar power measured in "low solar weeks" from both PV and CSP sources, although there may be a substantial increase in generated power in areas that are strongly negatively affected by climate change. Moreover, this picture is complicated, as Baur et al. [21] found a reduction in the optical thickness of cirrus clouds, which increases solar power generation. Due to the notable paucity of studies, it is hard to make robust conclusions that quantify effects of SRM on solar power generation, although there is consensus on the sign of the overall response.

3.1.2. Wind energy and relevant meteorological variables

At the time of this writing, there was unfortunately no published peer-reviewed literature on the effects of SRM on wind energy. A preprint from Baur et al. [84] suggests that while total global wind energy resources would be negligibly reduced with SRM (specifically SAI), regional trends can be large. Their study is limited to considering the effect of SAI that cools down from a Shared Socioeconomic Pathways (SSP) 585 baseline scenario (aggressive fossil fuel development, little climate change adaptation) to temperatures similar to an SSP245 scenario (moderate fossil fuel development and climate change adaptation), resulting in changes in 150-m winds of up to 16% in some regions.

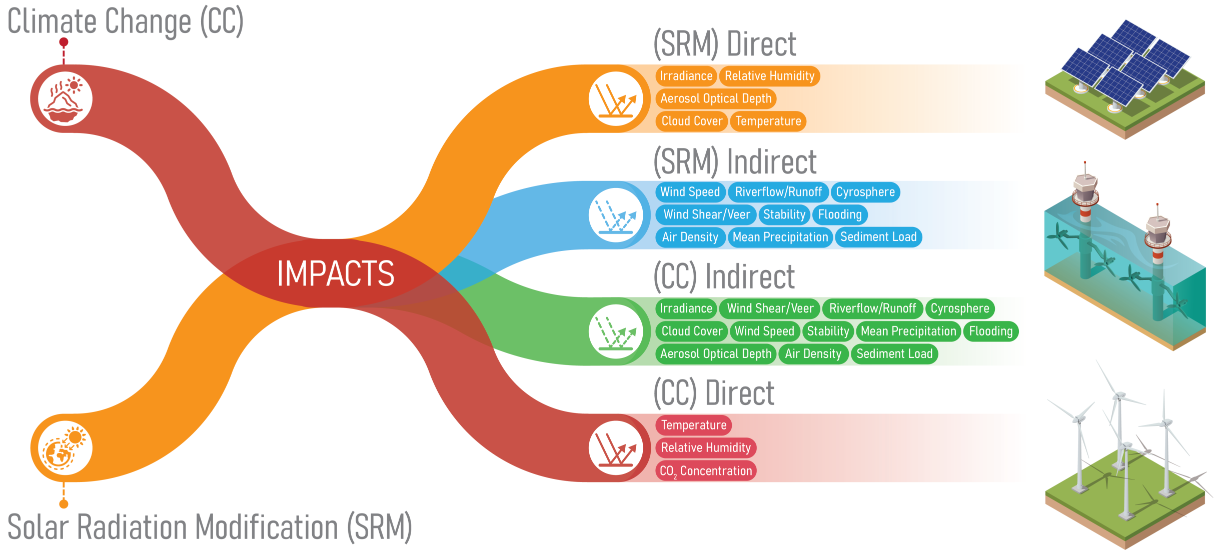

Figure 2: Direct and indirect impacts from climate change (CC) and solar radiation management (SRM) on many meteorological variables important to the renewable technologies discussed herein. Here, direct is defined as a relatively quick change in the climate system, and indirect defined as multiple processes are involved and/or a time lag for said variable to change.

3.1.3. Hydropower and relevant meteorological variables

In general, SRM would reverse many of the changes to hydropower caused by climate change (Section 2.1.3), although this would vary on a regional basis. SAI would reverse the "rich get richer, poor get poorer" effects of climate change across much of the globe, where climate change is projected to amplify many existing impacts [85]. It would also slow glacier melt and increase snowfall [86], leading to more consistent streamflow throughout the year. In addition, SAI would likely reduce aridity, as measured by the ratio of precipitation to potential evapotranspiration [87]. This would mean more water availability, which may not directly affect hydropower but will likely influence catchments in general.

Nevertheless, it is unlikely that SRM will be able to completely stop or reverse all of these changes. The amount of cooling needed to fully restore glaciers, and the cryosphere in general, far exceeds the amount of SAI in most projected scenarios of SRM [88]. Offsetting global mean temperature change with SAI results in "overdrying" of the planet, which is a consequence of the thermodynamics related to addressing a longwave radiation change (greenhouse gases) with a shortwave change (SAI). This thermodynamic mismatch leads to different direct and indirect impacts on the climate system, as illustrated in Figure 2. Projected mean climate change and SRM impacts on all renewable technologies considered herein are shown in Figure 3.

3.1.4. Bioenergy and relevant meteorological variables

The discussion of how SRM could impact bioenergy is a discussion of how SRM could impact agriculture. Of the studies that have investigated SRM and crops relevant for bioenergy, the main consensus is that an SRM climate will likely increase crop productivity worldwide. This finding is primarily the result of higher CO_2 concentrations from higher emissions that would not stop during SRM deployments, generally leading to higher crop productivity, and lower heat stress from an SRM-cooled climate [89, 90, 91]. Precipitation and overall water cycle changes can impact production as well, where an SRM climate generally reduces precipitation [23, 92]. Nitrogen availability can also limit crop productivity, and some studies have pointed to this limitation as a possible burden in future climates. To date, many climate models do not account for the nitrogen cycle, likely leading to overestimates of crop productivity during potential SRM deployments [22]. Increased diffuse radiation from SRM, particularly SAI, is considered a net positive for most crops, as diffuse radiation in most circumstances can be more efficiently used by crops [90, 23, 93, 94].

Regionally, differences can be found depending on the latitudinal band of focus and level of SRM implemented, with some findings indicating that no matter the level of SRM deployed, there will be countries who do not benefit

