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Avoiding the “Great Filter”: An assessment of climate change solutions and combinations for effective implementation

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Global climate temperatures have unmistakably risen, and naturally occurring climate variability alone cannot account for this trend. Human activities are estimated to have caused about 1°C of global warming above the preindustrial baseline, and if left unchecked, it will continue to drastically damage the Earth and its inhabitants. Attempts toward alleviating the effects of global warming have often been at odds and remain divided among a multitude of strategies, reducing the overall effectiveness of these efforts. It is evident that collaborative action is required for avoiding the most severe consequences of climate change. This article evaluates the main strategies (industrial/energy, political, economic, agricultural, atmospheric, geological, coastal, and social) toward both mitigating and adapting to climate change. Also, it provides an optimal combination of seven solutions that can be implemented simultaneously, working in tandem to limit and otherwise accommodate the harmful effects of climate change. Previous legislation and deployment techniques are also discussed as guides for future endeavors.

KEYWORDS

Great Filter, climate change, Earth, humanity, solution

Introduction

The Great Filter was a concept first proposed by Robin Hanson in 1996 in an online essay titled “The Great Filter—Are We Almost Past It?”. It was a theorized answer to the famous Fermi Paradox (Hart, 1975), essentially stating that the reason Earth has not contacted extraterrestrial civilization yet is the existence of a particular barrier that prevented most, if not all, life from developing to higher levels based on the Kardashev scale (Kardashev, 1964). Certainly, there are an almost infinite number of possibilities of what this filter could be, but as the problem of global warming comes into view, many fear that the consequences of climate change may be what ended other life and will soon fall upon Earth as well.

In 1988, global warming first became a major political concern when watershed events placed the issue in the spotlight (History.com Editors, 2017). However, since

the impacts, decades into the next century, were viewed as still very far off, the concern was largely dismissed and the attention of the public quickly returned to more immediate matters. However, with evidence of a relationship between human actions and global warming becoming apparent, climate change gradually surfaced as a relevant political topic. Such fear was justified owing to potential hazards resulting from global warming that included droughts, floods, hurricanes, severe storms, heatwaves, wildfires, cold spells, and landslides. Constant threats such as temperature shifts, precipitation variability, changing seasonal patterns, changes in disease distribution, desertification, ocean-related impacts, and soil and coastal degradation contribute to vulnerability across multiple sectors in many countries (UNCCS, 2019). It was later reported that the failure to reduce emissions from such hazards would cost the world at least \$2 billion per day in economic losses. In fact, the loss from the 2018 wildfires alone was approximately equal to the collective losses from all wildfires incurred over the past decade (Leahy, 2021). Despite this, 40% of adults on Earth have never even heard of climate change, emphasizing the need to further spread public awareness.

Climate change was first officially recognized by the political world in 1989 during the Geneva climate conference, where the Intergovernmental Panel on Climate Change (IPCC) was established under the UN to review further political and economic consequences of global warming. Since then, milestones for individual countries have slowly been set and edited by following conferences. Though multiple world leaders claimed that their countries have been putting in the best efforts to reach their stated goals, objective data show that many such efforts were, however, far from sufficient. On 4 November 2016, the Paris Agreement went into force as an internationally recognized treaty. The Agreement requires all states to align their efforts with the “nationally determined contributions” (NDCs) that they set themselves and to report regularly on these efforts (Unfccc.int, 2019). Yet 5 years later, as pointed out by Sir Robert Watson, former chair of the IPCC, most countries still need to triple their 2030 reduction commitments to be aligned with their own Paris Agreement targets. An analysis of the pledges for the 184 signatory countries found that almost 75% were insufficient (Leahy, 2021). Furthermore, individual solutions, although recommended, were not specified. For instance, Pakistan has not included a single measurable target in its contribution to a UN climate deal. Due to political drama and limited technology, governments around the globe are still debating on which solutions to implement and how much time, effort, and money should be put into each. This also applies similarly to the US when the Supreme Court on 30 June 2022 (West Virginia v. EPA) limited the Environmental Protection Agency’s ability to regulate carbon emissions from power plants, making emission reduction more difficult.

Numerous solutions have been proposed, and some complement each other better if implemented together as

opposed to utilizing a single solution or a different combination. The purpose of this article is to evaluate all aspects of these solutions and devise the optimal combinations that are the most cost-effective, easiest to implement, and that would benefit humanity the most from the devastating impact of global climate variability. Integrating different solutions that complement each other limits the consequences of others while boosting their combined benefits simultaneously. For instance, a carbon tax proposal by Professor Gilbert E. Metcalf of Tufts University not only included a straightforward tax of \$15 per metric ton of CO₂ but also proposed three different forms of tax credits that would benefit factory workers to compensate for the tax. With this innovative approach, manufacturers would not be incentivized to increase the market price level of their goods, eliminating the major concern of raising taxes leading to higher prices. The revenue from the carbon tax, estimated to be \$90.1 billion, could be reinvested in other programs (Metcalf and David, 2009). Another pair of complementary solutions include industrial enhancements in plants along with additional funding and research to maximize the efficiency of industrial capital in production. As an example, large-scale stationary sources of SO_x and NO_x dramatically reduced emissions by installing selective catalytic reduction (SCR) equipment on furnace stacks in the 1990s, which resulted in a landmark victory in combating smog, particulates, and acid rain (Richards, 2020).

Recently, the international community has categorized climate change solutions into two broad areas: mitigation and adaptation. Mitigation focuses on limiting the quantities of greenhouse gasses (GHGs) that foster climate change from being emitted into the atmosphere and decreasing the concentrations of existing gasses from the atmosphere. This is done by either regulating emission sources or enhancing negative emissions technologies (NETs) (Unfccc.int, 2019). Adaptation strategies stress the importance of preparing to cope with any potential hazards and evading damage. These include managing increasingly extreme conditions, protecting coastlines from rising sea levels, managing ecosystems, dealing with reduced water availability, developing resilient crop varieties, and protecting infrastructure (Oppenheimer et al., 2022). A blend of mitigative and adaptive solutions is needed to address the risks of climate change; mitigation solutions lessen the efforts needed for adaptation, and in turn, adaptation decreases the target intensity of mitigation, thus stressing again the value of integrating multiple policies. Suggested combinations in this article will include both adaptation and mitigation strategies.

This article first contains a thorough evaluation of 23 commonly discussed solutions. The solutions are separated into eight categories based on their fields of technology. The efficiency of each solution is deduced, standardized, and then used for comparison. The efficiency of a solution is usually determined by the estimated metric tons of GHGs reduced over a controlled variable of resources (capital, time, physical efforts, and funding) for mitigation solutions, while adaptation

solutions are measured from the risk reductions in disasters (number of lives, amount of property, and stability lost). In addition, the assessment also considers the solutions' unique advantages and disadvantages. Finally, the current viability and technological readiness of the strategy will also be provided to show when a solution should be implemented to achieve its maximum potential. For better comparison, compiling tables are constructed to weigh the data as well. Based on the evaluations, this article suggests an ideal combination of the assessed strategies for implementation at the international level.

Subsequently, an optimal combination of the most compatible and effective solutions is produced as a recommendation for consideration by governments and policymakers. In choosing the solutions for the combination, we preemptively established the criteria and framework. The criteria required an achievable balance between mitigation and adaptation solutions to be reached while addressing all aspects of the issue. Our framework consists of one economic measure, three NETs, one social impact solution, and a multistep, comprehensive government policy addressing diplomatic actions internationally regarding research and investment, constructing infrastructure, etc. Importantly, only those solutions within a given category are selected for comparison against each other. For instance, the carbon tax will not be compared to ocean alkalinity enhancement even though quantitative data technically would allow for their direct comparison. Instead, NETs, such as ocean alkalinity enhancement and ocean fertilization, will be evaluated alongside other NETs only, and ultimately three from that particular category will be chosen for the combination.

Mitigation and adaptation solutions

Energy

Nuclear

Nuclear energy and renewable energy are currently the two pillars of clean energy. While the use of renewable energy is steadily climbing, the future of nuclear energy is much less optimistic. Nuclear energy contributed to 18% of global energy in 1996, but has contributed to only 11% in recent times. This decline in energy production is a result of the increasing competition with renewable energy and low natural gas prices (Ray, 2021). In addition, fear of nuclear accidents and the possibility of countries transforming nuclear power plants to develop nuclear weapons also limits the support and funding for nuclear energy.

The main advantage of nuclear energy production is a nuclear reactor's high-capacity (i.e., operational) factor. In 2021, this value was estimated to be around 92%, suggesting that each nuclear unit produces energy ~92% of the time on average. This generates nearly 800 billion kWh of energy in the US annually,

avoiding more than 470 million tons of carbon emissions each year. Nuclear energy production will also lead to substantial economic benefits; some estimate that current nuclear units located in the US generate ~\$40–50 billion each year, providing a wide range of stable job opportunities. Furthermore, land requirements for nuclear energy production are notably lower than other clean-energy sources.

As stated in Table 1, while nuclear plants are relatively simple and inexpensive to maintain over long periods of time, capital costs for nuclear power plants are extremely expensive, ranging from \$6,500–12,250 per kilowatt for a 2,200-MW plant, and the levelized cost of energy (LCOE) ranges from \$112–189 per MWh generated. The decommissioning cost for nuclear plants also typically ranges from \$300–400 million (Comstock, 2020). As such, the high up-front cost of building each nuclear unit deters many investors and companies. In addition, false associations of nuclear power plants with nuclear weapons and nuclear accidents in the past also contribute to the lack of funding and support for this type of energy resource. A fair depiction of nuclear power plants to the public is vital for widespread support, as with many other mitigation strategies.

Nuclear energy is one of the few energy sources that can provide extensive amounts of energy without damaging the environment. Media misinterpretation of scientific investigations has led to a decline in nuclear energy support, a deficient supply chain, and an insufficient workforce. Reversal of this reality requires improved education and the development of a larger market.

Renewable

Renewable energy (RE) can be defined as energy that originates from sources that are naturally restored or regenerated and regarded as zero, low, or neutral in GHG emission during energy production. This energy type has been receiving the most positive attention as the use of fossil fuels is being challenged, encouraging the growth of renewable energy with support from a developing market, and leading RE to become the fastest-growing energy source globally. The future of RE depends heavily on both international and domestic policies and goals. Market conditions, such as resource availability, cost, demand, and regulations, also determine the growth of renewable energies.

The main sources of RE (in order from greatest to least generation) are hydroelectric, biomass/biofuels, geothermal, wind, and solar. Each type of renewable energy encompasses its distinct set of benefits and disadvantages, and it is difficult to list a detailed description of all commonalities between the types. However, it can be said that all of these renewable energy types generally increase job opportunities and efficiently use secure energy sources. The costs and land requirements for each of the renewable energy types are listed in Table 2, and it can be seen the land requirement and cost for wind energy are notably

TABLE 1 Nuclear energy data analysis.

Source	LCOE ^a	Cost (\$ per kWh) ^b	Energy required	Land required
Nuclear, <i>Levelized Cost of Energy (2017)</i>	\$148 (+20% from 2009)	Capital costs: \$6,500–\$12,250 LCOE: \$112–\$189 Decom. Cost: \$300–400 million	0.1–0.3 kWh of energy input required	Around 1 square mile for a 1,000-megawatt facility

^aLevelized cost of electricity (total cost of building and operating over an assumed lifetime).

^bKilowatt hours (3,600 kilojoules).

TABLE 2 Renewable energy data analysis.

<i>Levelized Cost of Energy (2017)</i>	LCOE ^a	Cost (\$ per kWh) ^b	Land required (square feet per kWh)
Hydroelectric	–	\$0.04	13,700
Biomass/biofuels	\$85	\$0.09	152
Geothermal	\$97	\$0.04	196
Wind	\$45 (–67% from 2009)	\$0.07	43.6 (direct land use only)
Solar	\$50 (–86% from 2009)	\$0.10	100

^aLevelized cost of electricity (total cost of building and operating over an assumed lifetime).

^bKilowatt hour (3,600 kilojoules).

low. In addition, wind turbines are easy to maintain and can be sold for fixed prices over long periods of time, enabling a steady income. However, geographical limitations and wind availability cause wind energy to be less effective among the renewable energy types.

Renewable energies have much lower energy capacity factors compared with nuclear power or fossil fuels. Some renewable energy sources are also largely intermittent; wind turbines and solar panels cannot produce electricity in the absence of the necessary ambient conditions. While battery storage of wind- and solar-derived power has been proposed as one way to mitigate the effects of these limitations on consumers, this option adds an additional layer of thermodynamic inefficiency and also increases capital cost. As indicated in Table 2, effective installation of wind turbines and solar panels requires large amounts of land (e.g., 43.6 kWh for wind turbines and 100 kWh for solar panels in accordance with land use) and may distress the local population. Situating wind farms away from cities would significantly lower its cost and reduce adverse consequences. However, transmission lines must then be built to deliver wind energy to population centers, further driving up costs and reducing efficiency from line losses. Moreover, wind energy development may not be the most profitable use of land and would need to compete with other high-value uses.

Historically, biomass/biofuels regularly demand substantial amounts of energy to operate, and unsustainable bioenergy practices could eventually lead to deforestation and damage to the natural habitats of various wildlife. Bioenergy utilization also requires considerable space as companies need to situate production plants close to sources of biomass to reduce feedstock transportation costs. Additionally, biomass companies should be encouraged to use agricultural waste instead of growing separate organic matter to reduce their land footprint. Hydroelectric energy production is similarly restricted in establishment areas due to its necessity to be located near bodies of flowing water. Without careful planning, this can disrupt the natural flow of rivers and animal migration paths, increase water toxicity, and generally displace both humans and animals from their local environments. While hydroelectricity can be produced for relatively low costs, decades after construction, as shown in Table 2, the initial financial investment remains significantly large and large-scale construction of hydroelectric plant costs may steadily increase as land areas for reservoirs are declining. Local environments must be suited for long-term energy production, and precipitation trends must be favorable for hydroelectric facilities to function properly and effectively. Much of the easily accessible locations for building hydroelectric facilities have already been developed, leaving few new opportunities for additional plants.

Currently, Iceland is completely independent of fossil fuels and other nonrenewable energy sources, producing electricity only from hydropower and geothermal facilities, specifically generating 75 and 25% of its total electricity consumption, respectively. In addition, Iceland has taken advantage of domestic volcanic activity and geothermal energy to obtain hot water and heat. Interestingly, Iceland only shifted to renewable energy because of economic reasons as opposed to environmental concerns because the country could not continue to sustain expensive oil importation prices and required a stable energy source. This transition suggests that reprioritized economic policies could be significantly more effective compared with prolonged discussions about global warming consequences, placing an emphasis on political and economic solutions that favor carbon taxation and discourage pollution. Another lesson that can be obtained from this example is to utilize regional environmental advantages, such as

Iceland's abundance of naturally occurring geothermal energy. For instance, Rock Port, Missouri exploits its wind resources to produce 125% of the town's energy consumption, and unused energy can then be sold to other areas as a source of income. While some areas are more suitable for the installation of solar panels, others may instead be incentivized to build geothermal plants due to local characteristics. Thus, each region should be responsible for procuring the maximum benefit based on its own natural atmospheric and geological advantages.

Economic/political

Carbon tax

Under a carbon tax, the government sets a price that GHG emitters must pay for each standardized quantity of greenhouse gasses they expel into the atmosphere. Sweden, Finland, and the Netherlands have already adopted such taxes. The desired result is that businesses will take steps to reduce their emissions to avoid paying the tax. Ultimately, the goal is to design a carbon tax to best internalize the effects of emissions and adjust the income or payroll tax for any distributive effects.

The lack of consensus can be viewed as the largest negative aspect of the carbon tax as a solution. Setting the exact price of the tax often poses a considerable challenge for politicians as equilibrium is hard to find in a dynamic economic environment due to concerns about raising consumer price levels. For example, tax proposals such as H.R. 2069, introduced by former US Representative Pete Stark in 2007 to Congress, included taxes of \$15.00/ton on coal, \$3.25/barrel on oil, and \$7.30/t on natural gas, but it eventually failed from a lack of agreement. International actions have been largely set back as well. If the tax rate is high enough to significantly reduce emissions, few, if any, countries will allow an international agency to collect the taxes. However, if the tax rate is low enough to make an international agency operational, it is unlikely to discourage significant cuts in fossil fuel usage (OECD, 2010). Even academic articles abroad do not provide a consensus view on the marginal damages of GHG emissions and the optimal tax rate for the United States either. For instance, the IPCC reports that \$12 per ton would be sufficient, Stern Review reports that at least \$85 is needed to implement an efficient carbon tax, while MIT researchers proposed an \$18 solution with an increase of 4% per year (Peters et al., 2006).

