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Incorporating Climate Engineering into Secondary Education: A New Direction for Indiana's Science Classrooms

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Abstract

Climate change represents a significant existential challenge in modern times, with widespread anxiety over its impacts. There's a growing desire among students to explore climate solutions and identify personal actions to address climate change. Despite mitigation efforts, current greenhouse gas emission reduction measures are insufficient, and development of negative emission technologies is slow and costly. Consequently, the past two decades have witnessed an escalating interest in alternative strategies to temporarily and intentionally cool the planet. Collectively known as climate engineering or geoengineering, these approaches could serve as a temporary shield against the most severe outcomes of climate change, buying time while efforts to mitigate emissions and enhance carbon sequestration reach the required scale.

In line with the Indiana state science standards (HS-ESS3-4), this article presents the Climate Engineering Teaching Module (CETM) and recounts firsthand experiences from its application in high school settings. Launched over three years ago, the CETM has been effectively integrated into fifteen Indiana classrooms. As the future citizens and leaders of Indiana, it is crucial that students are well-informed on climate engineering. Educating them about the scientific, ethical, political, and economic facets of climate engineering is imperative for fostering responsible decision-making. By examining the trade-offs associated with climate engineering and encouraging students to conceptualize ways to implement these technologies beneficially while minimizing risks, the CETM offers an innovative and practical approach to teaching climate change and engineering design. This method not only prepares students for active engagement in future discussions on climate engineering but also equips them with a comprehensive understanding of its complexities.

Introduction/Motivation

Climate change is one of the greatest existential threats of the modern age (Ripple et al., 2023), and anxiety about its consequences is pervasive (Crandon et al., 2022). There is increasing demand by students to figure out what can be done about climate change (Hickman et al., 2021). The only permanent solution to preventing further climate change is to reduce greenhouse gas emissions (Solomon et al., 2009; IPCC, 2023), potentially supplemented with negative emissions technologies (NRC, 2015a). However, these are both slow and expensive prospects (NASEM, 2019) and currently inadequate to match society's greenhouse gas emissions (Martin-Roberts et al., 2021). Adaptation to climate change will be necessary in the meantime (IPCC, 2022), but there are legitimate concerns that the increasingly harmful effects of climate change outpace humanity's ability to adapt (Costello et al., 2023). As the world approaches 1.5°C of global warming in the next decade or so (Matthews and Wynes, 2022; Diffenbaugh and Barnes, 2023), there is increasing discussion around alternative options to temporarily, deliberately modify the climate to prevent some of the worst effects of climate change while more permanent solutions are implemented (Shepherd et al., 2009). Technologies to cool the planet, like injecting large amounts of reflective particles into the stratosphere or brightening low clouds over the oceans, are part of a larger umbrella that we term *climate engineering*.

As a research field, climate engineering, also called

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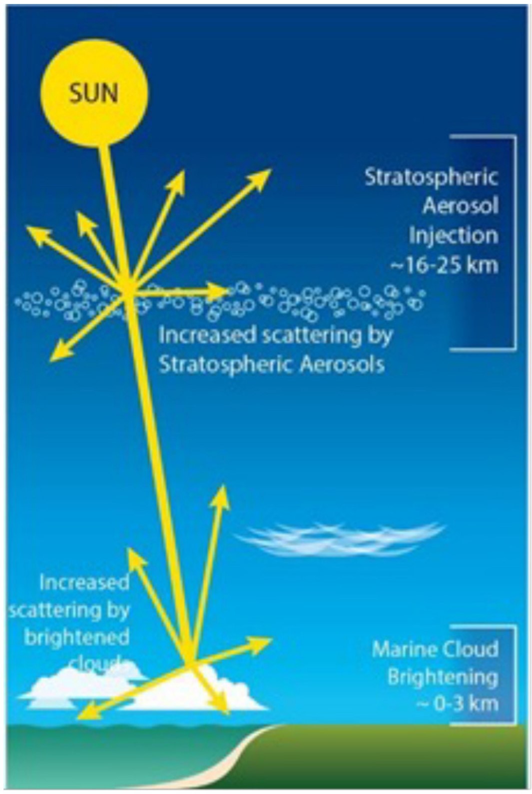

Figure 1. Schematic of Stratospheric Aerosol Injection and Marine Cloud Brightening. Modified from NASEM (2021).