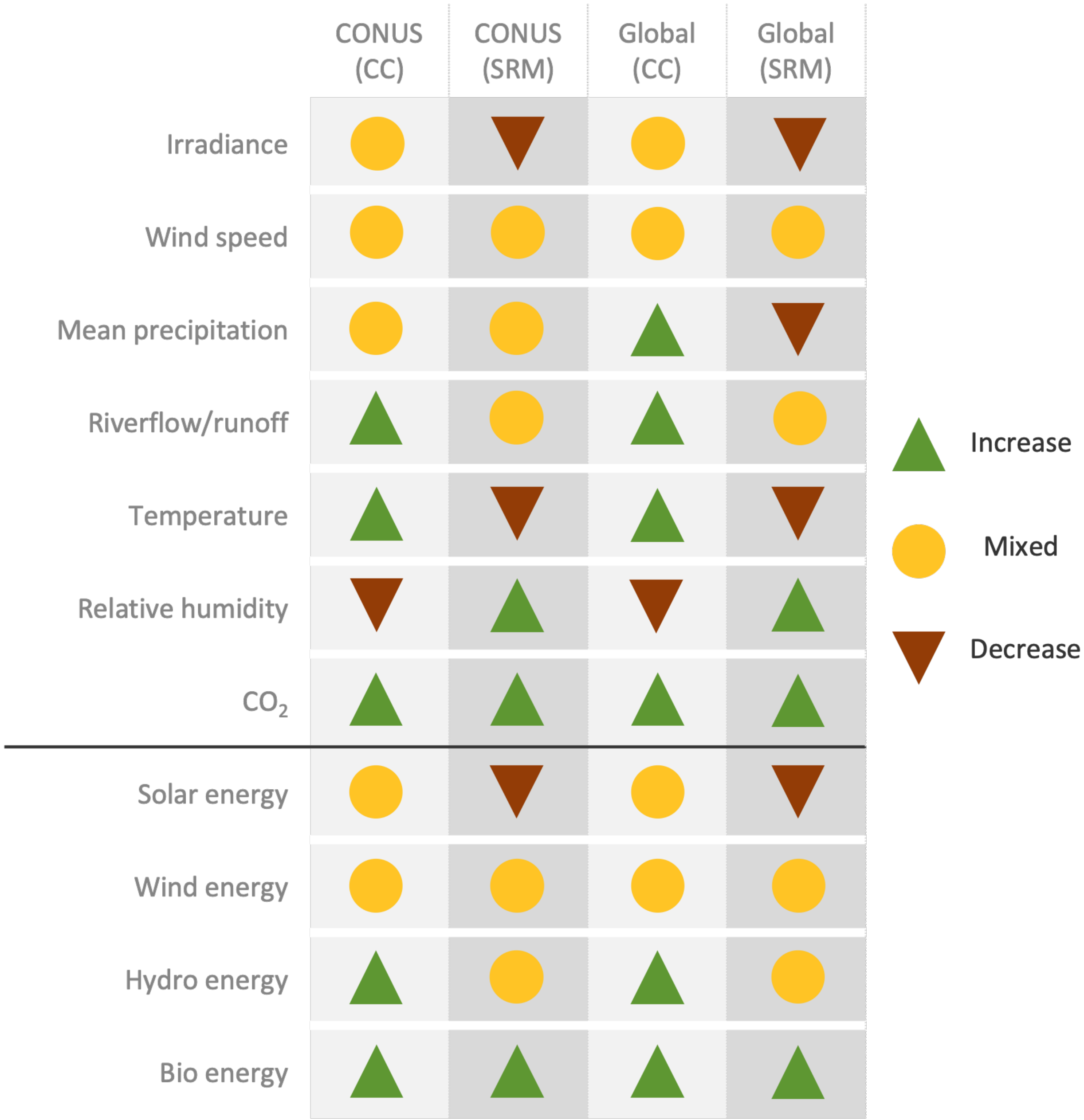

Figure 3: Projected mean climate change (CC) and solar radiation modification (SRM) impacts on meteorological variables relevant to renewable energy for CONUS and globally, and potential changes in solar energy, wind energy, hydropower, and bioenergy. Results are based on the literature herein, but do not reflect the spatiotemporal complexity of each variable, where the sign of change could be different than presented here.

[95]. Even if crop production were increased globally, the exact location of those increases is important because moving crop belts could mean the end of the existence for those in areas the crop belt is moving away from. For CONUS, crop production is projected to increase the most in a moderately SAI climate, with maize and soybeans experiencing the largest increases and wheat experiencing a more modest increase. More generally, the world's largest crop producers would generally benefit from some level of SAI. It should be noted that this same study highlighted that some countries gain to benefit from a non-SAI climate change scenario, leading to potential disagreements on how much, if any, SAI should be implemented.

4. Research needs at the intersection of climate change, solar radiation modification, and renewable energy

While a lot of research has been done in the last couple of decades to reveal potential changes and impacts to renewable energy from climate change and SRM, unknowns remain in the area of climate science and modeling and their implications on renewables. Unknowns also remain regarding uncertainty in climate and SRM modeling and detecting a signal in the uncertainty to be able to point to effects on renewable energy resources.

This section will discuss current scientific and computational limitations in climate and SRM research with regards to renewables and tools to address those limitations; discuss uncertainty in climate and SRM simulations and touch on designing potential SRM deployments; and relate SRM research to governance aspects and impacts on human systems.

4.1. Current scientific and computational limitations

4.1.1. Modeling uncertainties

Some of the largest issues in modeling SRM are related to model uncertainties. Indeed, many of the biggest issues with quantifying projections of future renewable energy production are issues in climate science and atmospheric science more generally, although renewable energy needs could serve as a useful impetus for further fundamental science research. Even in simple representations of SAI that involve turning down the sun in climate models, offsetting a quadrupling of CO_2 requires anywhere between 3.5% and 5.0% solar reduction [78], a result that is robust across multiple generations of models [91]. One of the largest reasons for this model spread is due to shortwave cloud forcing [91], which is consistent with the longstanding problem that clouds are the largest source of uncertainty in climate models and future projections of climate change [96]. Uncertainties in cloud representations are even more pronounced for marine cloud brightening, which relies on highly uncertain representations of aerosol-cloud interactions [97, 98]. However, clouds are not the only sources of uncertainty. For SAI, aerosol optical depth is difficult to represent accurately because of uncertainties in stratospheric circulation [99], aerosol microphysical growth, and stratospheric chemistry [100, 101]. All of these factors are computationally expensive to simulate [102], difficult to observe to constrain our models [103], and have important impacts on surface climate [104]. These issues directly affect our ability to simulate effects on renewable energy.

4.1.2. Design space

The expected effects of SRM on renewable energy are often not straightforward because the effects depend upon how SRM is deployed; that is, SRM can be designed [105]. For SAI, the latitude and season of the injection are critical parameters in determining the net climate effects [106]. As an example, in one model's simulations of using SAI to offset the effects of climate change, injecting in boreal autumn increases South Asian precipitation and reduces Amazon precipitation, and vice versa for injecting in boreal spring [107]. SAI in the mid- or high latitudes of one hemisphere tends to result in the aerosols staying in that hemisphere [108], with consequent differential cooling and shifts in tropical precipitation [109]. The amount of injection in each hemisphere that is required to meet particular climate objectives appears to be model-dependent due to different model sensitivities to aerosol [110] as well as representations of the Atlantic meridional overturning circulation [111]; neither of these is well constrained by observations [112].

4.2. Potential tools to address current limitations

Overall advancements in atmospheric science and climate modeling will advance the understanding of climate change and SRM effects on renewable energy. Here, we focus on the more specific actions that could reduce the uncertainty of these effects through improved modeling, measurements, metrics, simulation studies, and artificial intelligence.

4.2.1. Improved modeling

SRM strategies involving aerosol and clouds still have large uncertainties due to either insufficient understanding or crude representation of processes in climate models [32]. New relevant modeling capabilities (e.g., prognostic stratospheric sulfate aerosols, control of sea salt particles injection, heterogeneous/homogeneous ice nucleation processes) have continued to be developed in Earth system models, and more SRM simulations are designed to advance the understanding and assess the impacts. Recent Geoengineering Model Intercomparison Project (GeoMIP) experiments focused more on specific aspects of the climate system to closely understand processes involved in SRM simulations [106]. Future GeoMIP experiments will consider including plans laid out by the ScenarioMIP community for the next set of scenarios that would constitute the bulk of CMIP7 [113]. Decisions of experiment protocols will need to be made on aerosol emissions assumptions in the different scenarios. The high-forcing scenario is a logical candidate for high sulfur emissions, as aerosol emissions are expected to be low in stringent mitigation scenarios. However, high aerosol emissions in the high-forcing scenario can also slow down global warming. An alternative is to have a normal aerosol scenario with reduced aerosol emissions and have a high aerosol scenario with higher emission factors for AerChemMIP (Aerosol Chemistry Model Intercomparison Project) experiments. Such decisions would affect the design of GeoMIP experiments to counteract the expected warming. The GeoMIP modeling community finds it necessary to design an "intermediate" experiment for the current generation of Earth system models and current SSP scenarios [114]. The experiments will likely be replicated with the next generation of Earth system models and ScenarioMIP scenarios. As the longer-term plan for CMIP7, several themes have been discussed by the GeoMIP community, including 1) idealized experiments for the development of machine-learning emulators, 2) single forcing experiments with aerosol injections at specified locations (or more susceptible regimes) for both SAI and marine cloud brightening geoengineering strategies, and 3) experiments that will follow ScenarioMIP protocols.