If implemented, however, carbon taxes provide arguably the most economic returns when compared with any other solution. For instance, one estimation predicts that a carbon tax starting at \$25 per ton and rising at 2% over inflation annually would have raised \$1 trillion over its first decade (Impose a Tax on Emissions of Greenhouse Gases, 2018). The US currently raises a similar amount with all its other excise taxes. Projections of another study state that a carbon tax levied on all energy-related carbon emissions at a rate of \$50 per metric ton and an annual growth

rate of 5% would generate \$1.87 trillion in federal revenue over the next 10 years (Pomerleau and Asen, 2019). Furthermore, the same study also estimates that CO₂ emissions will reduce by 8.4% while total greenhouse gasses would be reduced by 14%. Reductions in coal consumption would be 59%, petroleum 34%, and natural gas 8%, and this benefit will continue. Simulations show that the carbon tax revenue for the United States stays constant after 3 or 4 decades at around 1.2% of the US GDP, which is equivalent to roughly 300 billion dollars currently (Metcalf and David, 2009).

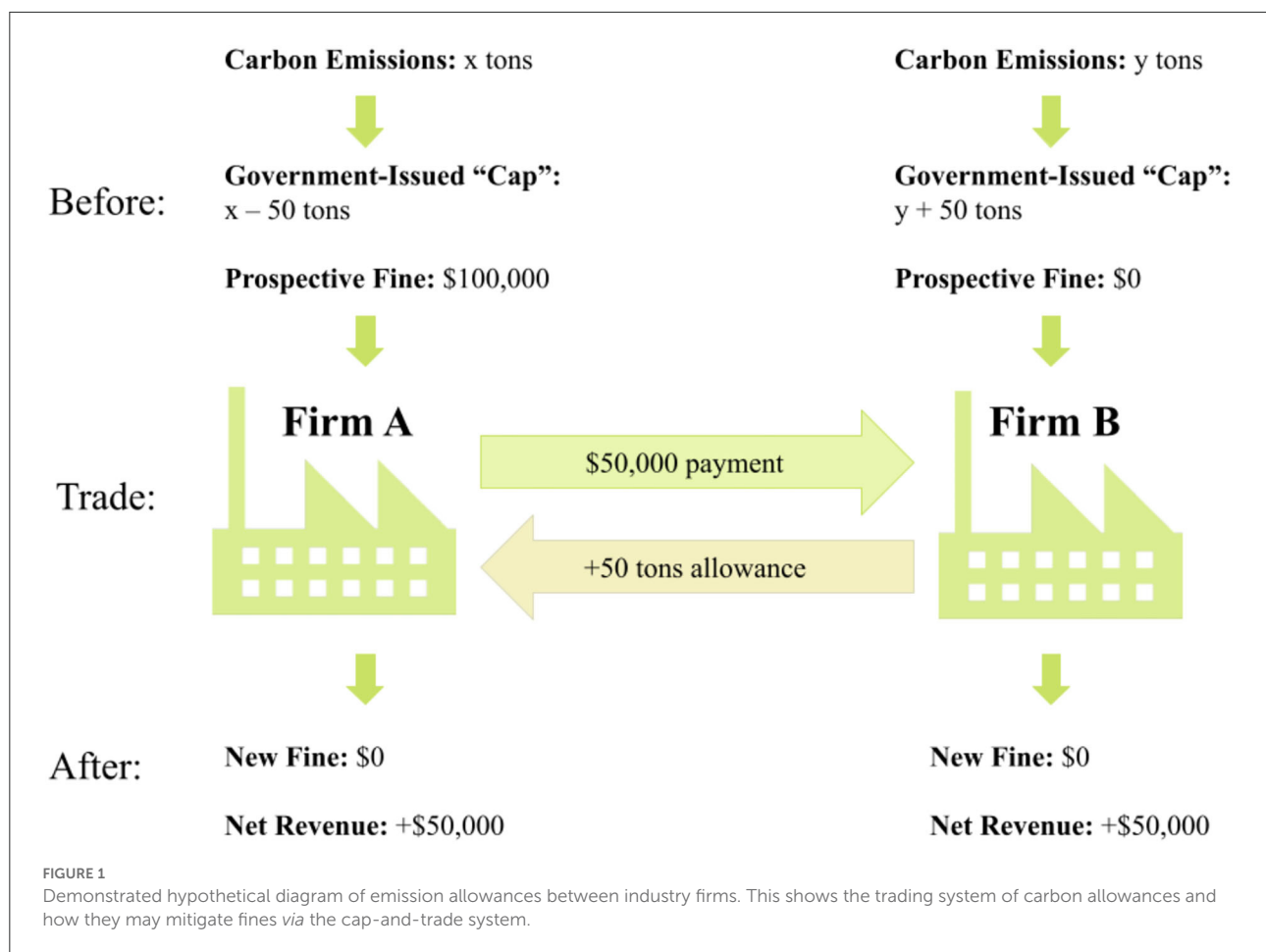
However, these calculations are based on participation only by the United States. The impact of a carbon tax on the entire world depends on the number of countries agreeing to implement the tax, their tax levels, and the ways revenues would be used. For example, rebating the revenues directly back to households in poor economic conditions, using them to aid and improve the welfare in low-income communities, or compensating workers in carbon-intensive industries are some applications of the carbon tax revenue by the government (Marron et al., 2016). Carbon tax revenues should be used to reduce other taxes in a way that maintains progressivity. A universal tax level is not recommended. However, we would propose an international system of carbon taxes that sets the taxation level for an individual country relative to its economic conditions.

Many other solutions have the potential to complement a carbon tax. In fact, comprehensive carbon policy packages have already been proposed by various professionals and credited sources. Increased spending on energy-related research and development, providing energy production subsidies that contribute to a continuing reliance on US fossil fuels, and implementing tax credits are all evidence-backed suggestions for complementary implementation (What Is a Carbon Tax?, 2020).

Cap and trade

Cap-and-trade is a term that represents a system of solutions that includes an implemented "cap," or a limit, on GHG emissions while simultaneously encouraging actions of "trade," or exchange, of quantities of emissions between producers. The cap represents the ceiling based on which individual firms and factories are allowed to emit their greenhouse gases. The limit would decrease over time and companies who exceed this limit would be financially penalized. The cap is thus relatively rigid. The trading aspect, however, accommodates this and makes the overall system uniquely flexible. It essentially allows firms to buy and sell the government caps with one another, meaning companies could conduct trade in their own favor to either profit or avoid additional expenses.

California began operating a cap-and-trade program in 2013. The program was one of the first in the world and is among the largest. California's greenhouse gas production has fallen 5.3% between 2013 and 2017, as California targets



economy-wide carbon neutrality by 2045. This improvement has not come at the expense of industrial output, with the state's manufacturing production increasing from \$250 billion to \$299 billion over the same period. To accommodate the recent downturn in global energy demand due to the pandemic, the state reduced the need for allowances as facilities have been producing fewer emissions.

The main benefit of a cap-and-trade system is its flexibility because it incentivizes businesses to choose the most cost-effective ways to stay under the cap while keeping compliance costs low. As shown in Figure 1, we can conduct a hypothetical scenario of two companies, Firm A and Firm B. They exist such that Firm A emits x tons of GHG per year while Firm B emits y tons. Due to their status as carbon-emitting producers, the firms have had “caps” imposed upon them by the government, thus constituting their GHG emission allowances. In this scenario, Firm A receives an allowance of $x - 50$ tons, meaning Firm A is over-emitting by 50 tons; Firm B receives $y + 50$ tons, meaning it has 50 tons of allowance left for utilization. Further, we assume the potential fine Firm A will receive is \$100,000 for exceeding its cap, but Firm B does not have to pay a fine because it is well

below its cap. Using the “trade” system, the firms can form a pact that will result in mutual benefit. Firm A could purchase 50 tons of allowance from Firm B for \$50,000 so that Firm A's emissions would not exceed its new “cap” and would not have to pay the \$100,000 fine, resulting in a net expenditure avoidance of \$50,000. Firm B would also benefit from the direct sale of its unused extra allowance, resulting in a revenue gain of \$50,000. Both firms not only keep their emissions in their respective caps but also profit from this exchange simultaneously. In comparison to the carbon tax, under cap-and-trade, businesses can seek to mitigate their emission fines whereas a carbon tax mandates a rigid, set rate for every ton of CO₂ emitted.

The cap-and-trade system also comes with its own drawbacks. When the government forces a complementary solution like renewable energy to businesses along with cap-and-trade instead of letting businesses choose for their own interests, the market will react negatively. Additionally, a systematic market approach may fail, preventing emitters subject to a cap-and-trade system from choosing the lowest-cost compliance options. As Ann Carlson explains, if no market failure exists, policymakers should recognize the trade-off inherent in limiting

the market mechanisms (Carlson, 2012). According to Richard Schmalensee of MIT and Robert N. Stavins of Harvard University, "...in several systems, the ability to bank allowances for later use has been an important source of cost savings. The ability to bank provides a margin of intertemporal flexibility with positive economic and environmental consequences. Changes in economic conditions can render caps non-binding or drive prices to intolerable levels" (Morris and Aparna, 2015).

Organizational and private investments

In August 2007, the Secretariat of the United Nations Framework Convention on Climate Change published a technical article, *Investment and Financial Flows to Address Climate Change*, estimating that ~\$205 billion in additional investment will be required annually by 2030 to meet emissions reduction targets. There exist previous efforts in climate investing such as the World Bank Group, the world's largest contributor to climate investment for developing countries, with \$26 billion in 2021. The Climate Investment Funds (CIF), which includes \$8.5 billion in total, describes its goal "to accelerate climate action by empowering transformations in clean technology, energy access, climate resilience, and sustainable forests in developing and middle-income countries" (About CIF, 2022). However, Bank of America has estimated that in the next 20 years, there will be more than \$20 trillion of material and financial growth in total investment in the global market, equal to about half of the current total market capitalization of the S&P 500, meaning relatively, current climate funding is still far from sufficient (Vadakkappatt et al., 2021).

Various barriers can hinder investment. Examples include the immaturity of climate change policy frameworks, absence of stable investment policies, constraints on decision-making within investor companies' fiduciary duties, perceptions of investors that returns on renewable infrastructure investments are too low and initial capital investment requirements are too high, risks associated with uncertain and unproven technologies, high transaction costs or fees transaction costs, and lack of proven knowledge/technical advisement (Hafner et al., 2019). In addition, the most outstanding reason is the disinterest of politicians, who may fear losing their positions of power from carbon-relying groups, such as automobile companies and people who tend to favor lower gasoline prices and more affordable vehicles. Fortunately, several policies and government interventions are being developed to reduce or manage barriers to investment (Unfccc.int, 2019). These include the use of regulatory measures as well as public finance mechanisms (PFMs) and public-private partnerships (PPPs). The mandates and targets set for renewables, such as the European Union's 20% of final energy from renewable sources by 2020 goal, have also shown a somewhat positive result. Several other approaches have been utilized, which include subsidies or stricter government regulations. Though such governmental policies do aid in investing efforts, most of the funding must come from the

private sector and public taxes [The Policy Framework for Investment (PFI), 2015].

Government subsidies and programs

Subsidies are the most common and important policy to stimulate the development of the renewable energy industry. In the United States, the federal government has paid \$145 billion for energy subsidies to support R&D for nuclear power (\$85 billion) and fossil fuels (\$60 billion) from 1950 to 2016. Comparatively, renewable energy technologies received a total of \$34 billion (Pernick and Wilder, 2007). In addition, most states have some financial incentives available to support or subsidize the installation of renewable energy equipment. Numerous types of subsidies have been implemented in European countries as well. The main policies are the Feed-in Tariff (FiT), the Feed-in Premium, and the Green Certificate (GC). To be successful, these policies usually include three key provisions: (1) guaranteed access to the grid; (2) stable, long-term purchase agreements (typically, about 15–20 years); and (3) payment levels based on the costs of renewable energy generation. It provides a fixed amount of money to be paid for renewable electricity production and an additional premium on top of the electricity market price (Mendonça, 2012). The implementation of such policies can also be seen in other European countries: In Italy, the Gestore dei Servizi Energetici published some reports on renewable energy support policies. The Spanish authority, Comisión Nacional de Energía (CNE), produces information on energy policies, and the British Office of Gas and Electricity Markets (OFGEM) publishes an annual report (Brown, 2013).

Though effective, government subsidies come with one negative aspect, high cost. Government subsidies can be a significant financial burden as an increase in the degree of attention to the environment can not only increase the price of energy products but can also bring about a decline in the output levels of renewable energy enterprises, following from the premise that the size of the market remains unchanged in the short term (Timmons et al., 2014). From the perspective of promoting the development of renewable energy, when the environmental pollution caused by energy enterprises is slight, mixed forms of subsidy policy appear to provide the optimal path forward. Different subsidy policies have their own advantages and there are also relevant limitations in some respects. Hence, policymakers should make and implement reasonable policies to fit their own needs according to their own carefully considered situations and targets (Guidelines for Public Expenditure Management, 1999).

Direct/indirect aid to other countries

Aiding developing world countries is a critical economic policy, whose impacts will still be minimal if only a small portion of the globe is taking or can take the initiative. Thus,

by providing aid in the form of investments, political and economic actions, or otherwise, we can ensure these countries take the necessary steps to also combat climate change. As recently reported, and amid the COVID pandemic in 2021, the United States decided to rejoin international efforts against climate change. President Joe Biden has publicly stated he wants to re-establish US leadership on climate. Doing so will require the United States to make an ambitious but achievable pledge and to assist other nations in doing the same. Nathan Hultman, a nonresident senior fellow in the Global Economy and Development program at Brookings, suggests that these subnational actors can share their skills and ambition with their counterparts abroad. Hultman also sees an opportunity for the United States to lead through its outsized role in the global financial sector. It can encourage greener investing by requiring disclosure of climate risks and support global efforts to finance emissions reduction and climate adaptation in developing countries (Hultman and Samantha, 2021).

Aid and interactions do not have to come directly from a given nation's political leadership. In fact, subnational actors with significant climate commitments represent roughly 70% of the US's GDP, which is roughly equivalent to the economy of China (Hultman, 2019). Using policy authorities at their disposal, many of which are significant, these actors have advanced climate action across multiple sectors and types of emissions, including electricity, clean transportation, land use, methane, chlorofluorocarbons, and more. Even outside of federal regulation and legislation, such policies are already driving significant reductions in US emissions and could do more if expanded in line with recent trends (Hultman et al., 2020). As another example, over 600 local governments in the United States have developed climate action plans. While many of these municipalities are lagging in their efforts to meet their targets, some large cities (Los Angeles, New York City, and Durham in North Carolina, for example) have achieved significant reductions and have highly qualified organizations to demonstrate how such reductions can be achieved (Markolf et al., 2022). The United States can leverage its non-federal entities in its diplomatic efforts to support and bolster climate action around the world. Several examples of these economic solutions are listed in Table 3 along with their leading benefits and consequences of implementation, which are clearly stated for better comparison. Thus, US cities, states, and businesses can collaborate with their counterparts in other countries to discuss opportunities and strategies, supported by the US diplomatic effort, as analyzed and recommended by Anthony F. Pipa, a senior fellow, and Max Bouchet, a project manager and senior policy analyst, both from the Center for Sustainable Development, housed in the Global Economy and Development program at Brookings, in their brief for this series. Lastly, the international perception of the US domestic commitment is also important; the commitment must be seen as sufficiently

TABLE 3 A summary of leading benefits and consequences of economic solutions.

	Leading benefit	Leading consequence
Carbon tax	Government revenue from tax returns	Lack of consensus on tax rate
Cap and trade	Market flexibility & satisfaction	Market setbacks from complementary solutions
Investments	Secure outcomes and returns	Difficulty motivating investors
Government action	Climate industry development	High cost and lowered output
International aid	Balanced global advancement	Difficulties cooperating internationally

ambitious to unlock other diplomatic opportunities available to the United States (Hultman, 2019).

