

En-ROADS User Guide

Table of Contents

[Introduction](#)

[About En-ROADS](#)

[En-ROADS Tutorial](#)

[En-ROADS Structure](#)

[En-ROADS Baseline Scenario](#)

[Kaya Graphs](#)

[En-ROADS Dynamics](#)

[Impacts of Climate Change](#)

[Coal](#)

[Oil](#)

[Natural Gas](#)

[Bioenergy](#)

[Renewables](#)

[Nuclear](#)

[New Zero-Carbon](#)

[Carbon Pricing and Energy Standards](#)

[Transport – Energy Efficiency](#)

[Transport – Electrification](#)

[Buildings and Industry – Energy Efficiency](#)

[Buildings and Industry – Electrification](#)

[Population Growth](#)

[Economic Growth](#)

[Agricultural Emissions and Food Choices](#)

[Waste and Leakage](#)

[Deforestation and Mature Forest Degradation](#)

[Nature-Based Carbon Dioxide Removal](#)

[Technological Carbon Dioxide Removal](#)

[Glossary](#)

En-ROADS User Guide

By Janet Chikofsky, Ellie Johnston, Andrew Jones, Yasmeen Zahar, Clara Iglesias, Chris Campbell, John Sterman, Lori Siegel, Cassandra Ceballos, Travis Franck, Florian Kapmeier, Stephanie McCauley, Rebecca Niles, Caroline Reed, Juliette Rooney-Varga, and Elizabeth Sawin

Last updated June 2025

The [En-ROADS Climate Solutions Simulator](#) is a fast, powerful climate solutions scenario tool for understanding how we can achieve our climate goals through changes in energy, land use, consumption, agriculture, and other policies. The simulator focuses on how changes in global GDP, energy efficiency, technological innovation, and carbon price influence carbon emissions, global temperature, and other factors. It is designed to provide a synthesis of the best available science on climate solutions and put it at the fingertips of groups in policy workshops and roleplaying games. These experiences enable people to explore the long-term climate impacts of global policy and investment decisions.

En-ROADS is being developed by [Climate Interactive](#), [Ventana Systems](#), [UML Climate Change Initiative](#), and [MIT Sloan](#).

This guide provides background on the dynamics of En-ROADS, tips for using the simulator, general descriptions, real-world examples, slider settings, and model structure notes for the different sliders in En-ROADS.

In addition to this User Guide there is:

- A general support knowledge base at support.climateinteractive.org with frequently asked questions and a contact form
- An in-depth [online training](#) on using En-ROADS that can be taken at anytime
- An extensive [En-ROADS Technical Reference](#) that covers model assumptions and structure, as well as references for data sources.

About En-ROADS

En-ROADS is a powerful simulation model for exploring how to address global energy and climate challenges through large-scale policy, technological, and societal shifts. With En-ROADS you can create scenarios that focus on how changes in taxes, subsidies, economic growth, energy efficiency, technological innovation, carbon pricing, fuel mix, and other factors will change global carbon emissions and temperature.

En-ROADS is designed to be used interactively with groups where it can be the basis for scientifically rigorous conversations around addressing climate change. This makes it ideal for decision-makers in government, business, and civil society; or for anyone who is curious about the choices of our world. Climate Interactive provides extensive materials to support people in leading activities with En-ROADS that range from [policy workshops](#) to [roleplaying games](#).

Relative to many global energy and climate system models, En-ROADS returns results in a few seconds, is transparent in its mathematical logic, and allows you to interactively test hundreds of factors. En-ROADS complements the other, more disaggregated models addressing similar questions, for example, those in the Integrated Assessment Modeling Consortium. These larger disaggregated models are used for comparing and calibrating results in En-ROADS.

En-ROADS stands for “Energy-Rapid Overview and Decision-Support,” although it has grown to include more than just the energy sector. Led by the team at Climate Interactive, En-ROADS has benefited from a close collaboration between Climate Interactive, Tom Fiddaman of Ventana Systems, Professor John Sterman of MIT Sloan, and Professor Juliette Rooney-Varga of UMass Lowell's Climate Change Initiative. En-ROADS is an extension of the award-winning simulator [C-ROADS](#), which thousands have used to assess national and regional greenhouse gas emission reduction pledges and lead climate negotiation exercises. Both tools were developed using the system dynamics modeling approach and draw on the MIT PhD theses of Dr. John Sterman and Dr. Tom Fiddaman.

The En-ROADS model emphasizes the system-wide interactions of policies. Behind the simulator is an extensive study of the latest research literature on factors such as delay times, progress ratios, price sensitivities, historical growth of energy sources, and energy efficiency potential. This enables En-ROADS to reveal the dynamic interactions between different levers, such as how energy efficiency affects renewable energy, and which feedback loops are most significant.

For those familiar with C-ROADS, the distinction between the two is that C-ROADS focuses on how changes in national and regional emissions could affect global carbon emissions and climate outcomes, while En-ROADS focuses on how global changes in energy, land use, economics, and public policy could affect global carbon emissions and climate outcomes.

Please visit support.climateinteractive.org for additional inquiries and support.

En-ROADS Tutorial

En-ROADS is designed to be an easy-to-use simulator for creating pathways to successfully address climate change globally. This 11-minute [introductory video tour](#) of En-ROADS offers guidance on the model's interface features. To go in-depth and learn about ways to use En-ROADS and the dynamics, join our free En-ROADS training program at learn.climateinteractive.org.

We encourage you to explore all the features of En-ROADS by clicking around. Here are some key features of En-ROADS to look for:

Graphs

There are over 100 output graphs available in En-ROADS. They show data from different parts of the global energy and climate system, and they update as you move sliders within En-ROADS.

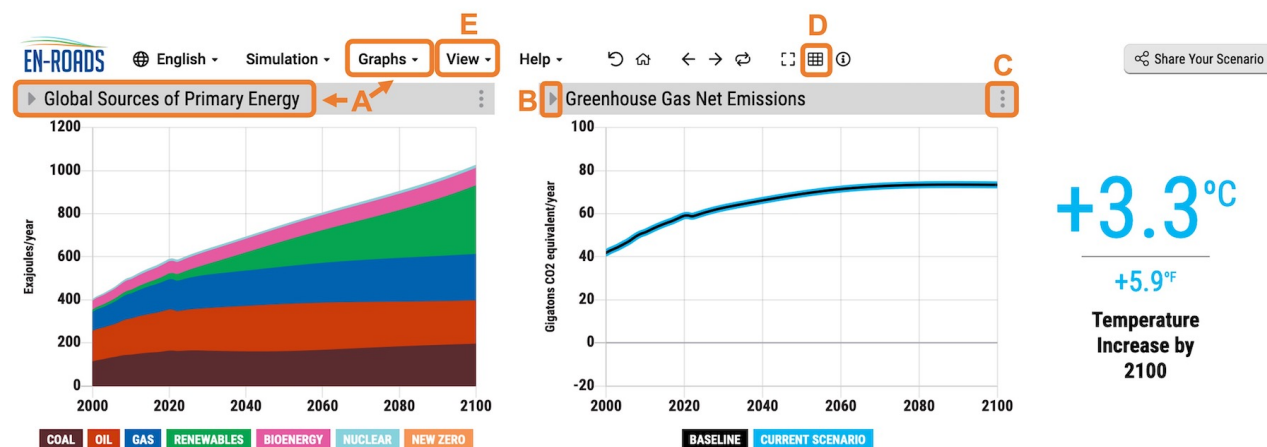
A. Select graphs – When you first open En-ROADS, you see the two default graphs. You can select from the full list of graphs by clicking the title of the left or right graph. You can also select from the Graphs menu in the top toolbar.

B. More info – For more information about a graph and what it shows, select the triangle icon to the left of the graph title.

C. Copy graph data – Copy the graph data to your clipboard by clicking on the three dots to the right of the graph title and selecting “Copy Data to Clipboard.” You can paste this data into a spreadsheet program such as Excel.

D. Shortcut to popular graphs – You can quickly jump to a selection of the most commonly used graphs from the “Show miniature graphs” icon on the top toolbar. You can click any of these miniature graphs to switch to that graph in the main graph view.

E. View larger graphs – If you want to expand one of the graphs to be larger or into a separate window, you can access this by clicking on the three dots to the right of the graph title and select “View Larger” or “View in New Window.” You can access our “Large Left Graph” or “Large Right Graph” feature from the View menu in the top toolbar.



Sliders/Actions

There are 19 sliders representing different actions you can test in the En-ROADS simulator. Click the title of the slider or the three dots on the right of each slider to access detailed slider settings:



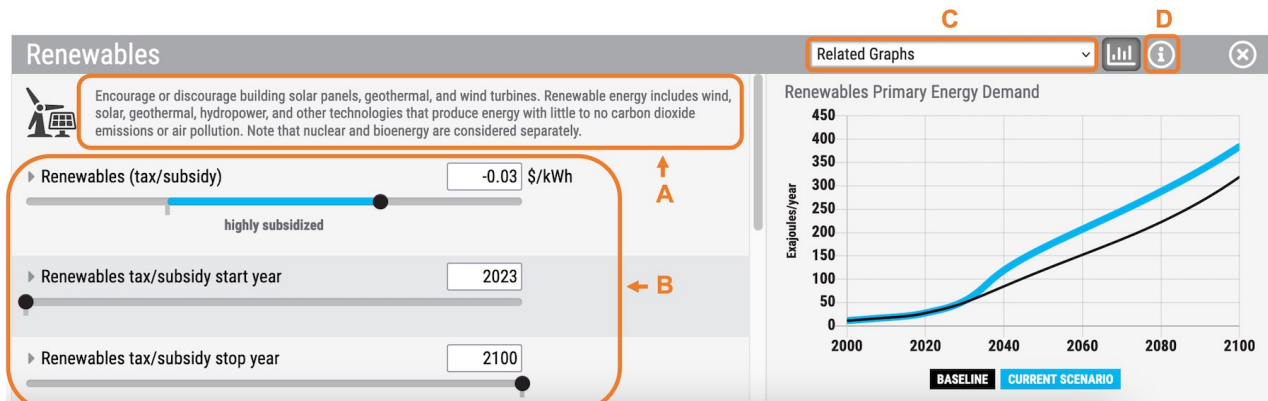
Here is what you will find in the detailed slider view:

A. A description of the overall slider – This description provides further detail about the particular solution.

B. More control of the main slider – You'll see the units associated with the slider and the numeric values of points along the slider. You can directly input numeric values to set the slider level to a specific value of your choice (within range). Scroll down to change and explore the related sliders. Click on the triangle to the left of each slider title to see a brief description of the slider.

C. Related graphs – In the right panel, you'll see a graph relevant to the main slider as well as a choice of additional Related Graphs. These are useful to reference in order to examine the changes that occur from moving the sliders in this view. Select from the dropdown list of Related Graphs to view other graphs. You will still be able to see your slider moves impact the main graphs as well.

D. Help – You can access more detailed information about the slider through the information button. This is the same information that is found for this topic in the En-ROADS User Guide.



Top Toolbar Features

Many useful features are just a click away from the top toolbar on En-ROADS. Here are some of the features that you can access.



A. **Share Your Scenario** – You can share your unique scenario link with others, who can open your En-ROADS scenario with all the settings you have chosen and the last main graphs you viewed. You can also share your scenario to social media channels. Grabbing the link from your browser’s URL bar will also work, but your last viewed graphs will not be captured.

B. **Replay Last Change** – This is a fun feature to rapidly replay your last change several times. This feature assists you in examining how the different parts of the system responded to your action by giving you more time to look for changes across related graphs. You can also use the other controls to Undo or Redo your last action (located left of the “replay last change” control on the top toolbar).

C. **Assumptions** [under the “Simulation” menu] – Access and change important assumptions driving the En-ROADS model.

D. **U.S. Units** [under the “View” menu] – Change from metric to U.S. units.

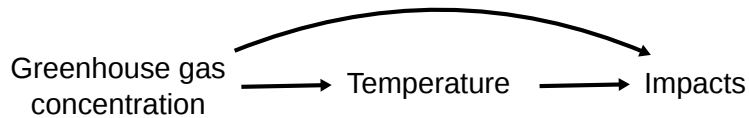
E. **Actions and Outcomes** [under the “View” menu] – This list summarizes the total actions and key climate outcomes from your scenario.

F. **Related Examples** [under the “Help” menu] – This list shares common examples of topics and solutions related to each of the 19 sliders. This is helpful when you need to quickly pull up a list of examples which relate to each of the sliders.

Please visit support.climateinteractive.org for additional inquiries and support.

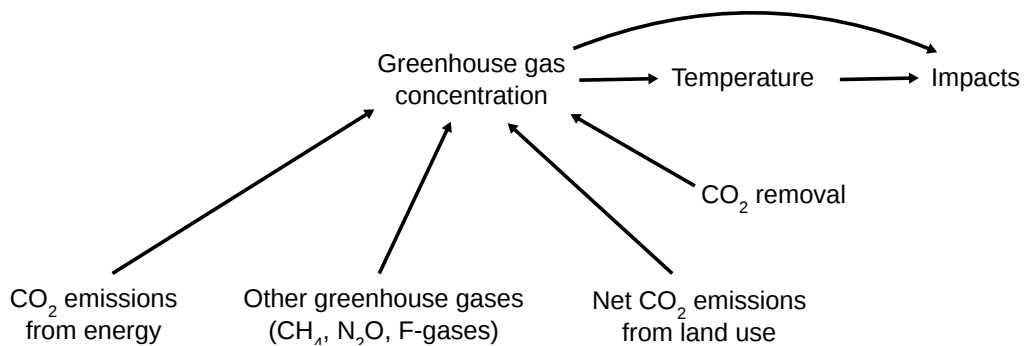
En-ROADS Structure

A simple way to think about the structure of En-ROADS is by considering the drivers of climate impacts. In the simulator, the concentration of greenhouse gases drives up global temperature, which leads to various impacts (e.g., sea level rise and ocean acidification).



The concentration of greenhouse gases in the atmosphere is driven by four main sources:

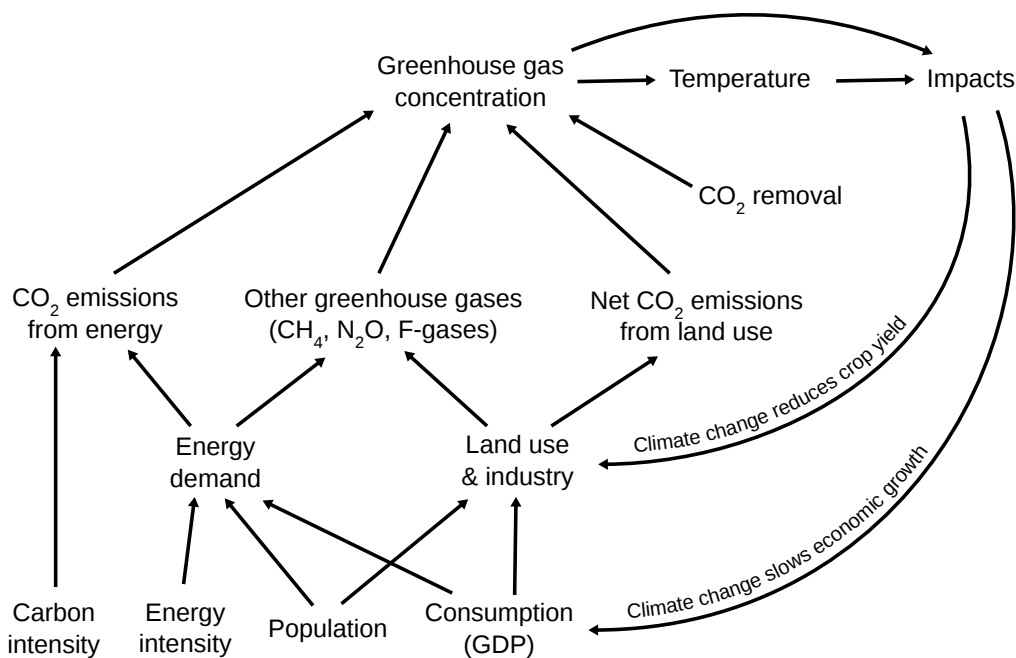
1. **Energy CO₂ Emissions** from burning coal, oil, gas, and biomass. CO₂ emissions from energy currently comprise about 67% of greenhouse gas emissions.
2. **Land Use CO₂ Emissions** such as forestry and land use change. CO₂ emissions from land use currently comprise about 7% of greenhouse gas emissions.
3. **Carbon Dioxide Removal** approaches that pull carbon dioxide out of the atmosphere and store it in plants, soils, or underground, leading to a decrease in CO₂ concentrations.
4. **Other Greenhouse Gas Emissions** such as methane, N₂O, and F-gases. Non-CO₂ emissions currently comprise about 26% of total greenhouse gas emissions.



Going further, CO₂ emissions from energy are driven by four factors, which is known as the [Kaya Identity](#). Population, consumption (GDP/capita), energy intensity (energy use per dollar of GDP), and carbon intensity (CO₂ emissions per unit of energy) are all multiplied together and the result is overall energy CO₂ emissions. In this way, at a high level, reducing energy CO₂ emissions is about four things: fewer people, less consumption, more efficiency, and less high-carbon energy supplies.

Population and consumption (GDP/capita) growth also drive the emissions from the agricultural, land use, land use change, and forestry sectors, due to increased demand for things like food, wood products, and bioenergy feedstocks. This increases the CO₂ emissions from land use and other greenhouse gases, which reinforces temperature increase and climate change.

In the model the impacts of climate change feed back to economic growth and crop yield. Higher global temperatures reduce GDP growth due to the costs of responding to extreme weather events, sea level rise, droughts, and flooding. Similarly, crop yield growth is harmed by these impacts too.



This is a simple way to understand the structure of En-ROADS. For a more in-depth explanation of the structure, view the videos below from our free [En-ROADS training course](#) or explore the [En-ROADS Technical Reference](#).

Videos

- [En-ROADS Model Structure \(with Professor John Sterman, MIT\)](#)
- [How we use research and data in En-ROADS](#)
- [Comparison to data and others' scenarios \(Part 1\)](#)
- [Comparison to data and others' scenarios \(Part 2\): En-ROADS June 2023 release](#)
- [Transparency, model updates, & extreme conditions testing](#)
- [Relevance to policymakers](#)
- [Our top critiques of En-ROADS \(with Professor John Sterman, MIT\)](#)
- [En-ROADS software mechanics](#)

FAQs

- [What sort of model is En-ROADS?](#)

En-ROADS Baseline Scenario

The En-ROADS Baseline Scenario represents **the state of the world if societal and technological changes were to continue at their current rate of progress**, without additional policies or action. The Baseline Scenario is designed to be a reasonable starting point from which to test various changes in policies and assumptions to see the impacts on our global climate. It is not a forecast of what is most likely to happen.

What is included in the En-ROADS Baseline Scenario?

En-ROADS does not explicitly represent local, national, international, and corporate policies, but instead estimates the overall effects of the conditions they create. The Baseline Scenario includes an approximate, aggregated implementation of current global technological, policy, and investment conditions. Climate policies in place around the world today, such as the United States' Inflation Reduction Act and China's "1+N" framework, are promoting renewables, continuing to subsidize oil and gas, and incentivizing energy efficiency and electrification. The Baseline Scenario assumes that such conditions will continue, but they do not strengthen or weaken.