geoengineering, has been gaining momentum over the past two decades (Boettcher and Schäfer, 2017). Computer modeling studies show that climate engineering, such as Stratospheric Aerosol Injection or Marine Cloud Brightening (Figure 1), can effectively cool the planet, offsetting warming from greenhouse gas emissions (Kravitz et al., 2013). This could prevent climate tipping points such as the loss of the Greenland (Moore et al., 2019) and Antarctic ice sheets (Goddard et al., 2023), melting of boreal permafrost, disappearance of Arctic Sea ice, and large-scale die-off of low-latitude coral reefs; for a summary of climate tipping points and how climate engineering may mitigate some of these tipping points, see McKay et al. (2022) and Hirasawa et al. (2023). It could also reduce the magnitude of and consequences of extreme heat and precipitation events (e.g., Tye et al., 2022).

Conversely, climate engineering also poses many risks (Robock, 2008), such as altering regional weather and climate patterns impacting agriculture, water availability, and ecosystems. Climate engineering may also result in slower carbon emission mitigation efforts (Reynolds, 2015) incurring a large risk of dangerous rapid warming if the deployment is abruptly halted (Jones et al., 2013). Climate engineering deployment raises potential geopolitical conflicts regarding who controls the technology and who pays for both deployment and negative consequences (Dalby, 2015). Understanding the tradeoffs of doing or not doing climate engineering has been the subject of several completed and ongoing federal efforts (NRC, 2015b; NASEM, 2021; OSTP, 2023). Nevertheless, decisions about whether and how climate engineering might be deployed in the future will need to be made in the absence of complete certainty.

Indiana's students are tomorrow's citizens and leaders. Our best shot at a responsible decision about climate engineering is to ensure that our teachers are prepared to teach our students about scientific, ethical, political, and economic implications. Exploring these various tradeoffs, as well as envisioning (in a classroom setting) ways of deploying climate engineering that maximize benefits and minimize risks is a novel and effective way of teaching both climate change and engineering design, while simultaneously preparing K-12 students to be knowledgeable and active participants in the climate engineering discourse ahead. Recognizing this imperative, the Next Generation Science Standards (NGSS) and the Indiana State Science Standards include climate engineering as an important learning outcome (NGSS Lead States, 2013; HS-ESS3-4).

Teacher Support

Our project team was formed under Indiana University's (IU) Educating for Environmental Change (EfEC) program, led by co-author Scribner, to support K-12 educators in teaching the science and policy of climate change through professional development. EfEC partners K-12 teachers with IU scientists to co-design classroom-ready lessons and activities based on the scientific research conducted at IU. In 2021, the EfEC team co-designed a new module on climate engineering, led by co-authors Goddard and Kravitz, IU climate scientists who study climate engineering. The Climate Engineering Teaching Module (CETM) was developed to help middle and high school students understand climate engineering solutions by applying critical thinking and problem-solving skills.

Since 2021, the CETM has been featured in four full-day and four half-day EfEC workshops, reaching over fifty K-12 educators, including co-authors Milks and Peterson. These workshops aim to enhance teachers' pedagogical content knowledge and teaching efficacy in the area of climate engineering. The project team helps to establish these essential skills and expertise through workshop sessions focused on in-depth exploration of climate engineering-related topics. These include:

1. Discussing strategies for mitigating climate change, enhancing community resilience, understanding negative emissions technologies, and introducing climate engineering.
2. Exploring the role of climate engineering as a complementary approach to emission mitigation efforts, and its potential for educational purposes, engaging in engineering design processes, and evaluating proposed climate engineering solutions.
3. Delving into the social, political, ethical, and economic dimensions of climate engineering, with a focus on fostering optimism among students when confronting environmental challenges.

The project team recognizes that teaching climate engineering is particularly challenging because climate engineering is, comparatively, quite a new field and has not fully entered the public sphere. To address these concerns, the project team created an introductory video (~20 min) on climate engineering and organized a continually updated list of content-relevant websites that teachers can view to help prepare them to teach this unit. To supplement this, Lesson 5 (described in more detail below) allows the classrooms to interact with climate engineering and climate change exerts. These interactions could easily involve a question-and-answer session, so teachers have an additional resource and do not feel that they have to know everything. This can also serve as an opportunity for teachers to gain more knowledge about this field, leading to greater confidence with the lessons. Nevertheless, providing the "right" amount of background is challenging, and we are constantly updating and improving the materials we provide.