Agricultural/agroforestry

Afforestation/reforestation

The Green Belt Movement (GBM), founded in 1977 by Wangari Maathai, planted 51 million trees in Kenya and restored 850 hectares of the countryside in 2018. GBM is one of the many practices of afforestation and reforestation, a mitigation strategy through land use management, serving as a reversal process to forest and soil degradation, reducing the negative impacts on the hydrological systems, and aiming to bury CO₂ in the soil through photosynthesis. Afforestation is the introduction of trees and plants to clearings, wastelands, and arid, barren areas, while reforestation is the restoration of forests experiencing a significant decrease in tree population due to deforestation, wildfire, and other natural/human-made disasters.

As indicated in Table 4, afforestation and deforestation have comparably low costs (\$0/tCO₂–\$50/tCO₂) with high carbon removal rates (3.6 GtCO₂ by 2050 and 7 GtCO₂ by 2100) and capacities (80–260 GtCO₂ removed in total) that enable them to cover larger landmasses (70–500 Mha) and extract abundant amounts of CO₂ with a relatively small budget. To put in perspective, an acre of matured trees absorbs 9.2 metric tons of CO₂ per year, yet the cost of planting one acre of trees does not exceed \$1,000 (Keystone 10 Million Trees Partnership, 2022). By introducing additional new trees and plants into this area, afforestation and reforestation help to prevent topsoil runoff and erosion as increasing the number of trees in near-barren lands pins down the soil with their interconnecting network of roots. Through transpiration, torrential rainfall, sturdy underground watersheds, and water tables are realized. An improved, cleaner environment assists in preserving endangered organisms and increasing the biodiversity of that area by providing a more supportive natural habitat. With new plants

TABLE 4 Afforestation/reforestation and forest management data analysis.

Work cited: Negative Emissions Technologies Reliable Sequestration: A Research Agenda (2009) and Institute for Carbon Removal Law (2022)	Approximate time span (#/yr ^a)	Global annual CO ₂ removal potential (GtCO ₂ ^b)	Global total CO ₂ removal capacity (GtCO ₂)	Global land mass required (Mha ^c)	Total cost for implementation of practice (\$/tCO ₂ ^d)
Afforestation/ Reforestation + Forest managements	1.9 billion	≈ 3.6 (2050) ≈ 7 (2100)	(OURCOAST II Project, 2020; 260) ^e	(Oak Ridge National Laboratory, 2021; 90) U ^f (350; 500)	[0, 50]

^aNumber of trees annually.

^bGigatons of CO₂ mitigated.

^cMillion hectare.

^dCost in United States Dollars (USD) for every ton of CO₂.

^e “[x,y]” represents the domain and limitation of the variable from x to y.

^f “[w,x] ∪ [y,z]” represents the conjunction of two (or more) domains, where it stands for “the limit is from w to x, and the limitation is also from y to z”.

and trees introduced, the replenishment of fresher air dilutes the concentration of different respiratory diseases. In addition, an environment with less air pollution helps to shield society from illness and discomfort. Other benefits such as social cohesion, leisure activities, and the raising of awareness and education for future generations can all be observed through the implementation of afforestation and reforestation (Gitau, 2019).

On the other hand, forest management, especially the creation of new forests on existing lands, can lead to the loss of land for urban development, habitats, biodiversity, agriculture, housing, and other public infrastructure. Ecotourism is also an unintended consequence of afforestation; those implemented solely for economic benefits and entertainment can bring more litter and destruction into forests and habitats rather than preserving them. Additionally, apart from natural disasters, expanding forest landmass increases land value and scarcity, which then contributes to an escalation of property prices (Gitau, 2019).

Afforestation and reforestation are widely executed by many states and regions. For example, the Republic of Korea (South Korea) has been conducting a national reforestation program since 1961 (Kinhal Vijayalaxmi, 2017), and the Korea Forest Service (KFS) has been intensively planting trees since the 1970s and 1980s. By 2008, 2,960 million trees were planted across 1,080 thousand hectares of South and North Korean territory, bringing an alliance between these two bitter rivals on this matter. This strategy is ready to be put into large-scale carbon removal practice immediately with public approvals, helping to bring about a greener world for future generations.

Bioenergy carbon capture and storage

In combating climate change, 23 bioenergy carbon capture and storage (BECCS) projects have been executed globally, with

the majority in Europe and North America. Currently, 6 of the 23 remained in operation, “capturing CO₂ from ethanol bio-refinery plants and MSW (Municipal Solid Waste) recycling centers,” and in 2019, 5 facilities were actively capturing ≈1.5 million tCO₂/y worldwide through BECCS technologies (Kemper, 2017). BECCS is one among an array of negative emissions technologies (NETs), a mitigation strategy. This technology entails the burning of biomasses such as forest woods and fast-growing crops (e.g., barley, wheat, corn, sugarcane, rice, and willow trees), from which bioenergy is generated (i.e., heat/electricity), and the CO₂ emitted from the process is captured into long-term underground storage (Bioenergy Carbon Capture Storage, 2021).

Naturally, photosynthesis creates a carbon-neutral process. However, by seizing the escaping CO₂ before it reaches the atmosphere, the net CO₂ emission can be negative, decreasing CO₂ concentration in the atmosphere, as represented in Table 5, and BECCS can mitigate up to 1,191 GtCO₂ globally over the span of the technology’s lifetime. Owing to its cultivation and burning of biomass, however, BECCS is largely limited by its high economic demand (\$100–200 per tCO₂) and biomass availability (a demand of nearly 50% of Earth’s agricultural landmass). Furthermore, this option will decrease land-use availability for housing and crops; increase utilization of water and fertilizers, damage local habitats, release CO₂ from the soil; and create pipeline-related concerns due to CO₂ injection into geological reservoirs. These downsides can lead to an increase in food insecurities, displacements, biodiversity loss, shortage of water, soil carbon loss and leakage, seismic activity, and air/water pollution (Institute for Carbon Removal Law, 2022).

Like afforestation and reforestation, BECCS implementation is also distributed worldwide. However, governments should take into consideration that research, development, and demonstration (RD&D), along with life cycle analysis,

TABLE 5 Bioenergy carbon capture and storage (BECCS) data analysis.

Work cited: Negative Emissions Technologies Reliable Sequestration: A Research Agenda (2009), Institute for Carbon Removal Law (2022) and Consoli (2019)	Approximate biomass/ bioenergy productivity (t/ha ^a)	Global annual CO ₂ removal potential (GtCO ₂ ^b)	Global total CO ₂ removal capacity (GtCO ₂)	Global land mass required (Mha/GtCO ₂)	Total cost for implementation of practice (\$/tCO ₂ ^c)
<i>Bioenergy Carbon Capture and Storage (BECCS)</i>	[1.8, 25.1] ^d	[0.5, 5] (2050) ^e (Leahy, 2021; Oppenheimer et al., 2022) (2100)	[0, 1191]	[31.7, 58.3]	(100; 200)

^aTons per hectare.

^bGigaton of CO₂.

^cCost in United State Dollars (USD) per ton of CO₂.

^d “[x,y]” represents the domain and limitation of the variable from x to y.

^e “(z)” represents the year said goal should be achieved.

agricultural policies, finance mechanisms, and cross-cutting considerations should be promoted and implemented for maximized benefits to be received from this program.

Bioengineering of crops/genetically modified organisms

With limited water and the degradation of soil health caused by climate change, food insecurity will continue to increase if no actions are taken. One of the possible adaptation strategies to climate change is the bioengineering of crops, where the alteration of a crop's DNA, genes, and alleles allows farmers to yield crop productivity with smaller land areas. Different methods of bioengineering crops in agricultural practices are available according to current technology: traditional breeding, mutagenesis, RNA interference, transgenesis, and gene editing.

Traditional breeding, scientifically established by Gregor Mendel in the 1860s, focuses on the selection of desirable alleles, and crossbreeding these selected crops together produces offspring that combine both beneficial traits while minimizing disadvantages against its environment. This method, dating back ~9,000–11,000 years, does not require further research and testing for large-scale implementation/organic use and can affect up to 10,000–300,000 genes in total. Mutagenesis, invented in 1983 by Kary B. Mullis, is a technique using chemicals and radiation that efficiently detects and escalates a targeted genome/DNA sequence, amplifying the desired genes without cloning. Although mutagenesis does not require testing for implementation and is approved for organic uses, it remains extremely unpredictable, therefore creating uncertainty on the number of genes it can affect during its process. RNA interference, discovered by Andrew Fire and Craig Mello in 1998, presents itself as a mechanism that can inhibit certain

gene expressions by degrading mRNA from that specifically chosen gene and neutralizing the mRNA. Yet it can only be conducted under the condition that the RNA molecules appear as double-stranded pairs. With future testing required for application and the ability to affect 1 to 2 genes, this method is not well-established for organic use, though RNA interference may be able to effectively reduce certain traits of the crop in the future. Transgenesis, developed in 1973 by Herbert Boyer and Stanley Cohen, involves the practice of transferring a section of the desired gene(s) from one organism to another in a specific location to promote chosen traits. This method requires further testing for implementation outside of organic use, and it can affect ~1–3 genes during each transferring process. With more technological development, transgenesis would allow crops that had been genetically modified to pass on their altered traits to future generations. Ultimately, there are gene-editing methods, such as the Clustered Regularly Interspaced Short Palindromic Repeats (CRISPR) technique, established by Emmanuelle Charpentier and Jennifer Doudna in the early 2010s, that through identification of the “problematic” genes conduct “operations” to alter those genes to the desired form and script. Even with testing required and an unknown certainty of organic utilization, it can accurately affect at least 1–3 genes when applied, ending with a result that is more specific, controlled, and predictable (Pacumbaba, 2020).

With the bioengineering of crops, the products can become much more resilient to the degrading environment on Earth caused by climate changes, maintaining increases in overall output from strengthened protection against extreme weather conditions (e.g., drought, flood, storm, strong wind, etc.). As a result, a greater portion of these crops will be saved from both unpredictable natural and human-caused disasters, expanding the suitable soil range for the crops to be planted

(i.e., ~10% increase of global arable land), reducing the use of chemicals/fertilizers (e.g., pesticides), and tillage (i.e., the process of turning the soil in the field), which in turn improves soil preparation efficiency and reduces greenhouse gas emissions. With better security, larger agricultural land dedication, and higher production, food security can increase dramatically, supporting the growing global population and leaving fewer people to contend with insufficient daily nutrition. However, developing the altered seeds will require large monetary investments, and the unpredictability in seed qualities further raises the investment rate, along with the complicating factor of often being mixed with regular seeds that do not match price-wise (Clements et al., 2011).

This adaptation technology has already been implemented by some countries and regions. Unfortunately, the bioengineering of crops still requires much more research to decrease the unpredictability of the genes that are being modified and to increase the effectiveness of the modified genes to maximize the advantages brought by the GMOs. In addition, better education and regulations for the farmers who utilize these GMOs should be established to raise awareness of the negative effects of all aspects brought by climate change and address the concerns of GMOs (Clements et al., 2011).

Irrigation systems

Worldwide, average agricultural water utilization practices equate to more than 70% of global freshwater consumption annually (Water and Agriculture, 1990), while ~40% of that water consumption is wasted through primitive irrigation methods and failure of resource management (i.e., “poor irrigation systems/[transportation], evaporation [water runoff], and overall poor water management”) (Paul, 2020). Correspondingly, some fruits and vegetables require more water usage than others. To put into perspective, growing one pound of wheat uses 130 gallons of water while the same quantity of coffee requires 2,500 gallons of water. In many cases, 40% of water not actually used for its intended task was returned to the environment rather than being used elsewhere, resulting in more input of money, time, and energy consumption to re-acquire and redistribute this water (Paul, 2020). Therefore, to better manage water distribution overall, better irrigation systems are needed for large-scale implementation.

Like the bioengineering of crops, there are many methods for this adaptation strategy from surface irrigation (i.e., traditional water delivery systems) and sprinkler irrigation to drip and airdrop irrigation systems. The drip irrigation system (i.e., micro/low-flow/low-volume/trickle irrigation system), first introduced by Simcha Blass and Kibbutz Hatzetim in 1959, creates a “dripping” system that maintains soil moisture at a fixed level through water-emitting technologies applying droplets and small streams of water to the soil

surface/plant roots. Water consumption is tightly controlled at up to 90% water-use efficiency while providing a much more effective and efficient way of applying chemicals and fertilizers to the soil. One example of the drip irrigation system is subsurface irrigation (SDI), which similarly irrigates the crop as the drip irrigation system from underground and within the plant root zone for better water delivery accuracy and overall management. With the more developed technologies, e.g., “pumps/pressurized water system, filtration systems, nutrients application system, backwash controllers, pressure control valves (i.e., pressure regulators), pipes (including main pipelines and branching tubes), control/safety valves, poly fittings, accessories, and emitters” (Clements et al., 2011), the accuracy of water usage can be greatly improved. Reducing deep percolation/evaporation water run-off to near zero decreases production input and diseases, and the unpredictability of crop growth results while increasing the yield and quality of the finished crops. Furthermore, the drip irrigation systems can be automated and applied across many climates, conditions, and soils (e.g., salinity, sandy, drought, and terrains) that other irrigation systems may not adapt to, supporting a wider variety of permanent/non-permanent crops, fruits, and vegetables. The biggest concern regarding the drip irrigation system is the cost. Due to the many instruments needed for this practice, the initial cost of implementation (\$800–\$2,500/hectare) can be considerably high. However, in maintaining the practice, fluctuations in the cost may be affected by unpredictable rainfall, climate/soil conditions, damage to wildlife, and the shifting of piping/instrumentation positions.

A more recently developed irrigation system, invented in 2011 by Edward Linacre, is the airdrop irrigation system. This technology essentially harvests H₂O molecules or moisture droplets from the air through a turbine that drives and cools the air to that of the underground space in a condensation process until it reaches 100% humidity, resulting in condensate formation. The produced water, stored in an underground tank, is then pumped to the roots of the plants during the watering process. As “the airdrop irrigation system is a low-tech, self-sufficient solar-powered solution,” (Bustler, 2011) it is suitable for arid and semi-arid land where water shortage presents as a recurring problem, and so less water can be used in a more cost-effective manner.

Most irrigation system types are currently widely implemented. However, with better economic management and public awareness, improved technologies and instruments can be applied to integrate the overall benefits provided by these systems. By implementing systems such as the drip and airdrop irrigation systems, water usage can be substantially decreased, while the creation of artificial ponds, lakes, and reservoirs can supply farmers with a constant water supply, relieving the otherwise persistent water shortage pressures in some regions.

TABLE 6 Carbon capture, utilization, and storage data analysis.

Global land mass required (km ²)	Cost for implementation of practice (\$/ton removed)	Total cost for implementation to remove 10 gigatons CO ₂ per year (see Introduction)	Energy consumption (kWh ^a /ton removed)	Water usage (ton/ton removed)
400–24,700 km ² per Gt (non-arable)	\$100–\$1,000/ton removed	\$1 trillion–\$10 trillion/year	2,000 kWh/ton of CO ₂ removed	1–7 tons/ton of CO ₂ removed

^aKilowatt hour (3,600 kilojoules).

Atmospheric/astronomical

Carbon capture, utilization, and storage

While technologies to decrease greenhouse gas emissions are vital to meeting climate goals, negative emission technologies must also be analyzed and considered to formulate the most optimal combination of strategies. Carbon capture, utilization, and storage (CCUS) is a type of negative emission technology (NET) designed to chemically capture CO₂ from the atmosphere, concentrate it, and inject it underground or into a storage reservoir.

The CCUS systems capture CO₂ from either the source of emission or the atmosphere *via* direct air capture (DAC) and permanently store the greenhouse gas underground. Globally, ~8 gigatons of CO₂ must be removed annually to stay within the goals mentioned previously corresponding to a relatively safe range of increasing temperature. The low-end cost of \$100 per metric ton of CO₂ captured and stored is higher than most other mitigation technologies, mainly due to the high levels of energy needed to separate CO₂ from the solutes or sorbents used in the capture of the GHG during the chemical process. In addition, captured CO₂ as a commodity does not attract a large market. However, there have been recent technological developments such as enhanced oil recovery and synthetic aggregates that could provide a large enough market to lower the cost barrier of CCUS. This negative emission technology requires very little land overall and does not require such land to be arable, which is one of its major advantages compared with other mitigation technologies. The water usage associated with CCUS depends on the humidity and ambient temperature of the environment (Lebling, 2021). Designating CCUS plants in cooler, more humid climates can minimize the amount of water lost due to evaporation, thus reducing the amount of water needed in the process.