To learn more about the drivers of emissions in the Baseline Scenario, explore the [Kaya graphs](#).

What is *not* included in the En-ROADS Baseline Scenario?

The En-ROADS Baseline Scenario is not intended to capture policy goals. It does not include national or corporate net-zero emissions pledges, for instance. It also does not include countries' Nationally Determined Contributions (NDCs) under the Paris Agreement or long-term continuation of other national policies. This is an important distinction from some other models' baseline or "stated policies" scenarios.

We chose to construct the En-ROADS Baseline Scenario in this way because "pledged" or "announced" policies can be altered or never be implemented. Governments change and priorities shift. As a result, you can use En-ROADS yourself to compare the globally averaged effects of NDCs to your scenario and the Baseline Scenario in which those policy actions are not taken. Learn more here: [Does the En-ROADS Baseline Scenario include countries' future policies or NDCs under the Paris Agreement?](#)

What if I disagree with some of the assumptions in the En-ROADS Baseline Scenario?

We picked one set of assumptions to be our default in the En-ROADS Baseline Scenario, but we encourage curious users to vary the assumptions in En-ROADS under the menu *Simulation > Assumptions*. There you can change factors tied to the climate, economy, land use, and energy system to explore how sensitive the model is to their changes or set up a different scenario for testing policies and engaging audiences.

FAQs

- [How does the En-ROADS Baseline Scenario compare to future scenarios from other models?](#)

Please visit support.climateinteractive.org for additional inquiries and support.

Kaya Graphs

The Kaya Graphs depict the drivers of growth in carbon dioxide emissions from energy, which reflects about two-thirds of all greenhouse gas emissions.

To access the Kaya Graphs view, click on the “View” menu bar item and then “Kaya Graphs.” It is called the “Kaya” view because the equation below was created by Yoichi Kaya:

Global Population × GDP per Capita × Energy Intensity of GDP × Carbon Intensity of Energy = CO₂ Emissions from Energy

Here is one way to understand its trends over time:

Global Population is growing—we are currently more than 8 billion people—and anticipate growth to 11 billion by the end of the century, according to UN projections. The rate of growth is slowing over time as people have smaller families.

GDP per Capita is growing steadily per year, and we assume it will continue, mostly as people in rapidly developing countries such as China, India, South Africa, Mexico, Brazil, and Indonesia attain higher standards of living.

Energy Intensity of GDP is decreasing over time, due to the world economy becoming more efficient, or using less energy per unit of economic output. Technologies are improving—for example, more efficient cars, buildings, and machines—and economies are shifting from manufacturing to services. The product of global population, GDP per capita, and the energy intensity of GDP is the total amount of energy used by the global economy.

Carbon Intensity of Final Energy, the amount of carbon dioxide emitted by energy use, is expected to slightly decline over time. Overall, this downward trend in carbon intensity is attributed to the gradual shifting away from fossil fuels and towards low-carbon energy sources.

Carbon Dioxide Emissions from Energy is the result of all four factors multiplied together, and you can see that in the Baseline Scenario emissions are growing. As the level of carbon dioxide in the atmosphere correlates with temperature, an increased concentration of carbon dioxide in the atmosphere leads to an increase in global temperatures.

These factors explain, in simple terms, why emissions are increasing in the Baseline Scenario. Improvements in efficiency and decarbonization are not yet keeping up with the strong growth in population and consumption.

Please visit support.climateinteractive.org for additional inquiries and support.

En-ROADS Dynamics

As you use En-ROADS, pay attention to when and how much slider adjustments result in departures from the Baseline Scenario. Ask your audience to reflect on why this happened to illuminate thinking about the dynamics of the climate and energy system that En-ROADS simulates.

Most of the dynamics in En-ROADS can be answered by these explanations:

Complex Interactions Between Competing Energy Supplies and Demand

1. Delays and Capital Stock Turnover

New energy sources (e.g., renewables and new zero-carbon energy sources) take decades (not years) to scale up sufficiently to compete with coal, oil, and gas globally. One of the main sources of these delays is that new energy infrastructure is only built when old infrastructure retires or there is a need to meet increased energy demand.

Only about 6% of all the world's energy infrastructure changes each year, since infrastructure like coal-fired power plants and oil refineries can be used for 30 or more years. So while new zero-carbon energy sources may make up the majority of the market share of new energy capital, it will take many years for the old capital to turn over and be retired. The climate is only helped when coal, oil, and gas is retired, and in the absence of other interventions, that amount is relatively small — approximately 3% per year.

Slow Capital Stock Turnover



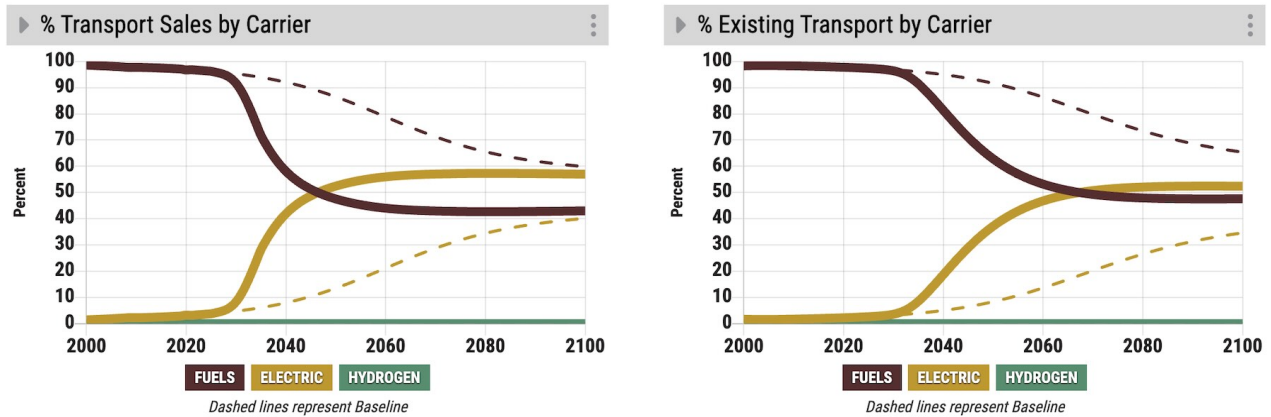
This addresses questions such as:

- "Why doesn't subsidizing renewables, nuclear, or a new zero-carbon energy source help avoid more warming?"

This dynamic is also relevant to increasing energy efficiency or electrification. However, energy-using capital, such as vehicles, buildings, and industry, has an average lifetime that is much shorter (10-15 years). One can promote the sale of electric cars immediately, for example, but the average amount of all cars that are electric takes decades to rise to the same level since it takes time for all the old fuel-based cars to be taken off the road.

To illustrate this point: Move the Transport Electrification slider to be highly subsidized. Examine the “% Existing Transport by Carrier” graph (see the yellow line in the right graph) and notice that, even as the amount of electric transport grows, it takes several decades before it can reach over 50% of total transport. Compare this to the graph “% Transport Sales by Carrier” which rises much faster (see the yellow line in the left graph), as sales more immediately reflect the impact of the subsidy.

[View this scenario in En-ROADS.](#)



Implications of this dynamic: Policies that merely promote alternatives to fossil fuels take several decades to reduce carbon dioxide emissions — the existing infrastructure takes a long time to retire.

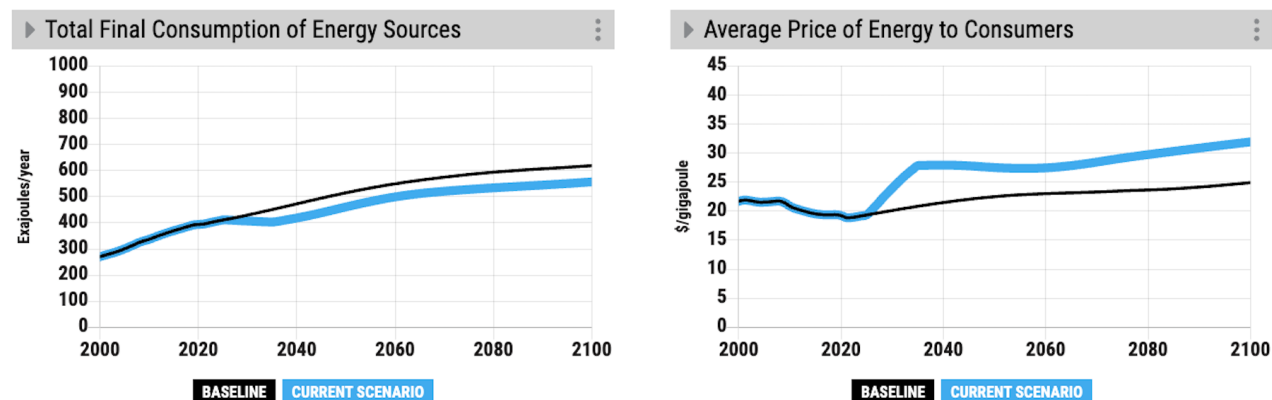
[To learn more, view this video on Capital Stock Turnover.](#)

2. Price and Demand Effects

Energy demand falls if energy prices rise, and demand increases if prices fall. People and companies are more likely to take actions to conserve energy (such as turning off lights when they're not being used), or invest in energy efficiency (such as buying energy-efficient appliances or insulating buildings) when energy prices are high. Policies should be designed to enable people who have a high energy burden (a large proportion of their income going to pay for energy) access to affordable energy and energy efficiency improvements.

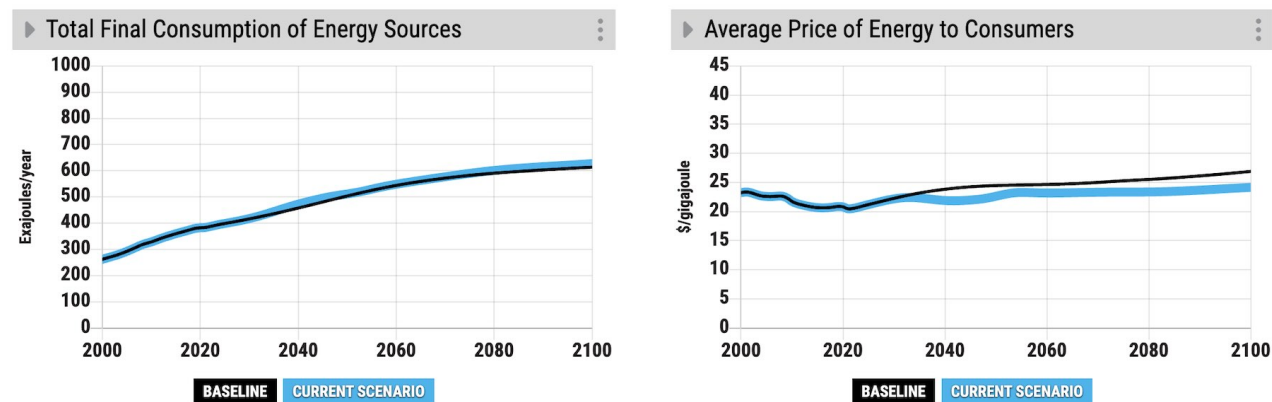
When a high carbon price is set, for example, energy demand falls because energy prices increase. Observe that Total Final Consumption of Energy Sources decreases, while the Average Price of Energy to Consumers increases:

[View this scenario in En-ROADS.](#)



Conversely, energy demand rises when prices fall when a type of energy such as renewables or a new zero-carbon energy source is subsidized or experiences a breakthrough in cost improvement. People and companies are less likely to take actions to conserve energy or invest in energy efficiency when energy prices are low.

[View this scenario in En-ROADS.](#)



Why does the price-demand feedback loop weaken some of the positive effects of subsidizing renewables or other zero-carbon energy sources?

The price-demand feedback loop is one reason why subsidizing renewable and other zero-carbon forms of energy is less effective at reducing CO₂ emissions than you might expect.

Here are the key points to remember about this dynamic:

1. Renewable energy or other low- or zero-carbon forms of energy only help the climate when they replace coal, oil, and gas, preventing those sources from emitting greenhouse gases.
2. When you subsidize renewable or nuclear energy, or you add a breakthrough in a new zero-carbon source of energy that is very cheap, this lowers the overall cost of energy and demand goes up.
3. This increased demand for energy weakens the positive effects of renewables/nuclear/new zero-carbon energy for two reasons:
 - The increased demand for energy is met for the most part by low-carbon energy, but as a result, less low-carbon energy is available to displace fossil fuels.
 - Some of the increased demand may be met by fossil fuels that would otherwise not be needed, which emit greenhouse gases.

If the only sources of energy available did not emit CO₂, then an increase in energy demand would not have an effect on the climate. But in most scenarios, it's important to disincentivize the burning of coal, oil, and gas in addition to incentivizing low-carbon energy sources.

To learn more, view [this video on the Price-Demand Feedback Loop](#).

3. Competition between Energy Sources: “Crowding Out” and “Squeezing the Balloon”

Many assume that if the world promoted several long-term zero-carbon energy sources such as nuclear, wind, and solar, their contribution to carbon mitigation would be additive. Instead, they actually compete. More of one, less of another.

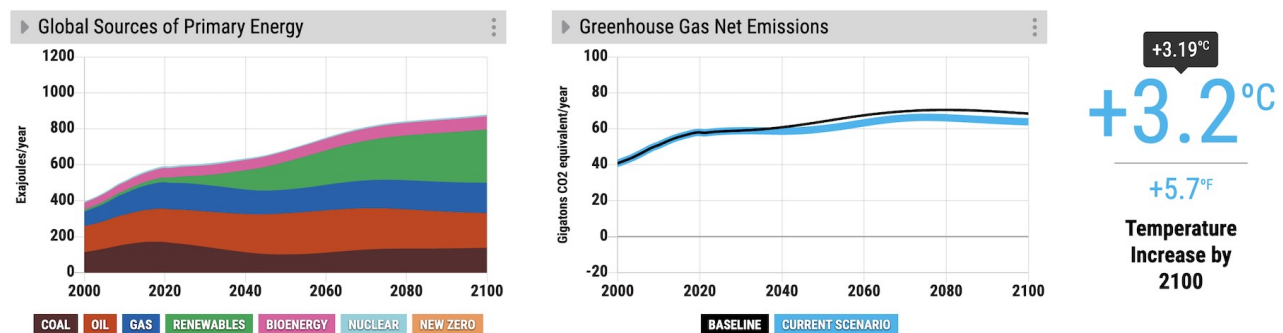
This addresses questions such as:

- “Why didn’t it help to have a breakthrough in a new zero-carbon energy supply in this renewables-dominated scenario?”

To illustrate this point: See the “Global Sources of Primary Energy” graph in the three scenarios below. In the first graph, we subsidize renewables alone; in the second, there is a breakthrough in a new zero-carbon energy supply; in the third graph, we see both a renewables subsidy and a new zero-carbon breakthrough. *Tip: To view the temperature in 2100 to two decimal places, hover over the temperature with your mouse.*

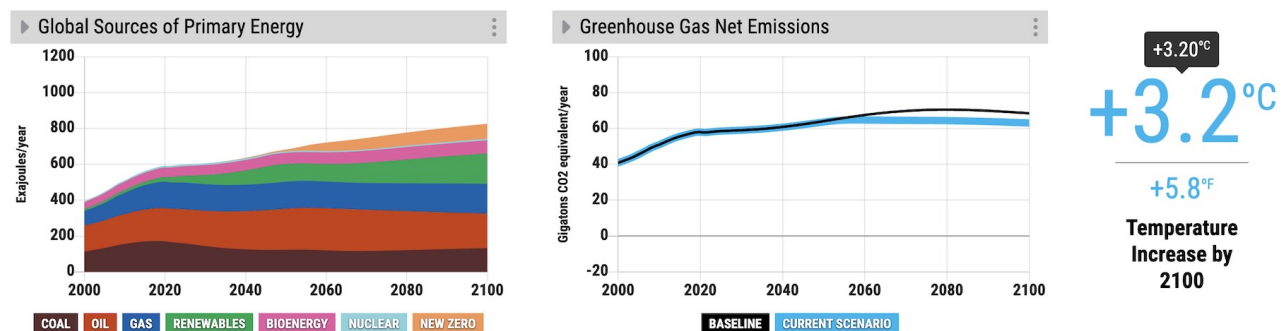
In the following scenario, a high Renewables subsidy leads to a 0.11°C (0.18°F) reduction in temperature from the Baseline:

[View this scenario in En-ROADS.](#)



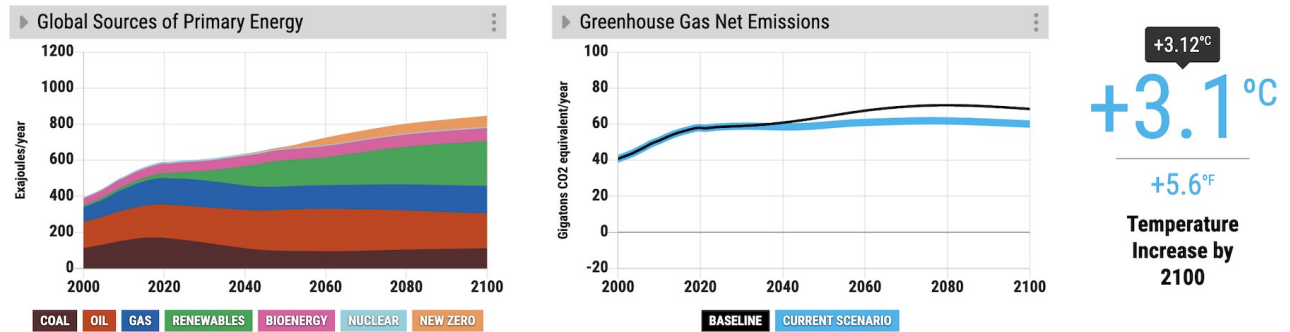
A huge breakthrough in New Zero-Carbon leads to a 0.10°C (0.17°F) reduction on its own:

[View this scenario in En-ROADS.](#)



When combined, instead of seeing a total 0.21°C (0.35°F) reduction, we only see a 0.18°C (0.31°F) reduction in temperature from the Baseline due to the energy supplies competing with each other for market share:

[View this scenario in En-ROADS.](#)

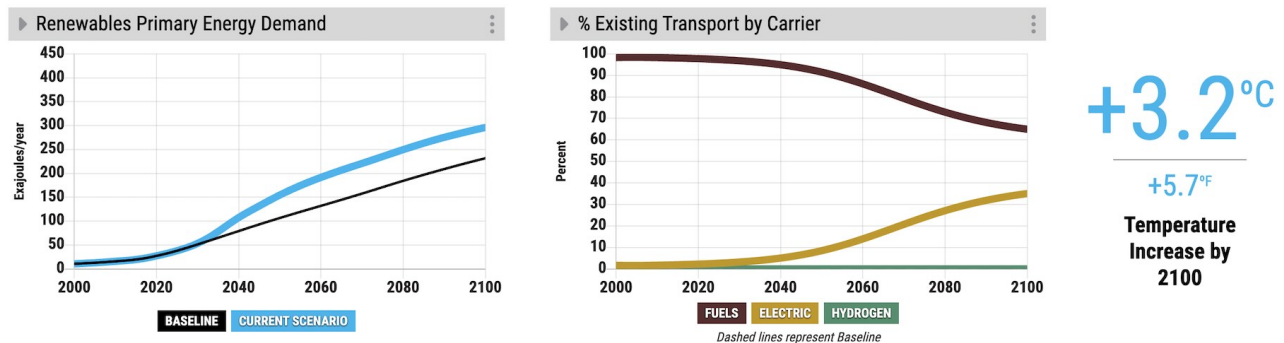


To learn more, view this video on "Crowding Out and Squeezing the Balloon."

