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Stabilization Wedges:
A Concept & Game

The **Carbon Mitigation Initiative** is a joint project of Princeton University, BP, and Ford Motor Company to find solutions to the greenhouse gas problem. To emphasize the need for early action, Co-Directors Robert Socolow and Stephen Pacala created the concept of stabilization wedges: 25-billion-ton "wedges" that need to be cut out of predicted future carbon emissions in the next 50 years to avoid a doubling of atmospheric carbon dioxide over pre-industrial levels.

The following pages contain:
- An introduction to the carbon and climate problem and the stabilization wedge concept (pp. 1-3)
- Descriptions of currently available mitigation tools that have the capacity to reduce future emissions by at least one wedge (pp. 4-8)
- Materials and instructions for carrying out the "Stabilization Wedges Game," an activity that drives home the scale of the carbon mitigation challenge and the tradeoffs involved in planning climate policy (pp. 9-16)

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You can download a free up-to-date copy of this guide and view additional resources at our wedge website:

http://cmi.princeton.edu/wedges/

We hope to revise these materials with your input! If you have questions or feedback, please contact Dr. Roberta Hotinski, Consultant to CMI, at **hotinski@princeton.edu**

The Carbon and Climate Problem

Evidence continues to accumulate that carbon dioxide, or CO_2, from fossil fuel burning is causing dangerous interference in the climate. Including 2006, six of the seven warmest years on record have occurred since 2001 and the ten warmest years have occurred since 1995. Tropical glaciers with ice thousands and tens of thousands years old are disappearing, offering graphic rebuttal to claims that the recent warming is part of a natural cycle. Models predict that, without action to curb the growth of greenhouse gases in the atmosphere, we risk triggering catastrophe -- cessation of the dominant pattern of ocean circulation, loss of the West Antarctic ice sheet, or a several-fold increase in category-five hurricanes.

CO_2 and some other gases in the atmosphere change the climate by letting sunlight pass through the atmosphere and warm the planet, but hindering the escape of heat to outer space (a phenomenon popularly known as "the greenhouse effect"). By burning fossil fuels, which are composed mainly of hydrogen and carbon, we add CO_2 to the atmosphere.

The Earth's atmosphere currently contains about **800 billion tons** of carbon as CO_2, and combustion of fossil fuels currently adds about **8 billion tons of carbon** every year. If we think of the atmosphere as a bathtub, these carbon emissions are like water coming out of the tap to fill the tub (**Figure 1**). The ocean and land biosphere act as two drains for this bathtub – carbon can be taken out of the atmosphere by being dissolved in the surface ocean or being taken up by growing forests. However, these two "drains" only take out about half the carbon we emit to the atmosphere every year. The remainder accumulates in the atmosphere (currently at a rate of roughly 4 billion tons per year), so the level of carbon in the tub is rising.

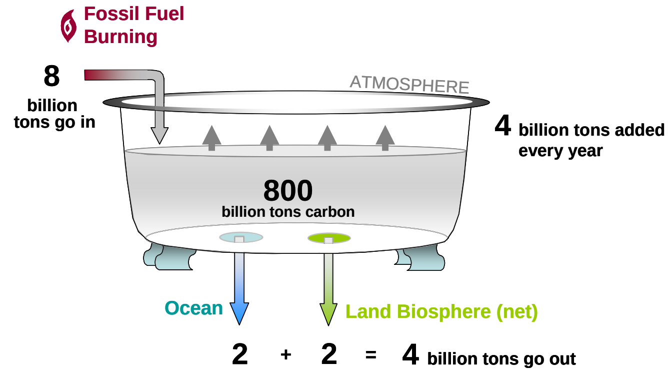


Figure 1. The atmosphere as a bathtub, with current annual inputs and outputs of carbon. The level in the tub is rising by about 4 billion tons per year.

The fossil fuel tap was "opened" with the Industrial Revolution. In pre-industrial times, the atmosphere contained only about 600 billion tons of carbon, 200 billion tons less than today (Figure 2). As an illustration of the importance of CO_2 to the Earth's climate, ice core records show that past atmospheric carbon changes of a similar magnitude have meant the difference between Ice Ages and the familiar warmer conditions of the past 10,000 years.

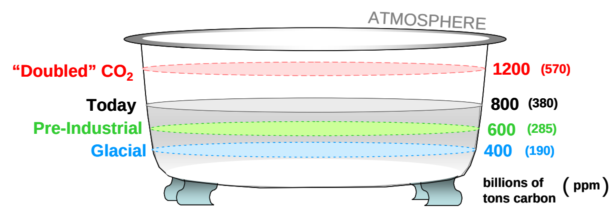


Figure 2. Past, present, and potential future levels of carbon in the atmosphere in two units. 2.1 billions of tons of carbon = 1 part per million (ppm).

Observations indicate that the carbon already added to the atmosphere has raised the global average temperature by around 1º Fahrenheit since the 19th century, and almost every year the fossil fuel tap is opened wider. An average of many forecasts predicts that we'll be adding **16 billion tons** of carbon per year to the "bathtub" in 50 years, twice today's rate, unless action is taken to control carbon emissions. If we follow this path, the amount of carbon in the atmosphere will reach 1200 billion tons -- **double its pre-industrial value** – well before the end of this century, **and will continue to increase** into the future. As a result, the Earth's temperature is expected to rise at a rate unprecedented in the last 10,000 years. **How can we get off this path?**

An Introduction to Stabilization Wedges

The "stabilization wedges" concept is a simple tool for conveying the emissions cuts that can be made to avoid dramatic climate change.

We consider two futures - **allowing emissions to double versus keeping emissions at current levels** for the next 50 years (Figure 3). The emissions-doubling path (black dotted line) falls in the middle of the field of most estimates of future carbon emissions. The climb approximately extends the climb for the past 50 years, during which the world's economy grew much faster than its carbon emissions. Emissions could be higher or lower in 50 years, but this path is a reasonable reference scenario.