Improved modeling techniques could address the uncertainty in projecting effects on wind energy that arises in part due to the coarse vertical resolution of climate models, where there may be only a couple of model levels within most wind turbine rotor diameters. With such limited data points of wind speed and direction within a rotor diameter, it is difficult to gauge future changes in wind shear and veer, which can have large impacts on power production. Setting up global and regional climate models with more model levels in the lowest few hundred meters above the surface could provide much-needed insight into this specific example, although doing so would likely also require improvements in boundary layer parameterizations.

Improved modeling techniques would also include advancements in the area of coupling crop models to climate models, as well as coupling models of marine ecosystems with climate models to holistically model the interactions of our entire ecosystem.

4.2.2. Measurements

Atmospheric measurement studies could improve the understanding of the effects of aerosols on solar energy. Measurement campaigns study stratospheric chemistry and its potential impacts on the lower troposphere, and are critical for filling in scientific gaps. For example, the recently launched Plankton, Aerosol, Cloud, and ocean Ecosystem (PACE) satellite from the National Aeronautics and Space Administration will provide critical data from numerous earth systems, including aerosol and cloud properties, two areas of the climate system that are arguably the most difficult to capture and represent in climate models [115]. The Stratospheric Aerosol processes, Budget, and Radiative Effects (SABRE) aircraft campaigns [103] are closing a longstanding gap by providing in situ measurements of stratospheric aerosols and chemistry. Recent advances in fire weather science and the utilization of unmanned aerial vehicles could shed light on how large plumes of smoke and aerosols could impact solar energy generation [116, 117]. These examples, both future and present, can further our understanding of potential impacts from real-world observations and analogues.

4.2.3. Metrics

Along with improvements to modeling and more measurement campaigns, efforts to create a set of standard metrics to use to compare changes across different models and observations would be beneficial. Lessons and processes from previous and current efforts, such as the IPCC assessment reports and GeoMIP experiments, could be leveraged to create a list of metrics that are consistent with respect to time, regions, technology, and projections, to name a few. For example, calculating normalized power for each renewable technology consistent with current IPCC sub-regions would make projected absolute and relative power changes simpler to evaluate against historical and future climates.

4.2.4. Artificial intelligence

Deploying machine learning (ML)/artificial intelligence (AI) in simulations of the impacts of geoengineering requires identifying how the physical processes simulated in geoengineered systems are likely to differ in ways that impact the use of ML/AI. It is likely that the use of ML/AI in understanding geoengineering will remain similar to how it is used in understanding climate in the absence of geoengineering. However, there is both the challenge of recognizing how geoengineering may complicate existing ML/AI work, and the opportunity to use ML/AI to improve geoengineering simulation.

A fundamental limitation of ML/AI algorithms is that predictions made outside of their training data should be treated with extreme skepticism. Simulating a geoengineered atmosphere has complicated implications for uncertainty and extrapolation. Because SRM can cause cooling in the presence of increasing greenhouse gases, changes in climate variables in a world with SRM will not scale with global mean temperature changes, unlike in a world with just climate change. However, because the climate under SRM is kept closer to an unperturbed baseline, there are fewer opportunities for uncertain feedback to cause strong climate responses [118]. The combined impacts of these effects on the ability to train ML/AI algorithms for SRM in the same way we do for climate change is not well understood. It is possible that, for instance, algorithms used to downscale data for energy resources prediction will no longer be accurate unless the training data are expanded to include data from geoengineered systems. It is also possible that different approaches to SRM, including changing particle sizes and concentrations, will require additional expansion of datasets.

4.3. Combining governance and human systems with energy systems in geoengineering

The potential costs and benefits of solar geoengineering go far beyond "moral hazard" arguments based on the possibility of geoengineering as a substitute for emissions reductions [119]. The potential for impacts in areas such as food systems, water availability, or ecosystems were identified early in consideration of geoengineering [120]. This, in turn led to initial work to quantify many of these impacts, which was incorporated into the 2022 IPCC report. These initial attempts to quantify impacts show both positive and negative outcomes from geoengineering. Simulations of the geoengineering impacts on agriculture, for instance, show that overall productivity decreases at higher latitudes due to a shorter growing season, but increases at lower latitudes due to reduced heat stresses [89, 121, 122]. Additional studies suggested that the risk of crop failures may be reduced [123]. Similar complex results were seen in infectious disease modeling under geoengineering scenarios [124]. In both agriculture and public health, positive and negative outcomes were unequally distributed internationally, suggesting a potential for international conflict [125]. These results suggest that a similar set of complex impacts from geoengineering may be encountered in energy systems, increasing the urgency of including these impacts in policy analysis of geoengineering. However, because prediction of renewable energy resources under geoengineering scenarios requires computationally expensive downscaling, quantifying potential impacts on energy systems from geoengineering lags other analysis.

Addressing this knowledge gap will require additional computational resources and research. Ensuring this knowledge gap is addressed in a truly global context will be challenging. Projections of energy resources and needs in various countries under various climate change, adaptation, and development scenarios will be most accurate when informed by in-country experts. Only the wealthiest countries have access to the computational resources needed to predict the impacts of geoengineering on renewable energy systems [126]. Individual research teams can build global partnerships. These issues should be recognized as part of a global structural problem of scientific inequity exacerbated by climate change that can only be resolved by funder-driven structural change in climate science.

The results of research into the impacts of SRM on energy systems have regional, national, and global policy implications, and interdisciplinary teams will be necessary to unpack and communicate them. If policymakers are simply confronted with an array of modeling results prepared ad hoc by individual researcher interest—as the status quo might suggest—then the result will be a noisy landscape of political actors using the results to support various political positions, which might end up further eroding trust in science. Supporting a mission-driven [127], coordinated research effort that systematically examines all types of renewable energy under multiple scenarios and is holistic and global in its effort is one way of reducing that risk. Within such a framework, policy research should explore the possible implications of unequal impacts on energy systems both within countries and at the global scale.

5. Conclusions

Earlier and current generations of climate model projections, including those that explicitly address SRM, have provided much-needed insight into potential impacts on meteorological variables relevant to renewable energy. While studies formally investigating SRM impacts on renewable energy sources such as solar energy, wind energy, hydropower, and bioenergy are currently limited, the results are nonetheless critical. According to the literature review herein, impacts on renewable energy are projected to occur under climate change and under climate change with SRM implemented. Despite this insight, many questions and uncertainties remain, ranging from the underlying climate science and physics realized in climate models to impacts on other aspects of the energy system, such as transmission and storage, the impact of climate change and SRM on the ocean and marine renewable energy resources, or whether designs of solar panels or wind turbines can be tailored to increase efficiency depending on the expected changes in the resource. Literature focused on cost analyses with regards to SRM; whether this is the cost of deploying SRM or the impacts on costs to the energy system or economies regardless of SRM deployment has not been included and can be the topic of a future study.

Climate change is anticipated to have an impact on the renewable energy resources discussed in this review. Likewise, as demonstrated in the literature, SRM has potential impacts on solar energy, wind energy, hydropower, and bioenergy. The global effects of climate change and SRM are highly uncertain. Effects on renewable energy will depend on site-specific, resource-specific effects as well as broader human systems effects. As the installed capacity of renewable energy increases across the globe, the site-specific, regional, and system changes that could affect renewable energy increase as well. These impacts vary substantially by emissions scenario and SRM implementation.