4. Complementary Policies: Electrification

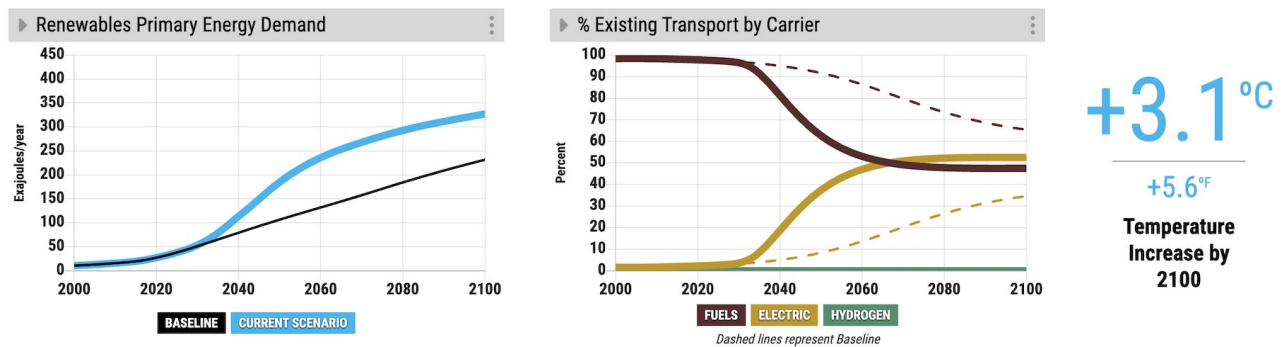
Renewables, nuclear, and new zero-carbon energy produce energy in the form of electricity in En-ROADS. Buildings, industry, and transportation need to be able to use electricity in order to use these cleaner sources of energy. Electrification of buildings and industry (for example, by switching to electric heat pumps) and transportation (switching from internal combustion engines to electric vehicles) is therefore essential for changing the energy mix. Notice in En-ROADS how significantly subsidizing Renewables leads to a 0.1 degree Celsius reduction in temperature:

[View this scenario in En-ROADS.](#)



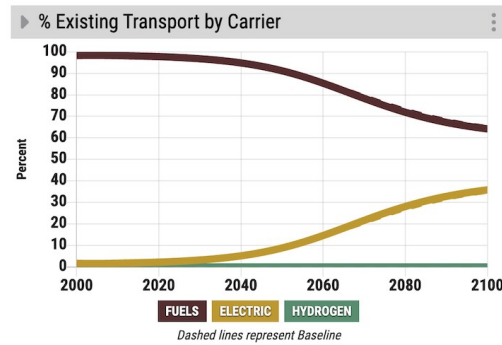
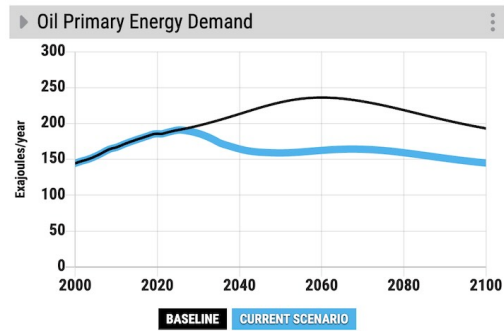
And then adding a policy to increase transport electrification lowers the temperature further and boosts demand for renewables:

[View this scenario in En-ROADS.](#)



Similarly, in a different scenario, taxing oil is not enough to discourage use of this fuel:

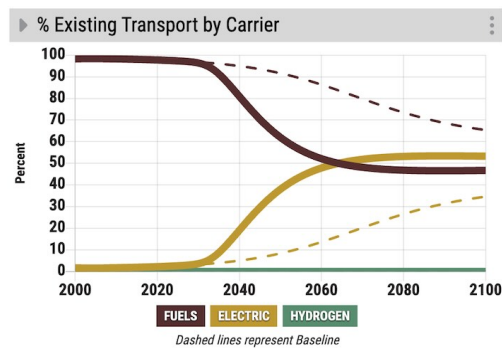
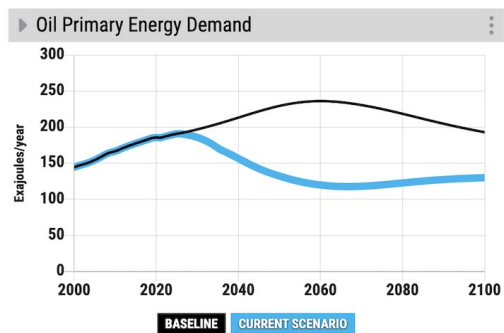
[View this scenario in En-ROADS.](#)



+3.2°C
+5.7°F
Temperature Increase by 2100

You must also add policies that encourage electrification, which enables things that were dependent on oil to use other sources of energy.

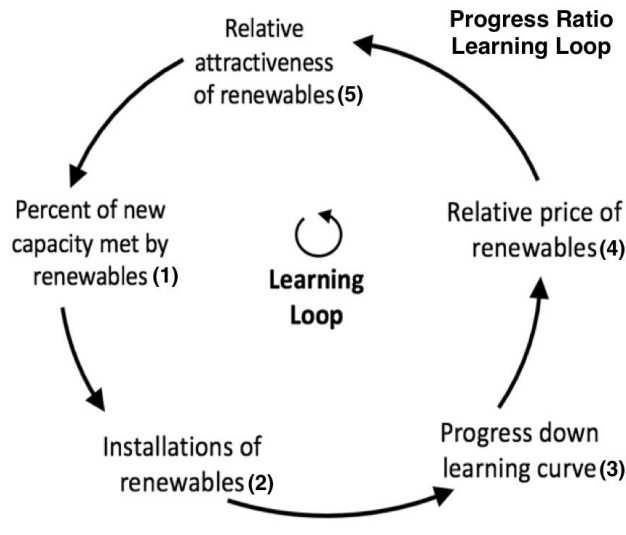
[View this scenario in En-ROADS.](#)



+3.2°C
+5.7°F
Temperature Increase by 2100

5. Economies of Scale and Learning

Costs of energy supplies such as renewables fall as cumulative experience is gained through a learning feedback loop, also known as “economies of scale.” Every doubling of cumulative installed capacity of renewables reduces costs by around 20%, creating a reinforcing loop (this is known as the “progress ratio”). In the graphic below, increasing the capacity (1) and installation (2) of new energy sources leads to increased learning (3), a decrease in price (4), increasing the attractiveness of renewables (5) and therefore even greater capacity and installations:



This addresses questions such as:

- “Why should we have hope?”
- “How can we afford a transition to a low-carbon economy?”
- “Aren’t the costs of renewables prohibitive?”

The Economies of Scale dynamic is good news when it comes to renewables. In the past couple decades, the price of renewable energy has dropped significantly and the installation of renewables has grown exponentially. (You can see these trends from 1990 to 2020 in the “Model Comparison - Historical” graphs in En-ROADS).

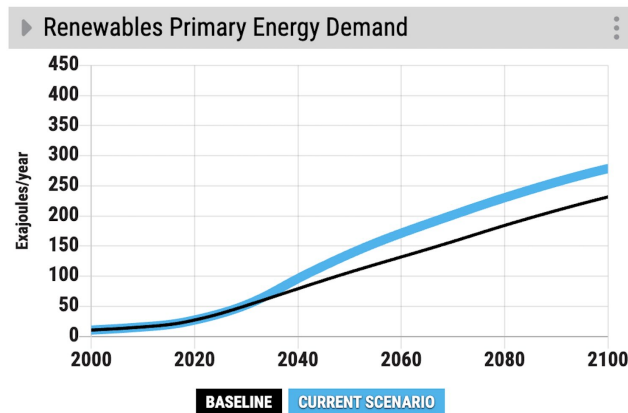
The progress ratio for renewables is 0.80, which is quite low compared to other sources of energy such as nuclear and coal (0.98). Remember, a progress ratio of 0.80 means that every doubling of cumulative installed capacity lowers costs 20%. For coal, every doubling of cumulative installed capacity lowers costs just 2%. Coal and other older energy sources have already achieved significant cost reductions due to technological advancements over the past decades.

This also addresses the question “Why is subsidizing renewables helpful?”

Subsidies reduce the cost of renewables, which leads to more installation of renewables, and more cumulative experience (social acceptance, training of installers and engineers, greater availability of factories to make the parts, etc.). The learning loop cycles faster than it would without the subsidies. The same thing would occur without subsidies, but it would be slower. In the meantime, more coal, oil, and gas would be burned and emit greenhouse gases.

To illustrate this point: Look at the “Renewables Primary Energy Demand” graph in a scenario in which Renewables are subsidized. It increases the exponential growth that is driven and sustained by the reinforcing learning loop figure shown above.

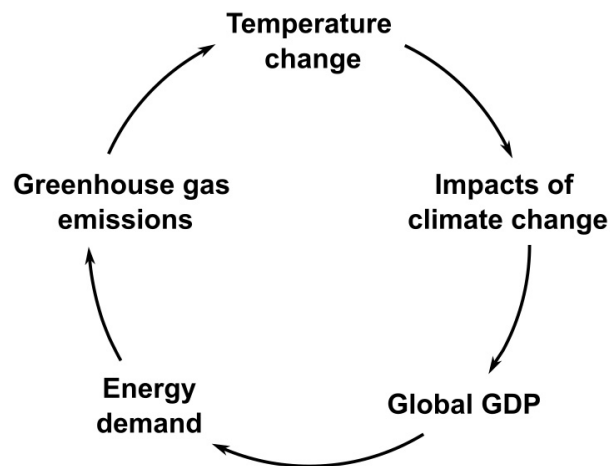
[View this scenario in En-ROADS.](#)



To learn more, view this video on Economies of Scale.

6. Economic Damage from Climate Change

Temperature increase from climate change damages the economy and reduces consumption, slightly reducing some of the future negative effects from climate change. An increase in global temperature is linked to changes in climate patterns—such as more frequent climate disasters, lower crop yields from droughts, etc.—which damage the economy. This reduces GDP growth and global energy consumption. Less consumption produces fewer greenhouse emissions, which results in lower temperature increase. This is a compensating or balancing feedback loop:



This addresses questions such as:

- “Does En-ROADS account for the costs of climate change impacts?”
- “Why do Carbon Removal actions increase Energy Consumption or CO₂ Emissions from Energy?”
- “Why does action on Agricultural Emissions or Waste and Leakage increase Energy Consumption?”

Here are the key points to remember about this dynamic:

1. This dynamic can be turned off with the “Climate change slows economic growth” switch under Simulation > Assumptions > Economy > “Economic impact of climate change.” This results in the economy continuing to grow without being affected by climate change, causing more greenhouse gas pollution and more climate change. Note that changing the Assumptions in En-ROADS only affects the Current Scenario, and the economic impact of climate change will continue to be present in the Baseline Scenario. [View this scenario in En-ROADS, and turn ON and OFF the “Climate change slows economic growth” switch.](#)
2. Actions (e.g., carbon removal, or reducing Agricultural Emissions or Waste and Leakage) that reduce temperature without affecting energy costs or energy efficiency will still cause energy consumption to increase. The temperature reduction caused by these actions reduces some of the economic impact of climate change, which leads to higher GDP growth and thus more energy consumption and greenhouse gas emissions.

Note that if the only sources of energy available do not emit CO₂, then an increase in energy demand due to higher GDP growth would not have an effect on the climate.

3. Estimates of the effect of climate change on the economy, known as the “damage function,” are varied. The basis of the Baseline Scenario damage function is a study from Burke et al. 2018. If users would like to choose a higher or lower pathway for the damage function, they can select from the functions of other peer-reviewed studies or create their own. Details can be found in this FAQ: [Why does En-ROADS include the damage function from Burke et al. \(2018\) in the Baseline Scenario?](#)

To learn more, read the [Explainer on the Economic Impact of Climate Change in En-ROADS](#).

Drivers of the Baseline Scenario

To gain a deeper understanding of the model's behaviors, it is important to comprehend what factors drive the Baseline Scenario. Learn more in the [En-ROADS Baseline Scenario chapter](#).

1. Drivers of Growth

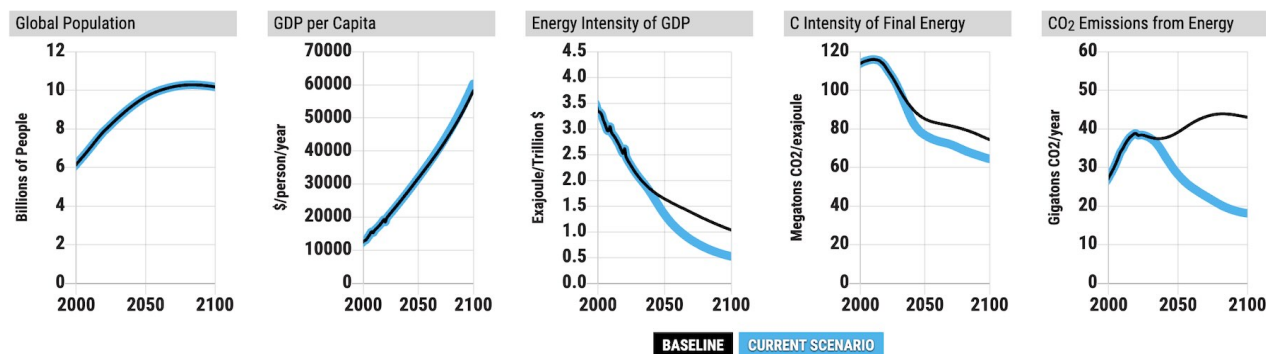
A challenge to limiting future warming in this simulation is the powerful growth in global GDP (Gross World Product). This is driven by the Population and Economic Growth sliders. More production and consumption of goods and services requires more energy. While energy efficiency and changes to the fuel mix can help reduce energy emissions, their success is dampened by the growth in GDP. Part of this growth is slowed down by climate change impacts such as lower crop yields, intensified natural disasters, sea level rise, and biodiversity loss. This impact on GDP is known as the “damage function” and slows the increase in consumption and energy demand. However, energy demand and CO₂ emissions from energy are still rising throughout the century, which leads many users to explore different futures for population (for example, by empowering women in developing countries, which could lower population growth) and economic growth measured in GDP per person (for example, by finding ways to meet economic needs without increasing consumption).

This addresses questions such as:

- “We’ve done a lot in energy efficiency and clean energy – why haven’t emissions reduced substantially enough?”

To illustrate this point: See the Kaya Graphs view below for a low-emissions scenario with increased energy efficiency and a transition to low-carbon energy sources. Even though Energy Intensity of GDP improves, and the Carbon Intensity of Energy decreases as well, Global Population and GDP per person continue to grow.

[View this scenario in En-ROADS.](#)



[To learn more, view this video on the Kaya graphs.](#)

2. Non-CO₂ Emissions Affect Temperature Significantly

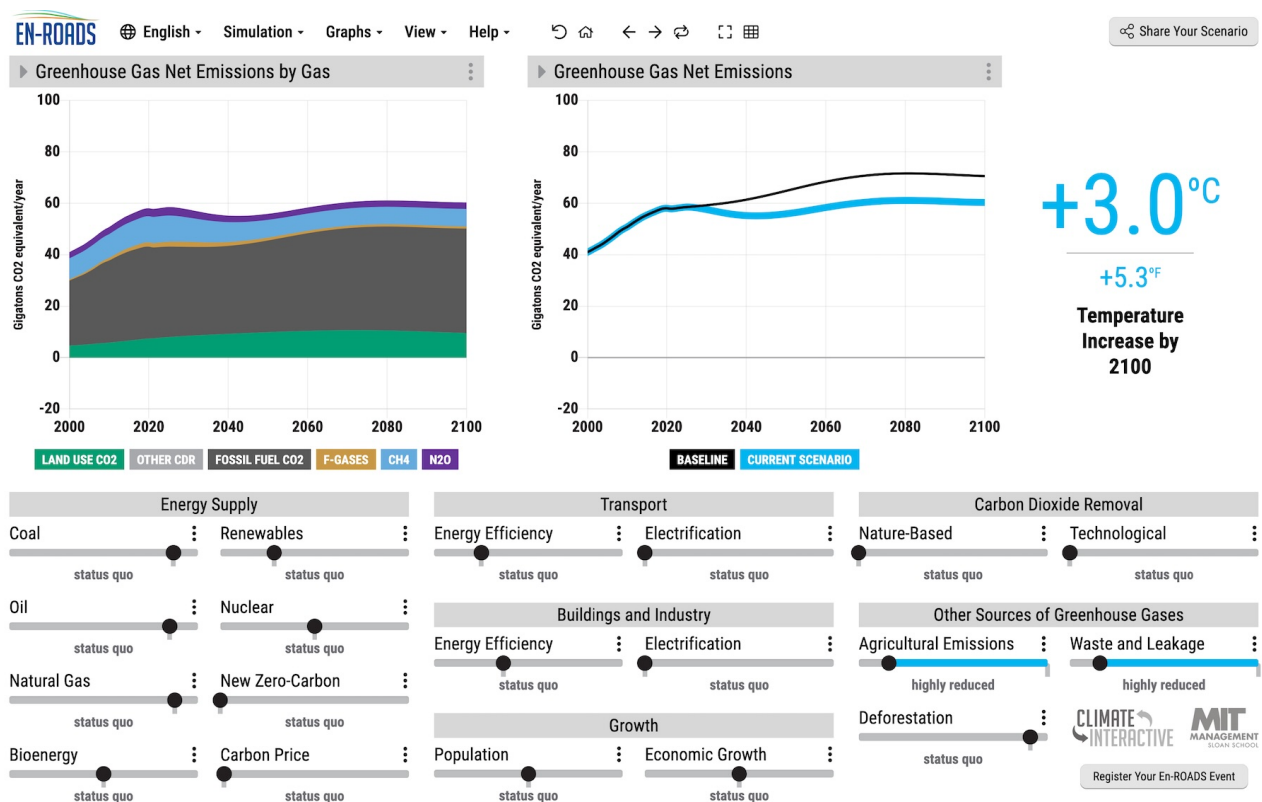
Methane (CH₄), N₂O, and the F-gases are controlled by the Agricultural Emissions and Waste and Leakage sliders. Adjusting these sliders has a large impact on temperature. This implies significant changes in livestock management and consumption, waste management, fertilizer use, and industry. These emissions currently make up around 26% of total greenhouse gas emissions.

This addresses questions such as:

- “We’ve done a lot in energy – why haven’t we solved the climate crisis?”

To illustrate this point: See the “Greenhouse Gas Net Emissions by Gas – Area” and “Greenhouse Gas Net Emissions” graphs and adjust the Agricultural Emissions slider and Waste and Leakage slider. See the scenario below – highly reducing CH₄, N₂O, and F-gas emissions achieves a significant reduction in 2100 temperature.