As greenhouse gas emissions rapidly increase, it becomes clear that simply reducing emissions will not be enough to reduce the effects of global warming; instead, climate change will only be fully moderated by removing CO₂ directly from the atmosphere in combination with converting it to renewable energy. In fact, the IPCC states that “all pathways that limit global warming to 1.5°C with limited or no overshoot project

the use of carbon dioxide removal” (Global Warming, 2018), emphasizing the importance of implementing carbon capture, utilization, and storage. One of the major benefits of CCUS is its practical land requirements for the system, which would lessen negative impacts on local food production or other land uses. Compared with other mitigation technologies, CCUS plants require much less space. Captured CO₂ can also be sold or recycled to bring in revenue and help lessen the cost of carbon capture such as being integrated into synthetic fuels or building insulation.

However, as shown in Table 6, carbon capture, utilization, and storage systems require substantial amounts of energy to power equipment and regulate the rate of carbon capture (i.e., 2,000 kWh/ton of CO₂ removed). One study found that the energy needed to provide enough power and heat to the process to meet the Paris Agreement objectives was approximately a quarter of global energy supplies by 2100 (Realmonte et al., 2019). Moreover, as indicated in Table 6, the process of CCUS is very expensive, in the range of \$1 trillion–10 trillion/year for the removal of 10 gigatons of CO₂ per year. As previously stated, the cost of adhering to the 1.5°C pathway would run into trillions of dollars. Accordingly, while CCUS is crucial to implement, it should not be heavily relied upon. Depending on CCUS to combat climate change can also lead to the misguided belief that emissions from burning fossil fuels can be offset with GHG removal technologies when CCUS is expensive and itself consumes an enormous amount of energy. This circumstance creates a challenging GHG balance and would demand zero, or at least low, GHG-emitting energy sources to be employed in powering CCUS facilities.

As of 2021, Climeworks, a notable company specializing in carbon air capture technology, operates three CCUS plants that capture ~1,100 tons of CO₂ per year. Climeworks plants are 90% efficient and emit ≈10 kg for every 100 kg of CO₂ removed from the atmosphere. After capturing CO₂, Climeworks either sequesters the collected greenhouse gas underground or sells it for commercial purposes. Although Climeworks has yet to reach profitability, there is still much reason to believe that they, along with many other similar for-profit businesses or even government-owned plants, can pull vast amounts of CO₂ out of the atmosphere and bury it underground while selling enough

CO₂ to provide an offset to their operational costs to continue. The most optimistic scenario is one in which a virtuous circle occurs: when copious amounts of CO₂ are produced and they attract a larger market that can leverage the economics of scale, thus driving the cycle.

Stratospheric aerosol injection

In June 1991, a volcano located in the Philippines (Mount Pinatubo) erupted, explosively ejecting about 20 million tons of sulfur dioxide into the atmosphere which, after forming particulates, reflected substantial amounts of sunlight back into space that would have otherwise reached the Earth's surface. As the contents of Pinatubo volcanic plumes became distributed across the planet, major cooling effects resulted. This eruption lowered the global temperature by nearly 0.6 °C. Stratospheric aerosol injection (SAI) aims to mimic this cooling effect by spraying large quantities of reflective particles into the stratosphere. As aerosol particles scatter and absorb sunlight, they can greatly influence plants to cool the climate. However, due to its many shortcomings, this proposed type of climate engineering is currently only theoretical.

Chiefly, the obvious benefit of SAI methodology involves the rapid cooling of the Earth. The amount of cooling and the duration of its effects depend on the type, amount, and persistence of the aerosols to remain suspended. Possible particle types range from sulfur dioxide (commonly used as sprayed reflective particles) to finely powdered salt or calcium. Unlike marine sky brightening (discussed later in this section), SAI is not deployed in the atmosphere but rather in the stratosphere, which does not contain heavy rain clouds that could quickly disperse these otherwise pollutants. Thus, it is likely that heavy influxes of aerosol particles could remain in the stratosphere for a longer period of time until removal by natural atmospheric chemical processes. If efforts were to be implemented successfully, most climate change mitigation objectives would follow, including the reduction or reversal of land/sea ice sheet melting, an increase in plant productivity, a reduction/reversal of sea-level rise, and an increase in terrestrial CO₂ sink from enhanced sequestration in soil and oceans.

On the contrary, SAI is dismissed by many members of the scientific community because of many potential negative consequences upon implementation. While SAI would lower global temperatures, droughts in certain continents would still likely ensue, if not worsen. According to the Geoengineering Model Intercomparison Project, temperatures in tropical areas would cool, yet areas with higher latitudes would warm, as well as cause increased extreme climates and ice sheet melting. Additionally, climate-change-related problems such as ocean acidification from CO₂ forming carbonic acid would not be addressed and resolved by SAI since this technique can only mitigate surface climate issues. A variety of atmospheric impediments would also arise from SAI, for example, solar

power and ground-based optical astronomy would be greatly hindered using this mitigation strategy. Commercial/military control of this technology should also be mentioned as a possible consequence of SAI. In addition, international conflicts would be extremely difficult to avoid because the implementation of SAI would require the agreement of each country, and withdrawal from the agreement at any time could cause the entire operation to fail. This could lead to the termination effect, which would have disastrous consequences once this grand-scale geoengineering strategy is paused. "If geoengineering were halted all at once, there would be rapid temperature and precipitation increases at 5–10 times the rates from gradual global warming" (Robock, 2014). Lastly, just as other mitigation strategies, such as space-based mirrors and direct air capture, which can introduce a moral hazard, success with SAI may cause global populations and governments to increase support toward these temporary technologies and reduce funds for permanent solutions such as renewable energy and better agricultural practices. Thus, it is vital for government leaders and policymakers to acknowledge that these solutions are short-term, flawed, and only considered temporary relief from the repercussions of global warming.

After examination of its many disadvantages in practice, SAI is suggested to be best regarded as only a theory in need of significantly more research rather than having real application potential in the near term. Other solutions that are more long-term and do not involve nearly so many negative consequences should be evaluated further and considered instead. If SAI is implemented, policymakers must remember that SAI is not and cannot be a substitute for permanent mitigation strategies.

Marine sky brightening

The basic idea of marine sky/cloud brightening (MSB) is to enhance cloud reflectivity by cloud seeding with seawater droplets or with other synthesized chemicals. Seawater is sprayed into the air to inject salt into the clouds, increasing albedo (fraction of incident sunlight reflected back into space), thereby aiming to offset climate change. This type of solar radiation management (SRM) would require enough salt crystals to ensure an effective reflection rate while also being small enough in size to not promote precipitation. If implemented successfully, cooling effects would promptly follow and could be effective in mitigating global warming.

The impacts of marine sky brightening would be immediate and reversible in the short term. Compared with other SRM techniques, marine sky brightening is considerably more financially feasible. According to a report published in 2008, in addition to ~£50 million for research, development, and tooling, "50 spray vessels costing approximately £1–2 million [\$2 million] each could cancel the thermal effects of a 1-year increase in world CO₂," adding up to nearly £50–110 million to offset the thermal damage done by 1 year of CO₂ increase

(Salter et al., 2008). By comparison, space-based mirrors require between one to ten trillion dollars for effectiveness. Furthermore, MSB also allows for the localization of solar radiation protection. This technology can be directed to shield specific regions, such as areas with ice sheets, that are at greater risk due to global warming.

Like deploying sunshade configurations in the atmosphere, MSB also concerns international law and politics. In particular, the United Nations Convention on the Law of the Sea (UNCLOS) states that parties are obligated to “protect and preserve the marine environment” from any polluting source. Whether MSB particles would be considered a polluting source remains unclear, and any negative effects of MSB could lead to immediate violation of the law. Moreover, a limited understanding of the complex nature of clouds could lead to unexpected consequences. Large-scale climate patterns and precipitation could be greatly affected, though climate experts suggest that SAI technology and usual climate change patterns would result in more drastic weather changes.

Enhancing cloud reflectivity has the most impact (both beneficial and detrimental) on local and regional precipitation, temperatures, and run-off. Thus, compared with SAI technology, MSB can localize its reflective effects and is roughly less expensive. While both should be considered as temporary fixes, MSB may be more moderate for known adverse effects while SAI involves several unknown effects. The brightness of clouds and reflectivity rates drop dramatically after a few days of cessation of the technology, thereby making MSB easily controllable and an ideal temporary relief solution. It is important to note, however, that a sharp halt of activity could lead to the termination effect, and the reduced carbon sink could lead to significantly warmer temperatures, like the usage case of SAI. Marine cloud brightening, although able to produce a reductive effect on both regional and global warming, will likely cause its own changes to climate, and constant cloud assessments and modifications will be required to ensure that there are no serious adverse effects of MSB.

Space-based mirrors

In addition to efforts for reducing GHG emissions and storing away GHG, alternative methods to counteract global warming have been theorized and researched for potential deployment. Among these include a newly developed yet promising field, space-based mirrors. Like the concepts of stratospheric aerosol injection and marine sky brightening, this idea aims to reflect solar energy away from Earth. It is important to note that this strategy, along with other solar radiation management techniques, should be viewed as a last resort rather than a continuously implemented policy. This is due, in part, to some of the disadvantages regarding these rapid GHG reduction processes that will be discussed later.

Although the deployment of large-scale space-based mirrors may pose too monumental a task to be practical, sunshade

configurations have been viewed to be one of the most efficient methods to solve climate change (Sánchez and Colin, 2015). Deploying large orbital sunshades allows for the concentration of specific areas that are most directly impacted by the effects of climate change. By erecting shields to prevent overheating in those areas, local and regional environments that face the greatest dangers can be temporarily rescued until other, more permanent solutions are implemented.

However, only by reducing GHG emissions and addressing the excess GHG already existing in our atmosphere and oceans can a permanently stable state of life on Earth be achieved. Future generations cannot rely on simply resisting climate change without addressing its root causes, and future implementation of space shades followed by their success might lead the public to demand more of the same, eventually resulting in the dependence on these short-term, “back-end of the pipe” relief measures. Ocean acidification, among other environmental issues caused by excessive GHGs in the atmosphere, would remain entirely unsolved by the blockage of sunlight, whether *via* mirrors or reflective particles. In addition, the present economic feasibility of this solution is low unless stronger motivations and funding for SAI emerge. Some estimations place the cost of space transportation and construction to be between 1 and 10 trillion dollars. Lastly, adverse effects such as unintended influences on Earth’s various natural cycles and cultivation of crops are also shortcomings to carefully consider.

While computer simulations have demonstrated that space-based mirrors are theoretically successful, experiments have not yet been conducted at a scale large enough to ensure the safety and effectiveness of this mitigation strategy in the real world. In addition, global consensus must be achieved before implementation, otherwise negative results may occur in some countries while success in others may prompt political blame and, in the worst case, global warfare. As per the general view of the scientific community, it would be most optimal to continue regarding solar radiation management techniques (SRM) as a last resort and undertake extreme caution during any implementation efforts.

Geological

Geologic reservoir sequestration

Geologic reservoir sequestration, or geological sequestration, is a mitigation strategy used after CO₂ is captured “at the point of emission” from industrial methods. This is done by storing captured CO₂ “in deep underground geological formations” through physical or chemical implementations. Like the storing process in the Bioenergy Carbon Capture and Storage (BECCS) solution, the CO₂ is physically stored “within a cavity in the rock underground,” regardless of whether these geological structures are “large man-made cavities” or “the pore space present within rock formations”

([Geological Sequestration: Climate Change Connection, 2018](#)). Differentiated from BECCS, CO₂ sequestered into geologic reservoirs is usually “pressurized until it becomes a liquid, and then... injected into porous rock formations in geologic basins,” and this process of carbon storage, also known as tertiary recovery, plays an important role in enhanced oil recovery ([Salter et al., 2008](#)). Other methods of storing fully oxidized carbon involve the transformation of CO₂, such as “dissolving CO₂ in underground water or reservoir oil,” “adsorption trapping,” “decomposing CO₂ into its ionic components,” and chemically combining and attaching these captured carbons with other underground substances by “locking CO₂ into a stable mineral precipitate” ([Geological Sequestration: Climate Change Connection, 2018](#)). Large volumes of these types of formations can be found in the US’s coastal plain regions (e.g., “The coastal basin from Texas to Georgia...accounts for 2,000 metric gigatons, or 65[%], of the storage potential” ([What’s the Difference between Geologic and Biologic Carbon Sequestration?](#)), and the abundance of carbon storage capacity in geologic reservoirs can also be observed in [Table 7](#), where the global capacity of carbon storage ranges from 5,000 to 25,000 GtCO₂. Therefore, it is crucial for organizations to pinpoint the most optimal locations for such implementation, such as “mature oil and natural gas reservoirs [,] oil and gas-rich organic shale [,] uneconomic coalbeds [,] deep aquifers saturated with brackish water or brine (saline) [,] salt caverns [, and] basalt formations,” ([Geological Sequestration: Climate Change Connection, 2018](#)) can help to ensure the process proceeds smoothly.

One of the most obvious benefits of geologic reservoir sequestration is the improvement in atmospheric concentrations of CO₂. By trapping the CO₂ before it reaches the atmosphere, CO₂ loading will be reduced, therefore slowing down the growth rate of greenhouse gases. This process, however, may generate a larger consumption of fossil fuels if no cleaner energy sources are broadly adopted, which leads to one of the main concerns regarding geologic reservoir sequestration, the location and transportation of CO₂ as it affects the overall balance of energy and CO₂. Due to the locations of most “oil sands and coal-burning electrical plants” being situated away from the suitable geological areas for carbon injection, CO₂ must be transported through pipes or on trucks over long distances to be stored underground ([Geological Sequestration: Climate Change Connection, 2018](#)). The transportation process entails extra costs and energy, and if not done carefully can emit a considerable amount of CO₂ itself, which undermines the strategy’s intent. To put in perspective, ~\$88.90 is required to transport 1 million tons per annum of CO₂ (MtpaCO₂) over 500 miles and “assumes extra monitoring requirements for CO₂ storage” ([Smith et al., 2021](#)). In addition, an increase in energy and resource consumption can be observed through the construction and operation of such facilities, bringing further concerns both economically and environmentally to the

surface. The number of carbon injections is ultimately limited to prevent increasing the probability of natural disasters, such as earthquakes. Current EPA underground injection control programs, such as the Maximum Allowable Surface Injection Pressure (MASIP), establish regulations for carbon injections based on “calculated, testable, and well-documented” pressure requirements that will prevent unintended formation fracturing, which may arise during the process of injections. Other substantive risks include fracking, which would potentially lead to brine water leakage and result in freshwater contamination. This, in turn, may also affect how the strategy is perceived by the government and the public ([Hovorka, 2009](#)).

As a contemporary of BECCS, geologic reservoir sequestration has been implemented in only a few instances and is still largely in its developmental stage. Some examples where geological sequestration is used include “offshore natural gas production” and “boost production from oil fields by displacing trapped oil and gas.” Similar uses of this strategy can be further adopted as the technology more fully develops (e.g., carbon transportation, pipe leakage prevention, injection methods/architectures, etc.), increasing its carbon capture potential and reducing the costs and landmass requirements, as shown in [Table 7](#) ([Which Area Is the Best for Geologic Carbon Sequestration?](#)). Geological sequestration is largely interconnected with many other mitigation technologies, so the increased implementation of others is likely to lead to an expansion of this practice as well.

Soil carbon sequestration

Throughout human history, most anthropogenic soil alterations usually resulted in a degradation of up to 50–70% of soil carbon storage and decreased more than 840 GtCO₂ of soil carbon. For example, forests were converted into farms or croplands, and farms were replaced by industrial factories or cities, etc. Therefore, soil carbon sequestration serves as a reversal process of these and other carbon-depleting practices, restoring the soil by using plants best suited to the land, transforming infertile soil back to its initial generative state, and re-introducing the chemicals that inhibit the mycorrhizal and microbial interactions that store carbon ([Judith, 2014](#)). Launched by France on 1 December 2015 at the COP 21, the 4 per 1,000 initiative is one of the many soil carbon sequestration organizations and initiatives ([Welcome to the ‘4 per 1000’ Initiative, 2015](#)). Intending to increase plant and soil (top 30–40 cm) carbon absorption and storage by 4% every year through afforestation and other agroecological practices, the initiative not only hopes to improve soil carbon storage but also improve food security and agricultural adaptation under climate change. Other practices, such as changes in agricultural methods and restoration of forests, grasslands, and wetlands, can all yield increases in soil carbon storage.