The emissions-doubling path is predicted to lead to significant global warming by the end of this century. This warming is expected be accompanied by decreased crop yields, increased threats to human health, and more frequent extreme weather events. The planet could also face rising sea-level from melting of the West Antarctic Ice Sheet and Greenland glaciers and destabilization of the ocean's thermohaline circulation that helps redistribute the planet's heat and warm Western Europe.

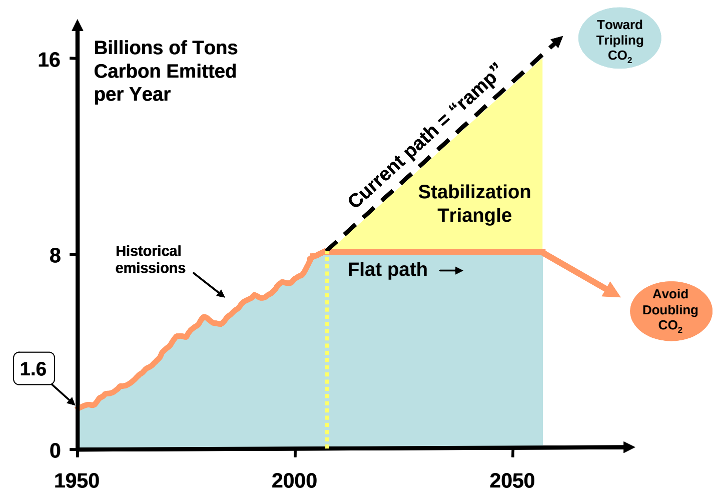


Figure 3. Two possible emissions scenarios define the "stabilization triangle."

In contrast, we can prevent a doubling of CO_2 if we can keep emissions flat for the next 50 years, then work to reduce emissions in the second half of the century (Figure 3, orange line). This path is predicted to keep atmospheric carbon under 1200 billion tons (which corresponds to about 570 parts per million (ppm)), allowing us to skirt the worst predicted consequences of climate change.

Keeping emissions flat will require cutting projected carbon output by about 8 billion tons per year by 2055, keeping a total of ~200 billion tons of carbon from entering the atmosphere (see yellow triangle in Figure 3). This carbon savings is what we call the **"stabilization triangle."**

The conventional wisdom has been that only revolutionary new technologies like nuclear fusion could enable such large emissions cuts. There is no reason, however, why one tool should have to solve the whole problem. CMI set out to quantify the impact that could be made by **a portfolio of existing technologies** deployed on a massive scale.

To make the problem more tractable, we divided the stabilization triangle into **eight "wedges."** (Figure 4) A wedge represents a carbon-cutting strategy that has the potential to grow from zero today to avoiding 1 billion tons of carbon emissions per year by 2055, or one-eighth of the stabilization triangle. The wedges can represent ways of either making energy with no or reduced carbon emissions (like nuclear or wind-produced electricity), or storing carbon dioxide to prevent it from building up as rapidly in the atmosphere (either through underground storage or biostorage).

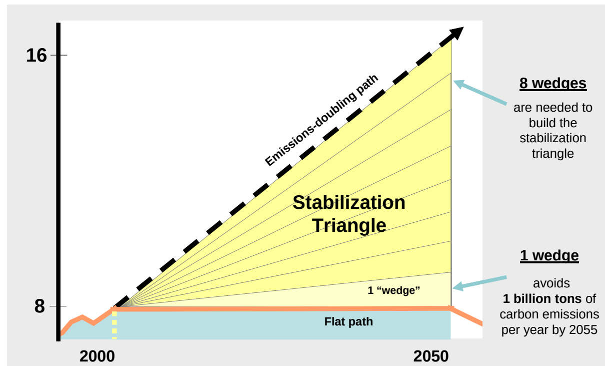


Figure 4. The eight "wedges" of the stabilization triangle.

Keeping emissions flat will require the world's societies to "fill in" the eight wedges of the stabilization triangle. In CMI's analysis, **at least 15 strategies are available <u>now</u>** that, with scaling up, could each take care of at least one wedge of emissions reduction. No one strategy can take care of the whole triangle -- new strategies will be needed to address both fuel and electricity needs, and some wedge strategies compete with others to replace emissions from the same source -- but there is already a more than adequate portfolio of tools available to control carbon emissions for the next 50 years.

Wedge Strategies Currently Available

The following pages contain descriptions of 15 strategies already available that could be scaled up over the next 50 years to reduce global carbon emissions by 1 billion tons per year, or **one wedge.** They are grouped into four major color-coded categories:

Efficiency & Conservation

- Increased transport efficiency
- Reducing miles traveled
- Increased building efficiency
- Increased efficiency of electricity production

Fossil-Fuel-Based Strategies

- Fuel switching (coal to gas)
- Fossil-based electricity with carbon capture & storage (CCS)
- Coal synfuels with CCS
- Fossil-based hydrogen fuel with CCS

Nuclear Energy

- Nuclear electricity

Renewables and Biostorage

- Wind-generated electricity
- Solar electricity
- Wind-generated hydrogen fuel
- Biofuels
- Forest storage
- Soil storage

Each strategy can be applied to one or more sectors, indicated by the following symbols:

= Electricity Production, =Heating and Direct Fuel Use, =Transportation, = Biostorage

Increased Efficiency & Conservation

1. Transport Efficiency

A typical 30 miles per gallon (30 mpg) car driving 10,000 miles per year emits a ton of carbon into the air annually. Today there are about about 600 million cars in the world, and it's predicted that there will be about 2 billion passenger vehicles on the road in 50 years. **A wedge of emissions savings would be achieved if the fuel efficiency of all the cars projected for 2055 were doubled from 30 mpg to 60 mpg**. Efficiency improvements could come from using hybrid and diesel engine technologies, as well as making vehicles out of strong but lighter materials.

Cutting carbon emissions from trucks and planes by making these engines more efficient can also help with this wedge. Aviation is the fastest growing component of transportation.