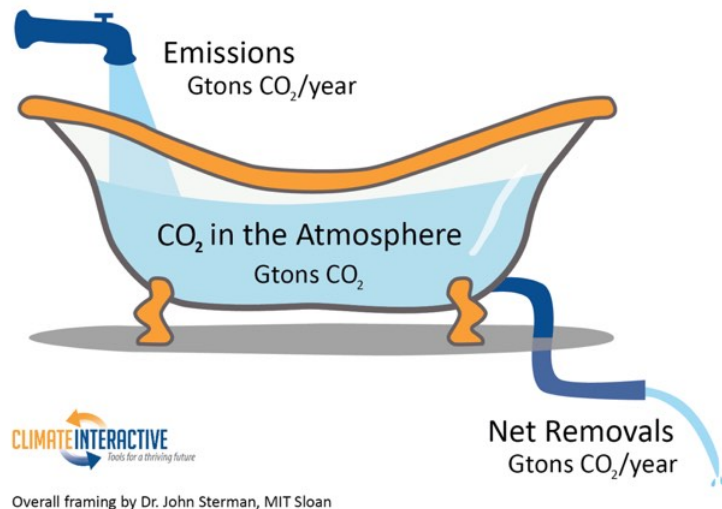
[View this scenario in En-ROADS.](#)



System Dynamics of the Climate

1. Bathtub Dynamics - CO₂ Emissions Must Be Equal to or Lower than CO₂ Removals for Temperature to Stabilize

The metaphor of a bathtub helps explain the dynamics of rising CO₂ concentration in the atmosphere. If more CO₂ enters the atmosphere (like water flowing into a tub) than is removed (like water draining from the tub), then the amount of CO₂ in the atmosphere (the amount of water in the tub) will continue to increase. To flatten CO₂ concentration and therefore temperature, we need to bring CO₂ emissions down to equal removals. If your bathtub is overflowing, you turn off the tap first.

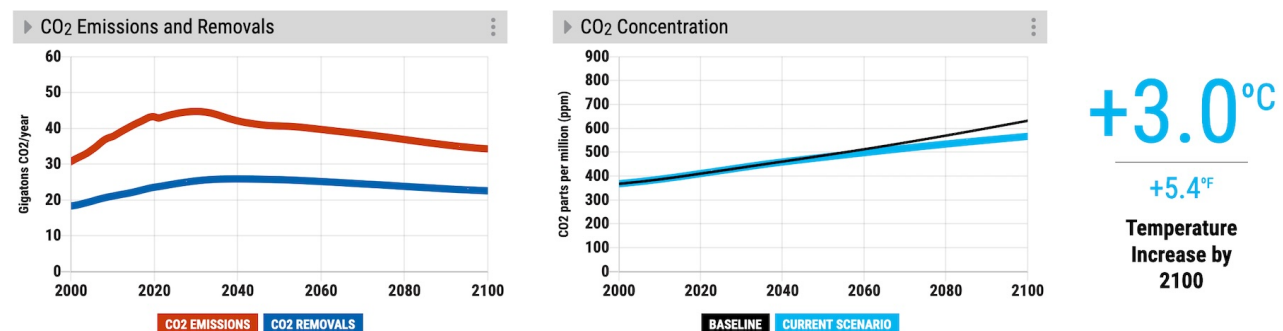


This addresses questions such as:

- "Emissions are stabilized, so why is temperature or CO₂ concentration still going up?"

To illustrate this point: See the "CO₂ Emissions and Removals" and "CO₂ Concentration" graphs in a scenario where CO₂ emissions stabilize. Even though CO₂ emissions (in red below) are declining, CO₂ concentration (in blue on the right below) continues to increase because emissions are greater than removals.

[View this scenario in En-ROADS.](#)



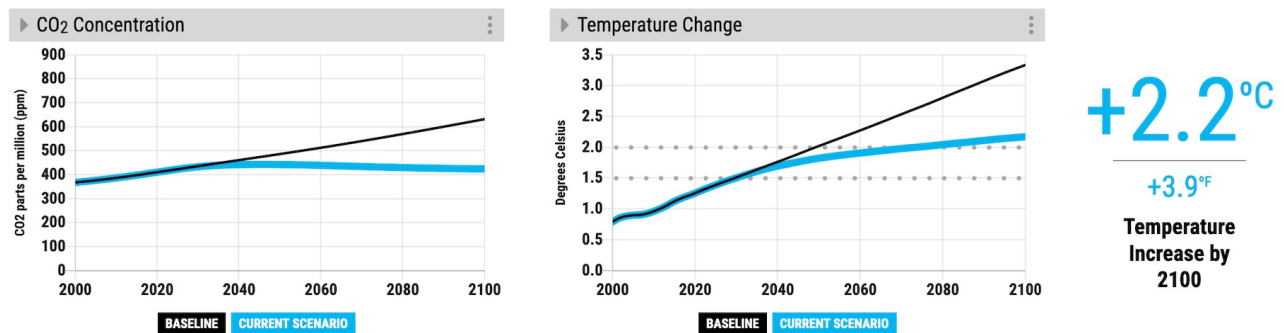
To learn more, view this video on the Carbon Dioxide Bathtub.

To understand more about stocks, flows, and the bathtub framing below, check out our [Climate Leader](#) learning series.

2. Delays in the Climate System

In a scenario where CO₂ concentration stabilizes, global surface temperature continues to increase for a number of years due to heat imbalances between the oceans and atmosphere (this is known as climate inertia). The ocean has absorbed most of the heat trapped by greenhouse gases, but it is slow to reach thermal equilibrium with the atmosphere. Note that the simulation ends in 2100 in En-ROADS, and the time for temperature to stabilize after CO₂ concentration has stabilized may be later than 2100.

[View this scenario in En-ROADS.](#)



Please visit support.climateinteractive.org for additional inquiries and support.

Impacts of Climate Change

Climate impacts refer to the effects of changes in the Earth's climate on people, economies, ecosystems, and infrastructure. These include reduced crop yields, more deaths due to extreme heat, and lower economic growth. Impacts may be caused directly by temperature increase, or by associated drivers such as CO₂ concentration and sea level rise.

Index of Impacts in En-ROADS

Atmosphere

- [Temperature Change](#)
- [CO₂ Concentration](#)
- [Methane Concentration](#)
- [Greenhouse Gas Concentration](#)

Extreme Weather

- [Extreme Heat Days—Map](#)
- [Extreme Humidity and Heat Days—Map](#)
- [Frequency of Extreme Heat](#)
- [Deaths from Extreme Heat](#)
- [Deaths from Extreme Heat by Region](#)
- [Outdoor Labor Losses from Extreme Heat](#)
- [Population Exposed to Hurricanes and Typhoons](#)
- [Population Exposed to River Flooding](#)

Health and Economy

- [Air Pollution from Energy](#)
- [Air Pollution from Energy by Source](#)
- [Malaria and Dengue Additional Exposure from Warming](#)
- [Crop Yield Decrease from Warming](#)
- [Crop Nutrient Decrease from CO₂ Concentration](#)
- [Global GDP Loss](#)

Oceans

- [Sea Level Rise](#)
- [Sea Level Rise—Flood Risk Map](#)
- [Population Exposed to Sea Level Rise](#)
- [Ocean Acidification](#)
- [Probability of Ice-free Arctic Summer](#)
- [Loss in Ocean Life from Warming](#)

Ecosystems and Biodiversity

- [Likelihood of Prolonged Drought—Map](#)
- [Wildfire Danger Days from Warming—Map](#)
- [Arid Land Expansion from Warming](#)
- [Ecosystem Shifts from Warming](#)
- [Extinction Risk of Endemic Species](#)
- [Species Losing More than 50% of Climatic Range](#)

Big Messages

- Climate impacts can highlight the importance of even a small change in temperature. Many impacts don't increase steadily as temperatures rise. Instead, they can become much worse very quickly.
- Mitigation brings immediate co-benefits, which are apparent by comparing the impact in 2030 or 2040 in the Baseline vs. the Current Scenario.

Key Dynamics

- **Temperature:** Most impacts are the result of global temperature increase or its consequences. Sea level rise, for example, is driven by a combination of melting ice and thermal expansion. Warmer oceans cause tropical cyclones to intensify in strength more quickly than in the past. Biodiversity declines when changing weather patterns and increasing heat cause ecosystems to shift or destabilize, altering species' habitats.
- **CO₂ concentration:** Ocean acidification, for example, is driven by an increase in the atmospheric concentration of CO₂. The oceans absorb about 30% of the CO₂ released into the atmosphere. Once dissolved in water, the CO₂ increases the acidity of the water through a series of chemical reactions. One important result is that less calcium carbonate is available, making it difficult for marine species to build seashells and coral skeletons.
- **Air pollution:** Air pollution from energy is the result of particulate matter emissions from burning coal, oil, and natural gas. Transforming the energy system to use renewables and other sources of clean energy will immediately improve air quality.

Facilitation Tips

- Highlight climate impacts throughout an En-ROADS workshop: at the beginning, to motivate action; after creating a scenario of climate success, to illustrate the improvements; and to emphasize the need for adaptation and resilience, even in a successful scenario.
- Maps, like those showing sea level rise, help people connect global changes to their local areas.

Equity Considerations

- Climate change disproportionately affects marginalized and vulnerable populations, including low-income communities, racial minorities, the elderly, and people with disabilities. For example, many elderly people are more vulnerable to heatwaves and extreme weather events due to chronic health conditions, reduced ability to regulate body temperature, and socioeconomic factors such as limited financial resources and a higher likelihood of living alone.
- Low-income communities often lack the resources to adapt or recover from climate impacts such as weather disasters, crop failures, or rising sea levels.

Videos

[Impacts of Climate Change](#)

Model Structure

Many of the climate impacts in En-ROADS are derived from research studies that have connected specific impacts to different global temperature scenarios. For more information on the climate impact and the study it is based on, view the graph description by clicking on the gray arrow on the top left of the graph title. Details on modeling are included in the [En-ROADS Technical Reference](#).

FAQs and Explainers

- [Where can I find detailed information about the research studies used for the impact graphs?](#)

Overviews for facilitators

- [Overview of extreme heat and humidity days maps](#)
- [Overview of deaths from extreme heat](#)
- [Overview of outdoor labor losses from extreme heat](#)
- [Overview of population exposed to hurricanes, typhoons, and river flooding](#)
- [Overview of malaria and dengue additional exposure from warming](#)
- [Overview of crop nutrient decrease from CO₂ concentration](#)
- [Overview of likelihood of prolonged drought map](#)
- [Overview of wildfire danger days from warming map](#)

Economic impact of climate change

- [Explainer: Economic impact of climate change in En-ROADS](#)

Crop yield

- [What is the relationship between crop yield and temperature in En-ROADS?](#)

Sea level rise

- [What does the “Land at risk” \(dark blue\) area in sea level rise \(SLR\) maps represent?](#)
- [What does the “Land saved by actions” \(green\) area in sea level rise \(SLR\) maps represent?](#)
- [Why do the sea level rise \(SLR\) maps show so much “Land at risk” \(blue\) in 2030?](#)
- [I think the 2030 sea level rise \(SLR\) maps for my region are unreliable. Does this mean the longer-term maps are wrong?](#)
- [What does the Long-term Equilibrium sea level rise \(SLR\) map mean?](#)
- [Where can I find out more information about the sea level rise \(SLR\) maps?](#)

Other

- [How do I simulate climate “tipping points” in En-ROADS?](#)

Please visit support.climateinteractive.org for additional inquiries and support.



Discourage or encourage mining coal and burning it in power plants. Coal is the most harmful fossil fuel in terms of carbon emissions, as well as in air pollutants that cause severe health impacts. It is a dominant source of energy globally, however, because it is relatively inexpensive to mine and transport. Carbon capture and storage (CCS) can capture some emissions from coal, but it is not yet used widely and faces barriers to deployment.

Examples

Discouraging coal:

- Government policies that phase out power plants or make them more expensive in any way, such as taxes on coal.
- Financial services industry (e.g., banks) or global development institutions (e.g., World Bank) limiting access to financial capital for new coal mining, refining, and power plant infrastructure.

Big Messages

- Discouraging coal is a high leverage strategy for reducing future temperature change. Coal emits more carbon dioxide when it is burned than either oil or natural gas (coal has the highest carbon intensity).
- Discouraging coal also improves public health and saves medical costs through improved air quality. Coal plants emit particulate matter and other forms of air pollution that lead to respiratory and cardiovascular diseases and premature deaths.¹

Key Dynamics

- **Impact.** When coal is discouraged, watch the brown area of Coal go down in the “Global Sources of Primary Energy” graph. It is one of the most sensitive energy supplies to any increase in cost because unlike oil, coal can often be replaced by natural gas (for heating or electricity) or renewables (for electricity).
- **“Squeezing the Balloon.”** When coal is taxed, notice what happens to natural gas in response. Unless there are restrictions on gas, its demand will go up in response to expensive coal. We call this the “[squeezing the balloon](#)” problem—reducing fossil fuel emissions in one area causes them to pop up in another. Renewables are also boosted slightly, but the impact on emissions from increased renewables is small. Solutions to the “squeezing the balloon” problem include taxing oil and natural gas as well, or adding a carbon price, which addresses all fossil fuels together.
- **Price-Demand Feedback.** Taxing coal also slightly reduces energy demand (see graphs “Total Primary Energy” and “Average Price of Energy to Consumers”). When energy prices are higher, people tend to use energy more efficiently and conserve energy. However, tax policies must be implemented with considerations for poor and working-class communities who can be negatively impacted by high energy prices. [Learn more.](#)

Potential Co-Benefits of Discouraging Coal

- Reduced air pollutants from coal burning improves air quality and health outcomes for surrounding communities. View this in the “Air Pollution from Energy” graph.
- Less coal mining reduces heavy metal drainage and waste from mine sites, which improves water quality for people and wildlife.

Equity Considerations

- Taxing coal can raise energy costs for households and businesses that rely on coal for energy needs.
- Low-income communities often suffer the worst health outcomes yet make up the majority of individuals who produce coal. Providing pathways for these people to find new jobs will be essential.

Videos

[Coal, Oil, and Natural Gas](#)

Slider Settings

The Coal slider is divided into 5 input levels: very highly taxed, highly taxed, taxed, status quo, and subsidized. Each of the energy supply sliders (Coal, Oil, Natural Gas, Bioenergy, Nuclear, and Renewables) is set to reflect a similar percentage cost increase or decrease for each input level. The following table displays the numerical ranges for each input level of the Coal slider.

	very highly taxed	highly taxed	taxed	status quo	subsidized
Change in price per ton of coal equivalent (tce)	+\$100 to +\$30	+\$30 to +\$15	+\$15 to +\$5	+\$5 to -\$5	-\$5 to -\$15
Cost increase or decrease	+200% to +60%	+60% to +30%	+30% to +10%	+10% to -10%	-10% to -30%

The coal industry is currently heavily subsidized. These subsidies are included in the “status quo” setting for the price of coal in En-ROADS. If you want to simulate the removal of these subsidies, move the slider to “taxed.” For more information, see this FAQ: [How do I simulate reducing coal, oil, and natural gas subsidies?](#)

Model Structure

The cost of coal affects three significant decisions regarding energy infrastructure:

1. Investment in new capacity (whether or not to build new processing and power plants)
2. Use of capacity (whether to run existing plants)
3. Retirement of capacity (whether to keep plants longer or shorter than the average of ~30 years)

Case Studies

United States: Replacing all coal-powered electricity in the US with solar power could save 52,000 lives per year, which is more than the number of people employed by the coal industry today.²

United States: The total cost of reliance on coal to the US economy is estimated to be \$344 billion per year. Of that cost, \$187B is from air pollution, \$74.6B is from public health effects in Appalachia, and \$61.7B from climate damages.³

India: A one gigawatt increase in coal-fired capacity corresponds to a nearly 15% increase in infant mortality in areas close to coal power plants. The effect was largest for older plants, plants in areas with relatively higher pollution levels, and plants burning domestic rather than imported coal.⁴

FAQs

- **How can I directly force deeper reductions in coal use?** Consider changing the “Reduce new coal infrastructure,” “% Reduction in coal utilization,” and “Coal plant accelerated retirement” sliders in the advanced view.
- **How do I simulate reducing coal subsidies?** Current coal subsidies are included in the En-ROADS Baseline Scenario, and you can remove them by moving the coal slider to “taxed.” [Click here for more information.](#)
- **How do I encourage carbon capture and storage (CCS)?** En-ROADS has three options to encourage CCS:
 1. **CCS subsidy:** In the advanced view of the Coal, Natural Gas, and Bioenergy sliders, you can set a subsidy to promote CCS for each fuel type.
 2. **Carbon Price:** CCS is also encouraged for all fuels if a carbon price is set, unless the “Carbon price encourages carbon capture and storage (CCS)” switch in the advanced view of the slider is turned off.
 3. **Clean Electricity Standard:** In the advanced view of the Carbon Price slider, you can also test a clean electricity standard that counts CCS as a qualifying source of clean power. However, due to the high cost of CCS, this policy alone may not significantly boost its adoption without additional subsidies.

Read the Explainer for more information: [Carbon Capture and Storage \(CCS\) in En-ROADS](#)

- [Why does coal demand decline and then rise again in the En-ROADS Baseline Scenario?](#)
- [What's the difference between a carbon price and a tax on a fuel \(coal, oil, natural gas, or bioenergy\)?](#)
- [Why aren't coal and natural gas carbon capture and storage \(CCS\) technologies included under "Technological Carbon Removal"?](#)
- [Why are the slider ranges \(min and max\) what they are? How did you decide the range of the sliders?](#)
- [What happens to the revenue from taxes or a carbon price in En-ROADS?](#)

Please visit support.climateinteractive.org for additional inquiries and support.

Footnotes

[1]: Markandya, A. & Wilkinson, P. (2007). Electricity generation and health. *The Lancet*, 370(9591), 979-990. [https://doi.org/10.1016/S0140-6736\(07\)61253-7](https://doi.org/10.1016/S0140-6736(07)61253-7)

[2]: Prehoda, E. W., & Pearce, J. M. (2017). [Potential lives saved by replacing coal with solar photovoltaic electricity production in the U.S.](#) *Renewable and Sustainable Energy Reviews*, 80, 710–715.

[3]: Epstein, P. R., Buonocore, J. J., Eckerle, K., Hendryx, M., Iii, B. M. S., Heinberg, R., ... Glustrom, L. (2011). [Full cost accounting for the life cycle of coal.](#) *Annals of the New York Academy of Sciences*, 1219(1), 73–98.

[4]: Barrows, G., Garg, T., & Jha, A. (2019). [The Health Costs of Coal-Fired Power Plants in India.](#) SSRN.



Discourage or encourage drilling, refining, and consuming oil for energy. Oil is a fossil fuel that is used widely in cars, ships, and planes; it is also used for industry, heating, and electricity. Access to oil has sparked major conflicts, and oil spills threaten ecosystems and water quality.

Examples

Discouraging oil:

- Governments imposing limits on oil drilling and exploration, removing subsidies, and taxing oil.
- Universities, corporations, and individuals divesting from oil companies.
- Financial services industry (e.g., banks) or global development institutions (e.g., World Bank) limiting access to capital for exploration, drilling, refining, and delivery.

Big Messages

- Oil is more difficult to replace than coal and natural gas because of its portability and high energy density, so oil demand is more resistant to changes in price. Replacing oil with less carbon-intensive sources of energy often requires electrification, like switching to electric cars.
- When a steep oil tax is the only action implemented, you will not see a dramatic change in temperature, as coal and natural gas demand increases in response, offsetting the reduction in emissions from oil.