Lessons

The five lessons of the CETM, detailed below, were initially developed by Goddard, Kravitz, and Scribner. After each workshop, the lessons are updated to reflect the ideas and concerns of the participants. Additionally, the CETM has been implemented at Bloomington High School South by teachers Milks and Peterson in their Earth and Space sciences courses. Their feedback has contributed to the ongoing collaborative design of each lesson, resulting in lesson plans that have been tested and refined for the classroom.

These lessons are aligned with NGSS and Indiana Science and Social Studies Standards (Table 1). PowerPoint presentations, instructional resources and videos, and all the necessary materials to conduct the activities are provided.

Table 1. Alignment of lessons with NGSS and Indiana Social Studies Standards (denoted by a leading "IN-").

HS-ESS2-2 Earth's Systems	Analyze geoscience data to make the claim that one change to Earth's surface can create feedbacks that cause changes to other Earth systems.	2,4,5
HS-ESS2-4 Earth's Systems	Use a model to describe how variations in the flow of energy into and out of Earth's systems result in changes in climate.	2,5
HS-ESS3-4 Earth and Human Activity	**Evaluate or refine a technological solution that reduces impacts of human activities on natural systems.**	1-5
HS-ESS3-5 Earth and Human Activity	Analyze geoscience data and the results from global climate models to make an evidence-based forecast of the current rate of global or regional climate change and associated future impacts to Earth systems.	2,4,5
HS-ESS3-6 Earth and Human Activity	Use a computational representation to illustrate the relationships among Earth systems and how those relationships are being modified due to human activity.	2,5
HS-ETS1-1 Engineering Design	Analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants.	1,3,4
HS-ETS1-2 Engineering Design	Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.	1,2,3
HS-ETS1-3 Engineering Design	Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics as well as possible social, cultural, and environmental impacts.	3,4,5
IN-WH.7.6 World History	Formulate and present a position or course of action on an issue by examining the underlying factors contributing to that issue, and support that position.	4, 5
IN-WG.5.2 World Geography	Identify solutions to problems caused by environmental changes brought on by human activity.	1,5
IN-S.8.11 Sociology	Evaluate a current issue that has resulted from scientific discoveries and/or technological innovations.	4

The module provides background information on the scientific and engineering principles underlying climate engineering and places a special focus on three critical STEM practices frequently neglected in climate change and engineering education: (1) the communication of results and ideas, (2) engagement in scientific and engineering debates, and (3) examination of the societal, political, and economic contexts surrounding these topics (e.g., Ford, 2008; Berland and Reiser, 2009; Chin and Osborne, 2010; Dawson, 2012; Herman et al., 2017). Moreover, grounded in problem-based learning (Hmelo-Silver, 2004), the lessons engage students by tasking them to collaboratively work through the engineering design process to help solve climate challenges. Through this process, students work together to develop climate engineering technologies aimed at slowing global warming and mitigating the adverse effects of climate change. At the conclusion of the module, we anticipate that students will have developed the skills to participate in informed argumentation and make informed decisions regarding climate engineering.

Lesson 1: *Climate Engineering Concept Generation*

Building on previous lessons about climate change, the initial lesson encourages students to brainstorm innovative technological solutions to mitigate global warming and its adverse effects. To begin, students work individually to conceive ideas, with an emphasis on creative, out-of-the-box thinking regarding potential technologies and their functionalities. They jot down these ideas on different-colored sticky notes (using different colors allows teachers to view everyone's individual ideas). Throughout this process, teachers encourage their students to go for quantity, generate wild ideas, build on previous ideas, and defer judgment. Subsequently, in small groups, students collaborate to generate additional ideas and organize their sticky notes into categories. These categories, forming each group's "Mind Map" (Edwards and Cooper, 2010), might include "Sunlight Reflection," "Carbon Uptake," "Emission Reduction," and "Miscellaneous" (Figure 2).

Figure 2. Student group's Mind Map, brainstorming climate engineering ideas.

Next, each student picks three climate engineering concepts to illustrate in three different sketches. These sketches are then circulated to group members who add details or commentary to the initial sketch. Each sketch is passed amongst group members until every sketch has feedback from 3 to 4 group members. We term this process concept sketching.