2. Transport Conservation

A wedge would be achieved if the number of miles traveled by the world's cars were cut in half. Such a reduction in driving could be achieved if urban planning leads to more use of mass transit and if electronic communication becomes a good substitute for face-to-face meetings.

3. Building Efficiency

Today carbon emissions arise about equally from providing electricity, transportation, and heat for industry and buildings. The largest potential savings in the buildings sector are in space heating and cooling, water heating, lighting, and electric appliances.

It's been projected that the buildings sector as a whole has the technological and economic potential to cut emissions in half. **Cutting emissions by 25% in all new and existing residential and commercial buildings would achieve a wedge worth of emissions reduction.** Carbon savings from space and water heating will come from both end-use efficiency strategies, like wall and roof insulation, and renewable energy strategies, like solar water heating and passive solar design.

4. Efficiency in Electricity Production

Today's coal-burning power plants produce about one-fourth of the world's carbon emissions, so increases in efficiency at these plants offer an important opportunity to reduce emissions**. Producing the world's current coal-based electricity with doubled efficiency would save a wedge worth of carbon emissions.**

More efficient conversion results at the plant level from better turbines, from using high-temperature fuel cells, and from combining fuel cells and turbines. At the system level, more efficient conversion results from more even distribution of electricity demand, from cogeneration (the co-production of electricity and useful heat), and from polygeneration (the co-production of chemicals and electricity).

Due to large contributions by hydropower and nuclear energy, the electricity sector already gets about 35% of its energy from non-carbon sources. Wedges can only come from the remaining 65%.

Suggested Link:
IPCC Working Group III Report "Mitigation of Climate Change", Chapters 4, 5 & 6
http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg3_report_mitigation_of_climate_change.htm

Carbon Capture & Storage (CCS)

If the CO_2 emissions from fossil fuels can be captured and stored, rather than vented to the atmosphere, then the world could continue to use coal, oil, and natural gas to meet energy demands without harmful climate consequences. The most economical way to pursue this is to capture CO_2 at large electricity or fuels plants, then store it underground. This strategy, called carbon capture and storage, or **CCS**, is already being tested in pilot projects around the world.

5. <u>CCS Electricity</u>

Today's coal-burning power plants produce about one fourth of the world's carbon emissions and are large point-sources of CO_2 to the atmosphere. **A wedge would be achieved by applying CCS to 800 large (1 billion watt) baseload coal power plants or 1600 large baseload natural gas power plants in 50 years. As with all CCS strategies, to provide low-carbon energy the captured CO_2 would need to be stored for centuries.**

There are currently 3 pilot storage projects in the world, which each store about 1 million tons of carbon underground per year. Storing a wedge worth of emissions will require 3500 times the capacity of one of these projects.

6. <u>CCS Hydrogen</u>

Hydrogen is a desirable fuel for a low-carbon society because when it's burned the only emission product is water vapor. Because fossil fuels are composed mainly of carbon and hydrogen they are potential sources of hydrogen, but to have a climate benefit the excess carbon must be captured and stored.

Pure hydrogen is now produced mainly in two industries: ammonia fertilizer production and petroleum refining. Today these hydrogen production plants generate about 100 million tons of capturable carbon. Now this CO_2 is vented, but only small changes would be needed to implement carbon capture. **The scale of hydrogen production today is only ten times smaller than the scale of a wedge of carbon capture.**

Distributing CCS hydrogen, however, requires building infrastructure to connect large hydrogen-producing plants with smaller-scale users.

7. <u>CCS Synfuels</u>

In 50 years a significant fraction of the fuels used in vehicles and buildings may not come from conventional oil, but from coal. When coal is heated and combined with steam and air or oxygen, carbon monoxide and hydrogen are released and can be processed to make a liquid fuel called a "synfuel."

Coal-based synfuels result in nearly twice the carbon emissions of petroleum-derived fuels, since large amounts of excess carbon are released during the conversion of coal into liquid fuel. The world's largest synfuels facility, located in South Africa, is the largest point source of atmospheric CO_2 emissions in the world. **A wedge is an activity that, over 50 years, can capture the CO_2 emissions from 180 such coal-to-synfuels facilities.**

Suggested link:
IPCC Special Report on Carbon dioxide Capture and Storage, SPM
http://www.ipcc.ch/pdf/specialreports/srccs/srccs_summaryforpolicymakers.pdf

Fuel Switching

8. Fuel-Switching for Electricity

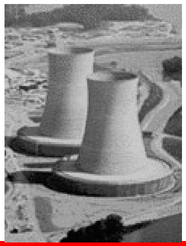
Because of the lower carbon content of natural gas and higher efficiencies of natural gas plants, producing electricity with natural gas results in only about half the emissions of coal. **A wedge would require 1400 large (1 billion watt) natural gas plants displacing similar coal-electric plants.**

This wedge would require generating approximately four times the Year 2000 global production of electricity from natural gas. In 2055, 1 billion tons of carbon per year would be emitted from natural gas power plants instead of 2 billion tons per year from coal-based power plants.

Materials flows equivalent to one billion tons of carbon per year are huge: a wedge of flowing natural gas is equivalent to 50 large liquefied natural gas (LNG) tankers docking and discharging every day. Current LNG shipments world-wide are about one-tenth as large.

Suggested link:
U.S. Environmental Protection Agency: Electricity from Natural Gas
http://www.epa.gov/RDEE/energy-and-you/affect/natural-gas.html

Nuclear Energy



9. Nuclear Electricity

Nuclear fission currently provides about 17% of the world's electricity, and produces no CO_2. **Adding new nuclear electric plants to triple the world's current nuclear capacity would cut emissions by one wedge if coal plants were displaced.**

In the 1960s, when nuclear power's promise as a substitute for coal was most highly regarded, a global installed nuclear capacity of about 2000 billion watts was projected for the year 2000. The world now has about one-sixth of that envisioned capacity. If the remainder were to be built over the next 50 years to displace coal-based electricity, roughly two wedges could be achieved.