Despite the uncertainties in the climate system and the effects of SRM, several tendencies can be identified in the literature. Climate change is projected to increase precipitation globally and increase extreme events (drought, flood) while SAI is projected to decrease precipitation and moderate the temperature increases arising from climate change. However, we do not live in a globally averaged world. We live in a world where the exact location of a drought or flood matters, where it matters whether it pours for a few weeks, potentially flooding our crops while we try to survive in a drought the rest of the year. On average, a flood followed by a drought might show up as zero impact. Likewise, these precipitation effects identified in the literature are ambiguous and region-specific, especially for renewable energy applications. According to the literature, CO_2 in the atmosphere will increase biomass growth (primary productivity) under climate change, and biomass may see additional benefits with SAI with reduced heat stress. Climate change will decrease the equator-to-pole temperature gradient, which drives certain wind patterns. Changes in wind speed matter on an hourly basis because we need wind energy to meet electricity demand, which in turn changes in the course of the day. These are some examples that underline that the trends found in the literature are uncertain and vary regionally, and that more research is needed to understand the effect of climate change and SRM on renewable energy.

Some of the uncertainties encountered in this review that are critical to answering key questions about SRM impacts on renewable energy can also be driving forces for future work that could include overall improvement in atmospheric science and climate modeling, as well as more specific research on effects on renewable energy model improvement, measurement campaigns, simulation studies, and application of AI. Such research could increase the understanding of the projected impacts of climate change and SRM at the surface, including effects on renewable energy.

Taking into account modeling uncertainties, one might ponder whether the impacts of climate change or SRM on renewable energy can be estimated at all. One of the options could be to conduct more modeling studies with the explicit intention of assessing the impacts on renewable energy. These studies need to have high spatial and temporal resolutions to be able to estimate the impact of power output on the future grid. Atmospheric data are usually needed in sub-hourly intervals. Studying the impact of climate change and SRM on hybrid systems (i.e., co-located wind energy, solar energy, marine energy, or hydrogen production plants) would be an important topic for renewable energy research. For co-located renewables, the results could be balanced or cascading.

This review documents the status of the scientific understanding at the intersection of climate change, SRM, and renewable energy, highlights gaps, and identifies potential avenues of research to address those gaps. But because SRM is a choice, scientific understanding alone is insufficient to address broader human systems considerations that include political, philosophical, and environmental justice dimensions. Any decision to use SRM, and any set of criteria for its design, could consider an array of values across various human systems, only one of which is the effect on renewable energy.

CRediT authorship contribution statement

Andrew Kumler: Conceptualization, Methodology, Formal Analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision. **Ben Kravitz:** Conceptualization, Investigation, Writing - Original Draft, Writing - Review & Editing. **Caroline Draxl:** Conceptualization, Resources, Writing - Original Draft, Writing - Review & Editing, Supervision, Project administration, Funding acquisition. **Laura Vimmerstedt:** Conceptualization, Resources, Writing - Original Draft, Writing - Review & Editing, Supervision, Project administration, Funding acquisition. **Brandon Benton:** Conceptualization, Investigation, Writing - Original Draft, Writing - Review & Editing. **Julie K. Lundquist:** Conceptualization, Investigation, Writing - Original Draft, Writing - Review & Editing. **Michael Martin:** Conceptualization, Investigation, Writing - Original Draft, Writing - Review & Editing. **Holly Jean Buck:** Conceptualization, Investigation, Writing - Original Draft, Writing - Review & Editing. **Hailong Wang:** Conceptualization, Investigation, Writing - Original Draft, Writing - Review & Editing.

Christopher Lennard: Conceptualization, Writing - Review & Editing. **Ling Tao:** Conceptualization, Writing - Review & Editing.

6. Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

7. Acknowledgements

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. This work was supported by the Laboratory Directed Research and Development (LDRD) Program at NREL. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

We would like to thank the United Nations Environment Programme for providing us with the high-resolution copy of Figure 1 for reproduction. Additionally, we would like to thank Kendra Ryan and Ulrike Egerer of NREL for internally reviewing this manuscript.

References

[1] IPCC, Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Technical Report, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2021. URL: https://doi.org/10.1017/9781009157896.
[2] IRENA, Renewable capacity statistics 2023, Technical Report, International Renewable Energy Agency, Abu Dhabi, 2023.
[3] A. Kumler, I. L. Carreño, M. T. Craig, B.-M. Hodge, W. Cole, C. Brancucci, Inter-annual variability of wind and solar electricity generation and capacity values in Texas, Environmental Research Letters 14 (2019) 044032. Publisher: IOP Publishing.
[4] M. T. Craig, I. Losada Carreño, M. Rossol, B.-M. Hodge, C. Brancucci, Effects on power system operations of potential changes in wind and solar generation potential under climate change, Environmental Research Letters 14 (2019) 034014. Publisher: IOP Publishing.
[5] I. L. Carreño, M. T. Craig, M. Rossol, M. Ashfaq, F. Batıbeniz, S. E. Haupt, C. Draxl, B.-M. Hodge, C. Brancucci, Potential impacts of climate change on wind and solar electricity generation in Texas, Climatic Change (2020).
[6] C. Tebaldi, P. Friedlingstein, Delayed detection of climate mitigation benefits due to climate inertia and variability, Proceedings of the National Academy of Sciences 110 (2013) 17229–17234. Publisher: Proceedings of the National Academy of Sciences.
[7] T. R. Knutson, M. V. Chung, G. Vecchi, J. Sun, T.-L. Hsieh, A. J. P. Smith, Climate change is probably increasing the intensity of tropical cyclones, 2021. URL: https://doi.org/10.5281/zenodo.4570334. doi:10.5281/zenodo.4570334.
[8] M. Ohba, Y. Kanno, S. Bando, Effects of meteorological and climatological factors on extremely high residual load and possible future changes, Renewable and Sustainable Energy Reviews 175 (2023) 113188.
[9] J. Doss-Gollin, Y. Amonkar, K. Schmeltzer, D. Cohan, Improving the Representation of Climate Risks in Long-Term Electricity Systems Planning: a Critical Review, Current Sustainable/Renewable Energy Reports 10 (2023) 206–217.
[10] G. Konapala, A. K. Mishra, Y. Wada, M. E. Mann, Climate change will affect global water availability through compounding changes in seasonal precipitation and evaporation, Nature Communications 11 (2020) 3044.
[11] J. Olesen, M. Trnka, K. Kersebaum, A. Skjelvåg, B. Seguin, P. Peltonen-Sainio, F. Rossi, J. Kozyra, F. Micale, Impacts and adaptation of European crop production systems to climate change, European Journal of Agronomy 34 (2011) 96–112.
[12] M. Kanoğlu, Y. A. Çengel, J. M. Cimbala, Fundamentals and applications of renewable energy, McGraw-Hill Education, 2020.
[13] K. B. Karnauskas, J. K. Lundquist, L. Zhang, Southward shift of the global wind energy resource under high carbon dioxide emissions, Nature Geoscience 11 (2018) 38–43. Number: 1 Publisher: Nature Publishing Group.
[14] D. E. Gernaat, H. S. d. Boer, V. Daioglou, S. Yalew, C. Müller, D. P. v. Vuuren, Climate change impacts on renewable energy supply, Nature Climate Change (2021).
[15] B. J. Soden, R. T. Wetherald, G. L. Stenchikov, A. Robock, Global Cooling After the Eruption of Mount Pinatubo: A Test of Climate Feedback by Water Vapor, Science 296 (2002) 727–730. Publisher: American Association for the Advancement of Science.
[16] D. G. MacMartin, K. L. Ricke, D. W. Keith, Solar geoengineering as part of an overall strategy for meeting the 1.5°C Paris target, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 376 (2018) 20160454. Publisher: Royal Society.
[17] A. Parker, P. J. Irvine, The Risk of Termination Shock From Solar Geoengineering, Earth's Future 6 (2018) 456–467. Publisher: John Wiley & Sons, Ltd.
[18] P. J. Irvine, B. Kravitz, M. G. Lawrence, H. Muri, An overview of the Earth system science of solar geoengineering, WIREs Climate Change 7 (2016) 815–833. _eprint: https://wires.onlinelibrary.wiley.com/doi/pdf/10.1002/wcc.423.