Key Dynamics

- **"Squeezing the Balloon."** When oil is taxed, notice what happens to coal and gas in response. Unless there are restrictions on coal and gas, their demand will go up in response to expensive oil. We call this the ["squeezing the balloon"](#) problem—reducing fossil fuel emissions in one area causes them to pop up in another. You can see this dynamic in the "CO₂ Emissions from Energy and Industry by Source" graph. Solutions to the "squeezing the balloon" problem include taxing oil and natural gas as well, or adding a carbon price, which addresses all fossil fuels together.
- **Fuel switching.** Notice that taxing oil results in an increase in electrification of the vehicle fleet as electric-powered modes of transport become more affordable in the face of higher oil prices. See this demonstrated in the "% Existing Transport by Carrier" graph. Energy sources used for electricity, such as coal, natural gas, and renewables, also increase due to this shift. To increase the impact of taxing oil, consider incentivizing transport electrification further.
- **Price-Demand Feedback.** Taxing oil also reduces energy demand (see graphs "Total Final Consumption of Energy Sources" and "Average Price of Energy to Consumers"). When energy prices are higher, people tend to use energy more efficiently and conserve energy. However, tax policies must be implemented with considerations for poor and working-class communities who can be negatively impacted by high energy prices. [Learn more.](#)

Potential Co-Benefits of Discouraging Oil

- A reduction in oil drilling could lead to fewer oil spills, helping protect wildlife habitats, biodiversity, and ecosystem services at production sites and along transportation routes.
- Reduced economic dependence on oil can improve national security and lower military costs.

Equity Considerations

- The oil industry provides many high-paying jobs for people with technical trade backgrounds. Providing pathways for these people to find new jobs will be essential.
- Oil companies wield enormous economic and political power locally and globally. In order to discourage oil, certain industry protections must be eliminated.
- There is a history of oil refineries being located in marginalized communities and companies working to avoid or limit environmental regulations.

Videos

[Coal, Oil, and Natural Gas](#)

Slider Settings

The Oil slider is divided into 5 input levels: very highly taxed, highly taxed, taxed, status quo, and subsidized. Each of the energy supply sliders (Coal, Oil, Natural Gas, Bioenergy, Nuclear, and Renewables) is set to reflect a similar percentage cost increase or decrease for each input level. The following table displays the numerical ranges for each input level of the Oil slider:

	very highly taxed	highly taxed	taxed	status quo	subsidized
Change in price per barrel of oil equivalent (boe)	+\$85 to +\$25	+\$25 to +\$12	+\$12 to +\$5	+\$5 to -\$5	-\$5 to -\$15
Cost increase or decrease	+200% to +60%	+60% to +30%	+30% to +10%	+10% to -10%	-10% to -30%

The oil industry is currently heavily subsidized. These subsidies are included in the “status quo” setting for the price of oil in En-ROADS. If you want to simulate the removal of these subsidies, move the slider to “taxed.” For more information, see this FAQ: [How do I simulate reducing coal, oil, and natural gas subsidies?](#)

Model Structure

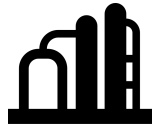
The cost of oil affects three significant decisions regarding energy infrastructure:

1. Investment in new capacity (whether or not to build new drilling operations and refineries)
2. Use of capacity (whether to run existing operations)
3. Retirement of capacity (whether to keep infrastructure longer or shorter than the average of ~30 years)

FAQs

- **How can I directly force deeper reductions in oil use?** Consider changing the “Reduce new oil infrastructure” and the “% Reduction in oil utilization” sliders in the advanced view.
- [Why are the slider ranges \(min and max\) what they are? How did you decide the range of the sliders?](#)
- [What happens to the revenue from taxes or a carbon price in En-ROADS?](#)
- [What's the difference between a carbon price and a tax on a fuel \(coal, oil, natural gas, or bioenergy\)?](#)

Please visit support.climateinteractive.org for additional inquiries and support.



Natural Gas

Discourage or encourage drilling and burning natural gas for energy. Natural Gas is a fossil fuel that is used for electricity, heating, and industry. When burned, it releases methane. Natural gas drilling uses large amounts of water and can cause contamination. Carbon capture and storage (CCS) can capture some emissions from gas, but is not yet used widely and faces barriers to deployment.

Examples

Discouraging natural gas:

- Governments implementing taxes on natural gas and laws against fracking.
- Financial services industry (e.g., banks) or global development institutions (e.g., World Bank) limiting access to capital.

Big Messages

- More natural gas is not an effective long-term strategy for the climate—it is less carbon intensive than coal, but it still emits carbon dioxide.
- Gas infrastructure has a long lifetime and it competes with the adoption of lower-carbon alternatives such as renewables as they scale up.

Key Dynamics

- **“Squeezing the Balloon.”** If natural gas is taxed, in absence of other policies, primary energy demand for gas decreases, but carbon-intensive coal demand increases slightly. We call this the “[squeezing the balloon](#)” problem—reducing fossil fuel emissions in one area causes them to pop up in another. Adding a carbon price is a good solution to the “squeezing the balloon” problem, as it addresses all fossil fuels together.
- **Methane leakage.** When gas is discouraged, by taxing it, watch the blue line of the Current Scenario go down in the “Methane Emissions” graph. Natural gas is primarily composed of methane, a powerful greenhouse gas. Methane from gas leaks to the atmosphere from wells, pipelines, and other gas infrastructure. Taxing natural gas decreases the leakage by incentivizing the fixing of leaks and discouraging the use of gas. Methane leakage can also be reduced by adopting best practices such as repairing pipelines, simulated with the Waste and Leakage slider.
- **Price-Demand Feedback.** Taxing gas also reduces energy demand (see graphs “Total Primary Energy” and “Average Price of Energy to Consumers”). When energy prices are higher, people tend to use energy more efficiently and conserve energy. However, tax policies must be implemented with considerations for poor and working-class communities who can be negatively impacted by high energy prices. [Learn more.](#)

Potential Co-Benefits of Discouraging Natural Gas

- Gas drilling is water intensive, so limiting extraction can improve water security and quality at the source of production and protect wildlife habitats, biodiversity, and ecosystem services.^{1 2}
- There are concerns about the health and environmental impacts of the gas drilling approach, known as fracking, that have led many places to ban it.^{3 4}

Equity Considerations

- Generally speaking, natural gas production in developed countries is disproportionately located near low-income and minority communities.^{5 6}
- There have been cases where wealthy white communities have successfully resisted natural gas development and it has shifted to low-income communities predominantly inhabited by people of color. Low-income communities often have less ability to influence development.^{7 8}
- Limited data on the placements of fracking and power plant sites in developing countries exists, yet macro-level research shows that low-income communities and communities of color disproportionately experience the negative impacts of natural gas drilling and burning.⁹

Videos

[Coal, Oil, and Natural Gas](#)

Slider Settings

The Natural Gas slider is divided into 5 input levels: very highly taxed, highly taxed, taxed, status quo, and subsidized. Each of the energy supply sliders (Coal, Oil, Natural Gas, Bioenergy, Nuclear, and Renewables) is set to reflect a similar percentage cost increase or decrease for each input level. The following table displays the numerical ranges for each input level of the Natural Gas slider:

	very highly taxed	highly taxed	taxed	status quo	subsidized
Change in price per thousand cubic feet (Mcf)	+\$5.00 to +\$1.40	+\$1.40 to +\$0.70	+\$0.70 to +\$0.20	+\$0.20 to -\$0.20	-\$0.20 to -\$0.70
Cost increase or decrease	+200% to +60%	+60% to +30%	+30% to +10%	+10% to -10%	-10% to -30%

The natural gas industry is currently heavily subsidized. These subsidies are included in the “status quo” setting for the price of natural gas in En-ROADS. If you want to simulate the removal of these subsidies, move the slider to “taxed.” For more information, see this FAQ: [How do I simulate reducing coal, oil, and natural gas subsidies?](#)

Model Structure

The cost of natural gas affects three significant decisions regarding energy infrastructure:

1. Investment in new capacity (whether or not to build new processing and power plants)
2. Use of capacity (whether to run existing plants)
3. Retirement of capacity (whether to keep plants longer or shorter than the average of ~30 years)

FAQs

- **How can I directly force deeper reductions in natural gas use?** Consider changing the “Reduce new gas infrastructure” and the “% Reduction in gas utilization” sliders in the advanced view.
- **How do I simulate reducing natural gas subsidies?** Current natural gas subsidies are included in the En-ROADS Baseline Scenario, and you can remove them by moving the natural gas slider to “taxed.” [Click here for more information.](#)
- **How do I simulate fixing natural gas pipeline leaks?** In the Waste and Leakage advanced view, move the “Methane leakage from energy systems” slider.
- **How do I encourage carbon capture and storage (CCS)?** En-ROADS has three options to encourage CCS:
 1. **CCS subsidy:** In the advanced view of the Coal, Natural Gas, and Bioenergy sliders, you can set a subsidy to promote CCS for each fuel type.
 2. **Carbon Price:** CCS is also encouraged for all fuels if a carbon price is set, unless the “Carbon price encourages carbon capture and storage (CCS)” switch in the advanced view of the slider is turned off.
 3. **Clean Electricity Standard:** In the advanced view of the Carbon Price slider, you can also test a clean electricity standard that counts CCS as a qualifying source of clean power. However, due to the high cost of CCS, this policy alone may not significantly boost its adoption without additional subsidies.

Read the Explainer for more information: [Carbon Capture and Storage \(CCS\) in En-ROADS](#)

- [Why are the slider ranges \(min and max\) what they are? How did you decide the range of the sliders?](#)
- [What happens to the revenue from taxes or a carbon price in En-ROADS?](#)
- [What's the difference between a carbon price and a tax on a fuel \(coal, oil, natural gas, or bioenergy\)?](#)
- [Why aren't coal and natural gas carbon capture and storage \(CCS\) technologies included under “Technological Carbon Removal”?](#)

Please visit support.climateinteractive.org for additional inquiries and support.

Footnotes

[1]: Bamberger, M., & Oswald, R. E. (2012). [Impacts of Gas Drilling on Human and Animal Health](#). *NEW SOLUTIONS: A Journal of Environmental and Occupational Health Policy*, 22(1), 51–77.

[2]: Ridlington, E., & Rumpler, J. (2013). [Fracking by the Numbers: Key Impacts of Dirty Drilling at the State and National Level](#). *Environment America*.

[3]: Good, K. (2015, February 12). [These 4 Countries Have Banned Fracking ... Why Can't the U.S. Get On Board?](#)

- [4]: Carpenter, D. O. (2016). [Hydraulic fracturing for natural gas: impact on health and environment](#). *Reviews on Environmental Health*, 31(1).
- [5]: Clough, E. (2018). [Environmental justice and fracking: A review](#). *Current Opinion in Environmental Science & Health*, 3, 14–18.
- [6]: Bienkowski, B. (2016, February 17). [Fracking's Costs Fall Disproportionately on the Poor and Minorities in South Texas](#). *Inside Climate News*.
- [7]: Jula, M. (2018, April 17). [Parents didn't want fracking near their school. So the oil company chose a poorer school, instead](#). *Mother Jones*.
- [8]: Gislason, M., & Andersen, H. (2016). [The Interacting Axes of Environmental, Health, and Social Justice Cumulative Impacts: A Case Study of the Blueberry River First Nations](#). *Healthcare*, 4(4), 78.
- [9]: Perera, F. (2017). [Pollution from Fossil-Fuel Combustion is the Leading Environmental Threat to Global Pediatric Health and Equity: Solutions Exist](#). *International Journal of Environmental Research and Public Health*, 15(1), 16.



Discourage or encourage the use of trees, waste, and agricultural crops to create energy. These sources (feedstocks) produce energy when burned as solids (e.g., wood), liquids (e.g., ethanol), or gas (e.g., methane from decomposition). Some feedstocks can be sustainable and others can be worse than burning coal. Carbon capture and storage technology could be used with bioenergy (BECCS), but is not yet used widely and faces barriers to deployment.

Examples

Discouraging bioenergy:

- Government policies that phase out the investment in new bioenergy infrastructure or make it more expensive, such as taxes on bioenergy feedstocks.
- Public information campaigns that criticize sources of bioenergy that are not sustainable and raise public concerns about the downsides of bioenergy.

Encouraging bioenergy:

- Government incentives and/or targets to convert land into growing feedstocks that provide the plant material and biomass needed to produce bioenergy.
- Research, development, and investment into new technologies that can produce new forms of biofuels, and vehicles and industry that can use or support these biofuels.
- Government policies that exempt bioenergy, regardless of feedstock, from greenhouse gas accounting frameworks designed to limit emissions.

Big Messages

- Bioenergy is not a high leverage response to climate change – while it uses a potentially renewable resource, it still emits large amounts of carbon dioxide and faces supply constraints with scale up.
- Subsidizing bioenergy from wood increases temperature because it results in higher net CO₂ emissions.

Key Dynamics

- As bioenergy is subsidized or taxed, notice that the temperature changes very little and bioenergy's contribution to the mix of global sources of primary energy does not change much. The main constraint on bioenergy is the amount of biomass that is available each year to be turned into energy. This limitation means that there are only small changes to other energy sources, if bioenergy is subsidized.
- Subsidizing wood bioenergy increases CO₂ emissions (shown in the “CO₂ Gross Emissions from Forest Bioenergy” graph) and reduces the removal of CO₂ from the atmosphere (shown in the “CO₂ Removals from Land” graph). Together, the change in emissions and removals results in more CO₂ in the atmosphere, shown in the “CO₂ Net Emissions from Forest Bioenergy” graph. For an in-depth understanding of this dynamic, read the [Bioenergy Explainer](#).

- Bioenergy is only zero-carbon if the biomass is regrown to account for the carbon emitted. This is not guaranteed, and in some areas, bioenergy is produced from trees, which take decades to regrow to make up for the carbon released when burned.
- Bioenergy carbon capture and storage (BECCS) is proposed as a source of energy and a way to remove additional carbon from the atmosphere. For this to result in a process that stores more carbon than it releases, the biomass used would need to be fully regrown and the emissions captured when the biomass is burned to produce energy. This has yet to be proven feasible at large scales.

Potential Co-Benefits of Discouraging Bioenergy

- Crops and arable land are freed for other uses, such as food production, when bioenergy is discouraged.
- Leaving sources of biomass intact, like forests, enables biodiversity to be preserved.
- A reduction in biomass burning can improve indoor and outdoor air quality from reduced soot and particulates.
- Bioenergy can accelerate mature forest degradation through dependence on wood for fuels or through the expansion of bioenergy crops, particularly in the tropics. Less deforestation has many benefits including additional carbon sequestration.

Equity Considerations

- Land used for bioenergy crops can reduce land availability for food production and compromise food security.
- Farmer livelihoods can be severely impacted by shifting agriculture markets, so steps should be taken to help workers and farmers transition to shifting crop demands.

Videos

[Bioenergy](#)

Slider Settings

The Bioenergy slider is divided into 5 input levels: highly taxed, taxed, status quo, subsidized, and highly subsidized. Each of the energy supply sliders (Coal, Oil, Natural Gas, Bioenergy, Nuclear, and Renewables) is set to reflect a similar percentage cost increase or decrease for each input level. The following table displays the numerical ranges for each input level of the Bioenergy slider:

	highly taxed	taxed	status quo	subsidized	highly subsidized
Change in price per barrel of oil equivalent (boe)	+\$25 to +\$15	+\$15 to +\$5	+\$5 to -\$5	-\$5 to -\$15	-\$15 to -\$25
Cost increase or decrease	+60% to +30%	+30% to +10%	+10% to -10%	-10% to -30%	-30% to -60%

Model Structure

- Bioenergy sources, known as “feedstocks,” are categorized into wood, crops, and waste/other. These feedstocks can be separately subsidized or taxed. Wood feedstocks result in net CO₂ emissions due to the delays in regrowing trees, while the other types of feedstocks do not result in net CO₂ emissions due to their faster regeneration times (e.g., bioenergy crops are regrown within a year).
- Subsidizing bioenergy drives more deforestation and forest degradation due to harvesting of wood as feedstock or clearing land to grow crops for bioenergy.
- This sector tracks several stages of bioenergy installations, or energy supply capacity including: capacity under development, under construction, and actually producing energy, as well as the delays between each stage.

FAQs and Explainers

- **How do I encourage carbon capture and storage (CCS)?** En-ROADS has three options to encourage CCS:

1. **CCS subsidy:** In the advanced view of the Coal, Natural Gas, and Bioenergy sliders, you can set a subsidy to promote CCS for each fuel type.
2. **Carbon Price:** CCS is also encouraged for all fuels if a carbon price is set, unless the “Carbon price encourages carbon capture and storage (CCS)” switch in the advanced view of the slider is turned off.
3. **Clean Electricity Standard:** In the advanced view of the Carbon Price slider, you can also test a clean electricity standard that counts CCS as a qualifying source of clean power. However, due to the high cost of CCS, this policy alone may not significantly boost its adoption without additional subsidies.

Read the explainer for more information: [Carbon Capture and Storage \(CCS\) in En-ROADS](#)

- [Explainer: Bioenergy in En-ROADS](#)
- [What does the bioenergy slider represent, and why is bioenergy not included in renewables?](#)

Please visit support.climateinteractive.org for additional inquiries and support.



Renewables

Encourage or discourage building solar panels, geothermal, and wind turbines. Renewable energy includes wind, solar, geothermal, hydropower, and other technologies that produce energy with little to no carbon dioxide emissions or air pollution. Note that nuclear and bioenergy are considered separately. Also, support hydrogen production from renewables, and deploy storage to balance variable renewable energy.

Examples

- Governments offering tax incentives to families installing solar panels on their roofs.
- Farmers and landowners allowing the installation of wind turbines on their land.
- Research and development for improvements to renewable energy technologies in order to improve efficiencies and/or reduce costs.
- Businesses committing to powering themselves with 100% renewable energy.

Big Messages

- Subsidizing renewable energy helps to limit coal and gas demand and reduce future temperature as it becomes the most affordable source of electricity.
- Renewable subsidies can more significantly displace coal, oil, and gas demand when complemented with other actions, particularly the electrification of transport, buildings, and industry.
- Achieving a high share of renewable energy for electricity requires energy storage and other solutions to balance the variability of wind and solar.

Key Dynamics

- **Impact.** As you encourage renewables, watch demand for Renewables (in green) grow and the demand for Coal (in brown) and Natural Gas (in blue) reduce in the “Global Sources of Primary Energy” graph. Renewable energy is already growing steadily in the Baseline Scenario, so the additional subsidies help reduce emissions but only so much.
- **Price-Demand Feedback.** Subsidies to renewables decrease energy costs, which increase energy demand over what it would have been otherwise (people use more energy when it is cheap). This feedback effect somewhat reduces the positive impact of encouraging renewable energy. View this dynamic with the graph “Total Final Consumption of Energy Sources.” [Learn more.](#)
- **Economies of Scale.** The Baseline Scenario already assumes a high growth of renewable energy based on historical trends in cost reductions and high adoption rates (see the “Marginal Cost of Solar Electricity History” and “Primary Energy Demand of Wind and Solar History” graphs in the “Model Comparison—Historical” section), and for more details on the dynamics [read here.](#)
- **Delays.** It takes time for the subsidies and encouragement of renewables to show up in installed capacity. New energy infrastructure is only added as demand grows or as the old infrastructure is retired and makes space for new infrastructure (this is known as “[capital stock turnover delays](#)”). The new infrastructure takes time to build. Subsidies and taxes are also phased in over 10 years, creating some of the delay in the speed at which actions make an impact.