In contrast, phasing out the worlds' current capacity of nuclear power would require adding an additional half wedge of emissions cuts to keep emissions at today's levels.

Nuclear fission power generates plutonium, a fuel for nuclear weapons. These new reactors would add several thousand tons of plutonium to the world's current stock of reactor plutonium (roughly 1000 tons).

Renewable Energy & Biostorage

10. Wind Electricity

Wind currently produces less than 1% of total global electricity, but wind electricity is growing at a rate of about 30% per year. **To gain a wedge of emissions savings from wind displacing coal-based electricity, current wind capacity would need to be scaled up by a factor of 30.**

Based on current turbine spacing on wind farms, a wedge of wind power would require a combined area roughly the size of Germany. However, land from which wind is harvested can be used for many other purposes, notably for crops or pasture.

11. Solar Electricity

Photovoltaic (PV) cells convert sunlight to electricity, providing a source of CO_2-free and renewable energy. The land demand for solar is less than with other renewables, but **installing a wedge worth of PV would still require arrays with an area of two million hectares, or 20,000 km^2.** The arrays could be located on either dedicated land or on multiple-use surfaces such as the roofs and walls of buildings. The combined area of the arrays would cover an area the size of the U.S. state of New Jersey, or about 12 times the size of the London metropolitan area.

Since PV currently provides less than a tenth of one percent of global electricity, achieving a wedge of emissions reduction would require increasing the deployment of PV by a factor of 700 in 50 years, or installing PV at 60 times the current rate for 50 years.

A current drawback for PV electricity is its price, which is declining but is still 2-5 times higher than fossil-fuel-based electricity. Also, PV can not be collected at night and, like wind, is an intermittent energy source.

12. Wind Hydrogen

Hydrogen is a desirable fuel for a low-carbon society because when it's burned the only emission product is water vapor. To produce hydrogen with wind energy, electricity generated by wind turbines is used in electrolysis, a process that liberates hydrogen from water. **Wind hydrogen displacing vehicle fuel is only about half as efficient at reducing carbon emissions as wind electricity displacing coal electricity, and 4 million (rather than 2 million) windmills would be needed for one wedge of emissions reduction.** That increase would require scaling up current wind capacity by about 80 times, requiring a land area roughly the size of France.

Unlike hydrogen produced from fossil fuels with CCS, wind hydrogen could be produced at small scales where it is needed. Wind hydrogen thus would require less investment in infrastructure for fuel distribution to homes and vehicles.

Renewables & Biostorage (cont'd)

13. Biofuels

Because plants take up carbon dioxide from the atmosphere, combustion of biofuels made from plants like corn and sugar cane simply returns "borrowed" carbon to the atmosphere. Thus burning biofuels for transportation and heating will not raise the atmosphere's net CO_2 concentration.

The land constraints for biofuels, however, are more severe than for wind and solar electricity. Using current practices, just one wedge worth of carbon-neutral biofuels would require 1/6th of the world's cropland and an area roughly the size of India. Bioengineering to increase the efficiency of plant photosynthesis and use of crop residues could reduce that land demand, but large-scale production of plant-based biofuels will always be a land-intensive proposition.

Ethanol programs in the U.S. and Brazil currently produce over 35 billion liters of biofuel per year from corn and sugarcane, respectively. **One wedge of biofuels savings would require increasing today's ethanol production by about 30 times, and making it sustainable.**

14. Forest Storage

Land plants and soils contain large amounts of carbon. Today, there is a net *removal* of carbon from the atmosphere by these "natural sinks," in spite of deliberate deforestation by people that *adds* between 1 and 2 billion tons of carbon to the atmosphere. Evidently, the carbon in forests is increasing elsewhere on the planet.

Land plant biomass can be increased by both reducing deforestation and planting new forests. **Halting global deforestation in 50 years would provide one wedge of emissions savings.** To achieve a wedge through forest planting alone, new forests would have to be established over an area the size of the contiguous United States.

15. Soil Storage

Conversion of natural vegetation to cropland reduces soil carbon content by one-half to one-third. However, soil carbon loss can be reversed by agricultural practices that build up the carbon in soils, such as reducing the period of bare fallow, planting cover crops, and reducing aeration of the soil (such as by no till, ridge till, or chisel plow planting). **A wedge of emissions savings could be achieved by applying carbon management strategies to all of the world's existing agricultural soils.**

Suggested links:
U.S. DOE, Energy Efficiency & Renewable Energy
http://www.eere.energy.gov/

IPCC Working Group III Report "Mitigation of Climate Change", Chapters 8 & 9
http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg3_report_mitigation_of_climate_change.htm

The Stabilization Wedges Game – Lesson Plan

Goals
The core purpose of this game is to convey the scale of effort needed to address the carbon and climate situation and the necessity of developing a portfolio of options. By the end of the exercise, students should understand the magnitude of human-sourced carbon emissions and feel comfortable comparing the effectiveness, benefits, and drawbacks of a variety of carbon-cutting strategies. The students should appreciate that **there is no easy or "right" solution to the carbon and climate problem.**

Objectives
Students will learn about the technologies currently available that can substantially cut carbon emissions, develop critical reasoning skills as they create their own portfolio of strategies to cut emissions, and verbally communicate the rationale for their selections. Working in teams, students will develop the skills to negotiate a solution that is both physically plausible and politically acceptable, and defend their solution to a larger group.

National Science Content Standards

- Systems, Order and Organization
- Science as Inquiry
- Science in Personal and Social Perspectives
  Natural and Human Induced Hazards
  Environmental Quality

Materials (see **Student Game Materials** at end of packet)

- 1 copy of Instructions and Wedge Table **per student (print single-sided to allow use of gameboard pieces!)**
- 1 Wedge Worksheet and 1 Gameboard with multi-colored wedge pieces **per group**, plus scissors for cutting out game pieces and glue sticks or tape to secure pieces to gameboard
- Optional - overhead transparencies, posters, or other materials for group presentations

Time Required
We suggest using 2-3 standard (40-50 minute) class periods to prepare for and play the Stabilization Wedges game. In the first period, the Stabilization Triangle and the concept of wedges are discussed and the technologies introduced. Students can further research the technologies as homework. In the second period, students play the game and present their results. Depending on the number of groups in the class, an additional period may be needed for the presentation of results. Assessment and application questions are included and may be assigned as homework after the game has been played, or discussed as a group as part of an additional class period/assignment.