TABLE 7 Geologic reservoir sequestration data analysis.

Work cited: Negative Emissions Technologies Reliable Sequestration: A Research Agenda (2009)	Approximate CO ₂ sequestered in depleted oil reservoirs	Global annual CO ₂ removal potential (GtCO ₂)	Global total CO ₂ removal capacity (GtCO ₂) ^a	Global land mass required (Mt) to store CO ₂ (km ²)	Total cost for implementation of practice (\$/tCO ₂)
<i>Geologic Reservoir Sequestration</i>	30 GtCO ₂	≈ 35	5,000–25,000	50–100 Mt ≈ 100 km ²	7–13

^aGigaton of CO₂.

The main benefits brought through soil carbon sequestration are that healthier soil obtains a stronger defense against challenges brought by climate change such as drought, flood, and heavy rainfall, and by requiring fewer fertilizers to be used, it is economically, ecologically, and environmentally less of a burden, and as indicated in Table 8, it demands a minimal amount of cost (cost of technique does not exceed \$100/tCO₂ while it is able to cost as low as \$0/tCO₂) and soil while capable of storing a significant amount of carbon dioxide in the soil (soil carbon storage will be able to increase to as high as 130 GtCO₂ globally by 2100). In addition, by improving and restoring the health of the soil, afforestation and reforestation can encourage an increase in agricultural productivity.

However, soil carbon storage is limited by the soil's natural capacity at a given location, so residents and farmers are encouraged to better understand the details of new techniques and their role in increasing soil carbon storage. Transitioning from one agricultural technique to another requires time and money, so providing a considerable amount of financial support to the people involved can efficiently improve the smoothness of this transition. In addition, the composition of soils varies worldwide, so to truly understand which species of plant or crop and farming techniques are best for a specific region and its type of soil requires a large amount of research. By encouraging research, different areas will have a better understanding of the particulars of their soil and, accordingly, will be better equipped to maximize improvements by implementing the most optimal techniques for their soil rather than merely planting more trees.

Similarly, “blue carbon” (discussed further in the following section) serves the same purpose as soil carbon sequestration; only here sequestration is implemented in coastal and other regions involving bodies of water (e.g., mangroves, tidal marshlands, seagrass beds, and other tidal or saltwater wetlands).

Coastal/oceanic

For coastal and oceanic areas, CO₂ removal techniques are separated into four general sub-sections: ecosystem restoration (e.g., mangrove/seaweed/wetland restoration, marine permaculture, and restocking of whale populations),

ocean fertilization (e.g., iron/nitrogen/phosphorus fertilization, and artificial upwelling/downwelling), modification of ocean chemistry (e.g., ocean alkalinity enhancement and seawater CO₂ stripping), and CO₂ storage (e.g., seabed/sub-seabed storage of CO₂ capture on land and deep-sea storage of crop waste/macroalgae deposition). Although not all the listed solutions will be explored, some of the most optimal and beneficial sub-sections and solutions are included below (e.g., ocean alkalinity enhancement, ocean fertilization, and enhanced ocean productivity) (Webb et al., 2021).

Ocean alkalinity enhancement

Affected by the worsening climate change and global warming conditions, the ocean presents many concerns, such as sea level and temperature rise, melting of the polar ice caps, and ecosystem and biohabitat imbalances. This has caused the escalation of ocean acidity, disrupting the complex food web of the oceans. Utilizing the vast material for carbon capture and storage provided by the ocean, a mitigation strategy can be implemented that can chemically lock away CO₂ from the atmosphere in the ocean basin for hundreds and possibly thousands of years. Currently, ocean basins worldwide naturally hold roughly 39,000 GtCO₂, while Earth's atmosphere holds 412 parts per million (ppm), about 50% above the pre-industrial level. Alkalinity can neutralize ocean acidity through weathering and eroding of alkaline minerals (e.g., limestone and basalt), from which the alkaline minerals extract hydrogen ions (H⁺) from the ocean basin to drive up the basicity of the seawater. This restoration of equilibrium can be achieved, albeit over geologically long periods of time, *via* the reaction where “[the] chemical change shifts the carbonate chemistry equilibrium from dissolved CO₂ and carbonic acid (H₂O + CO₂) to bicarbonate (HCO₃⁻) and carbonate (CO₃²⁻) ions,” so “[t]he conversion of dissolv[ing] CO₂ into bicarbonate [would be able to] create a CO₂-deficiency in surface waters, thereby pulling more atmospheric CO₂ into the ocean.” In another CO₂ mitigation path, carbonic acid, produced when CO₂ reacts with the seawater, is broken into hydrogen ions and bicarbonate ions, and calcifying organisms then transform these bicarbonate ions into calcium carbonate as the chief components of their

TABLE 8 Soil carbon sequestration data analysis.

Work cited: Global Warming (2018) and Fact Sheet: Forestation (2020)	Measurable amount of soil for CO ₂ (cm)	Global annual CO ₂ removal potential (GtCO ₂) ^a	Global total CO ₂ removal capacity (GtCO ₂) ^a	Global soil carbon storage capability (tCO ₂ /acre)	Total cost for implementation of practice (\$/tCO ₂)
Soil carbon sequestration	(15–40) ^b	(1–5) ^b : 2050 ^c	(104–130) ^b : 2100 ^c	≈ 8	(0–100) ^b

^aGigaton of CO₂.

^b“x - y” represents the domain and limitation of the variable from x to y.

^c“(z)” represents the year said goal should be achieved.

shells and skeletons. As these organisms expire, they bury the calcium carbonate they carry within themselves on the ocean floor and the CO₂ is locked away in the form of minerals. Throughout recent human history, this natural process alone managed to “absorb approximately 30% of [the] anthropogenic carbon CO₂ emissions since the beginning of the Industrial Revolution” (Judith, 2014). Regardless of the natural process of the ocean, acidity neutralization and carbon storage might exceed the human survival timeline itself, and this constitutes only a minimal force in combating climate change. Therefore, artificial ocean alkalinity enhancement such as the “accelerated weathering of alkaline rock,” “addition of manufactured alkalinity products,” and molecular pumps are recommended for consideration when adapting this negative emission technology to increase this process’ efficiency and effectiveness in carbon extraction and sequestration (Ocean CDR, 2022).

Ocean alkalinity enhancement can be put into practice by accelerating the natural process of locking CO₂ and ocean acidity in the basin in a variety of ways, requiring ≈30% of the ocean body. Table 9 provides a detailed description of the potential and requirements for ocean alkalinity enhancement technology, demonstrating its benefits and hurdles to implementation. Two ocean alkalinity enhancement methods will be explored in this section. The first strategy is to use controlled accelerated weathering reactors that combine crushed limestone, extracted seawater, and CO₂-rich flue gases to separate the acidic seawater and create an alkalized seawater solution that is then injected back into the ocean and locked away in the deep ocean’s carbon vault. The second strategy is to insert finely ground alkaline rocks (e.g., limestone? lime and silicate-rich rocks) into the ocean floor, thereby promoting and advancing the natural geological cycle of securing CO₂ in the ocean basin. Both strategies mimic oceanic carbon extraction processes that have been occurring over the past billions of years but are accelerated in this practice to greatly compress its naturally long timescale (Ocean CDR, 2022).

When implemented to scale, ocean alkalinity enhancement would be in proportion to the threats posed by climate change. A significant amount of CO₂ can then be mitigated (Bach et al., 2019) by electrochemical weathering, a technology that pumps seawater through an electrochemical system,

rearranging the water and salt molecules to produce two separate solutions: acidic and basic. The acidic solution is removed and can be sampled for scientific research enabling better ocean alkalinity enhancement methods, this while the basic solution is injected back into the ocean to neutralize ocean acidity and increase the ocean’s carbon extraction ability (Ocean CDR, 2022). For this method, specifically, valuable by-products such as hydrogen and oxygen gas, silica, and nickel/iron hydroxides are created as a source of energy. Other methods, such as the utilization of silicate-rich minerals (e.g., olivine), produce carbonate sediments that are discharged into the seawater, where they release iron and silica, fertilizing the ocean’s biodiversity in various scales. Moreover, as described in Table 9, this method alone can mitigate 12% of the global energy-related CO₂ emissions annually (roughly 2.5–2.9GtCO₂), hence ocean alkalinity enhancement methods can capture and sequester vast amounts of CO₂ from the atmosphere for an extremely long duration lasting up to hundreds of thousands of years.

The biggest concern regarding ocean alkalinity enhancement technologies is the uncertainties of the processes. Biogeochemical side effects such as alteration of ocean chemistry and damage to the marine ecosystem are likely to be introduced by this mitigation strategy, where such changes can intensify the vulnerability of biodiversity, food security, resident health, water quality, etc., and possibly disrupt and degrade local and even regional economics (Fact Sheet: Ocean Alkalinization, 2020). The root cause of biogeochemical side effects is largely found in the heavy metals embedded in the alkaline materials that are dumped into the ocean, which can become widespread among the oceanic food chains, and the extensive mining of alkaline raw materials raises environmental, societal, and local health concerns along with those processes that have a comparably high level of energy consumption (Masindi and Khathutshelo, 2018).

Despite developments in research on ocean alkalinization and ocean-chemistry-associated techniques, ocean alkalinity enhancement technology still resides at an early theoretical level. Therefore, the government should regard research, development, operational regulations, environmental restrictions, and social sustainability to be applied and carried out with the implementation of the ocean alkalinity

TABLE 9 Ocean alkalinity enhancement data analysis.

Work cited: Webb et al. (2021) , Fact Sheet: Ocean Alkalinization (2020) , Monroe (2020) and Jamie (2020)	Proportion of carbon (t) \Leftrightarrow material (t ^a)	Global annual CO ₂ removal potential (GtCO ₂) ^b	Global total anthropogenic activity CO ₂ extraction (GtCO ₂)	Global land mass require (% of Earth's surface)	Total cost for implementation of practice (\$/tCO ₂) ^c
<i>Ocean alkalinity enhancement</i>	1tCO ₂ = 1–3.5	≥ 2.5–2.9	≈ 67	≥ 70.9%	5–160

^aTon.^bGigaton of CO₂.^cCost in United States Dollars (USD) per ton of CO₂.

enhancement to promote the beneficial factors of this technology, while not neglecting the negative effects it brings ([Fact Sheet: Ocean Alkalinization, 2020](#)).

Ocean fertilization

Ocean fertilization (OF) utilizes the alteration of geoengineering on the ocean surface and ecosystem by adding nutrients (e.g., iron) to the upper layer of the ocean (i.e., euphotic zone) to increase the phytoplankton population and activity, increasing the ocean's carbon extraction efficiency and capacity. Since the marine carbon and nutrient cycle is considerably complex, to safely implement this mitigation strategy, a detailed understanding of marine biology and the carbon/nutrient cycle must be obtained.

Vertical characterization of the ocean can be roughly described as four layers: surface ocean (i.e., euphotic zone: 0–100 m), twilight zone (i.e., mesopelagic zone: 100–1,000 m), deep ocean (≥3,700 m), and the seafloor (i.e., benthic zone). Activities and exchanges of carbon and nutrients thrive between the first three layers, while the seafloor contains mostly reactive sediments and the burial of CO₂. Starting from the first layer, the large phytoplankton resides at the ocean surface, consuming CO₂ and atmospheric depositions (e.g., iron [Fe] and nitrogen [N]) through photosynthesis, which is then consumed by the bacteria, viruses, and zooplankton in the microbial loop. Zooplankton, which also preys on the small phytoplankton and microzooplankton populations, is then captured by a higher trophic level of marine organisms, which are then devoured by the predators such as birds and fish. Through aquatic respiration, marine organisms extract the dissolved oxygen from the ocean water and excrete metabolic waste products (e.g., carbon dioxide, dimethyl sulfide, nitrous oxide, and methane) into the water, where those compounds move down the oceanic layers from the surface ocean to the twilight zone through the process of physical mixing. In addition, marine phytoplankton aggregate formations and detritus from the ocean surface drop down into the mesopelagic zone and combine to form the sinking particles of carbon and nutrients, where they settle into

the deep ocean and are then decomposed by bacteria. There they are consumed by archaea who produce CO₂ through aquatic respiration and will be captured by the migrating zooplankton population in the twilight zone, or they condense their carbon and nutrient storage to create organic carbon. Regardless of the different pathways presented for these sinking particles, all pathways will eventually find their way into sediments and descend to the benthic zone where the carbon and nutrients they carry within them are locked away below the seafloor ([Oak Ridge National Laboratory, 2021](#)). Moreover, when the temperature of the ocean's surface water decreases and its salinity increases, the surface becomes much denser than the water beneath, causing it to sink to the deep sea, in turn causing downwelling and deep-water formations which can lock away the CO₂ from the surface in the ocean floor. Moreover, ocean upwelling occurs when the surface currents become dislocated from each other, bringing up the deep water to the surface while pushing down the surface water to the deeper layers (i.e., ventilation). This leads to a redistribution of water and with that heat, nutrients, and oxygen within the ocean, fertilizing the surface water and increasing the biological productivity of the surface ocean ([NOAA Ocean Explorer, 2020](#)). With the pathogen/pollutant/nutrient runoff from the coastal land area and the emission of CO₂ from the ocean floor sediments during its organic matter decomposition process (i.e., benthic CO₂ flux), which produces nitrogen, phosphorus, iron, and silicon, ocean upwelling, downwelling, and ventilation can regulate and better distribute these materials, maximizing the ocean fertilization goals ([Oak Ridge National Laboratory, 2021](#)). Since leveraging the ocean's carbon storage capacity is well into the distant future, by artificially accelerating these two processes (i.e., phytoplankton population activities & ocean upwelling/downwelling), the ocean carbon extraction effectiveness and efficiency can be greatly improved.

As ocean fertilization is implemented to accelerate a natural process that extracts CO₂ from the atmosphere, it stands to reason that it is a relatively safe practice and technology. However, due to the lack of research on certain aspects of marine carbon and nutrient cycling, which have not been fully explored, some unexpected problems may be created from the fertilization

TABLE 10 Ocean fertilization data analysis.

Work cited: Powell Hugh (2008), Harrison (2013) and IPCC (2018)	Lasting effect period (week/cycle)	Global annual CO ₂ removal potential (GtCO ₂)	Global ocean CO ₂ storage (100-year net carbon sequestered)	Surface area needed (km ² /GtCO ₂) ^a	Total cost for implementation of practice (\$/tCO ₂)
<i>Ocean Fertilization</i>	≈ 1	(1–2) ^b	0.4–8.3%: carbon biomass 2–44%: carbon exported through iron fertilization	≈ 1,000	(30–60) ^b

^aGigaton of CO₂.

^b“x – y” represents the domain and limitation of the variable from x to y.

of ocean phytoplankton populations and the cumulative effects of ocean up/downwelling. Ocean fertilization will aid in the ocean alkalinity enhancement strategy to reduce seawater acidity and will serve to pull more CO₂ from the atmosphere in less time, as shown in Table 10, where each cycle would only have 1 week of lasting effects with relatively high annual rate and potential of carbon storage in the ocean. Nevertheless, ocean eutrophication (i.e., “excessive richness of nutrients in a body of water, frequently due to runoff from the land, which causes a dense growth of plant life and death of animal life from lack of oxygen” (Oxford Languages and Google, 2022) presents as a disadvantage of ocean fertilization, whereby the nutrient needs of the ocean may be exceeded, causing potential negative side effects. Ocean fertilization on the phytoplankton population has a short-term effect and requires further research to be conducted for confirmation of longer-lasting results.

Calculations and data collection based on the “current technological readiness [and] the time needed to reach full implementation” (Gattuso et al., 2018) reflect the technological feasibility of ocean fertilization and is comparably low to other mitigation and adaptation technologies (e.g., reef restoration, renewable energy, vegetation, etc.) Furthermore, the cost-effectiveness of ocean fertilization is relatively lower than most other technologies in the same broad category, resulting in a desired “good” result with lesser economic input. Ultimately, to achieve high levels of carbon extraction without provoking ocean eutrophication and/or other negative effects, governments are recommended to establish restrictions, regulations, and distribution of resources that can promote ocean carbon uptake only within tight controls.