[19] J. L. Reynolds, Solar geoengineering to reduce climate change: a review of governance proposals, Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 475 (2019) 20190255. _eprint: https://royalsocietypublishing.org/doi/pdf/10.1098/rspa.2019.0255.

[20] C. J. Smith, J. A. Crook, R. Crook, L. S. Jackson, S. M. Osprey, P. M. Forster, Impacts of Stratospheric Sulfate Geoengineering on Global Solar Photovoltaic and Concentrating Solar Power Resource, Journal of Applied Meteorology and Climatology 56 (2017) 1483 – 1497. Place: Boston MA, USA Publisher: American Meteorological Society.

[21] S. Baur, B. M. Sanderson, R. Séférian, L. Terray, Solar radiation modification challenges decarbonization with renewable solar energy, Earth System Dynamics (2024) 307–322.

[22] K. Dagon, D. P. Schrag, Quantifying the effects of solar geoengineering on vegetation, Climatic Change 153 (2019) 235–251.

[23] W. Cheng, D. G. MacMartin, K. Dagon, B. Kravitz, S. Tilmes, J. H. Richter, M. J. Mills, I. R. Simpson, Soil Moisture and Other Hydrological Changes in a Stratospheric Aerosol Geoengineering Large Ensemble, Journal of Geophysical Research: Atmospheres 124 (2019) 12773–12793. Publisher: John Wiley & Sons, Ltd.

[24] United Nations Environment Programme, One Atmosphere: An Independent Expert Review on Solar Radiation Modification Research and Deployment (2023).

[25] N. Gökmen, W. Hu, P. Hou, Z. Chen, D. Sera, S. Spataru, Investigation of wind speed cooling effect on PV panels in windy locations, Renewable Energy 90 (2016) 283–290.

[26] M. Romero, J. González-Aguilar, Solar thermal CSP technology, WIREs Energy and Environment 3 (2014) 42–59. Publisher: John Wiley & Sons, Ltd.

[27] M. AL-Rasheedi, C. A. Gueymard, M. Al-Khayat, A. Ismail, J. A. Lee, H. Al-Duaj, Performance evaluation of a utility-scale dual-technology photovoltaic power plant at the Shagaya Renewable Energy Park in Kuwait, Renewable and Sustainable Energy Reviews 133 (2020) 110139.

[28] R. Conceição, H. G. Silva, M. Collares-Pereira, CSP mirror soiling characterization and modeling, Solar Energy Materials and Solar Cells 185 (2018) 233–239.

[29] C. D. Zamuda, D. E. Bilello, J. Carmack, X. J. Davis, R. A. Efroymson, K. M. Goff, T. Hong, A. Karimjee, D. H. Loughlin, S. Upchurch, N. Voisin, Energy supply, delivery, and demand, in: A. Crimmins, C. Avery, D. Easterling, K. Kunkel, B. Stewart, T. Maycock (Eds.), Fifth National Climate Assessment, U.S. Global Change Research Program, Washington, DC, USA, 2023. doi:10.7930/NCA5.2023.CH5, section: 5 Type: Book Section.

[30] M. Wild, D. Folini, F. Henschel, N. Fischer, B. Müller, Projections of long-term changes in solar radiation based on CMIP5 climate models and their influence on energy yields of photovoltaic systems, Solar Energy 116 (2015) 12–24.

[31] W. Sawadogo, M. S. Reboita, A. Faye, R. P. da Rocha, R. C. Odoulami, C. Olusegun, M. Adeniyi, B. J. Abiodun, M. B. Sylla, I. Diallo, E. Coppola, F. Giorgi, Current and future potential of solar and wind energy over Africa using the RegCM4 CORDEX-CORE ensemble, Climate Dynamics (2020).

[32] The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity, in: Intergovernmental Panel on Climate Change (IPCC) (Ed.), Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2023, pp. 923–1054. URL: https://www.cambridge.org/core/product/AE57C97E588FF3060C7C7E47DD4F3C6E. doi:10.1017/9781009157896.009.

[33] J. Crook, L. Jones, P. Forster, R. Crook, Climate change impacts on future photovoltaic and concentrated solar power energy output (2011).

[34] T. R. McVicar, M. L. Roderick, R. J. Donohue, L. T. Li, T. G. V. Niel, A. Thomas, J. Grieser, D. Jhajharia, Y. Himri, N. M. Mahowald, A. V. Mescherskaya, A. C. Kruger, S. Rehman, Y. Dinpashoh, Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation, Journal of Hydrology 416-417 (2012) 182–205.

[35] R. Cherian, J. Quaas, Trends in AOD, Clouds, and Cloud Radiative Effects in Satellite Data and CMIP5 and CMIP6 Model Simulations Over Aerosol Source Regions, Geophysical Research Letters 47 (2020) e2020GL087132. Publisher: John Wiley & Sons, Ltd.

[36] M. Wild, D. Folini, F. Henschel, Impact of climate change on future concentrated solar power (CSP) production (2017).

[37] R. Dutta, K. Chanda, R. Maity, Future of solar energy potential in a changing climate across the world: A CMIP6 multi-model ensemble analysis, Renewable Energy 188 (2022) 819–829.

[38] L. Chen, Uncertainties in solar radiation assessment in the United States using climate models, Climate Dynamics 56 (2021) 665–678.

[39] M. T. Craig, S. Cohen, J. Macknick, C. Draxl, O. J. Guerra, M. Sengupta, S. E. Haupt, B.-M. Hodge, C. Brancucci, A review of the potential impacts of climate change on bulk power system planning and operations in the United States, Renewable and Sustainable Energy Reviews 98 (2018) 255–267.

[40] S. Feron, R. R. Cordero, A. Damiani, R. B. Jackson, Climate change extremes and photovoltaic power output, Nature Sustainability 4 (2021) 270–276.

[41] D. Watson-Parris, C. J. Smith, Large uncertainty in future warming due to aerosol forcing, Nature Climate Change 12 (2022) 1111–1113.

[42] M. D. Zelinka, C. J. Smith, Y. Qin, K. E. Taylor, Comparison of methods to estimate aerosol effective radiative forcings in climate models, Atmospheric Chemistry and Physics 23 (2023) 8879–8898.

[43] J. T. Kiehl, Twentieth century climate model response and climate sensitivity, Geophysical Research Letters 34 (2007). Publisher: John Wiley & Sons, Ltd.

[44] A. J. Schuddeboom, A. J. McDonald, The Southern Ocean Radiative Bias, Cloud Compensating Errors, and Equilibrium Climate Sensitivity in CMIP6 Models, Journal of Geophysical Research: Atmospheres 126 (2021) e2021JD035310. _eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2021JD035310.

[45] L. Zhao, Y. Wang, C. Zhao, X. Dong, Y. L. Yung, Compensating Errors in Cloud Radiative and Physical Properties over the Southern Ocean in the CMIP6 Climate Models, Advances in Atmospheric Sciences 39 (2022) 2156–2171.

[46] A. N. Hahmann, O. García-Santiago, A. Peña, Current and future wind energy resources in the North Sea according to CMIP6, Wind Energy Science 7 (2022) 2373–2391.

[47] M. Brower, Wind Resource Assessment: A Practical Guide to Developing a Wind Project, 1. aufl. ed., Wiley, Somerset, 2012. Book Title: Wind Resource Assessment.

[48] A. K. Blackadar, Boundary Layer Wind Maxima and Their Significance for the Growth of Nocturnal Inversions, Bulletin of the American Meteorological Society 38 (1957) 283 – 290. Place: Boston MA, USA Publisher: American Meteorological Society.