Lesson Procedure / Methodology

I. **<u>Introduction</u> (40 minutes)**

a. **Motivation.** Review the urgency of the carbon and climate problem and potential ways it may impact the students' futures.

b. **Present the Concepts**. Introduce the ideas of the Stabilization Triangle and its eight "wedges".

c. **Introduce the Technologies.** Briefly describe the 15 wedge strategies identified by CMI, then have students familiarize themselves with the strategies as homework. Participants are free to critique any of the wedge strategies that CMI has identified, and teams should feel free to use strategies not on our list.

d. **Form Teams.** Teams of 3 to 6 players are best, and it is particularly helpful to have each student be an appointed "expert" in a few of the technologies to promote good discussions. You may want to identify a recorder and reporter in each group.

e. **Explain the Rules.** See instructions in **Student Game Materials** at back of packet

II. Playing the Game (40 minutes)

a. **Filling in the Stabilization Triangle**. Teammates should work together to build a team stabilization triangle using 8 color-coded wedges labeled with specific strategies. Many strategies can be used more than once.

b. **Wedge Worksheet.** Each team should fill in one **stabilization wedge worksheet** to make sure players haven't violated the constraints of the game, to tally costs, and to predict judges' ratings of their solution. NOTE: Costs are for guidance only – they are not meant to be used to produce a numerical score that wins or loses the game!

c. **Reviewing the Triangle.** Each team should review the strengths and weaknesses of its strategies in preparation for reporting and defending its solutions to the class.

III. Reports (depending on the number of groups this may require an additional class period)

a. Representatives from each team will defend their solutions to the class in a 5-minute report. The presentation can be a simple verbal discussion by the group or a reporter designated by the group. If additional time is available, the presentations could include visual aids, such as a poster, PowerPoint presentation, etc.

b. Students should address not only the technical viability of their wedges, but also the economic, social, environmental and political implications of implementing their chosen strategies on a massive scale.

IV. Judging

In CMI workshops, the teams' triangles have been judged by experts from various global stakeholder groups, such as an environmental advocacy organization, the auto industry, a developing country, or the U.S. Judging ensures that economic and political impacts are considered and emphasizes the need for consensus among a broad coalition of stakeholders. For a classroom, judges can be recruited from local government, colleges, businesses, and non-profit organizations, or a teacher/facilitator can probe each team about the viability of its strategies.

V. Closure/Assessment of Student Learning

In addition to addressing the game and lessons learned, discussion questions are provided below that give opportunity to develop and assess the students' understanding of the wedges concept and its applications.

1) Given physical challenges and risks, how many wedges do you think each wedge strategy can each realistically provide?

2) In choosing wedge strategies, it's important to avoid double counting – removing the same emissions with two different strategies. For example, there are 6 strategies for cutting emissions from electricity, but we project only 5 wedges worth of carbon produced from the electric sector 50 years from now. Can you think of reasons, other than the adoption of alternative or nuclear energy, that emissions from electricity would be lower or higher than we predict? Examples: increased use of carbon-intensive coal versus natural gas (higher), slower population growth (lower), substitution of electricity for fuel, as via plug-in electric cars (higher).

3) Industrialized countries and developing countries now each contribute about half the world's emissions, although the poorer countries have about 85% of the world's population. (The U.S. alone emits one fourth of the world's CO_2.) If we agree to freeze global emissions at current levels, that means if **emissions in one region of the world go up as a result of economic/industrial development, then emissions must be cut elsewhere**. Should the richer countries reduce their emissions 50 years from now so that extra carbon emissions can be available to developing countries? If so, by how much?

4) Nuclear energy is already providing one-half wedge of emissions savings – what do you think the future of these plants should be?

5) Automobile emissions are a popular target for greenhouse gas cuts. What percent of greenhouse gases do you think come from the world's passenger vehicles? (answer: about 18%)

Resources & Feedback

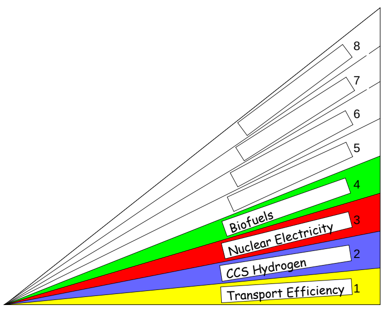
More stabilization wedge resources, including background articles and slides, and a form for feedback are available at **http://www.princeton.edu/~cmi/resources/stabwedge.htm**

Student Game Instructions & Materials

The goal of this game is to **construct a stabilization triangle using eight wedge strategies**, with only a few constraints to guide you. From the 15 potential strategies, choose 8 wedges that your team considers the best global solutions. Keep costs and impacts in mind.

1) Find the Wedge Gameboard in the back of this packet and cut apart the red, green, yellow, and blue wedge pieces supplied (if not already done for you).

2) Read the information on each of the 15 strategies in the **Wedge Table** below. Costs ($, $$, $$$) are indicated on a relative basis, and are intended only to provide guidance, not a numerical score.



3) Each team should **choose one wedge strategy at a time** to fill the 8 spots on the wedge gameboard (see illustration of gameboard with 4 wedges filled in at left – this is only an example!).

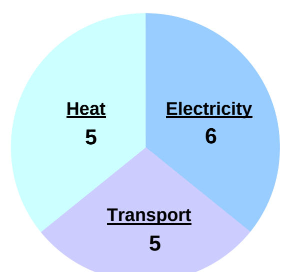
4) The four colors of the wedge pieces indicate the major category (fossil fuel-based (blue), efficiency and conservation (yellow), nuclear (red), and renewables and biostorage (green)). Choose a red, yellow, blue, or green wedge for your strategy, then **label the wedge to indicate the specific strategy** (examples shown in illustration at left).