By the end of Lesson 1, each student will have developed three climate engineering designs enriched with collaborative input and ideas from their peers. It is expected that many of the students' ideas may not be feasible in the real world, but as they work through the brainstorming → mind mapping → concept sketching process, they begin to understand what a climate engineering technology may look like - and possibly, what they still need to learn to inform the next steps in the engineering design process (selecting a design, refining and testing the design, and finalizing and sharing the design, as shown in Figure 3).

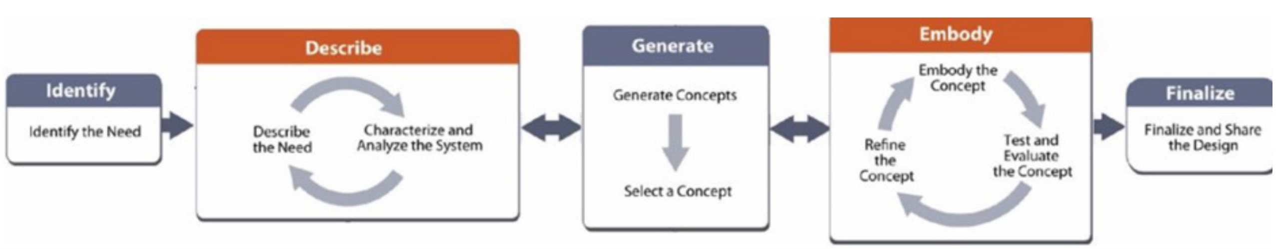

Figure 3. An engineering design process emphasizing concept generation, modified from Guerra et al. (2012).

This initial lesson was designed for the ABC, Activity Before Content (Cavanagh, 2007), approach to effectively elevate students' understanding of climate engineering to the creation of three distinct technological solutions addressing global warming and climate change. We also want to note here that the "wild ideas" that the students come up with during this lesson are probably all ideas that climate engineers are actually looking into - like this idea to have a giant umbrella in space.

Lesson 2: Marine Cloud Brightening Experiment

Lesson 2 challenges the students with designing and conducting an experiment to brighten clouds. This lesson is based on the real-world climate engineering science of co-authors Goddard and Kravitz (e.g., Goddard et al., 2022). Continuing the ABC (Cavanagh, 2007) and problem-based learning (Hmelo-Silver, 2004) approaches, teachers refrain from providing specific details about the climate engineering technology that the lesson models (marine cloud brightening) in favor of student discovery. To scaffold this task, teachers guide students by revisiting the composition of clouds (including cloud condensation nuclei), clarifying the concept of albedo, and demonstrating how to create a cloud inside a plastic bottle. Following this, teachers assist students in developing a research protocol that involves comparing the brightness of clouds formed in environments with high aerosol levels to those in environments with low aerosol levels.

The subsequent lesson amplifies the classic "cloud-in-a-bottle" experiment and reveals to the students the relationship between the number of cloud droplets and the cloud's reflective properties (Figure 4). In turn, students are primed to apply this knowledge towards understanding marine cloud brightening as a potential climate engineering solution. This climate engineering technology proposes to spray sea salt particles into low level clouds to increase the cloud droplet number and, ultimately, the cloud's albedo.

During the lesson, students will measure the reflectance of clouds created in environments with low and high aerosol concentrations. We have found that the clouds resulting from this protocol are impressive to students, especially when higher concentrations of aerosols are present. The data collected will be pooled across the classroom, and students will conduct statistical analyses, including calculations of the mean, median, mode, and range of the reflectance. To further scale up this analysis and student understanding for more

Figure 4. Student group measuring cloud reflectance, Tri-North Middle School, Bloomington, IN.

advanced learners, students can calculate a T-test statistic to determine if the difference in mean reflectance between the two experiments is statistically significant. Instructions for conducting these statistics are provided in the lesson materials.

Lesson 2 highlights the significance of developing an engineering prototype that enables testing and iterative refinement of technology on a small scale, which assists in decision-making for large-scale deployment. The lesson concludes with teacher-led discussions regarding marine cloud brightening's associated limitations and risks.