[49] N. Bodini, J. K. Lundquist, A. Kirincich, U.S. East Coast Lidar Measurements Show Offshore Wind Turbines Will Encounter Very Low Atmospheric Turbulence, Geophysical Research Letters 46 (2019) 5582–5591. _eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2019GL082636.

[50] I. Tobin, S. Jerez, R. Vautard, F. Thais, E. v. Meijgaard, A. Prein, M. Déqué, S. Kotlarski, C. F. Maule, G. Nikulin, T. Noël, C. Teichmann, Climate change impacts on the power generation potential of a European mid-century wind farms scenario, Environmental Research Letters 11 (2016) 034013. Publisher: IOP Publishing.

[51] J. Moemken, M. Reyers, H. Feldmann, J. G. Pinto, Future Changes of Wind Speed and Wind Energy Potentials in EURO-CORDEX Ensemble Simulations, Journal of Geophysical Research: Atmospheres 123 (2018) 6373–6389. _eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2018JD028473.

[52] S. C. Pryor, R. J. Barthelmie, M. S. Bukovsky, L. R. Leung, K. Sakaguchi, Climate change impacts on wind power generation, Nature Reviews Earth & Environment 1 (2020) 627–643.

[53] I. Barstad, A. Sorteberg, M. d.-S. Mesquita, Present and future offshore wind power potential in northern Europe based on downscaled global climate runs with adjusted SST and sea ice cover, Renewable Energy 44 (2012) 398–405.

[54] H. Hueging, R. Haas, K. Born, D. Jacob, J. Pinto, Regional Changes in Wind Energy Potential over Europe Using Regional Climate Model Ensemble Projections (2013).

[55] M. Reyers, J. Moemken, J. G. Pinto, Future changes of wind energy potentials over Europe in a large CMIP5 multi-model ensemble, International Journal of Climatology (2016).

[56] I. Tobin, R. Vautard, I. Balog, F.-M. Bréon, S. Jerez, P. Ruti, F. Thais, M. Vrac, P. Yiou, Assessing climate change impacts on European wind energy from ENSEMBLES high-resolution climate projections, Climatic Change (2015).

[57] K. Walter, C. C. Weiss, A. H. P. Swift, J. Chapman, N. D. Kelley, Speed and Direction Shear in the Stable Nocturnal Boundary Layer, Journal of Solar Energy Engineering 131 (2009) 011013. _eprint: https://asmedigitalcollection.asme.org/solarenergyengineering/article-pdf/131/1/011013/5714480/011013_1.pdf.

[58] J. K. Lundquist, K. K. DuVivier, D. Kaffine, J. M. Tomaszewski, Costs and consequences of wind turbine wake effects arising from uncoordinated wind energy development, Nature Energy 4 (2019) 26–34.

[59] M. Caretta, A. Mukherji, M. Arfanuzzaman, R. Betts, A. Gelfan, Y. Hirabayashi, T. Lissner, J. Liu, E. Lopez Gunn, R. Morgan, S. Mwanga, S. Supratid, Water, Cambridge University Press, Cambridge, UK and New York, NY, USA, 2022, pp. 551–712. doi:10.1017/9781009325844.006.

[60] A. Wasti, P. Ray, S. Wi, C. Folch, M. Ubierna, P. Karki, Climate change and the hydropower sector: A global review, WIREs Climate Change 13 (2022) e757. _eprint: https://wires.onlinelibrary.wiley.com/doi/pdf/10.1002/wcc.757.

[61] K. N. Musselman, F. Lehner, K. Ikeda, M. P. Clark, A. F. Prein, C. Liu, M. Barlage, R. Rasmussen, Projected increases and shifts in rain-on-snow flood risk over western North America, Nature Climate Change 8 (2018) 808–812.

[62] M. Ombadi, M. D. Risser, A. M. Rhoades, C. Varadharajan, A warming-induced reduction in snow fraction amplifies rainfall extremes, Nature 619 (2023) 305–310.

[63] S.-C. Kao, M. Ashfaq, D. Rastogi, S. Gangrade, R. Uria Martinez, A. Fernandez, G. Konapala, N. Voisin, T. Zhou, W. Xu, H. Gao, B. Zhao, G. Zhao, The Third Assessment of the Effects of Climate Change on Federal Hydropower, Technical Report, United States, 2022. URL: https://www.osti.gov/biblio/1887712. doi:10.2172/1887712.

[64] D. Rastogi, S.-C. Kao, M. Ashfaq, How May the Choice of Downscaling Techniques and Meteorological Reference Observations Affect Future Hydroclimate Projections?, Earth's Future 10 (2022) e2022EF002734. Publisher: John Wiley & Sons, Ltd.

[65] T. Zhou, S.-C. Kao, W. Xu, S. Gangrade, N. Voisin, Impacts of climate change on subannual hydropower generation: a multi-model assessment of the United States federal hydropower plant, Environmental Research Letters 18 (2023) 034009. Publisher: IOP Publishing.

[66] C. Rosenzweig, J. Elliott, D. Deryng, A. C. Ruane, C. Müller, A. Arneth, K. J. Boote, C. Folberth, M. Glotter, N. Khabarov, K. Neumann, F. Piontek, T. A. M. Pugh, E. Schmid, E. Stehfest, H. Yang, J. W. Jones, Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison, Proceedings of the National Academy of Sciences 111 (2014) 3268–3273. Publisher: Proceedings of the National Academy of Sciences.

[67] K. Solaun, E. Cerdá, Climate change impacts on renewable energy generation. A review of quantitative projections, Renewable and Sustainable Energy Reviews 116 (2019) 109415.

[68] J. Jägermeyr, C. Müller, A. C. Ruane, J. Elliott, J. Balkovic, O. Castillo, B. Faye, I. Foster, C. Folberth, J. A. Franke, K. Fuchs, J. R. Guarin, J. Heinke, G. Hoogenboom, T. Iizumi, A. K. Jain, D. Kelly, N. Khabarov, S. Lange, T.-S. Lin, W. Liu, O. Mialyk, S. Minoli, E. J. Moyer, M. Okada, M. Phillips, C. Porter, S. S. Rabin, C. Scheer, J. M. Schneider, J. F. Schyns, R. Skalsky, A. Smerald, T. Stella, H. Stephens, H. Webber, F. Zabel, C. Rosenzweig, Climate impacts on global agriculture emerge earlier in new generation of climate and crop models, Nature Food 2 (2021) 873–885.

[69] V. Zapata, D. E. H. J. Gernaat, S. G. Yalew, S. R. Santos da Silva, G. Iyer, M. Hejazi, D. P. van Vuuren, Climate change impacts on the energy system: a model comparison, Environmental Research Letters 17 (2022) 034036. Publisher: IOP Publishing.

[70] J. Cronin, G. Anandarajah, O. Dessens, Climate change impacts on the energy system: a review of trends and gaps, Climatic Change 151 (2018) 79–93.

[71] H. Haberl, K.-H. Erb, F. Krausmann, A. Bondeau, C. Lauk, C. Müller, C. Plutzar, J. K. Steinberger, Global bioenergy potentials from agricultural land in 2050: Sensitivity to climate change, diets and yields, Land use impacts of bioenergy. Selected papers from the IEA Bioenergy Task 38 Meetings in Helsinki, 2009 and Brussels, 2010 35 (2011) 4753–4769.

[72] F. Groundstroem, S. Juhola, Using systems thinking and causal loop diagrams to identify cascading climate change impacts on bioenergy supply systems, Mitigation and Adaptation Strategies for Global Change 26 (2021) 29.