- **Electrification to increase impact.** Incentivizing electrification of buildings & industry and transport enables electricity from renewables to replace fuel (such as oil). [Learn more.](#)

Potential Co-Benefits of Encouraging Renewables

- Decreased air and water pollution from switching away from fossil fuel sources can improve public health, worker productivity, and savings for governments and households.
- Renewables can help expand energy access during power outages.
- Renewable energy offers opportunities for high- and low-skilled employment.

Equity Considerations

- Although the price of renewable energy infrastructure continues to fall, many low-income communities remain unable to access the technology in both developed and developing countries. Working to ensure an equitable energy transition can help everyone to reap the benefits.¹
- Policies in many developed countries limit solar and wind subsidy programs to homeowners, who often occupy higher income brackets.

Videos

[Renewables](#)

Slider Settings

The Renewables slider is divided into 4 input levels: taxed, status quo, subsidized, and highly subsidized. Each of the energy supply sliders (Coal, Oil, Natural Gas, Bioenergy, Nuclear, and Renewables) is set to reflect a similar percentage cost increase or decrease for each input level. The following table displays the numerical ranges for each input level of the Renewables slider:

	taxed	status quo	subsidized	highly subsidized
Change in price per kilowatt hour (kWh)	+\$0.02 to +\$0.01	+\$0.01 to -\$0.01	-\$0.01 to -\$0.02	-\$0.02 to -\$0.05
Cost increase or decrease	+30% to +10%	+10% to -10%	-10% to -30%	-30% to -60%

Model Structure

This sector tracks the time it takes wind and solar installations to move through several stages – capacity under development, under construction, and actually producing energy.

The most important feedback loops in the renewables sector include:

1. Overheating – costs go up when demand grows faster than the manufacturing and support industries can keep up.
2. Site availability – efficiency goes down and costs go up when renewables are sited in less optimal locations (e.g., solar power in rainy climates).
3. Learning effect – every doubling of cumulative production will bring costs down 20% (aka, the progress ratio). Costs come down as supply chains, business models, and production industries grow.

Case Studies

United States: Scaling up wind and solar energy sources is estimated to have avoided 7,000 premature deaths and saved \$87.6 billion in health costs and climate impacts from 2007-2015.²

Benin: Solar-powered drip irrigation for women farmers was shown to increase household vegetable production and consumption, increase income level, and decrease food insecurity.³

Global: Increasing the share of renewable energy in the global energy supply to 65% could generate 6 million jobs and add \$19 trillion to the world economy by 2050.⁴

FAQs

- **Why doesn't encouraging renewables with a big subsidy avoid much future warming alone?**
 - Renewables only reduce CO₂ emissions when they displace fossil fuels. In some cases renewable energy just meets new energy demand and doesn't replace the demand met by coal and gas.
 - There is a price-demand feedback effect – in order to grow, renewables are made less expensive. The drop in energy price boosts demand, undoing some of the positive effect.
- **How can I get renewables to grow faster?**
 - Discourage fossil fuels by taxing them individually or setting a carbon price.
 - Adjust the "Renewables breakthrough cost reduction" slider to simulate a sudden breakthrough that would dramatically lower the cost of renewable energy.
 - Incentivize electrification of buildings & industry and transport, which enables electricity from renewables to replace fuel.
 - Adjust the "Green hydrogen production subsidy" and/or "Other storage breakthrough cost reduction" sliders to simulate a breakthrough that would lower the cost of the energy storage needed to accommodate the variability of wind and solar power.
- **How does En-ROADS handle the availability and cost of storage of electricity from variable renewables?**

En-ROADS explicitly models the cost and availability of energy storage technologies needed to accommodate wind and solar power. As the share of electricity from variable renewables grows, storage demand increases to ensure a reliable energy supply. As a result, storage costs make up a larger share of the "Marginal Cost of Wind and Solar" graph. The "Green hydrogen production subsidy" and "Other storage breakthrough cost reduction" sliders can lower these costs and enable further expansion.
- [How do I simulate energy storage for wind and solar?](#)
- [How do I simulate innovations in wave energy and tidal energy?](#)
- [How do I simulate hydrogen use?](#)
- [Why are all renewable energy sources grouped together in En-ROADS?](#)

Please visit support.climateinteractive.org for additional inquiries and support.

Footnotes

[1]: Eisenberg, A. (2018). [Just Transitions](#). *Southern California Law Review*, Vol. 92, No. 101, 2019.

- [2]: Millstein, D., Wiser, R., Bolinger, M., & Barbose, G. (2017). [The climate and air-quality benefits of wind and solar power in the United States](#). *Nature Energy*, 2(9).
- [3]: Burney, J., Woltering, L., Burke, M., Naylor, R., & Pasternak, D. (2010). [Solar-powered drip irrigation enhances food security in the Sudano–Sahel](#). *Proceedings of the National Academy of Sciences*, 107(5), 1848–1853.
- [4]: IEA & IRENA. (2017). [Perspectives for the Energy Transition – Investment Needs for a Low-carbon Energy System](#).



Encourage or discourage building nuclear power plants. Nuclear power production does not release carbon dioxide, but it produces harmful nuclear waste.

Examples

Discouraging nuclear:

- Public information campaigns to raise public concerns about the risks of nuclear power.
- Policies to retire existing nuclear power plants.

Encouraging nuclear:

- Government policies aimed at handling nuclear waste and reducing costs of nuclear power.
- Corporate efforts to promote public acceptance of nuclear power plants.

Big Messages

- Nuclear has not benefited from the significant cost reductions that wind and solar energy have experienced in the last decade, so it remains a relatively expensive option. Nuclear energy expansion continues, however, and can become more competitive with renewables and new zero-carbon technology through subsidies and/or a technological breakthrough. See the “Marginal Cost of Electricity Production” graph to examine this further.
- It could be part of a suite of climate actions if one is willing to accept the environmental costs – e.g., handling waste materials and the risk of radiation damage near the plants.

Key Dynamics

- **Impact.** As you subsidize nuclear, watch Nuclear (light blue) grow, and Coal (brown) and Natural Gas (dark blue) decrease in the “Global Sources of Primary Energy” graph. Nuclear displaces some fossil fuel sources, which keeps more carbon in the ground and helps reduce temperature modestly.
- **“Crowding Out.”** Nuclear competes with all sources of electricity available, so notice also what happens to Renewables (green) when nuclear is incentivized—it decreases. [Learn more.](#)
- **Delays.** It takes time for the subsidies and encouragement of nuclear to show up in installed capacity. Subsidies are phased in over 10 years and nuclear plants take a while to plan and construct, so note in the “Nuclear Primary Energy Demand” graph that the Current Scenario does not immediately differ from the Baseline.
- **Electrification to increase impact.** Incentivizing electrification of buildings & industry and transport enables electricity from nuclear to replace fuel (such as oil). [Learn more.](#)

Potential Co-Benefits of Discouraging Nuclear

- Risk of exposure to radiation from a nuclear meltdown or hazardous waste is reduced.
- Nuclear energy can use more water than coal for electricity production, so discouraging nuclear power can increase water security and help protect wildlife habitats, biodiversity, and ecosystem services.¹
- Nuclear energy is fueled by uranium which can be harmful to mine, so discouraging nuclear energy can reduce risks to miners.

Equity Considerations

- Nuclear power plants, uranium mines (which provide the fuel for nuclear power), and waste sites are often located in low-income, marginalized communities that often lack resources to advocate for stricter environmental regulations and oversight.²
- Mining uranium poses significant health risks to miners as well as surrounding communities due to water contamination and toxic waste.

Videos

[Nuclear](#)

Slider Settings

The Nuclear slider is divided into 5 input levels: highly taxed, taxed, status quo, subsidized, and highly subsidized. Each of the energy supply sliders (Coal, Oil, Natural Gas, Bioenergy, Nuclear, and Renewables) is set to reflect a similar percentage cost increase or decrease for each input level. The following table displays the numerical ranges for each input level of the Nuclear slider:

	highly taxed	taxed	status quo	subsidized	highly subsidized
Change in price per kilowatt hour (kWh)	+\$0.07 to +\$0.04	+\$0.04 to +\$0.01	+\$0.01 to -\$0.01	-\$0.01 to -\$0.04	-\$0.04 to -\$0.07
Cost increase or decrease	+60% to +30%	+30% to +10%	+10% to -10%	-10% to -30%	-30% to -60%

Model Structure

This sector tracks several stages of nuclear power plants, or energy supply capacity: capacity under development, under construction, and actually producing energy, including delays between each stage.

FAQs

- **How do I simulate the deployment of small modular reactors (SMRs)?** The best way to simulate SMRs in En-ROADS is using the New Zero-Carbon slider rather than the Nuclear slider. [Read more here.](#)

Please visit support.climateinteractive.org for additional inquiries and support.

Footnotes

[1]: Union of Concerned Scientists. (2013, July). [How it Works: Water for Nuclear.](#)

[2]: Kyne, D., & Bolin, B. (2016). [Emerging Environmental Justice Issues in Nuclear Power and Radioactive Contamination.](#) *International Journal of Environmental Research and Public Health*, 13(7), 700.



New Zero-Carbon

Discover a brand-new cheap source of electricity that does not emit greenhouse gases. Some speculate that such a breakthrough could be nuclear fusion, thorium-based nuclear fission, or small modular reactors (SMRs). However, there are unknown risks associated with any new energy supply. Decide when the breakthrough occurs, its initial cost relative to coal, and how long the delays in commercialization and scale up would be.

Note, this does not include new technologies in CO₂ removal, transportation, electrification, or energy efficiency.

Examples

- Research and development, or other investment into new sources of energy supply such as thorium fission, nuclear fusion, or small modular reactors (SMRs).

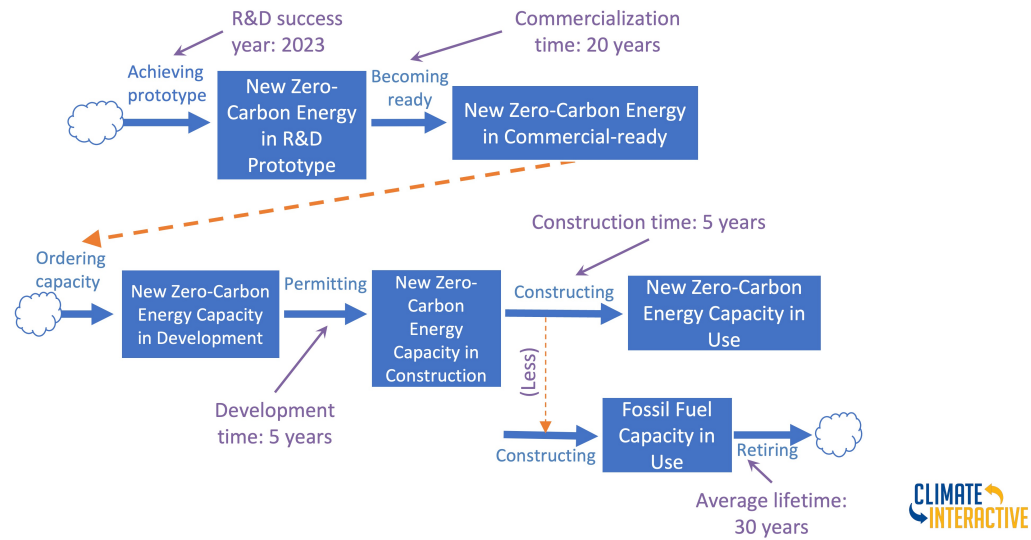
Big Messages

- The potential contribution of a new energy supply technology is severely hampered by the long amount of time it takes new technologies to scale up. Even under optimal conditions, it would take decades to displace fossil fuels, and actually reduce greenhouse gas emissions.
- A new zero-carbon energy supply would compete with other low-carbon energy sources, diminishing some of its impact.

Key Dynamics

- **Impact.** Watch the orange area of New Zero-Carbon go up as a breakthrough in a new zero-carbon energy supply occurs in the “Global Sources of Primary Energy” graph. Notice that temperature drops only modestly.
- **Delays.** It takes a long time for the new technology to grow and become a large part of the global energy mix. There is a long delay between discovery of the zero-carbon energy technology and its dominance in the market – 20 years to commercialize, several years to plan and build, and then growing only as existing coal and natural gas plants (which have a lifetime of 30 years) are retired. Watch how little Coal (brown area) and Natural Gas (dark blue area) go down before 2040. Because of this, very little carbon is kept underground during this critical period.
- **Price-Demand Feedback.** The reason the new zero-carbon technology grows quickly is that it is cheaper than all other energy supplies, so the abundance of inexpensive energy increases demand to higher than it would be otherwise. View this in the “Total Final Consumption of Energy Sources” graph. [Learn more.](#)
- **Competition with renewables and nuclear.** The new zero-carbon energy competes with all energy sources available, so notice also what happens to Renewables (green) and Nuclear (light blue) – they decrease. This is the “[Crowding Out](#)” dynamic.

Example of the time delays in commercializing a new zero-carbon energy technology:



Potential Co-Benefits of a Breakthrough in New Zero-Carbon

- A breakthrough in a new energy source would create jobs along the supply chain from research and development to construction to operations.
- Research advancements in new technologies may be useful for other applications.

Equity Considerations

- There are unknown consequences and risks associated with new energy sources, and oftentimes these technologies can end up being located in vulnerable communities.

Videos

[New Zero-Carbon](#)

Slider Settings

	status quo	breakthrough	huge breakthrough
Breakthrough year	no breakthrough	current year	current year
Time to commercialize		20 years	20 years
Initial cost relative to coal		2	1

The "Initial cost relative to coal" slider adjusts the cost of the new zero-carbon energy source relative to the cost of coal. If the new zero-carbon energy is less than the cost of coal, demand will increase significantly, because it will be cost competitive with other energy sources. A value of "2" means that the initial cost of electricity from the new zero-carbon energy source in its breakthrough year is twice the marginal cost of electricity from coal in 2020.

Model Structure

The path to deployment will take some time after the success of the technology in the laboratory: commercialization (set at 20 years); development, e.g., planning, financing, and permitting (5 years); and construction (5 years). Then the new energy source must compete with other energy sources.

Please visit support.climateinteractive.org for additional inquiries and support.

FAQs

- [How do I simulate the deployment of small modular reactors \(SMRs\)?](#)



Carbon Pricing and Energy Standards

Set a global carbon price that makes energy sources more expensive depending on how much carbon dioxide they release, or enact a clean electricity standard or emissions performance standard. Energy producers frequently pass additional costs to their customers, so policy must be designed to minimize the impacts on the poorest.

Note, the Carbon Price slider in En-ROADS only affects CO₂ emissions from energy.

Examples

- Countries and regions implementing carbon taxes.
- Grassroots campaigns generating public support for carbon pricing.
- Clean Electricity Standards, similar to Renewable Portfolio Standards in use in several US states or the Renewables Obligation in the UK.
- Emissions Performance Standards that set limits on the amount of carbon dioxide per unit energy that power plants can emit.
- Cap-and-trade programs in which governments set an emissions limit and issue a limited number of emissions allowances that can be traded by municipalities and corporations.

Big Messages

- Pricing carbon is a high leverage strategy, as it both reduces the carbon intensity of the energy supply and reduces the overall energy demand.
- Clean Electricity Standards only affect part of the energy system, and so their leverage depends on being used in conjunction with electrification of transport and buildings and industry.

Key Dynamics

- **Impact.** When the carbon price is increased, notice that Coal (in brown) reduces the most in the “Global Sources of Primary Energy” graph. It is the most carbon intensive source of energy, which makes it the most sensitive to a carbon price. Natural Gas (in dark blue) decreases as well, although more modestly. Oil (in red) decreases only slightly, even though it is more carbon intensive than gas, it is not easily substituted for other energy sources (e.g., a diesel truck can’t be powered with solar). Bioenergy (in pink) increases as its relative cost makes it more attractive, unless you decide to apply the carbon price to bioenergy net emissions by turning on the “Carbon price applies to bioenergy emissions” switch in the advanced view. Renewables (in green) increases as the relative cost of wind and solar make them more attractive.
- **Price-Demand Feedback.** Just like taxing coal, a significant carbon price increases energy costs, which reduces energy demand. View this in the “Total Final Consumption of Energy Sources” graph, where a high carbon price Current Scenario (blue line) is lower than the Baseline Scenario (black line). [Learn more.](#)
- **Methane leakage.** When a carbon price is implemented, watch in the “Methane Emissions” graph as the blue line of the Current Scenario goes down. Natural gas is primarily composed of methane (CH₄), a powerful greenhouse gas. Methane from gas leaks to the atmosphere from wells, pipelines, and other gas infrastructure. A carbon price decreases the leakage by incentivizing the fixing of leaks and discouraging the use of gas.

Potential Co-Benefits of a Carbon Price

- Renewable energy becomes relatively cheaper, which can incentivize job creation in the sector.
- Reducing the use of fossil fuels improves air quality, increasing healthcare savings and worker productivity. View this in the “Air Pollution from Energy” graph.
- Revenue from carbon pricing can be allocated to social programs that can be shared with everyone.

Equity Considerations

- As carbon taxes reach effective levels, companies may try to pass costs to customers, where the poor are most at risk of being impacted. Policies can be developed that limit this impact. Use the “Market Price of...” graphs to see how the price may be impacted for each fuel.
- Workers employed in fossil fuel industries risk losing their jobs if companies shrink workforces in response to higher costs of production, so job transition plans should be in place and protections for workers ensured.
- Due to the political nature of fossil fuel production, government corruption and rent-seeking could create the possibility of certain industries avoiding the carbon price due to loopholes or exemptions.

Videos

[Carbon Pricing and Energy Standards](#)

Slider Settings

	status quo	low	medium	high	very high
Carbon price per ton of CO ₂	\$0 to \$5 *	\$5 to \$20	\$20 to \$60	\$60 to \$100	\$100 to \$250

*Source for \$5 default carbon price: Dolphin, G. (2022). [World Carbon Pricing Database](#). Resources for the Future.

Carbon price applies to bioenergy emissions

The switch “Carbon price applies to bioenergy emissions” in the Carbon Price advanced settings determines whether the CO₂ emissions from bioenergy are exempt from a carbon price. Many current policies exempt bioenergy from climate regulations or treat it as “net zero” even when it is not, so we default to the same for carbon pricing. If switched on, this will apply carbon prices to the net intensity of bioenergy the same as other sources of CO₂.

Carbon price encourages carbon capture and storage (CCS)

The switch “Carbon price encourages carbon capture and storage (CCS)” in the Carbon Price advanced settings determines whether CCS receives funding due to a carbon price. If this switch is turned off, CCS could only be encouraged by a CCS subsidy in the Coal, Natural Gas, and Bioenergy advanced settings.

Carbon price encourages direct air carbon capture and storage (DACCS)

The switch “Carbon price encourages direct air carbon capture and storage (DACCS)” in the Carbon Price advanced settings determines whether DACCS receives funding due to a carbon price. If this switch is turned off, DACCS could only be encouraged by a DACCS subsidy, either by moving the main Technological Carbon Removal slider or adjusting the DACCS slider in the Technological Carbon Removal advanced settings.