Lesson 3: Climate Engineering Blueprint

In Lesson 3, each student selects one of their three initial designs to refine and develop further throughout the module, creating an engineering blueprint of a technology they develop. Students use a decision matrix (Table 2) to quantitatively evaluate how well each concept adheres to new design constraints and criteria; high scores indicate strong solutions. Key considerations include the feasibility of small-scale testing to uncover potential issues or side effects, the scalability of the design for regional or global climate impact, and the estimated costs and resource requirements. Students are prompted to use technology resources for their research. They also assess the uniqueness of their designs compared to their peers' proposed climate engineering technologies. Peer evaluation is encouraged, with students helping each other rate their preliminary designs. Evaluating, revising, and selecting designs are

Table 2. A decision matrix to aid the students in selecting one design to move forward to the blueprint creation step.

Criteria to Consider when Selecting and Revising your Designs	Score 1-5
How well does your design slow global warming and/or climate change? (1 - not well, 5 - very well)	
Does your technology modify or work with an environmental system? (1 - does not, 5 - perfect match)	
What is the cost of your technology (consider materials, resources, and upkeep)? (1 - high cost, 5 - low cost)	
Does your design scale well (can you test your technology on a small-scale, then expand to large-scale deployment)? (1 - not well, 5 - very well)	
Rate the amount of unintended negative consequences of deploying your technology? (1 - many, 5 - few)	
Is your design unique? (1 – other students have similar designs, 5 – it's one-of-a-kind!)	
Total (max 30 points)	

essential steps in the engineering design process (Figure 3). These steps offer students the opportunity to emulate engineers effectively.

It is worth noting that students - and their teachers! - might not have a complete understanding of what materials might be used for different products and/or the cost of those materials and still encourage students to use their resources, previous experiences, and problem-solving skills to make educated guesses as they create their engineering designs. Some of our students have enjoyed designing "wild" climate engineering solutions, like those from Peterson's classroom shown in Lesson 5's section, while others take a more practical approach, often designing new applications of renewable energy and/or low-carbon technologies and practices. This year, Milks' students' designs have included car-free street plans, bicycle shares, portable solar-powered charge banks, luxury bus stops, and plans very similar to those currently locking atmospheric carbon away via concrete production.

This lesson leaves students with an appreciation for the need to balance innovation and practicality in engineering designs while addressing the identified need. After choosing the design that best fits the constraints and criteria, each student drafts an informative engineering blueprint. By the end of this lesson, students have nearly completed the modified engineering design process shown in Figure 3, with only one step remaining: sharing the design, which is the focus of Lesson 5.

Lesson 4: Model U.N.

In Lesson 4, students engage in a challenging activity designed to explore the multifaceted issues surrounding the deployment of climate engineering technologies, focusing on their social, ethical, economic, and political implications. Working in groups (usually groups of four to six), students assume the roles of delegates from six fictional countries during a United Nations summit set in 2030 (Figure 5). These countries differ significantly in wealth, fossil fuel resources, renewable energy availability, and access to climate engineering technologies. Furthermore, each nation has its own economic ambitions in the context of climate change. The summit's key goal is to make a decision on the implementation of climate engineering by 2035, a critical juncture when the global mean temperature is projected to be 1.5°C higher than pre-industrial levels.

Conducting a Model U.N. lesson presents unique challenges, especially for science teachers who may lack experience in facilitating discussions on socio-economic-political issues. Our lesson plan includes several strategies to enhance teacher efficacy and tips on adapting the lesson to different levels of students. Based on feedback from teachers who have conducted the lesson and our EfEC workshop participants, we recommend the following tips for a successful lesson:

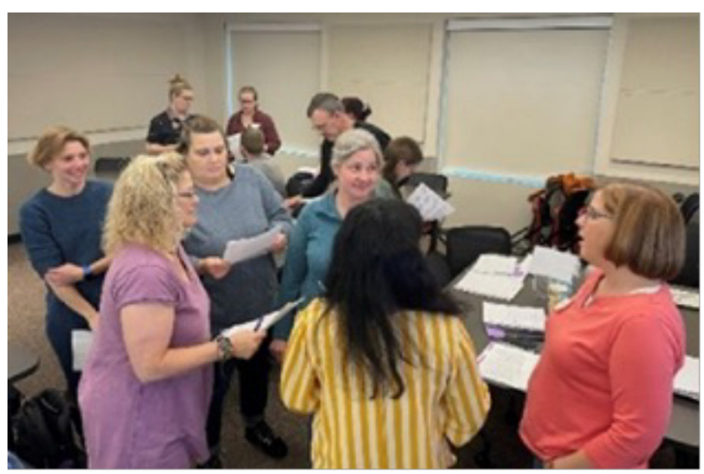

Figure 5. Teachers partcipating in Model UN activity.