[73] Y. Cheng, M. Huang, D. M. Lawrence, K. Calvin, D. L. Lombardozzi, E. Sinha, M. Pan, X. He, Future bioenergy expansion could alter carbon sequestration potential and exacerbate water stress in the United States, Science Advances 8 (2022) eabm8237. Publisher: American Association for the Advancement of Science.

[74] Food, Fibre and Other Ecosystem Products, in: Intergovernmental Panel on Climate Change (IPCC) (Ed.), Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2023, pp. 713–906. URL: https://www.cambridge.org/core/product/16B2DB8BEC0790EA6DB2856CD8897DFF. doi:10.1017/9781009325844.007.

[75] M. A. Delucchi, Impacts of biofuels on climate change, water use, and land use, Annals of the New York Academy of Sciences 1195 (2010) 28–45. _eprint: https://nyaspubs.onlinelibrary.wiley.com/doi/pdf/10.1111/j.1749-6632.2010.05457.x.

[76] M. Georgescu, D. B. Lobell, C. B. Field, Direct climate effects of perennial bioenergy crops in the United States, Proceedings of the National Academy of Sciences of the United States of America (2011).

[77] B. Kravitz, K. Caldeira, O. Boucher, A. Robock, P. Rasch, K. Alterskjær, D. Karam, J. Cole, C. Curry, J. Haywood, P. Irvine, D. Ji, A. Jones, J. Kristjánsson, D. Lunt, J. C. Moore, U. Niemeier, H. Schmidt, M. Schulz, B. Singh, S. Tilmes, S. Watanabe, S. Yang, J. Yoon, Climate model response from the Geoengineering Model Intercomparison Project (GeoMIP) (2013).

[78] B. Kravitz, D. G. MacMartin, K. Caldeira, Geoengineering: Whiter skies?, Geophysical Research Letters 39 (2012). _eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2012GL051652.

[79] A. Robock, Volcanic eruptions and climate, Reviews of Geophysics 38 (2000) 191–219. _eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/1998RG000054.

[80] L. M. Mercado, N. Bellouin, S. Sitch, O. Boucher, C. Huntingford, M. Wild, P. M. Cox, Impact of changes in diffuse radiation on the global land carbon sink, Nature 458 (2009) 1014–1017.

[81] D. M. Murphy, Effect of Stratospheric Aerosols on Direct Sunlight and Implications for Concentrating Solar Power, Environmental Science & Technology 43 (2009) 2784–2786. Publisher: American Chemical Society.

[82] J. M. Haywood, A. Jones, A. C. Jones, P. Halloran, P. J. Rasch, Climate intervention using marine cloud brightening (MCB) compared with stratospheric aerosol injection (SAI) in the UKESM1 climate model, Atmospheric Chemistry and Physics 23 (2023) 15305–15324.

[83] B. Kravitz, D. G. MacMartin, Uncertainty and the basis for confidence in solar geoengineering research, Nature Reviews Earth & Environment (2020).

[84] S. Baur, B. M. Sanderson, R. Séférian, L. Terray, Change in Wind Renewable Energy Potential under Stratospheric Aerosol Injections, 2024. URL: https://hal.science/hal-04449996, working paper or preprint.

[85] S. Tilmes, J. Fasullo, J. Lamarque, D. Marsh, M. Mills, K. Alterskjær, H. Muri, J. Kristjánsson, O. Boucher, M. Schulz, J. Cole, C. Curry, A. Jones, J. Haywood, P. Irvine, D. Ji, J. C. Moore, D. Karam, B. Kravitz, P. Rasch, B. Singh, J. Yoon, U. Niemeier, H. Schmidt, A. Robock, S. Yang, S. Watanabe, The hydrological impact of geoengineering in the Geoengineering Model Intercomparison Project (GeoMIP) (2013).

[86] J. C. Moore, R. Greve, C. Yue, T. Zwinger, F. Gillet-Chaulet, L. Zhao, Reduced Ice Loss From Greenland Under Stratospheric Aerosol Injection, Journal of Geophysical Research: Earth Surface 128 (2023) e2023JF007112. Publisher: John Wiley & Sons, Ltd.

[87] I. R. Simpson, S. Tilmes, J. H. Richter, B. Kravitz, D. G. MacMartin, M. J. Mills, J. T. Fasullo, A. G. Pendergrass, The Regional Hydroclimate Response to Stratospheric Sulfate Geoengineering and the Role of Stratospheric Heating, Journal of Geophysical Research (2019).

[88] P. J. Irvine, D. J. Lunt, E. J. Stone, A. Ridgwell, The fate of the Greenland Ice Sheet in a geoengineered, high CO2 world, Environmental Research Letters 4 (2009) 045109.

[89] J. Pongratz, D. B. Lobell, L. Cao, K. Caldeira, Crop yields in a geoengineered climate, Nature Climate Change 2 (2012) 101–105.

[90] Y. Fan, J. Tjiputra, H. Muri, D. Lombardozzi, C.-E. Park, S. Wu, D. Keith, Solar geoengineering can alleviate climate change pressures on crop yields, Nature Food 2 (2021) 373–381.

[91] B. Kravitz, D. G. MacMartin, D. Visioni, O. Boucher, J. N. S. Cole, J. Haywood, A. Jones, T. Lurton, P. Nabat, U. Niemeier, A. Robock, R. Séférian, S. Tilmes, Comparing different generations of idealized solar geoengineering simulations in the Geoengineering Model Intercomparison Project (GeoMIP), Atmospheric Chemistry and Physics (2021).

[92] C.-E. Yang, F. Hoffman, D. Ricciuto, S. Tilmes, L. Xia, D. MacMartin, B. Kravitz, J. Richter, M. Mills, J. S. Fu, Assessing terrestrial biogeochemical feedbacks in a strategically geoengineered climate, Environmental Research Letters (2020).

[93] L. Xia, A. Robock, S. Tilmes, R. R. Neely III, Stratospheric sulfate geoengineering could enhance the terrestrial photosynthesis rate, Atmospheric Chemistry and Physics 16 (2016) 1479–1489.

[94] B. Clark, L. Xia, A. Robock, S. Tilmes, J. H. Richter, D. Visioni, S. S. Rabin, Optimal climate intervention scenarios for crop production vary by nation, Nature Food 4 (2023) 902–911.

[95] Y. Fan, Unequal effects of climate intervention on agriculture, Nature Food 4 (2023) 835–836.

[96] M. D. Zelinka, T. A. Myers, D. T. McCoy, S. Po-Chedley, P. M. Caldwell, P. Ceppi, S. A. Klein, K. E. Taylor, Causes of Higher Climate Sensitivity in CMIP6 Models, Geophysical Research Letters 47 (2020) e2019GL085782. _eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2019GL085782.

[97] C. W. Stjern, H. Muri, L. Ahlm, O. Boucher, J. Cole, D. Ji, A. Jones, J. Haywood, B. Kravitz, A. Lenton, J. Moore, U. Niemeier, S. Phipps, H. Schmidt, S. Watanabe, J. Kristjánsson, Response to marine cloud brightening in a multi-model ensemble (2017).

[98] L. Ahlm, A. Jones, C. W. Stjern, H. Muri, B. Kravitz, J. Kristjánsson, Marine cloud brightening – as effective without clouds (2017).

[99] D. Visioni, D. MacMartin, B. Kravitz, O. Boucher, A. Jones, T. Lurton, M. Martine, M. Mills, P. Nabat, U. Niemeier, R. Séférian, S. Tilmes, Identifying the sources of uncertainty in climate model simulations of solar radiation modification with the G6sulfur and G6solar Geoengineering Model Intercomparison Project (GeoMIP) simulations, Atmospheric Chemistry and Physics (2021).

[100] S. Tilmes, R. Garcia, D. Kinnison, A. Gettelman, P. Rasch, Impact of geoengineered aerosols on the troposphere and stratosphere (2009).