Artificial sand dunes and dune rehabilitation

Worldwide, including the 95 nations and states that appear as islands, the total shoreline length stands at 356,000 km, and the total coastal area globally, including the land (148.94 million km²) and water (361.132 million km²) portions, amounts to 510.072 million km² (Central Intelligence Agency, 2020). Using these natural resources, artificial dunes and dune nourishment can be widely distributed and implemented as

an adaptation technology in response to oceanic and coastal threats introduced by climate change. The goal of artificial dunes and dune regeneration is similar to the construction of seawalls, where both aim to establish a barrier between the sea and the land, protecting the residents and natural habitats from coastal erosion and flooding. The dynamic ability of dunes, whether artificially or naturally assembled, enables this technology to adjust and shift in shape and size as the sea level, ocean currents, wind, and wave climate fluctuates, thereby, allowing the dunes to supply and store sediments to the beach according to their prevailing environment. In total, there are five general types of sand dunes: “transverse, linear/longitudinal, star, barchan/crescentic, and parabolic/blowout,” (Kate, 2017). Whether accomplished by artificial construction or by natural formation, dredged sources as well as naturally occurring deposits such as mud and sediment on the coastal regions of the beach can create or restore the dunes. Furthermore, by attaching supplementary defense structures (e.g., fences and planted vegetation) on these dunes, wherein such fences built next to the sea are constructed with natural materials that can easily decompose while vegetation can collect sediments near their location, both are done to promote dune growth, trap sand, and stabilize dune/sand surfaces. Artificial dunes and dune stabilization are not limited to developed beaches alone. Rather, they can be implemented on a variety of land, including “existing beaches, beaches built through nourishment, existing dunes, undeveloped land, undeveloped portions of developed areas [,] areas that are currently fully developed, but may be purchased so that dunes can be restored,” minimizing the limitations and prior restrictions of sand dune creation and restoration (Zhu et al., 2010).

Different from sea walls, dune nourishment/creation occurs and can be maintained more naturally, leaving less waste and pollutants on the coasts. Additionally, the dunes contribute largely to the maintenance of wide coastal zones on the beaches they reside in. Further, dunes can dissipate wind, wave, and storm energy and present an ablative barrier to coastal erosion where sand from the dunes will be eroded away during different seasons, coming to rest as sediments at the bottom of the coastal regions’ waters instead of

decreasing landmass of beaches that are being eroded without the protection. Likewise, due to the protection provided by the dunes that shield local inland residents from coastal erosion and flooding, sustainable commercial and other developments are more likely to be promoted as a result. This, in turn, benefits local regions economically, just as naturally created dunes can benefit the residents, habitats, and organisms environmentally and ecologically (Zhu et al., 2010).

Although dune regeneration and creation can be implemented with fewer costs and are flexible with many other mitigation and adaptation technologies, some negative side effects of this practice, more specifically with the introduction of new dunes, can still be encountered. The dunes will present as a barrier that protects the residents from oceanic hazards and creates an obstruction that can impede residents from access to the beach, which was once much easier. As well, when implemented in unsuitable regions, dunes may create the destruction of natural habitats, killing and/or dislocating native species. This result can occur most likely when dune creation and regeneration necessitate that construction areas be zoned off from the public and wildlife residents to maximize the growth process of the dunes. Correspondingly, dunes take up a considerable amount of land area, yet some may not have sufficient protective effects on the land designated for protection as the residents and government may desire. This may commercially and recreationally affect the residents, where land loss may arise as a potential problem, and the public, where fewer tourist activities may be enabled (Zhu et al., 2010). Furthermore, even though dunes can dissipate wave energies, some may not be sufficiently robust to stand against strong storms and wave action, and thus are easily destroyed by such coastal activities. Given that dunes cannot regenerate themselves in a relatively short period, the costly process of reconstruction must then be repeated to maintain the dissipating and erosion process.

Technologically, artificial dune and dune rehabilitation are at a matured and developed level for implementation, where the practice has been adopted for roughly 70–100 years (e.g., in the United States [1920s] and Europe [1950s]) (OURCOAST II Project, 2020). However, residents and governments are yet to reach a compromise or agreement on the size, type, frequency, and other factors concerning this adaptation technology to avoid conflicts of interest, public opposition, and additional negative effects from both which would otherwise be avoidable. Nevertheless, dunes can serve as an opportunity to educate the public about climate change concerns and the threats posed to Earth's ecosystems, environments, and essentially, their everyday life, physically and mentally preparing residents as well as the public at large for possible future events. As more and more people accept the challenges and dangers climate change brings, dune rehabilitation and creation can be implemented

for wider areas, better protecting inland regions as it serves its multipurpose functions.

Social

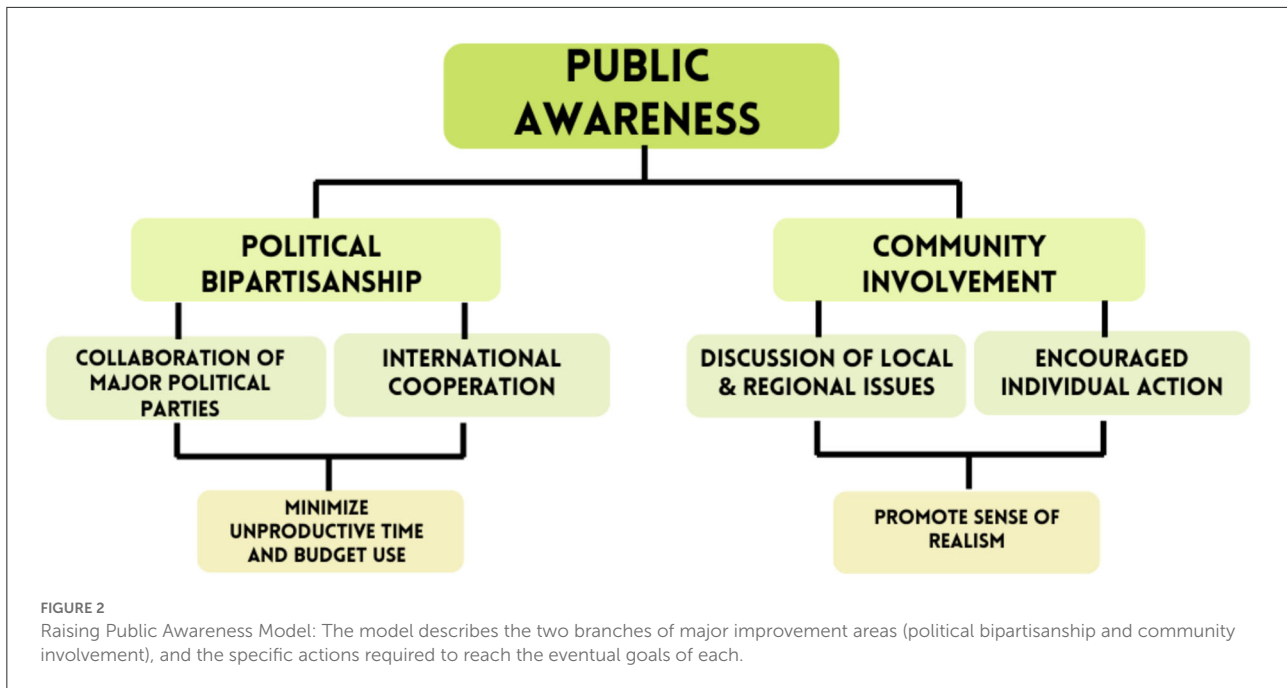
Raising public awareness

The disastrous effects of climate change on life around the globe are undeniable even as public urgency remains severely below that which is necessary to bring about an effective change. According to a study conducted in 2019, 63% of Americans support climate change policies and believe their necessity is worth the economic cost (Funk and Brian, 2020). This public view, however, is nearly identical to the response given 25 years ago, indicating that there has been little improvement, if any, in public support of global warming's consequences. If, for instance, the decision to mitigate climate change were reduced to a single bill to be passed by Congress, a two-thirds vote by Congress represented identically with the views of the American public would likely not be achieved and the bill would fail. Although numerous communication campaigns have been established during this period, many are criticized for being inadequate to provoke real action. In addition, although knowledge about climate change may be more advanced with the spread of information *via* digital media, changing attitudes and behaviors are crucial for enacting actual improvements on the issue. To combat the lack of public awareness, Figure 2 provides a detailed and clear layout of the approach to take on such a strategy.

Increasing public awareness can best be arrived at from two different angles: incentivizing political bipartisanship and promoting community involvement with the goals of minimizing unproductive time and budget use and creating a sense of realism, respectively, as shown below in Figure 2.

Youth education

The societal, economic, and welfare impacts of global warming will endure into the indeterminate future, affecting many generations to come unless the threat is successfully and absolutely confronted. Therefore, each generation that inherits the Earth plays a critical role in protecting it and empowering future generations to be knowledgeable about climate change. As such, this should be an important goal in education. Although the scientific community has largely reached a consensus view regarding the importance of youth education to help bring about climate change action, details of such plans are unclear. Most controversy surrounds the topic of the value of the individual's contributions. The old argument that "if everyone does their small part, it will make a difference" is, according to some, simply not valid, because individual contributions on a global scale are simply too



microscopic (Schreiner et al., 2005). In addition, cooperation of all citizens of the world, or even only most people across the world, is likely impossible unless impactful economic policies are initiated.

Climate education is unfavored by traditional subject-based curriculums. This is apparent in the “compartmentalization” of subjects, such as a split of different areas of science. While climate change touches on a diverse range of topics, traditional education separates these into distinct topics and oftentimes is taught at different grade levels and various depths, leading to a disadvantageous division of time and energy. In addition, traditional education places heavy emphasis on academic grading and standardized test results, leading to primarily extrinsic motivations for students to learn and participate in mitigating global warming. Once students are independent of these stimuli, they may no longer feel the need to actively engage as before. Thus, climate education requires the reform of public education, for example, reorganizing academic topics to point out that school subjects are interrelated with each other and are embedded into a complex network of real-world cause and effect. A robust standardized curriculum related specifically to climate education across all states should be considered to ensure future generations are equipped to understand the challenges their generation will face in combating this issue.

Importantly, educators who directly interact with students must be willing to provide climate education and support the cause. Daily interactions between students and teachers can be highly influential on young students’ minds and beliefs. One study observed that teachers do not consider “the role of science education to try to solve today’s major social, political, economic,

technical, or scientific problems” (Schreiner et al., 2005), which is detrimental to students’ knowledge and views on climate change, especially if such teachers are involved in the child’s education early on. In addition to actively endorsing climate intervention, teachers must be accurately trained in climate education using sources of unbiased data. Misinterpretation, bias, and lack of support must all be eliminated before an educator can satisfy the requirements of climate education training. This consistency must also apply to teachers across different schools, districts, counties, and states, as well as teachers of other subjects such as the arts or English to avoid confusion and doubt. The students will then realize that climate change affects life in general and is not just a remote issue that is discussed only in science class.

Lastly, youth education must be strictly bipartisan and unbiased in every aspect. Teachers, although entitled to their own opinions, should not advocate for their personal beliefs but rather bring different perspectives based on broadly verified facts and sound, logical reasoning, as well as encourage sensible discussion from everyone in the class. Educators should not fear but rather embrace diverse opinions in the classroom, welcoming these opinions by approaching them with patience and understanding, demonstrating to their students this important component of climate education discussion. Furthermore, discussions should incorporate both formal and informal elements, for example, technical terminology can be explained in relatively more vernacular language and thus still carry authoritative weight and a sense of reliability while also being more accessible to students’ developing level of understanding.

Domestic funding

Domestic funding is closely linked with public awareness and youth education, which if successful, will lead to greater public support and more investments and funding toward mitigation and adaptation strategies. Domestic funding is vital as well for the encouragement of technological innovation and providing a financially secure and stable motivation for the continuation of climate change research. One example of a new climate mitigation technology with major potential is the Traveling Wave Technology, which “offers 30 times more efficient use of mined uranium and a factor of five reduction in waste, all based on a once-through fuel cycle without the safety and proliferation concerns of reprocessing used fuel” (TerraPower, 2021). Its key characteristic is that it employs depleted uranium, or the “excess” uranium that is not fissile, to generate nuclear energy, thus enabling a significantly more efficient method of obtaining nuclear energy. Similar technologies that are still in the earlier research stages must have sufficient funding to continue development.

Before 2017, the United States had been one of the largest contributors toward financing climate change action; however, this trend was halted by former President Donald Trump. Current President Joe Biden budgets more than \$36 billion to combat global warming, including \$10 billion for clean energy innovation, \$7 billion for NOAA research, \$6.5 billion for rural clean energy storage and transmission projects, \$4 billion for advancing climate research, \$3.6 billion for water infrastructure, \$1.7 billion for retrofitting homes and federal buildings, \$1.4 billion for environmental justice initiatives, and another \$21 billion for research.

In addition, domestic funding will very likely originate from economic needs for conversion instead of from environmental concerns, unless areas of the United States are damaged or otherwise experience direct and irrefutable consequences from climate change specifically. While environmental complaints are beneficial to reformation, true change will require a certain critical amount of economic and financial momentum for politicians and policymakers to become sufficiently incentivized to initiate them.

Combination

Optimal combination

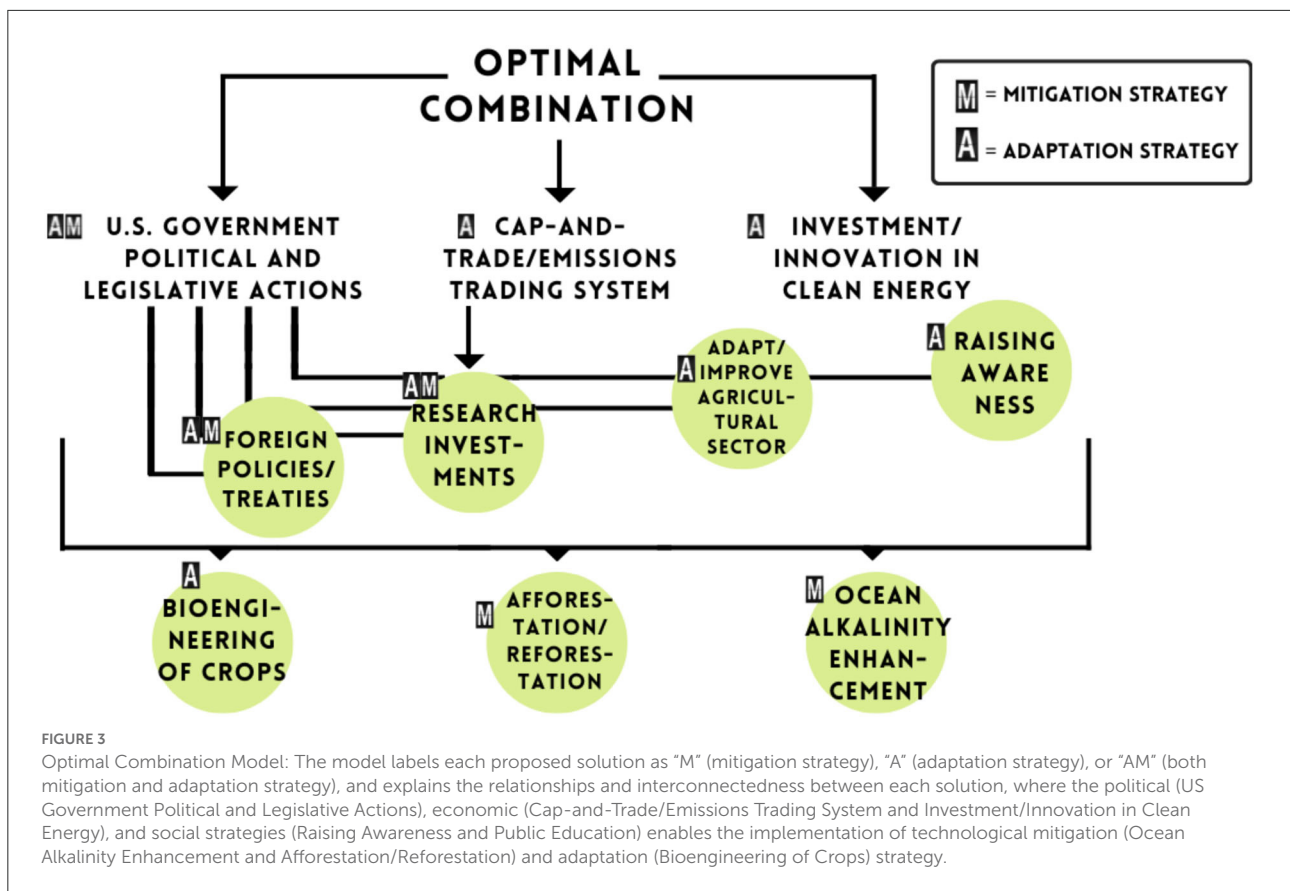
After analyzing the solutions above in terms of potential effectiveness, financial feasibility, current readiness, and most importantly, compatibility, we present an optimal combination as a suggestion and reference for governments when making political decisions regarding climate change and corresponding actions, as shown in Figure 3.