1. *Selecting Student Groups*. Although Milks and Peterson group students randomly for many science activities, we've learned that "casting" is important for this lesson in two ways.
   - First, Molvania's (one of the activity's six fictional countries) representatives must be duplicitous in their negotiations, and we suggest selecting students who will be up to the play-acting and in-the-moment critical thinking that is required by the role.
   - Second, we are highly intentional about which students are asked to pretend to be the low-power states in the simulation (Tanoa, an island nation soon to be underwater, and Durhan, a financially struggling country who has a long history of being exploited by other countries). If your class of students is socioeconomically diverse, make sure to select students with high socioeconomic status as representatives of these countries. Similarly, if your class of students is racially diverse, we strongly suggest placing students of color in teams representing the higher-power nations.
2. *Student Preparation*. Prior to negotiations, students should familiarize themselves with the public and private information of their country and the public information of other countries. Then, work within their groups to establish what resources or bargaining chips they have to drive negotiations and develop treaties with other countries. Finally, each group (country) should decide whether climate engineering should be deployed and why. This decision should be framed in terms of advantages or disadvantages for their country.
3. *Group Structure*. If desired, teachers may define roles for members in each country's delegation:
   - President (1): Remains at the group's table overseeing diplomats and consulting with the science advisor. The President approves or vetoes treaties.
   - Diplomats (2-4): Engage in negotiations and treaty writing with delegates from other countries. This includes both diplomats that visit other tables (countries) and one who stays at their table to receive other delegations.
   - Treaty Writer (1): Collaborates with the delegation to compile information and draft treaties. All treaties require the signatures of the country's President, the treaty writer, and the involved diplomats.
   - Science Advisor (1): Supports the President and diplomats by integrating relevant climate science and climate engineering knowledge into the negotiations.
4. *Lesson Implementation*. Smooth operation of the lesson can be aided by simple measures, such as providing name tags indicating each student's country and role, distributing printouts or having students self-construct documents showing public and private information, and utilizing the provided worksheets to facilitate treaty negotiations and strategic planning following disruptive news briefs at the summit.

This lesson encourages students to consider the complex socio-political and ethical dimensions of climate change and climate engineering, highlighting the often-secondary role of scientific and technological understanding in geopolitical negotiations. Milks, who facilitated this project with her co-taught Earth and Space science students, notes that science teachers might be tempted to skip this lesson, but she strongly suggests giving it a try. She's been impressed with how students, with appropriate scaffolds, can pick up on important ideas and learn to explain the connections between climate science and climate policy.

Lesson 5: Climate Engineering Presentations

In the fifth lesson, students apply their acquired climate engineering knowledge and the understanding of socio-scientific issues surrounding its implementation by presenting their technological solutions to a select audience of scientists, engineers, and policymakers. First, presentations (either in-person or via Zoom) of their technological blueprints are observed by scientists (and co-authors) Goddard and Kravitz, along with IU graduate students and postdoctoral researchers. This activity provides a platform for students to communicate their design ideas effectively to a knowledgeable audience, allowing them to converse and receive feedback from science professionals. Sharing their designs (Figure 6) represents the culmination of the engineering design process (Figure 3). It also serves as a mock exercise in presenting their ideas to potential investors or decision-makers.

Additionally, students may participate in drafting letters to state politicians as a capstone activity, expressing their concerns and viewpoints on climate mitigation and engineering strategies. A provided template assists students in composing letters that outline