5) Most strategies may be used more than once, but not all cuts can come from one energy sector.

Of the 16 billion tons of carbon emitted in the 2055 baseline scenario, we assume electricity production accounts for 6 wedges, transportation fuels accounts for 5 wedges, and direct fuel use for heat and other purposes accounts for 5 wedges (see pie chart right).

Because biostorage takes carbon from all sources out of the atmosphere, biostorage wedges do not count toward an energy sector.

Carbon Emissions by Sector



Need 8 wedges – not all wedges can come from one energy sector!

6) Cost and impacts must be considered. Each wedge should be viewed in terms of both technical and political viability.

7) For each of the 8 strategies chosen, each team should **fill out one line in the Wedge Worksheet**. After all 8 wedges have been chosen, tally total cuts from each energy sector (Electricity, Transport, and Heat) and costs. Use the scoring table to predict how different interest groups would rate your wedge on a scale from 1 to 5.

8) Each team should **give a 5-minute oral report** on the reasoning behind its triangle. The report should justify your choice of wedges to the judge(s) and to the other teams. **Note: There is no "right" answer** – the team that makes the best case wins, not necessarily the team with the cheapest or least challenging solution

Stabilization Wedges – 15 Ways to Cut Carbon

= Electricity Production, =Heating and Direct Fuel Use, =Transportation, = Biostorage

Strategy	Sector	Description	1 wedge could come from…	Cost	Challenges
1. Efficiency – Transport		Increase automobile fuel efficiency (2 billion cars projected in 2050)	**… doubling the efficiency of all world's cars from 30 to 60 mpg**	**$**	Car size & power
2. Conservation - Transport		Reduce miles traveled by passenger and/or freight vehicles	**… cutting miles traveled by all passenger vehicles in half**	**$**	Increased public transport, urban design
3. Efficiency - Buildings		Increase insulation, furnace and lighting efficiency	**… using best available technology in all new and existing buildings**	**$**	House size, consumer demand for appliances
4. Efficiency – Electricity		Increase efficiency of power generation	**… raising plant efficiency from 40% to 60%**	**$**	Increased plant costs
5. CCS Electricity		CO_2 from fossil fuel power plants captured, then stored underground (700 large coal plants or 1400 natural gas plants)	**… injecting a volume of CO_2 every year equal to the volume of oil extracted**	**$$**	Possibility of CO_2 leakage
6. CCS Hydrogen		Hydrogen fuel from fossil sources with CCS displaces hydrocarbon fuels	**… producing hydrogen at 10 times the current rate**	**$$$**	New infrastructure needed, hydrogen safety issues
7. CCS Synfuels		Capture and store CO_2 emitted during synfuels production from coal	**… using CCS at 180 large synfuels plants**	**$$**	Emissions still only break even with gasoline
8. Fuel Switching – Electricity		Replacing coal-burning electric plants with natural gas plants (1400 1 GW coal plants)	**… using an amount of natural gas equal to that used for all purposes today**	**$**	Natural gas availability
9. Nuclear Electricity		Displace coal-burning electric plants with nuclear plants (2 x current capacity)	**… ~3 times the effort France put into expanding nuclear power in the 1980's, sustained for 50 years**	**$$**	Weapons proliferation, nuclear waste, local opposition
10. Wind Electricity		Wind displaces coal-based electricity (30 x current capacity)	**… using area equal to ~3% of U.S. land area for wind farms**	**$$**	Not In My Back Yard (NIMBY)
11. Solar Electricity		Solar PV displaces coal-based electricity (700 x current capacity)	**.. using the equivalent of a 100 x 200 km PV array**	**$$$**	PV cell materials
12. Wind Hydrogen		Produce hydrogen with wind electricity	**… powering half the world's cars predicted for 2050 with hydrogen**	**$$$**	NIMBY, Hydrogen infrastructure, safety
13. Biofuels		Biomass fuels from plantations replace petroleum fuels	**… scaling up world ethanol production by a factor of 30**	**$$**	Biodiversity, competing land use
14. Forest Storage		Carbon stored in new forests	**… halting deforestation in 50 years**	**$**	Biodiversity, competing land use
15. Soil Storage		Farming techiques increase carbon retention or storage in soils	**… practicing carbon management on all the world's agricultural soils**	**$**	Reversed if land is deep-plowed later

For more information, visit our website at http://www.princeton.edu/wedges.

Wedge Worksheet

1. Record your strategies to reduce total fossil fuel emissions by 8 wedges by 2055.
(1 "wedge" = 1 billion tons carbon per year)

- You may use a strategy more than once
- Use only whole numbers of wedges
- You may use a maximum of
  - 6 electricity wedges (E)
  - 5 transportation wedges(T)
  - 5 heat or direct fuel use wedges (H)

	Strategy	Sector (E,T,H or B)	Cost ($)	Challenges
1				
2				
3				
4				
5				
6				
7				
8				
	TOTALS			