[101] H. N. Huynh, V. F. McNeill, The potential environmental and climate impacts of stratospheric aerosol injection: a review, Environ. Sci.: Atmos. 4 (2024) 114–143. Publisher: RSC.

[102] S. Tilmes, M. J. Mills, Y. Zhu, C. G. Bardeen, F. Vitt, P. Yu, D. Fillmore, X. Liu, B. Toon, T. Deshler, Description and performance of a sectional aerosol microphysical model in the Community Earth System Model (CESM2), Geoscientific Model Development 16 (2023) 6087–6125.

[103] D. M. Murphy, M. Abou-Ghanem, D. J. Cziczo, K. D. Froyd, J. Jacquot, M. J. Lawler, C. Maloney, J. M. C. Plane, M. N. Ross, G. P. Schill, X. Shen, Metals from spacecraft reentry in stratospheric aerosol particles, Proceedings of the National Academy of Sciences 120 (2023) e2313374120. Publisher: Proceedings of the National Academy of Sciences.

[104] D. Visioni, E. M. Bednarz, W. R. Lee, B. Kravitz, A. Jones, J. M. Haywood, D. G. MacMartin, Climate response to off-equatorial stratospheric sulfur injections in three Earth system models – Part 1: Experimental protocols and surface changes, Atmospheric Chemistry and Physics 23 (2023) 663–685.

[105] B. Kravitz, D. G. MacMartin, H. Wang, P. J. Rasch, Geoengineering as a design problem, Earth System Dynamics Discussions (2016).

[106] D. Visioni, A. Robock, A. Duffey, I. Quaglia, Process-Level Experiments and Policy-Relevant Scenarios in Future GeoMIP Iterations, Bulletin of the American Meteorological Society 104 (2023) E501–E503. Place: Boston MA, USA Publisher: American Meteorological Society.

[107] D. Visioni, D. G. MacMartin, B. Kravitz, J. H. Richter, S. Tilmes, M. J. Mills, Seasonally Modulated Stratospheric Aerosol Geoengineering Alters the Climate Outcomes, Geophysical Research Letters 47 (2020) e2020GL088337. _eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2020GL088337.

[108] S. Tilmes, J. H. Richter, M. J. Mills, B. Kravitz, D. G. MacMartin, F. Vitt, J. J. Tribbia, J.-F. Lamarque, Sensitivity of Aerosol Distribution and Climate Response to Stratospheric SO2 Injection Locations, Journal of Geophysical Research: Atmospheres 122 (2017) 12,591–12,615. _eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2017JD026888.

[109] J. M. Haywood, A. Jones, N. Bellouin, D. Stephenson, Asymmetric forcing from stratospheric aerosols impacts Sahelian rainfall, Nature Climate Change 3 (2013) 660–665.

[110] M. Henry, J. Haywood, A. Jones, M. Dalvi, A. Wells, D. Visioni, E. M. Bednarz, D. G. MacMartin, W. Lee, M. R. Tye, Comparison of UKESM1 and CESM2 simulations using the same multi-target stratospheric aerosol injection strategy, Atmospheric Chemistry and Physics 23 (2023) 13369–13385.

[111] J. T. Fasullo, J. H. Richter, Dependence of strategic solar climate intervention on background scenario and model physics, Atmospheric Chemistry and Physics 23 (2023) 163–182.

[112] Technical Summary, in: Intergovernmental Panel on Climate Change (IPCC) (Ed.), Climate Change 2022 - Mitigation of Climate Change: Working Group III Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, 2023, pp. 51–148. URL: https://www.cambridge.org/core/product/5B255A3E29E6976F492038261E811206. doi:10.1017/9781009157926.002.

[113] D. van Vuuren, C. Tebaldi, B. O'Neill, S. SSC, W. participants, ScenarioMIP workshop: Pathway to next generation scenarios for CMIP7, 2023. URL: https://doi.org/10.5281/zenodo.8186116. doi:10.5281/zenodo.8186116.

[114] D. Visioni, A. Robock, J. Haywood, M. Henry, A. Wells, A New Era for the Geoengineering Model Intercomparison Project (GeoMIP), Bulletin of the American Meteorological Society 104 (2023) E1950 – E1955. Place: Boston MA, USA.

[115] O. P. Hasekamp, G. Fu, S. P. Rusli, L. Wu, A. Di Noia, J. a. d. Brugh, J. Landgraf, J. Martijn Smit, J. Rietjens, A. van Amerongen, Aerosol measurements by SPEXone on the NASA PACE mission: expected retrieval capabilities, Journal of Quantitative Spectroscopy and Radiative Transfer 227 (2019) 170–184.

[116] M. J. Brewer, C. B. Clements, Meteorological Profiling in the Fire Environment Using UAS, Fire 3 (2020).

[117] D. L. Donaldson, D. M. Piper, D. Jayaweera, Temporal Solar Photovoltaic Generation Capacity Reduction From Wildfire Smoke, IEEE Access 9 (2021) 79841–79852.

[118] D. G. MacMartin, B. Kravitz, P. J. Rasch, On solar geoengineering and climate uncertainty, Geophysical Research Letters 42 (2015) 7156–7161. _eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1002/2015GL065391.

[119] A. Corner, N. Pidgeon, Geoengineering, climate change scepticism and the 'moral hazard' argument: an experimental study of UK public perceptions, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 372 (2014) 20140063. _eprint: https://royalsocietypublishing.org/doi/pdf/10.1098/rsta.2014.0063.

[120] P. J. Irvine, B. Kravitz, M. G. Lawrence, D. Gerten, C. Caminade, S. N. Gosling, E. J. Hendy, B. T. Kassie, W. D. Kissling, H. Muri, A. Oschlies, S. J. Smith, Towards a comprehensive climate impacts assessment of solar geoengineering, Earth's Future 5 (2017) 93–106. Publisher: John Wiley & Sons, Ltd.

[121] L. Xia, A. Robock, J. Cole, C. L. Curry, D. Ji, A. Jones, B. Kravitz, J. C. Moore, H. Muri, U. Niemeier, B. Singh, S. Tilmes, S. Watanabe, J.-H. Yoon, Solar radiation management impacts on agriculture in China: A case study in the Geoengineering Model Intercomparison Project (GeoMIP), Journal of Geophysical Research: Atmospheres 119 (2014) 8695–8711. Publisher: John Wiley & Sons, Ltd.

[122] P. Zhan, W. Zhu, T. Zhang, X. Cui, N. Li, Impacts of Sulfate Geoengineering on Rice Yield in China: Results From a Multimodel Ensemble, Earth's Future 7 (2019) 395–410. Publisher: John Wiley & Sons, Ltd.

[123] B. Parkes, A. Challinor, K. Nicklin, Crop failure rates in a geoengineered climate: impact of climate change and marine cloud brightening, Environmental Research Letters 10 (2015) 084003. Publisher: IOP Publishing.

[124] C. J. Carlson, R. Colwell, M. S. Hossain, M. M. Rahman, A. Robock, S. J. Ryan, M. S. Alam, C. H. Trisos, Solar geoengineering could redistribute malaria risk in developing countries, Nature Communications 13 (2022) 2150.

[125] A. Parker, J. B. Horton, D. W. Keith, Stopping Solar Geoengineering Through Technical Means: A Preliminary Assessment of Counter-Geoengineering, Earth's Future 6 (2018) 1058–1065. _eprint: https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2018EF000864.

[126] J. Tollefson, Climate scientists push for access to world's biggest supercomputers to build better Earth models., Nature (2023).

[127] D. R. Morrow, A mission-driven research program on solar geoengineering could promote justice and legitimacy, Critical Review of International Social and Political Philosophy 23 (2020) 618–640. Publisher: Routledge.