As the combination draws from solutions in various topics, it has a better likelihood of resolving more aspects of the fundamental problem, complementing one another to increase

benefits. Incorporating both mitigation (M) and adaptation (A) strategies, this combination merges and emphasizes the benefits acquired both from selected negative emissions technologies (i.e., afforestation, ocean alkalinity enhancement, and bioengineering) and governmental policy solutions (i.e., cap-and-trade, clean energy industry establishment and expansion, and international contract proposals) while constraining the concerns and side-effects generated by each strategy to a minimum through a beneficial cycle of systems.

To commence, climate intervention will have to come about through economic forces driving countries and corporations to change their former methods and adopt new net carbon-free practices that they decide are most efficient and cost-effective. Thus, the need for an economic framework that compels policymakers and others with the potential to bring about change (e.g., corporation leaders) to reduce the need for energy derived from pollution-heavy sources is inevitable. From this, a cap-and-trade system is recommended, as described in Figure 3, since compared to the other proposed economic systems mentioned in the article, carbon tax presents more flexibility in the marketplace. For instance, minimum government intervention will produce the best price for carbon credits, and the establishment of this price would be assimilated into the market automatically. On the other hand, a carbon tax would have the opposite effect on businesses as its strict regulatory regime would lead to overall dissatisfaction from the entire industrial sector, making cooperation more challenging and risks politically charged lobbying or price spikes in consumer goods and services. Moreover, cap-and-trade systems bring with them more freedom to consumers by allowing them to shift their purchasing from a given company to its competitors offering relatively lower-cost products because they utilize the trading aspect of cap-and-trade. The “Cap and Trade/Emission Trading System” category in Figure 3 emphasizes that the system allows the government to better control the carbon emissions of these large corporations as well as generate additional revenue that can be implemented in research and development investments, serving as a support for other technology’s implementation.

In addition to being economic drivers, direct financial investments, including government subsidies, donations, private investments, and funding from NGOs, are just as important. Specifically, research and investment shall be directed into renewable energy, as described under the branch of “Investment/Innovation in Clean Energy” in Figure 3. Heated debates have occurred between supporters of nuclear energy and renewable energy, and this disunity of the scientific and political communities has greatly hindered progress in legitimate action. Therefore, to ensure all aspects of the issue have been addressed, a blend of both clean energy sources is recommended since a greater positive effect can be achieved with emphasis set around a clearly defined goal that involves both rather than unproductive disputes, which only serve to squander time and avert attention from the environment to



politics. A coexistence of renewable and nuclear energy allows these clean energy forms to be utilized to their maximum potential. For instance, nuclear plants can be established away from residential areas while highly localized renewable sources such as home and office-based solar panel installation will be subsidized to compensate for the expense of nuclear power plant construction and expansion.

Furthermore, the US government itself must ensure that it is maintaining necessary progress in terms of political and legislative actions. Specific suggestions for legislative decisions are listed in Figure 3, under the “US Government Political and Legislative Actions” section. With the goal of increasing support toward such efforts, raising awareness is vital and thus is the need for reform in the education system. All schools and other educational facilities in the United States need to incorporate a consistent and robust study of climate change into the curriculum. Detailed precautions for implementing this curriculum can be found above. Second, the US government needs to support adaptation for its agricultural sector. As climate change impacts the country, the agricultural sector faces especially destructive consequences from severe weather and the longer-term implications of a changing climate. Adaptation measures such as improving infrastructure, constructing dams or other forms of crop protection, and providing subsidies

to farms most directly exposed to the impacts should be considered. Third, scientific research targeted toward the sustainability of crops must be conducted to support maximum yields. The protection of the agricultural industry is crucial as it is responsible for maintaining the nation’s food supply and occupies a major role in international trade. Extreme events caused by climate change, such as droughts and floods, have historically crumbled certain areas of agriculture. Fourth, technological advancements should be supported. This refers to all types of technology for combating climate change efforts, including the development of new, more efficient NETs and the improvement of current methods. Fourth, the US government needs to match and aid in efforts by non-governmental organizations already involved in research and investment. The budget would come from either revenue generated by the cap-and-trade system recommended above and/or cuts in funding for less urgent issues. Finally, the government ultimately needs to interact with other countries through foreign policies. For instance, cooperation, discourse, economic pressure, and potentially political pressure are most of the time necessary for America to initiate a chain of desired actions. Drafting well-intentioned treaties, although commendable, ultimately will result in a lack of legitimate action if administered with poor oversight or supervision. Stepping beyond the stage of

only discourse and into concrete actions is now needed to move forward on improved efforts for cooperation and results on a global scale. Consequently, governments are encouraged to allocate a considerable portion of their total budgets for climate change mitigation and adaptation technology research and development purposes (e.g., ~5% of total spending), and this should be redirected from the overall growth of revenue and otherwise continuously escalating military budgets. With better utilization of capital resources, countries increase the likelihood to fund critical technologies to combat climate change, resulting in more realistic goals and achievements that can reduce climate change damage and threats far more effectively.

As shown in [Figure 3](#), the above actions serve as a synergistic economic and political support system for the implementation of technological mitigation and adaptation technologies. Through comparisons between costs and effectiveness, technologies that can bring the most beneficial factors together are selected to be included in the mitigation section. Thus, the technologies most suitable to be in the optimal combination for maximizing positive impact in combating climate change are bioengineering of crops, afforestation/reforestation, and ocean alkalinity enhancement. In the case where no action is conducted in response to climate change, the global environment will begin to largely degrade worldwide, punctuated by the declining condition of soils (e.g., salinification and desertification) and habitats (e.g., increase of temperature, water shortage, and loss of habitats in general) causing and exacerbating many problems within individual nations and the society in general (e.g., food insecurity, economic inequalities, etc.). In response to this concern, bioengineering of crops serves to upgrade their adaptability and create more crops with desired characteristics for their growing conditions. Subsequently, this allows for more crops to be produced within a more compact land area, which reduces food insecurities and excessive water usage by keeping pace with the demands for food production and storage to feed the rapidly growing populations. In areas that previously proved inefficient to support large quantities of agricultural plants to be grown and harvested, crop bioengineering allows local and regional farmers to select appropriate crops that are genetically modified to withstand the prevailing harsh environment, therefore making use of many wastelands or empty spaces that would otherwise not be usable. Although techniques involving crops, trees, and other types of vegetation may require a significant amount of time to have impacts that can change our society's way of life and benefit a large segment of the population, bioengineering of crops and afforestation/reforestation require relatively little cost for implementation. Therefore, when combined with ocean alkalinity enhancement, which is effective and efficient in its beneficial climate impacts but requires an abundance of funds, a balance in economic input can be achieved. By maintaining a steady production of food without incurring overwhelming economic pressure, the impact of climate change on people's lives will be substantially diminished,

enabling society a longer period to counter climate change while minimizing serious consequences such as famine and conflicts over resources.

Summary

By implementing technologies through the acceleration of natural mitigation processes found in forests (i.e., afforestation/reforestation) and oceans (i.e., alkalinity enhancement), the negative environmental effects are reduced to a manageable, controlled rate with benefits that are much more predictable. Given that Earth's soil and ocean's carbon storage capacities well exceed many other methods, and the processes required demand much less economic investment than many other more technologically challenged approaches, these can be conducted to scale over a long period of time to mitigate the desired amount of CO₂ from the atmosphere with little concern of reaching carbon storage capacity or economic limitations, as shown below in [Table 11](#). With minimized interference vs. other technologies, afforestation and ocean alkalinity enhancement can be conducted over large portions of the globe without incurring serious social, economic, or environmental disputes. Moreover, if the technologies studied and listed in [Table 11](#) are implemented in a manner that maximizes benefit, then these technologies would prove to be advantageous to the environment and would benefit local habitats by restoring many that have been lost due to degrading natural structures while improving residents' living conditions socially (e.g., lessen unemployment rate, reduce food insecurity, etc.) and economically (e.g., boost of food production and trade). With all three steps combined, countries can work together within their states and provinces to maximize the beneficial effects of their applied technologies. Mitigation techniques included in [Table 11](#) can be paired with adaptation technologies examined above to slow the rise in, and eventually lower, atmospheric CO₂ efficiently and effectively with realistic and adequate economic support and investments from governments and private industry.

Conclusion

The contents of this article could essentially be separated into two parts. The first consists of a detailed analysis and breakdown of almost 25 different climate change combating solutions, ranging from a cap-and-trade system to stratospheric aerosol injection. These proposals include both mitigation solutions, referring to those that directly decrease greenhouse gas emissions per year or total quantity in the atmosphere, and adaptation solutions, those that prepare vulnerable communities to better face the consequences of climate change. Arranged into seven categories, the approaches listed are classified as energy (i.e., nuclear and renewable), economic

TABLE 11 Mitigation technologies data analysis.

Measurable mitigation strategies	Cost per Gt of CO ₂ mitigated (\$)	Total CO ₂ mitigation capacity by 2030 (Gt)	Technological readiness for large-scale implementation
CCUS	\$100 billion–\$1 trillion	N/A	Yes
BECCS	\$20–\$100 billion	0.5–5 (2050)	Yes
Afforestation/Reforestation	\$0–\$50 / \$104 billion	3.6 (2050)	Yes
Geologic Reservoir Sequestration	\$7–\$30 billion	62.5 (2050)	No
Soil Carbon Sequestration	\$0–\$100 billion	1 - 5 (2050)	Yes
Ocean Fertilization	\$18–\$60 billion	3.2–9.4	No
Ocean Alkalinity Enhancement	\$55–\$160 billion	2.5–10	No
Carbon Tax (\$40)	+\$26 billion net revenue	20	Yes
Cap and Trade (\$40)	+\$7.9 billion net revenue	38	Yes

Summarizes the mitigation solutions to provide a comparison of their effectiveness through their cost per Gt of CO₂ mitigated, total CO₂ mitigation capacity by 2030, and technological readiness for nationwide implementation.

and political (i.e., carbon tax, cap-and-trade, research and investment, government subsidies, and direct/indirect aid to other countries), agricultural and agroforestry (i.e., afforestation, reforestation, bioenergy carbon capture and storage [BECCS], bioengineering [BE] of crops/genetically modified organisms [GMOs], and irrigation systems), atmospheric and astronomical (i.e., carbon capture, utilization and storage, stratospheric aerosol injection, marine sky brightening, and space-based mirrors), geological (i.e., geologic reservoir sequestration and soil carbon sequestration), coastal and oceanic (i.e., ocean alkalinity enhancement, ocean fertilization [OF], and artificial sand dunes and dune rehabilitation), or social (i.e., raising public awareness, youth education, and domestic funding) applications. The analysis of each solution includes a detailed description of its functions, advantages and disadvantages, numeric data, and/or any historic implementations.

Since it is impractical for governments to attempt to utilize all 23 solutions at once, only a selected few should be chosen for implementation. The second part of the article provides the most optimal combination, considering the perspective of the US government at the present, to achieve maximum potential positive outcomes. It is important to note that combining certain solutions can provide unique benefits that would not exist if any one of them were to be implemented individually. In this section, the article explains the reason for the selection of every solution in the optimized combination and why those would outperform other solutions in their respective categories, along with how these chosen solution components can enhance the effectiveness of other component solutions contained in the optimized group. The final combination includes the implementation of a cap-and-trade system, an energy industry reformation plan, recommended actions to be taken by the US government (i.e., education, research, and foreign aid), negative emissions mitigation solutions (i.e., afforestation and ocean alkalinity enhancement), and an adaption solution by way of cautious bioengineering.

As the effects of climate change are nearing irreversibility, we sincerely and strongly suggest governments worldwide to take into careful consideration the proposal and unite together to combat this serious challenge that all of humanity faces.

Author contributions

Conceptualization, resources, supervision, project administration, funding acquisition, and methodology: JJ. Validation: JJ and KF. Data curation and visualization: JZ, KZ, and MZ. Writing-review and editing: JZ, KZ, MZ, JJ, and PR. Investigation: All authors. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