Clean Electricity Standard

The switch “Use clean electricity standard” in the Carbon Price advanced settings sets a policy which requires a certain percentage of electricity to come from qualifying sources. This creates a system of incentives: producers of qualifying electricity receive additional revenue, like a subsidy, except that the money comes through electricity prices rather than government spending. The added costs and revenues affect electricity markets and investment, pushing the mix of generation toward the target standards. The value of the incentive depends on the gap between target and actual generation, and on how ambitious the target is.

Under “Sources that qualify as clean electricity,” check the boxes for which sources qualify as “clean.” You can see the percent these sources contribute on the graph “% Electricity Consumption from Qualifying Sources.” Use the “Target % electricity from qualifying sources” slider to set the required amount of qualifying electricity.

Emissions Performance Standard

The “Emissions performance standard” slider in the Carbon Price advanced settings models a performance standard based on the carbon intensity of electric generation (tons of CO₂ emitted per terajoule (TJ) of energy generated). Electricity sources above the standard are disincentivized—the more a fuel exceeds the standard, the fewer electric power plants of that type will be built. Energy sources have different carbon intensities, with coal emitting the most carbon dioxide per unit of energy (approximately 90 tons CO₂ per TJ energy), followed by oil (66 tons CO₂ /TJ), and then natural gas (51 tons CO₂/TJ).

Case Studies

Northeast United States: A 2016 MIT study examined a scenario where the Northeast United States implemented a carbon cap and trade program and found that the annual health savings to the region could be five times greater than the costs of the changes needed to satisfy the policy.¹

FAQs

- [What's the difference between a carbon price and a tax on a fuel \(coal, oil, natural gas, or bioenergy\)?](#)
- [What happens to the revenue from taxes or a carbon price in En-ROADS?](#)
- [How does an emissions performance standard work?](#)
- [How do I simulate a carbon price that increases over time, such as the carbon price structure in the U.S. “Energy Innovation and Carbon Dividend Act” \(EICDA\)?](#)

Please visit support.climateinteractive.org for additional inquiries and support.

Footnotes

[1]: Thompson, T. M., Rausch, S., Saari, R. K., & Selin, N. E. (2016). [Air quality co-benefits of subnational carbon policies](#). *Journal of the Air & Waste Management Association*, 66(10), 988–1002.



Transport – Energy Efficiency

Increase or decrease the energy efficiency of vehicles, shipping, air travel, and transportation systems. Energy efficiency includes things like hybrid cars, expanded public transport, and ways that people can get around using less energy. Adopting more energy efficient practices, such as cycling and walking, can improve public health and save money.

Examples

- Individuals changing their personal behavior to increase walking, biking, using public transit, carpooling, living in higher density neighborhoods, purchasing more efficient vehicles, reducing flying, or telecommuting.
- Public or corporate policies such as increasing parking prices, investing in public transit, offering tax breaks for efficient vehicles, rewarding carpooling, building bike lanes, creating high density pedestrian friendly urban areas, or performance standards that mandate specific fuel efficiency.
- Research and development into high efficiency technologies for shipping, vehicles, and air travel.

Big Messages

- Improving transport energy efficiency is helpful, especially for reducing emissions from oil. Energy efficient vehicles, access to public transportation, and alternative modes of transport, such as walking and biking, reduce energy demand and therefore reliance on oil.

Key Dynamics

- **Impacts.**
 - Watch Oil (in red) decrease in the “Global Sources of Primary Energy” graph as the world increases the efficiency of its transport. Less oil is burned, and coal and gas fall as well, as electrified transport becomes more efficient.
 - View the “Total Final Consumption of Energy Sources” graph to see the fall in energy demand.
 - To see another benefit, look at the “Average Price of Energy to Consumers” graph. Less demand for energy means prices are lower.
- **Delay.** There is some delay in how fast this accelerates because energy use is driven by the overall average of all vehicles (not just the new ones). It takes time to replace older vehicles with newer ones, and this will happen faster in some countries than in others.

Potential Co-Benefits of Encouraging Energy Efficiency

- Improved air quality as a result of less burning of fossil fuels increases healthcare savings and worker productivity.
- Better fuel efficiency means energy costs are lower.
- Mass transit, like buses and trains, can reduce traffic congestion and noise.
- Improved biking and walking infrastructure increases physical activity and safety, which results in sizable health savings.

Equity Considerations

- In some developed countries, such as the United States, pedestrian and cycle-friendly infrastructure has been concentrated in wealthy communities, leaving out low-income families and people of color.¹
- When mass transit options improve or operating costs decrease with fuel efficient vehicle use, social equality may improve, as low-income individuals have more transportation options to meet their needs.

Videos

[Energy Efficiency](#)

Slider Settings

The variable being changed is the annual improvement rate in the energy intensity of new transport capital such as vehicles, trains, and ships.

	discouraged	status quo	increased	highly increased
Annual rate	-1% to 0%	0% to +1%	+1% to +3%	+3% to +5%

Model Structure

Increasing the improvement rate in energy use for new vehicles and other infrastructure helps drive reductions in greenhouse gas emissions across the transport sector. The model structure tracks overall efficiency, which includes retrofitting of existing capital.

Case Studies

New York City: A program that supports students walking and biking to school spent \$10 million and saved \$230 million from increased physical activity, reduced air pollution, and decreased injury rates.²

Barcelona, Spain: Replacing 20% of Barcelona's car trips with bikes could save 38 lives per year from decreased air pollution and increased physical activity, while also reducing 21,000 tons of CO₂ per year.³

Please visit support.climateinteractive.org for additional inquiries and support.

Footnotes

[1]: Lusk, A. (2019, August 23). [Bike-friendly cities should be designed for everyone, not just wealthy white cyclists](#). *The Conversation*.

[2]: Muennig, P. A., Epstein, M., Li, G., & Dimaggio, C. (2014). [The Cost-Effectiveness of New York City's Safe Routes to School Program](#). *American Journal of Public Health*, 104(7), 1294–1299.

[3]: Rojas-Rueda, D., Nazelle, A. D., Teixidó, O., & Nieuwenhuijsen, M. (2012). [Replacing car trips by increasing bike and public transport in the greater Barcelona metropolitan area: A health impact assessment study](#). *Environment International*, 49, 100–109.



Transport – Electrification

Increase adoption of electric cars, trucks, buses, and trains, as well as hydrogen-powered ships and aircraft.

Using electric or hydrogen motors for transport only helps reduce greenhouse gas emissions and air pollution if the electricity or hydrogen is from low-carbon sources like solar and wind.

Examples

- Investments into electric vehicle charging infrastructure.
- Research and development into the technologies for vehicles, batteries, and charging.
- Corporate commitments to sales of electric vehicles.
- Programs to offer rebates and incentives to electric car purchases.

Big Messages

- Electrification of transport can help, particularly when renewable energy is already encouraged or fossil fuels are discouraged.

Key Dynamics

- **Efficiency.** Overall efficiency is greater for electrified transport than for internal combustion engines—in general, less fuel is used to power transport with electricity than oil.
- **Changes in the energy mix.** Oil, in the “Global Sources of Primary Energy” graph, goes down as we electrify transport. At the same time, primary energy demand for coal, renewables, and to a more limited extent, natural gas, all increase to power the rise in electric demand. For electrification to reduce emissions further, try subsidizing renewables, discouraging coal and natural gas, or adding a carbon price.
- **Renewables growth.** Electrification is necessary in order for transport to use renewables or other zero-carbon electricity. Notice how electrification enables Renewables Primary Energy Demand to grow much faster than in the Baseline Scenario. In some cases, hydrogen produced from renewables can be an alternative to electrification.
- **Delays.** It takes decades for existing fossil fuel-based vehicles to retire and be replaced by alternatives (this is known as “[capital stock turnover delays](#)”). As a result, when sales of electric vehicles are subsidized, the Electric line (solid yellow) in the “% Transport Sales by Carrier” graph rises faster than the corresponding line in the “% Existing Transport by Carrier” graph.

Potential Co-Benefits of Encouraging Electrification

- Improved air quality from fewer internal combustion engines increases healthcare savings and worker productivity.
- Jobs are created in the manufacturing and sales of electric batteries and engines.

Equity Considerations

- Although costs are coming down, electric vehicles may not be affordable or available to everyone.
- Mining of lithium and copper, two necessary ingredients for the batteries used in electric vehicles, can be damaging to precious ecosystems and threaten the well-being of communities near mining sites.¹
- Electric charging station locations may not be accessible or the electric battery range may be insufficient for some situations.

Videos

[Electrification](#)

Slider Settings

The main Transport Electrification slider adds a subsidy for new road and rail electric transport (cars, trucks, buses, and trains to be powered by electricity rather than fuels) and ensures that enough charging infrastructure is built for it.

	status quo	subsidized	highly subsidized
Electric transport subsidy and charging infrastructure*	0% to 10%	10% to 25%	25% to 50%

**Subsidy applies to sticker price or purchase cost.*

Because it is more challenging technologically to electrify airplanes, boats, and ships, those forms of transport are in a separate “Air and Water” section of sliders in the advanced settings, where hydrogen is a potential alternative fuel.

Model Structure

The main transport electrification input changes the financial attractiveness of electric vehicles to drive future behavior, as well as the availability of complementary charging infrastructure. The assumptions in the model can change how much a buyer’s attention is on the total cost of ownership of electric vehicles versus fuel-powered vehicles, and cost reductions from learning.

Note that the Baseline Scenario accounts for an increase in electrified transport over the century (see “% Existing Transport by Carrier” graph).

FAQs and Explainers

- [Explainer: Electrification in En-ROADS](#)
- [How do I simulate energy storage for wind and solar?](#)
- [How do I simulate hydrogen use?](#)

Please visit support.climateinteractive.org for additional inquiries and support.

Footnotes

[1]: Lombrana, L. M. (2019, June 11). [Saving the Planet With Electric Cars Means Strangling This Desert.](#)
Bloomberg Green.



Buildings and Industry – Energy Efficiency

Increase or decrease the energy efficiency of buildings, appliances, and other machines. Energy efficiency includes things like building well-insulated homes and reducing the amount of energy factories use. Energy efficient practices can save money through reduced energy needs as well as improve the health of people in those buildings.

Examples

- Individuals and businesses insulating buildings, purchasing energy efficient technologies (motors, lighting, appliances, servers, HVAC systems), and conserving energy.
- Government policies such as tax breaks and performance standards to incentivize energy efficient products and practices.
- Research and development into high efficiency technologies.

Big Messages

- Energy efficiency of buildings and industry is high leverage. It leads to less overall energy use, which leads to less coal, oil, and gas being used. It also saves families, business, and communities money.

Key Dynamics

- **Impact.** As less energy is used for buildings and industry, notice how all the energy sources decline in the “Global Sources of Primary Energy” graph—particularly coal and gas when they are the main sources of electricity. Less fossil fuels are burned so CO₂ emissions go down and global temperature change is lowered dramatically.
- **Energy demand.** Improvements in energy intensity of new capital also reduce energy demand. Explore this in the “Total Final Consumption of Energy Sources” graph, where the Current Scenario (blue line) is lower than the Baseline (black line).
- **Delay.** There is some delay in how fast this accelerates because energy use is driven by the overall average of all capital (not just the new things).

Potential Co-Benefits of Encouraging Energy Efficiency

- Increased industrial efficiency and reduced energy demand can reduce air pollution, which increases healthcare savings and worker productivity.
- Lowering electricity bills for households, businesses, and governments increases energy security.
- Insulated homes remain cooler in the summer and warmer in the winter, when weather events and grid-overload cause outages.
- Retrofitting buildings and homes to be more efficient can create many jobs.

Equity Considerations

- The up-front capital costs of efficiency improvements may not be accessible to lower income individuals and small businesses.
- In some places, policies are directed at property owners, inhibiting renters, who are often lower income, from accessing the benefits.

Videos

[Energy Efficiency](#)

Slider Settings

The variable being changed is the annual improvement rate in the energy intensity of new capital for buildings and industry.

	discouraged	status quo	increased	highly increased
Annual rate	-1% to 0%	0% to +1.5%	+1.5% to +3%	+3% to +5%

Model Structure

Increasing the rate of improvement in energy use for buildings and industry lowers emissions gradually, because energy use is driven by the overall average of all infrastructure in this area (not just new things). Many buildings and industrial facilities last decades. The model structure tracks overall efficiency, which includes retrofitting of existing capital.

Case Studies

Global: Through LEED-certified energy efficient buildings, a group of six major economies saved \$13.3 billion in energy, health, and climate benefits and avoided emitting dozens of air pollutants.¹

United Kingdom: If the UK were to reduce its household energy expenditures by one-quarter using energy efficiency measures, households could save £270 per year. The net present value of this investment is £7.5 billion, and the wider health, economic, and energy benefits could reach £47 billion.²

FAQs

- [How do I simulate reducing waste or inefficiency?](#)
- [How do I simulate recycling or reducing plastic?](#)
- [How do I simulate reducing emissions from cement production?](#)

Please visit support.climateinteractive.org for additional inquiries and support.

Footnotes

[1]: P, M., X., C., J., B., J., C.-L., J., S., A., B., & J., A. (2018). [Energy savings, emission reductions, and health co-benefits of the green building movement](#). *Journal of Exposure Science & Environmental Epidemiology*, 28(4), 307–318.

[2]: Rosenow, J., Eyre, N., Sorrell, S., & Guertler, P. (2017). [Unlocking Britain's First Fuel: The potential for energy savings in UK housing.](#)



Buildings and Industry – Electrification

Increase the use of electricity or hydrogen, instead of fuels like oil or gas, in buildings, appliances, heating systems, and other machines. Using electric or hydrogen-powered equipment only helps reduce emissions and improve air quality if the electricity or hydrogen is from low-carbon sources like solar and wind.

Examples

- Increase in public interest for replacing oil and gas furnaces in buildings with electric heating systems.
- Research and development into various electric motors and systems that could enable wind and solar to replace oil and gas fired industrial facilities.

Big Messages

- Electrification of buildings and industry can help, particularly when renewable energy is already encouraged or fossil fuels are discouraged.

Key Dynamics

- **Fuel switching.** When buildings and industry are electrified, sources of fuel that are used in buildings (e.g., oil for furnaces) are reduced and replaced with sources of electricity. Some types of energy, like coal, are used as both fuels and sources of electricity in buildings and industry, so electrification by itself does not change demand significantly. Other types of energy, like oil, are mostly used as fuel and infrequently used for electricity, so when electrification is increased, oil demand goes down significantly. Notice these changes on the Primary Energy Demand graphs.
- **Renewables growth.** Electrification is necessary in order for buildings and industries to use renewables or other zero-carbon electricity. Notice how electrification enables Renewables primary energy demand to grow much faster than in the Baseline Scenario. In some cases, hydrogen produced from renewables can be an alternative to electrification.
- **Delays.** It takes decades for existing fossil fuel-based equipment to retire and be replaced by electric equipment (this is known as “[capital stock turnover delays](#)”). As a result, when sales of electric buildings and industry equipment are subsidized, the Electric line (solid yellow) in the “% Buildings & Industry Equipment Sales by Carrier” graph rises faster than the corresponding line in the “% Existing Buildings & Industry Equipment by Carrier” graph.

Potential Co-Benefits of Encouraging Electrification

- Improved air quality near the energy source increases healthcare savings and worker productivity.
- Eliminating demand for natural gas lines to buildings also eliminates the risks from fire and explosion.
- Noise pollution from motor engines, generators, and furnaces is reduced.
- Air quality for individuals working/living in and around the structures is improved, which increases healthcare savings and worker productivity.

Equity Considerations

- The up-front capital costs of retrofitting buildings and heating systems to be entirely electric may not be accessible to lower-income individuals and small businesses.
- Exposure to household air pollution is unevenly distributed within and across countries, to which negative health effects and poverty are strongly correlated.¹

Videos

[Electrification](#)

Slider Settings

The Buildings & Industry Electrification slider adds a subsidy for electric equipment in buildings and industrial facilities to encourage electric equipment to be used over equipment that requires fuels to be used (e.g., an electric heater or stove instead of one that is powered by gas).

Note that the Assumptions and other actions can contribute to electrification and can result in higher levels of electrification than what the slider target is set to.

	status quo	subsidized	highly subsidized
Electric equipment subsidy*	0% to 5%	5% to 25%	25% to 50%

**Subsidy applies to sticker price or purchase cost.*

Model Structure

This input changes the financial attractiveness of electric appliances and equipment used in buildings and industry.

FAQs and Explainers

- [Explainer: Electrification in En-ROADS](#)
- [How do I simulate energy storage for wind and solar?](#)

Please visit support.climateinteractive.org for additional inquiries and support.

Footnotes

[1]: World Health Organization. (2021, Sep 22). [Household air pollution and health](#).



Population Growth

Assume higher or lower population growth. Population is a key driver of increased greenhouse gases; however, this is also tied heavily to consumption habits. Women's education and access to family planning could accelerate shifts to smaller families worldwide.

Examples

- Different assumptions for future fertility rates and demographics.
- Greater empowerment of women and girls, resulting in lower fertility rates.
- Increased education on and access to reproductive health services.

Big Messages

- Limiting population growth is not a silver bullet for addressing climate change.
- Decisions around population and family choice are personal decisions and efforts to shift these decisions have many ethical implications.

Key Dynamics

- **Impact.** Since energy demand depends on the number of people, watch all the sources of energy change as you change population growth. Use the [Kaya graphs](#) to understand how population growth affects emissions in your scenario.
- **Delay.** Lower population growth takes a long time to affect emissions because global population shifts do not occur quickly and instead play out over many decades.

Potential Co-Benefits of Lower Growth

- Lower population growth reduces global consumption of resources.
- Ensuring safe access to family planning, reproductive health services, and women's education enhances quality of life and income for women.

Equity Considerations

- Policies around population should be voluntary and empower women to make the choices that are best for them.
- A higher percentage of women of color live in countries with severe gender inequities in access to education, full economic and political participation, and adequate family planning. Reducing population growth necessitates a large investment in that particular group.
- There is a history of women of color in both high- and low-income countries being forcibly sterilized to prevent giving birth; this should never be encouraged.^{1 2}

Videos

[Population & Economic Growth](#)

Slider Settings

The slider reflects the 95% probability range of population deviating from the United Nation's medium population growth path.³ The variable being changed reflects the global population by 2100, in billions of people.

	lowest growth	low growth	status quo	high growth	highest growth
UN Scenario	low end of UN's 95% range		middle of of UN's 95% range		high end of UN's 95% range
Population in 2100	9.0 to 9.3 billion	9.3 to 10.0 billion	10.0 to 10.4 billion	10.4 to 11.2 billion	11.2 to 11.4 billion

Model Structure

Population gets multiplied with economic growth (GDP per capita) to equal total global GDP, or Gross World Product.

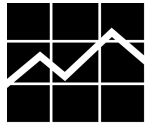
Please visit support.climateinteractive.org for additional inquiries and support.

Footnotes

[1]: Bi, S. (2015). [Forced Sterilizations of HIV-Positive Women: A Global Ethics and Policy Failure](#). *AMA Journal of Ethics*, 17(10), 952–957.

[2]: Blakemore, E. (2016, August 25). [The Little-Known History of the Forced Sterilization of Native American Women](#). *JSTOR Daily*.

[3]: United Nations. (2024). [World Population Prospects 2024](#).