2. Guess the score each stakeholder group would give your team's triangle on a scale of 1 to 5 (5 = best).

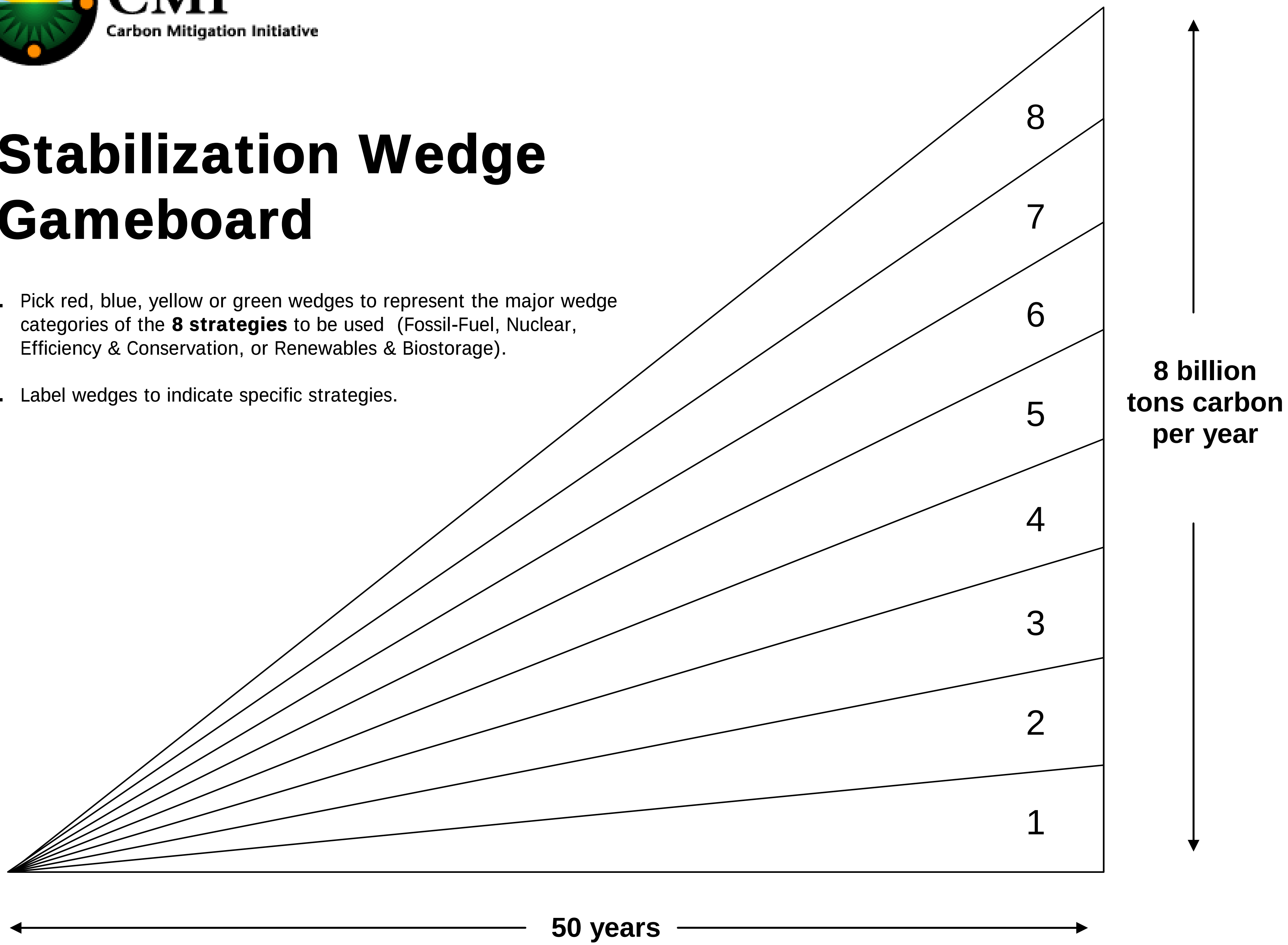
Judge:	**Taxpayers/ Consumers**	**Energy Companies**	**Environmental Groups**	**Manufacturers**	**Industrialized country governments**	**Developing country governments**
Score:			E = ___ (6 max) T = ___ (5 max) H = ___ (5 max) B = ___	______		