- About CIF (2022). *Climate Investment Funds*. Available online at: www.climateinvestmentfunds.org/about-cif (accessed November 1, 2022).
- Bach, L. T., Gill, S. J., Rickaby, R. E. M., Gore, S., Renforth, P. (2019). Removal with enhanced weathering and ocean alkalinity enhancement: potential risks and co-benefits for marine pelagic ecosystems. *Front. Clim.* 1, 7. doi: 10.3389/fclim.2019.00007
- Bioenergy Carbon Capture and Storage (2021). *Chatham House – International Affairs Think Tank*. Available online at: www.chathamhouse.org/about-us/our-departments/energy-environment-and-resources-programme/bioenergy-carbon-capture-and (accessed November 1, 2022).
- Brown, P. (2013). *European Union Wind and Solar Electricity Policies: Overview and Considerations*. Congressional Research Service (CRS) (2013). Available online at: <https://sgp.fas.org/crs/row/R43176.pdf>
- Bustler (2011). *AirDrop Irrigation Wins First Prize at 2011*. James Dyson Awards. Bustler. Available online at: bustler.net/news/2383/airdrop-irrigation-wins-first-prize-at-2011-james-dyson-awards
- Carlson, A. E. (2012). Designing effective climate policy: cap-and-trade and complementary policies. *Harv. J. on Legis.* 49, 207. Available online at: <https://harvardjoi.com/wp-content/uploads/sites/17/2013/09/Carlson1.pdf>
- Central Intelligence Agency. (2020). *Field Listing: Area - The World Factbook - Central Intelligence Agency*. Available online at: web.archive.org/web/20201022070334/www.cia.gov/library/publications/resources/the-world-factbook/fields/279.html (accessed November 1, 2022).
- Clements, R., J., Haggard, A., and Quezada, J., Torres (2011). *Technologies for Climate Change Adaptation – Agriculture Sector*. Zhu, X. (Ed.). UNEP Riso Centre, Roskilde.
- Comstock, O. (2020). *Less Electricity Was Generated by Coal than Nuclear in the United States in 2020 - Today in Energy - U.S. Energy Information Administration (EIA)*. U.S. Energy Information Administration. Available online at: www.eia.gov/todayinenergy/detail.php?id=547196 (accessed November 1, 2022).
- Consoli, C. (2019). *Bioenergy and Carbon Capture and Storage, Global CCS Institute*. Available online at: https://www.globalccsinstitute.com/wp-content/uploads/2019/03/BECCS-Perspective_FINAL_18-March.pdf (accessed November 1, 2022).
- Fact Sheet: Forestation. (2020). *American University*. Available online at: www.american.edu/sis/centers/carbon-removal/fact-sheet-forestation.cfm
- Fact Sheet: Ocean Alkalinization. (2020). *American University*. Available online at: www.american.edu/sis/centers/carbon-removal/fact-sheet-ocean-alkalinization.cfm
- Funk, C., and Brian, K. (2020). *How Americans See Climate Change and the Environment in 7 Charts*. Pew Research Center. Available online at: www.pewresearch.org/fact-tank/2020/04/21/how-americans-see-climate-change-and-the-environment-in-7-charts (accessed November 1, 2022).
- Gattuso, J.-P., Magnan, A. K., Bopp, L., Cheung, W. W. L., Duarte, C. M., Hinkel, J., et al. (2018). Ocean Solutions to Address Climate Change and Its Effects on Marine Ecosystems. *Front. Mar. Sci.* 5:337. doi: 10.3389/fmars.2018.00337
- Geological Sequestration: Climate Change Connection (2018). *Climate Change Connection | Connecting Manitobans to Climate Change Facts and Solutions*. Available online at: climatechangeconnection.org/solutions/carbon-sequestration/geological-sequestration/ (accessed November 1, 2022).
- Gitau, J. (2019). *The Green Belt Movement Annual Report 2019. The Green Belt Movement (GBM)*. Available online at: <http://www.greenbeltmovement.org/sites/greenbeltmovement.org/files/GBM%20AR%202019.pdf#overlay-context=user/494> (accessed November 1, 2022).
- Global Warming. (2018). *Global Warming of 1.5°C*. Available online at: www.ipcc.ch/sr15/
- Guidelines for Public Expenditure Management. (1999). Guidelines for Public Expenditure Management—Section 3—Budget Preparation. *International Monetary Fund*. Available online at: www.imf.org/external/pubs/ft/expend/guide3.htm (accessed November 1, 2022).
- Hafner, S., James, O., and Jones, A. (2019). *A Scoping Review of Barriers to Investment in Climate Change Solutions*. MDPI, Multidisciplinary Digital Publishing Institute. Available online at: www.mdpi.com/476418 (accessed November 1, 2022).
- Harrison, D. (2013). A method for estimating the cost to sequester carbon dioxide by delivering iron to the ocean. *Int. J. of Global Warming*. 5, 231–254. doi: 10.1504/IJGW.2013.055360
- Hart, M. H. (1975). Explanation for the absence of extraterrestrials on earth. *Q. J. R. Astron.* 16, 128–135.
- History.com Editors (2017). *Climate Change History*. History.com, A&E Television Networks. Available online at: [https://www.history.com/topics/natural-disasters-and-environment/history-of-climate-change#:~:text=1988%3A%20Global%20Warming%20Gets%20Real,-The%20early%201980s&text=\\$%20Many%20experts%20point%20to%201988,wildfires%20within%20the%20United%20States](https://www.history.com/topics/natural-disasters-and-environment/history-of-climate-change#:~:text=1988%3A%20Global%20Warming%20Gets%20Real,-The%20early%201980s&text=$%20Many%20experts%20point%20to%201988,wildfires%20within%20the%20United%20States) (accessed November 1, 2022).
- Hovorka, S. (2009). *Risks and Benefits of Geologic Sequestration of Carbon Dioxide - How Do the Pieces Fit? AAPG Annual Convention*. Available online at: https://www.searchanddiscovery.com/pdfz/documents/2009/80058hovorka/ndx_hovorka.pdf.html (accessed November 1, 2022).
- Hultman, N. (2019). *Accelerating America's Pledge: Going All in to Build a Prosperous, Low Carbon Economy for the United States*. Center for Global Sustainability, Available online at: <https://cgs.umd.edu/research-impact/publications/accelerating-americas-pledge-going-all-build-prosperous-low-carbon> (accessed November 1, 2022).
- Hultman, N., and Samantha, G. (2021). *How the United States Can Return to Credible Climate Leadership*. Brookings. Available online at: www.brookings.edu/research/us-action-is-the-lynchpin-for-successful-international-climate-policy-in-2021/ (accessed November 1, 2022).
- Hultman, N. E., Clarke, E., Frisch, C., Kennedy, K., McJeon, H., Cyrs, T., et al. (2020). Fusing subnational with national climate action is central to decarbonization: the case of the United States. *Nat. Communicat.* 11, 5255. doi: 10.1038/s41467-020-18903-w
- Impose a Tax on Emissions of Greenhouse Gases (2018). *Congressional Budget Office*. Available online at: www.cbo.gov/budget-options/54821 (accessed November 1, 2022).
- Institute for Carbon Removal Law, Policy. (2022). *American University*. Available online at: www.american.edu/sis/centers/carbon-removal/
- IPCC (2018). “Summary for Policymakers. In: *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*,” Masson-Delmotte, V., Zhai, P., Pörtner, H. O., Roberts, D., Skea, J., Shukla, P. R., et al. Geneva, Switzerland: World Meteorological Organization. p. 32.
- Jamie, S. (2020). *Associate professor in earth observation. The Oceans Are Absorbing More Carbon than Previously Thought*. World Economic Forum. Available online at: <https://www.carbonbrief.org/guest-post-the-oceans-are-absorbing-more-carbon-than-previously-thought/> (accessed November 1, 2022).
- Judith, D. S. (2014). *Soil as Carbon Storehouse: New Weapon in Climate Fight?* Yale E360. Available online at: e360.yale.edu/features/soil_as_carbon_storehouse_new_weapon_in_climate_fight
- Kardashev, N. S. (1964). Transmission of information by extraterrestrial civilizations. *Soviet Astron.* 8, 217.
- Kate, M. (2017). *What are the Different Types of Sand Dunes? Socratic QandA*. Available online at: <https://socratic.org/questions/what-are-the-different-types-of-sand-dunes#394492>
- Kemper, J. (2017). *Biomass with Carbon Capture and Storage (BECCS/Bio-CCS), IEA Greenhouse Gas RandD Programme*. Imperial College London. Available online at: https://ieaghg.org/docs/General_Docs/IEAGHG_Presentations/2017-03-10_Bioenergy_lecture_2_Read-Only.pdf
- Keystone 10 Million Trees Partnership. (2022). *All About Trees. Chesapeake Bay Foundation*, 2022. Available online at: <https://tenmilliontrees.org/> (accessed November 22, 2022).
- Kinhal Vijayalaxmi (2017). *Afforestation And Reforestation*. WorldAtlas, WorldAtlas. Available online at: www.worldatlas.com/articles/afforestation-and-reforestation.html
- Leahy, S. (2021). *Most Countries Aren't Hitting Paris Climate Goals, and Everyone Will Pay the Price*. Science, National Geographic. Available online at: www.nationalgeographic.com/science/article/nations-miss-paris-targets-climate-driven-weather-events-cost-billions (accessed November 1, 2022).
- Lebling K. (2021). *Direct Air Capture: Resource Considerations and Costs for Carbon Removal*. World Resources Institute. Available online at: www.wri.org/insights/direct-air-capture-resource-considerations-and-costs-carbon-removal
- Levelized Cost of Energy (2017). *Lazard.Com*. Available online at: www.lazard.com/perspective/levelized-cost-of-energy-2017 (accessed November 1, 2022).
- Markolf, S., Azevedo, I. M. L., Muro, M., and Victor, D. G. (2022). *Pledges and Progress: Steps toward Greenhouse Gas Emissions Reductions in the*

- 100 Largest Cities across the United States. Brookings, Brookings. Available online at: www.brookings.edu/research/pledges-and-progress-steps-toward-greenhouse-gas-emissions-reductions-in-the-100-largest-cities-across-the-united-states/ (accessed November 1, 2022).
- Marron, D.B., and Adele, C., Morris. (2016). *How to Use Carbon Tax Revenues*. Tax Policy Center (TPC) & Urban Institute and Brookings Institution. Available online at: <https://www.brookings.edu/wp-content/uploads/2016/07/howtousecarbontaxrevenuearronmorris.pdf>
- Masindi, V., and Khatutshelo, L. M. (2018). Environmental Contamination by Heavy Metals Heavy Metals. doi: 10.5772/intechopen.76082
- Mendonça, M. (2012). *Feed-in Tariffs*. London: Routledge. doi: 10.4324/9781849771313
- Metcalf, G. E., and David, A. W. (2009). Design of a carbon tax. *SSRN Electronic J.* 33, 500–556. doi: 10.2139/ssrn.1324854 Available online at: https://chicagounbound.uchicago.edu/cgi/viewcontent.cgi?article=3033&context=journal_articles
- Monroe, R. (2020). *How Much CO2 Can The Oceans Take Up? The Keeling Curve*. Available online at: keelingcurve.ucsd.edu/2013/07/03/how-much-co2-can-the-oceans-take-up/ (accessed November 1, 2022).
- Morris, A., and Aparna, M. (2015). *The Distributional Burden of a Carbon Tax: Evidence and Implications for Policy*. Imfsg, International Monetary Fund. Available online at: <https://www.taylorfrancis.com/chapters/edit/10.4324/9781315747682-15/distributional-burden-carbon-tax-evidence-implications-policy-adele-morris-aparna-mathur>
- Negative Emissions Technologies and Reliable Sequestration: A Research Agenda (2009). *Read 'Negative Emissions Technologies and Reliable Sequestration: A Research Agenda'*. National Academies Press: OpenBook. Available online at: www.nap.edu/read/25259/chapter/1
- NOAA Ocean Explorer. (2020). *Education - Multimedia Discovery Missions: Lesson 8 - Ocean Currents: Activities: Currents and Marine Life*. NOAA Ocean Explorer Podcast RSS 20. Available online at: oceanexplorer.noaa.gov/edu/learning/8_ocean_currents/activities/currents.html
- Oak Ridge National Laboratory (2021). *The Ocean Carbon Cycle, Earthlabs*. Available online at: <https://serc.carleton.edu/eslabs/carbon/6a.html>
- Ocean CDR. (2022). Available online at: oceancdr.net/approaches/alkalinity
- OECD (2010). A guide to environmentally related taxation for policy makers. *Taxation, Innovat. Environ.* (2010) 135–149. doi: 10.1787/9789264087637-8-en
- Oppenheimer, M., Glavovic, B. C., Hinkel, J., van de Wal, R., Magnan, A. K., Abd-Elgawad, A., et al. (2022). "Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities," in *The Ocean and Cryosphere in a Changing Climate*. p. 321–446. doi: 10.1017/9781009157964.006
- OURCOAST II Project (2020). *Beach and Shoreface Nourishment, Climate-ADAPT*. Available online at: <https://climate-adapt.eea.europa.eu/metadata/adaptation-options/beach-and-shoreface-nourishment> (accessed November 1, 2022).
- Oxford Languages and Google. (2022). *English. Oxford Languages*. Available online at: languages.oup.com/google-dictionary-en/
- Pacumbaba (2020). *Posted by: Rudy. GMO Food Facts: Bioengineered Crops - A Look at Modern Agriculture*. Alabama Cooperative Extension System. Available online at: www.aces.edu/blog/topics/fruits-vegetables-urban/gmo-food-facts-bioengineered-crops/ (accessed November 1, 2022).
- Paul, B. (2020). *Water Usage In The Agricultural Industry: High Tide Technologies*. High Tide. Available online at: <http://water-usage-in-the-agricultural-industry/>
- Pernick, R., and Wilder, C. (2007). *The Clean Tech Revolution: The Next Big Growth and Investment Opportunity*. Silicon Valley, CA: Collins. p. 280. Available online at: <https://www.semanticscholar.org/paper/The-Clean-Tech-Revolution%3A-The-Next-Big-Growth-and-Pernick-Wilder/55235774265407dce395026efa4c8171086a762c>
- Peters, S., Bakhshi, V., Bowen, A., Cameron, C., Catovsky, S., Crane, D., et al. (2006). *Stern Review: The Economics of Climate Change*. London: Chancellor of the Exchequer. Available online at: http://mudancasclimaticas.cptec.inpe.br/~rmclima/pdfs/destaques/sternreview_report_complete.pdf
- Pomerleau, K., and Asen, E. (2019). *Carbon tax and revenue recycling: revenue, economic, and distributional implications*. Tax Foundation. Available online at: <https://taxfoundation.org>
- Powell Hugh (2008). *Dumping Iron and Trading Carbon*. Woods Hole Oceanographic Institution. Available online at: www.whoi.edu/oceanus/feature/dumping-iron-and-trading-carbon/
- Ray, S. (2021). *Nuclear and Coal Will Account for Majority of U.S. Generating Capacity Retirements in 2021 - Today in Energy - U.S. Energy Information Administration (EIA)*. U.S. Energy Information Administration. Available online at: [www.eia.gov/todayinenergy/detail.php?id=\\$46436](http://www.eia.gov/todayinenergy/detail.php?id=$46436) (accessed November 1, 2022).
- Realmonde, G., Drouet, L., Gambhir, A., Glynn, J., Hawkes, A., Köberle, A. C., et al. (2019). An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nat. Communicat.* 10, 2019. doi: 10.1038/s41467-019-10842-5
- Richards, J. R. (2020). *Control of Nitrogen Oxides Emissions - 4cleanair.Org. National Association of Clean Air Agencies*. Available online at: <https://www.4cleanair.org/wp-content/uploads/APTI/418Combinedchapters.pdf>
- Robock, A. (2014). Stratospheric aerosol geoengineering. *Issues Env. Sci. Tech.* 38, 162–185. doi: 10.1039/9781782621225-00162
- Salter, S., Sortino, G., and Latham, J. (2008). Sea-going hardware for the cloud albedo method of reversing global warming. *Philos. Trans. R. Soc. A.* 366, 3989–4006. doi: 10.1098/rsta.2008.0136
- Sánchez, J-P., and Colin, R. M. (2015). Optimal sunshade configurations for space-based geoengineering near the sun-earth L1 point. *Plos ONE*. 10, e0136648. doi: 10.1371/journal.pone.0136648
- Schreiner, C., Henriksen, E. K., and Hansen, P. J. K. (2005). Climate education: empowering today's youth to meet tomorrow's challenges. *Stud. Sci. Edu.* 41, 3–49. doi: 10.1080/03057260508560213
- Smith, E., Morris, J., Khesghi, H., Teletzke, G., Herzog, H., and Paltsev, S. (2021). *The Cost of CO2 Transport and Storage in Global Integrated Assessment Modeling*. doi: 10.2139/ssrn.3816593
- TerraPower (2021). *Traveling Wave Reactor Technology*. TerraPower. Available online at: www.terrapower.com/our-work/traveling-wave-reactor-technology
- The Policy Framework for Investment (PFI). (2015). OECD. Available online at: www.oecd.org/investment/pfi.htm
- Timmons, D., Jonathan, M. H., and Brian, R. (2014). *The economics of renewable energy*. Global Development And Environment Institute, Tufts University. (2014) p. 1–52.
- UNCCS (2019). *Climate action and support trends, United Nations Climate Change Secretariat*. Available online at: https://unfccc.int/sites/default/files/resource/Climate_Action_Support_Trends_2019.pdf (accessed November 1, 2022).
- Unfccc.int. (2019). Available online at: unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement/key-aspects-of-the-paris-agreement (accessed November 1, 2022).
- Unfccc.int. (2019). Available online at: unfccc.int/resource/ccsites/zimbab/convent/text/art02.htm (accessed November 1, 2022).
- Unfccc.int. (2019). Available online at: unfccc.int/topics/climate-finance/the-big-picture/introduction-to-climate-finance (accessed November 1, 2022).
- Vadakkappatt, G., Shankar, V., and Varadarajan, R. (2021). Should firms invest more in marketing or RandD to maintain sales leadership? An empirical analysis of sales leader firms. *J. Acad. Mark. Sci.* 49, 1088–1108. doi: 10.1007/s11747-021-00774-2
- Water and Agriculture. (1990). *OECD*. Available online at: www.oecd.org/agriculture/topics/water-and-agriculture/ (accessed November 1, 2022).
- Webb, R. M., Silverman-Roati, K., and Michael, B. G. (2021). *Removing Carbon Dioxide Through Ocean Alkalinity Enhancement and Seaweed Cultivation: Legal Challenges and Opportunities*. Columbia Law School: Sabin Center for Climate Change Law; February. Available online at: <https://climate.law.columbia.edu/sites/default/files/content/Webb%20et%20al%20-%20Removing%20CO2%20Through%20Ocean%20Alkalinity%20Enhancement%20and%20Seaweed%20Cultivation%20-%20Feb.%202021.pdf>
- Welcome to the '4 per 1000' Initiative. (2015). Available online at: www.4p1000.org/
- What Is a Carbon Tax? (2020). *Tax Policy Center*. Available online at: www.taxpolicycenter.org/briefing-book/what-carbon-tax (accessed November 1, 2022).
- What's the Difference between Geologic and Biologic Carbon Sequestration? Available online at: [www.usgs.gov/faqs/what-s-difference-between-geologic-and-biologic-carbon-sequestration?qt-news_science_products\\$=0\\$qt-news_science_products](https://www.usgs.gov/faqs/what-s-difference-between-geologic-and-biologic-carbon-sequestration?qt-news_science_products$=0$qt-news_science_products) (accessed November 1, 2022).
- Which Area Is the Best for Geologic Carbon Sequestration? Available online at: [www.usgs.gov/faqs/which-area-best-geologic-carbon-sequestration?qt-news_science_products\\$=0\\$qt-news_science_products](https://www.usgs.gov/faqs/which-area-best-geologic-carbon-sequestration?qt-news_science_products$=0$qt-news_science_products) (accessed November 1, 2022).
- Zhu, X., Linham, M. M., and Nicholls, R. J. (2010). *Technologies for Climate Change Adaptation - Coastal Erosion and Flooding*. Danmarks Tekniske Universitet, Risø Nationallaboratoriet for Bæredygtig Energi. TNA Guidebook Series.