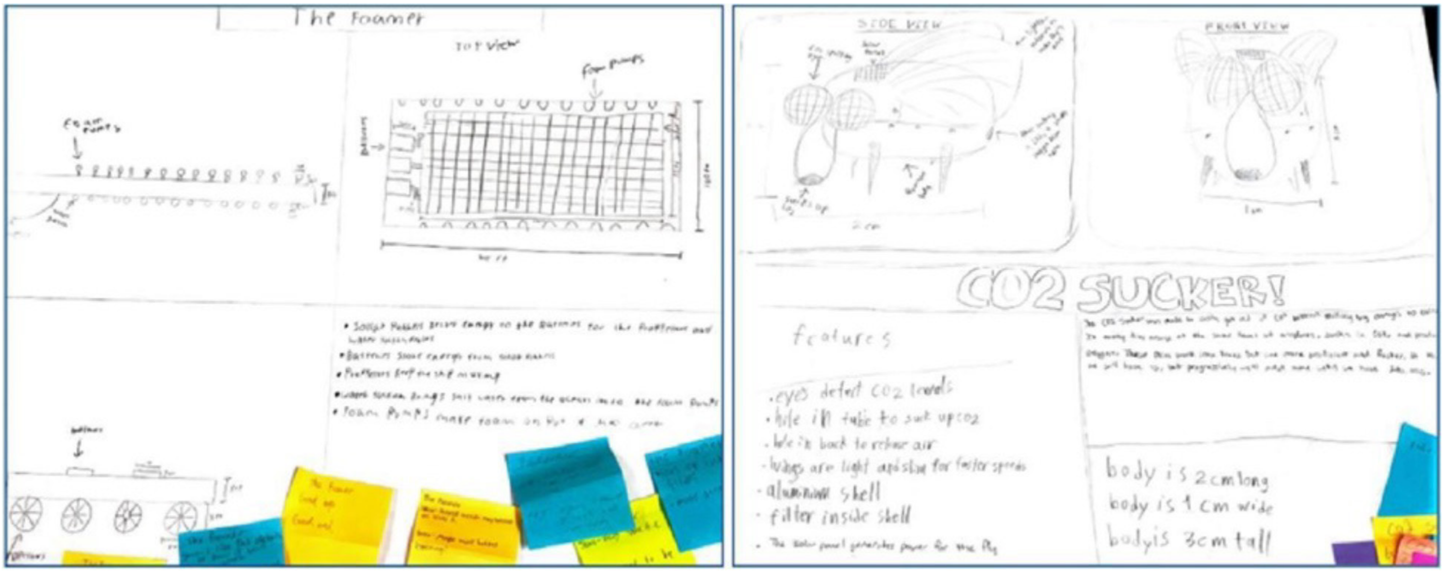

Figure 6. Student geoengineering designs from Peterson's classroom depicting autonomous solar-powered boats (left)and a swarm of flying, insect-sized CO2 scrubbers (right).

potential actions the state of Indiana could undertake to reduce greenhouse gas emissions, along with the advantages and disadvantages of climate engineering. This activity serves as an excellent opportunity to demonstrate to students the importance and power of advocacy and communication in science.

Next Steps

Teachers, including co-authors Milks and Peterson, who have implemented the module, reported high levels of student engagement and expressed a desire to teach the unit again. Peterson observes that many students have mentioned their enjoyment of the unit, stating it provided information that "actually mattered" and found it empowering to learn about actionable climate change solutions.

The project team will persist in updating our CETM workshops and lessons to enhance teachers' pedagogical content knowledge and efficacy in teaching climate engineering. However, one aspect we have yet to specifically address is how to tailor these lessons to fit individual classroom needs and curriculums.

We are seeking funding to establish an annual autumn workshop focused on tailoring our climate engineering lessons to specific subject areas, grade levels, and curricular needs. Initially, teachers and the project team will work together to either create new lesson plans or adapt existing ones, ensuring they align with the specific needs of each teacher's subject area and grade level. This collaborative effort is designed to continuously improve and expand the CETM lessons. Additionally, teachers will develop a comprehensive plan for integrating climate engineering education into their classrooms. This plan will detail the concepts and activities to be covered, learning objectives, required materials, and other critical information. These plans will be finalized during or shortly after the workshop and reviewed by the project team. Each teacher will then receive feedback, enabling them to integrate climate engineering education seamlessly into their winter or spring curriculum.

Finally, as part of our website's future development, we will introduce a discussion forum to enable better communication between the project team and teacher cohorts. Through this forum, teachers will have the opportunity to share strategies for tailoring lessons to their specific classroom and curriculum needs, as well as pose questions directly to the project team. With this publication and launch of the CETM website, our ultimate goal is to facilitate the integration of climate engineering education in classrooms across the country and the world.

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