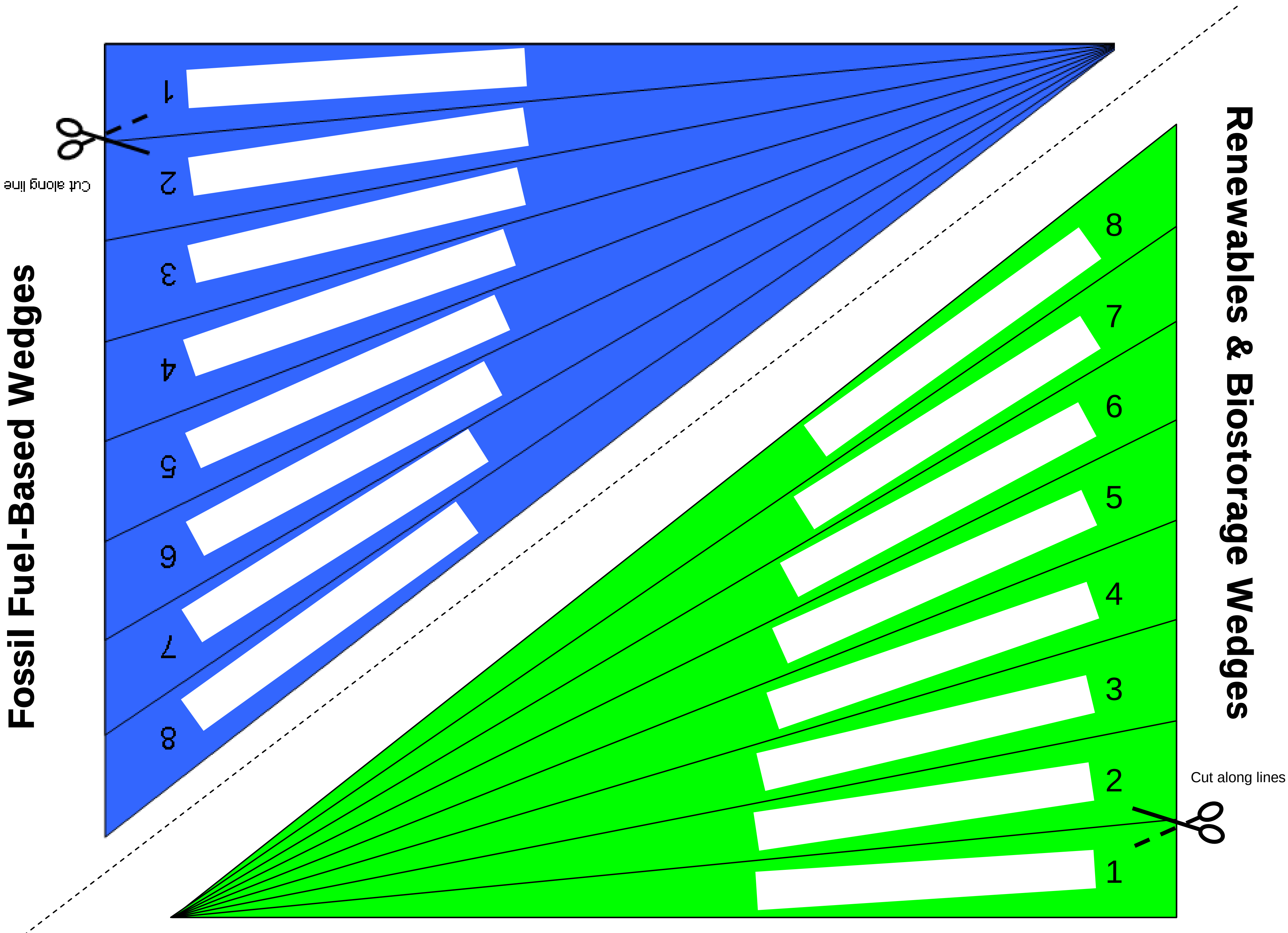
CMI
Carbon Mitigation Initiative

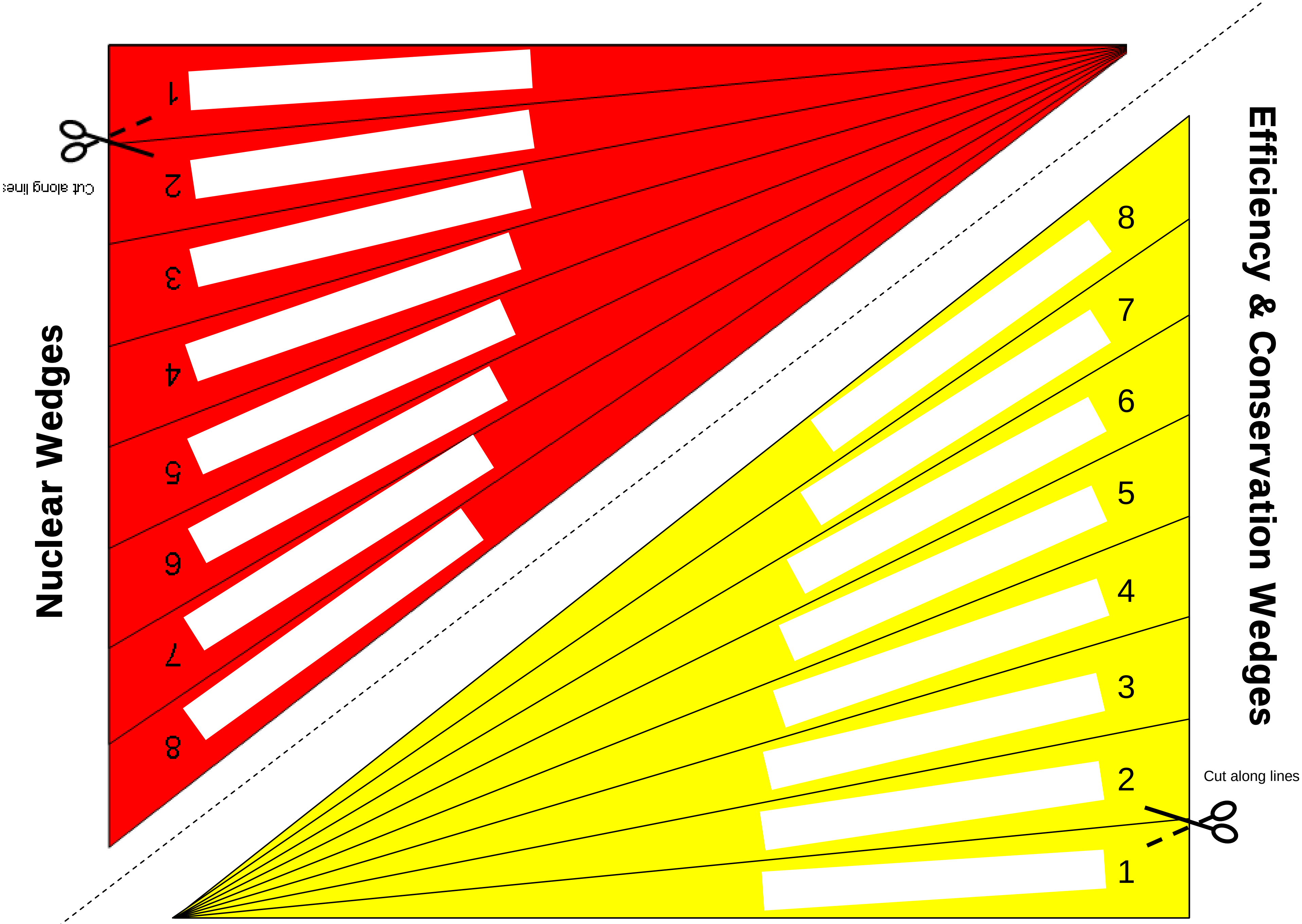
Stabilization Wedge Gameboard

1. Pick red, blue, yellow or green wedges to represent the major wedge categories of the **8 strategies** to be used (Fossil-Fuel, Nuclear, Efficiency & Conservation, or Renewables & Biostorage).

2. Label wedges to indicate specific strategies.




Fossil Fuel-Based Wedges
1
2
3
4
5
6
7
8
Cut along line
Renewables & Biostorage Wedges
8
7
6
5
4
3
2
1
Cut along lines


Nuclear Wedges
Cut along lines
1
2
3
4
5
6
7
8
Efficiency & Conservation Wedges
Cut along lines
8
7
6
5
4
3
2
1