Economic Growth

Assume higher or lower growth in goods produced and services provided. Economic Growth is measured in Gross Domestic Product (GDP) per person and is a key driver in energy consumption. Alternatives exist to meeting people's needs through economic frameworks not based on constant GDP growth.

Examples

- Global efforts to reduce overconsumption and embrace voluntary simplicity.
- High economic growth driving increased consumption of resources and higher emissions.

Big Messages

- Slower economic growth would be a high-leverage approach for avoiding future temperature increases, however, there are lots of questions about how this might occur and be done in a way that is equitable.
- Climate change impacts have the power to significantly reduce economic growth.

Key Dynamics

- **Impact.** Watch all the sources of energy change as you change economic growth. Population gets multiplied with GDP per capita to equal total global GDP, or Gross World Product. Increases in GDP per capita accelerate the exponential growth of total global GDP, arguably the most important driver of carbon dioxide emissions currently. Use the [Kaya graphs](#) to understand how economic growth affects emissions in your scenario.
- If the energy system is decarbonized, higher economic growth won't have as much impact on temperature.
- Climate change slows economic growth, which reduces energy demand and the greenhouse gas emissions, producing a balancing loop that then limits climate change. You can turn off this behavior by switching off the Assumption under "Economic impact of climate change."

Potential Co-Benefits of Lower Growth

- Focus may be shifted to alternative measures of prosperity that enhance people's wellbeing, such as gross national happiness.
- Greater focus on resource conservation and less on material consumption can lead to less waste.

Equity Considerations

- Economic growth is tied to pulling people out of poverty worldwide. Although, in recent decades, many gains in economic growth have gone to the world's wealthiest. Regardless, policies must be tailored to specific local and regional circumstances.
- When GDP growth slows or contracts, governments can incur higher budget deficits, often implementing austerity measures—cutting spending and raising taxes—to offset the difference. These reforms can severely impact the poor and working class, causing job losses and all the inequities that come with loss of livelihood.¹

- Actions that limit climate change reduce the economic damage from climate impacts, which increases GDP per person, consumption, and energy demand.

Videos

Population & Economic Growth

Slider Settings

Economic Growth

	low growth	status quo	high growth
Long-term economic growth	0.5% to 1.2%	1.2% to 1.9%	1.9% to 2.5%
Near-term economic growth	1.7% to 2.1%	2.2% to 2.9%	3.0% to 3.7%

The “Long-term economic growth” slider is the main slider that is used for controlling economic growth. However, more precise assumptions about economic growth can be set by also adjusting the “Near-term economic growth” slider. This slider sets the initial global average growth in GDP per person. The slider “Transition time” is available to change the amount of time it takes for the “Near-term economic growth” level to reach the “Long-term economic growth” level.

Reduction in GDP from Climate Impacts

Climate change is expected to have multiple adverse effects on the economy, such as decreased investment in goods and services due to the cost of responding to changes in extreme weather events, sea level rise, desertification, crop yield decreases, flooding, and resulting migration. To account for this, En-ROADS includes a feedback in the Baseline Scenario where increased temperature lowers the estimated amount of economic growth. This is known as the “damage function.” The switch “Climate change slows economic growth” (under Simulation > Assumptions > Economic impact of climate change) enables the user to explore scenarios with and without damage to the economy due to climate change impacts. When the switch is activated, the user can specify which damage function to use in the “Economic damage formulation” slider.

Several economists formulated this impact as a percentage reduction to global GDP, and they estimated it as a function of temperature change. Four main functions from the research literature are included in En-ROADS: Burke et al. (2018), Burke et al. (2015), Dietz & Stern (2015), and Howard & Sterner (2017). Users can also create a custom formulation to test their own estimated impact on GDP from climate change. View the resulting estimates for economic damage in the “Reduction in GDP vs Temperature” graph.

To learn more, visit the [Economic Damage from Climate Change section of the En-ROADS Dynamics page](#).

The “Social discount rate” (SDR) slider under Simulation > Assumptions > Economic impact of climate change is used to calculate the present value of the benefits of actions to reduce global warming because these occur gradually, over the next few hundred years, due to the long lifetime of greenhouse gases in the atmosphere. It represents the concern people alive today have for the welfare of future generations. The higher the social discount rate, the less the welfare of future generations counts.

Model Structure

En-ROADS uses historical economic growth data from the World Bank and then projects that GDP per capita growth for all regions so that it eventually converges on a long-term economic growth rate of 1.5%/year. Economic growth in En-ROADS takes into account the impact on GDP of climate change impacts so actual long-term growth in the Baseline Scenario is less than 1.5%/year. The differences between a scenario that factors in the economic impact from temperature change, and one that doesn't, can be explored on the "GDP per capita" and "Gross World Product" graphs.

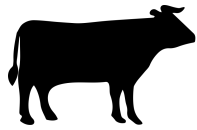
FAQs and Explainers

- [Are the financial or economic costs or benefits of actions modeled in En-ROADS?](#)
- [Explainer: Economic impact of climate change in En-ROADS](#)
- [How is the economic impact of climate change \(the climate "damage function"\) modeled in En-ROADS?](#)
- [Why does En-ROADS include the damage function from Burke et al. \(2018\) in the Baseline Scenario?](#)

Please visit support.climateinteractive.org for additional inquiries and support.

Footnotes

[1]: Ruckert, A., & Labonté, R. (2017). [Health inequities in the age of austerity: The need for social protection policies](#). *Social Science & Medicine*, 187, 306–311.



Agricultural Emissions and Food Choices

Change the level of adoption of emissions best practices in agriculture and food habits. Methane (CH_4) arises from sources like cows and rice paddies, while nitrous oxide (N_2O) comes from fertilizers and manure. Improved farming methods can directly lower emissions, and changing food habits can reduce demand for livestock and crops, cutting the need for new farmland and helping prevent deforestation.

Examples

Methane:

- Reducing methane production in livestock (enteric fermentation), through methods like enhanced livestock health, diet optimization, genetic selection, and feed additives.
- Manure management techniques such as covered methane-capturing lagoons, anaerobic digesters, and composting.
- Improved rice cultivation techniques, including alternate wetting and drying methods and water management.
- Sustainable agricultural practices such as rotational grazing, crop rotation, and soil health management.

Nitrous Oxide (N_2O):

- Adopting agricultural methods such as precision fertilization, controlled-release fertilizers, rotational grazing, crop rotation, soil health management, and nitrification inhibitors.
- Improving water management practices, including using drip irrigation and timing irrigation to match nitrogen demand.

Big Messages

- Improving agricultural practices can substantially decrease the amount of methane and nitrous oxide produced per unit of agricultural products.
- To maximize total emissions reduction, it is also important to consider reducing the amount of livestock and methane-intensive crops. Options include reducing food from animals and food waste.
- Agricultural emissions cannot be reduced to zero; they are inherent to crop and livestock production to feed the world, even when the world's agricultural systems follow best management practices.

Key Dynamics

- **Contribution.** Methane and N_2O emissions comprise approximately 22% of current greenhouse gas emissions, and their reduction is key to addressing climate change.
- **Challenges to diffusion.** It takes time for best practices to be developed, improved, and implemented, and for policy to support their adoption.
- **Scale and intensity.** There are two ways to change emissions: decrease the overall scale of production, and decrease the emissions intensity of that production through adoption of improved management practices and technological advances.
- **Other sources of CH_4 and N_2O .** Besides agriculture, methane and N_2O are also produced by energy and waste. For an in-depth understanding of methane emissions, read the [Methane Explainer](#).

Potential Co-Benefits of Reducing Agricultural Emissions

- Sustainable and plant-based agriculture produces more food with fewer resources, which increases food security.
- Good manure management and less nitrogen-rich fertilizer runoff can reduce water pollution, decrease eutrophication, and increase the health of aquatic ecosystems.
- Reducing methane emissions contributes to reduced ground-level ozone, an air quality concern, which affects human health and diminishes crop yields.

Equity Considerations

- Policies implemented without care may threaten food security for certain individuals and communities. For example, rice paddies, a significant source of methane, produce a main dietary staple for many countries.
- Changes in agricultural practices that increase costs can threaten local economies and employment in communities that rely on farming as their main livelihood.
- Many cultural values are attached to certain foods, meaning a change to more plant-based diets could require a large societal shift.

Slider Settings

Moving the main slider changes the level of global adoption of best practices in two areas—livestock and crops—and affects the methane emissions intensity (kilograms of methane released per ton of agricultural production). One can change the overall scale of agricultural production via the [“Food from animals”](#) and [“Food waste”](#) sliders. Note that a 100% reduction of the “Methane and nitrous oxide from agriculture” slider is not a 100% total emissions reduction, since some emissions from agriculture are considered unavoidable.

	highly reduced	reduced	status quo	increased
Percent of potential reduction	100% to 70%	70% to 20%	20% to 0%	0% to -10%

Model Structure

En-ROADS distinguishes between the scale of Total Agricultural Production (measured in gigatons per year) and the Methane Intensity of Agriculture (measured in kilograms of methane per ton produced).

In the Baseline Scenario, the methane emissions intensity of agricultural production continues to decrease, with a small amount of improvement each year. When the Agricultural Emissions slider is reduced and a higher potential reduction is selected, best practices for reducing emissions are adopted over a 30-year time period. This speeds the improvement towards even lower values for emissions intensities, with a lower bound defined by the least-emitting systems for crops and livestock.

Each greenhouse gas is modeled separately within En-ROADS, which enables the impact of each gas on global temperature to be handled without using global warming potential (GWP) and CO₂ equivalency conversions. Greenhouse gases other than CO₂ that are reflected in graphs with the units CO₂e use GWP100 to enable comparison and reporting of all greenhouse gases together, but only for documentation purposes.

FAQs

- [Explainer: Methane in En-ROADS](#)
- [Explainer: Food and agriculture in En-ROADS](#)
- [How do I simulate the full impact of the switch to plant-based, vegetarian, or vegan diets in En-ROADS?](#)

Please visit support.climateinteractive.org for additional inquiries and support.



Waste and Leakage

Change the level of adoption of emissions best practices related to waste, energy, and industry. Methane (CH_4) and nitrous oxide (N_2O) emissions from landfills and wastewater systems can be reduced through improved design and waste management. Address methane leaks from fossil fuel operations, and manage N_2O emissions from industrial processes like fertilizer production. Manage F-gases (HFCs, PFCs, SF_6 , and others) in the chemical industry and in consumer goods like air conditioners.

Examples

Methane leakage from energy systems:

- Detection of leaks using drones and satellites; repair of leaks; and upgrade of valves and pumps to prevent leaks.
- Methane recovery during fossil fuel extraction and processing, either for power generation or for flaring instead of venting.

Methane and nitrous oxide (N_2O) from waste:

- Education and policies to reduce waste.
- Capture of methane from landfills.
- Careful control of oxygen levels in wastewater treatment systems to prevent methane and N_2O formation.

Nitrous oxide (N_2O) from industry:

- Removal of N_2O during manufacturing processes by converting it to nitrogen and oxygen.

Fluorinated gases:

- Recovery and recycling of refrigerant gases and use of alternative refrigerants such as CO_2 , propane, and isobutane.
- Destruction of F-gases in equipment and stockpiles at the end of their useful life.

Big Messages

- Improving waste management practices and reducing leakage from energy systems can substantially decrease the amount of methane, nitrous oxide, and F-gases produced.
- Methane, N_2O , and F-gases have a greater heat-trapping effect (per unit weight) in the atmosphere, and certain types can persist in the atmosphere for longer periods, compared to CO_2 . Addressing these emissions is a powerful mitigation strategy.

Key Dynamics

- **Diffusion dynamics.** It takes time for best practices to be developed, improved, and implemented, and for policy to support their adoption.
- **Capital stock turnover delays.** It also takes time for higher-emitting infrastructure (e.g., power plants, fuel processing facilities, and industrial plants) to be retired and replaced by new, lower-emitting capital or retrofitted to produce less emissions.
- **Scale and intensity.** There are two ways to change emissions: decrease the overall **scale** of production, and decrease the **emissions intensity** of that production through adoption of improved practices. For an in-depth understanding of methane emissions, read the [Methane Explainer](#).

Potential Co-Benefits of Reducing Waste and Leakage

- Reducing methane leakage from natural gas systems can save money.
- Composting food waste instead of sending it to landfills yields nutrient-rich soil amendments.
- Reducing N₂O emissions helps protect the ozone layer, since N₂O is currently the biggest source of ozone-depleting emissions.

Equity Considerations

- Adoption of practices to limit emissions in some industries requires technologies or methods that add costs to goods, potentially raising prices for consumers.
- Alternative substances used to replace F-gases may have different safety considerations, such as flammability or toxicity, which need to be carefully evaluated and managed.

Slider Settings

Moving the main Waste and Leakage slider changes the level of global adoption of best practices in all four areas: methane leakage from energy, methane and nitrous oxide from waste, nitrous oxide from industry, and F-gases.

	highly reduced	reduced	status quo	increased
Percent of potential reduction	100% to 70%	70% to 20%	20% to 0%	0% to -10%

Best practices for the **energy and leakage** area only reduce the sector's methane **emissions intensity** (methane released per unit produced). One can change the overall **scale** of fossil fuel energy production via various energy sector sliders and see the results in the "[Methane Intensity of Primary Energy](#)" graph.

Best practices for methane and nitrous oxide from **waste**, reduce both the **scale** of waste production (particularly organic materials entering landfills and wastewater treatment) and also the emissions intensity (how much pollution per unit of waste).

For **nitrous oxide from industry**, the maximum potential represents a 95% reduction from the 1990 emissions value, consistent with the maximum potentials reported by [Jörß et al. \(2023\)](#). The slider sets how much of that maximum reduction is achieved over 30 years.

For **fluorinated gases**, the maximum potential depends on Assumptions under the "Methane, N₂O, and F-gases" category; the default represents a 90% reduction of F-gas emissions intensities.

Note that a 100% reduction of the “Methane and other gases from waste and leakage” slider is not a 100% total emissions reduction, since some emissions are considered unavoidable.

Model Structure

En-ROADS calculates the methane intensity of energy (measured in kilotons of methane per exajoule of energy produced). Emissions can be reduced through retrofits or replacement as newer lower-emitting technology becomes available. Emissions can also be reduced by changing practices (e.g., not flaring) and maintenance and monitoring (e.g., fixing leaks). Similar dynamics drive methane emissions from waste, nitrous oxide (N₂O) emissions, and F-gases.

About 10% of the methane from fossil fuels, and 100% of the methane from bioenergy generation, comes from incomplete combustion and is not affected by this slider. It can only be reduced by not burning the fuel.

Each greenhouse gas is modeled separately within En-ROADS, which enables the impact of each gas on global temperature to be handled without using global warming potential (GWP) and CO₂ equivalency conversions. Greenhouse gases other than CO₂ that are reflected in graphs with the units CO₂e use GWP100 to enable comparison and reporting of all greenhouse gases together, but only for documentation purposes.

FAQs and Explainers

- [Explainer: Methane in En-ROADS](#)
- [Explainer: F-gases matter to climate success](#)
- [How do I reduce F-gas emissions, simulating policies like the Kigali Amendment to the Montreal Protocol or a similar policy?](#)

Please visit support.climateinteractive.org for additional inquiries and support.



Deforestation and Mature Forest Degradation

Encourage or discourage the protection of forests to change the current trend of deforestation and degradation. Deforestation is the conversion of forest land to other uses, primarily for agriculture. Forest degradation is the temporary loss of forests due to harvesting for wood products or bioenergy. Deforestation is driven by the need for farmland, which can be affected by changes in the food system under Agricultural Emissions.

Examples

- Government policy to preserve forested land and place restrictions on industries such as soybean and/or palm oil.
- Increased support for Indigenous land rights.
- Public support and campaigns to encourage land preservation.

Big Messages

- Reducing deforestation is part of a multi-pronged effort to address climate change. However, deforestation emissions are overshadowed by the enormous amount of carbon dioxide released through fossil fuel combustion.
- Protecting forests is helpful for many reasons other than climate action, including biodiversity conservation and protection of Indigenous peoples' lands.

Key Dynamics

- Highly reducing deforestation emissions reduces temperature less than most people would estimate. View the “Greenhouse Gas Net Emissions by Gas – Area” graph to see the role of land use, land use change, and forestry relative to all the other sources of emissions.
- As consumption grows, food waste and animal-based food demand increase the amount of cropland needed, which drives more deforestation.
- Drivers of forest degradation also include logging and harvesting forests for products like wood bioenergy (e.g., firewood and wood pellets), lumber, and paper products.
- Reducing deforestation and forest degradation reduces the net emissions from the land use sector. There is more carbon removal capacity from the forests if they are left to grow, and there are less gross emissions from carbon taken from forests through logging and harvesting. For an in-depth understanding of this dynamic, read the [Land and Forests Explainer](#).

Potential Co-Benefits of Decreasing Deforestation

- Forests protect biodiversity and provide ecosystem services and food sources.
- Trees reduce erosion and prevent soil loss, which can negatively impact water quality downstream.
- Forests provide livelihoods for people (e.g., small-scale resource gathering and sustainable forestry) that can be lost when land is shifted to other uses.

Equity Considerations

- Forest preservation efforts have sometimes restricted the land access of Indigenous people who have lived sustainably on the land for generations. Policies should be created with local stakeholder engagement.^{1 2}

Videos

[Deforestation and Mature Forest Degradation](#)

Slider Settings

	highly reduced	moderately reduced	status quo	increased
Percent per year reduction or increase	-10% to -4%	-4% to -1%	-1% to 0%	0% to +1%

Model Structure

This sector tracks multiple different types of land to assess the impacts of forest gain, loss, and degradation, and the associated land use, land use change, and forestry greenhouse gas emissions. The key aspects are:

- Deforestation is driven primarily by the growing need for crops and grazing land. As a result, more food waste and more animal-based products consumption lead to more deforestation. Reducing these drivers (located under Agricultural Emissions), or implementing forest protection policies, leads to less deforestation.
- Mature forest degradation is driven by the need for wood bioenergy and other forest products, such as paper and lumber. Taxing bioenergy or having a target reduction in mature forest degradation policy can reduce the harvesting of older forests that store large amounts of carbon.
- Crop yield: higher yields avoid the need for cropland expansion through deforestation. Larger crop demand—due to population growth and higher GDP (which increases animal-based products consumption)—can be met by higher yields in the existing cropland area rather than its expansion (slider is in the En-ROADS Assumptions).
- Crop yield reduction from temperature: crop yield is steadily growing in the Baseline Scenario, following historical trends, although climate change slows down this growth (slider is in the En-ROADS Assumptions).

FAQs and Explainers

- [Explainer: Land and forests in En-ROADS](#)
- [How do I simulate the full impact of the switch to plant-based, vegetarian, or vegan diets in En-ROADS?](#)

Please visit support.climateinteractive.org for additional inquiries and support.

Footnotes

[1]: Salopek, P. (2019, May 16). [Millions of indigenous people face eviction from their forest homes](#). *National Geographic*.

[2]: De Sam Lazaro, F. & Hartman, S. C. (2021, October 21). [Uganda's Batwa tribe, considered conservation refugees, see little government support](#). *PBS NewsHour*.



Nature-Based Carbon Dioxide Removal

Encourage the expansion of forests (afforestation), the restoration of former or degraded forests (reforestation), the implementation of agricultural practices that capture carbon, and the production of biochar. These nature-based methods can remove carbon dioxide from the atmosphere and store it in plants and soils. However, this carbon may be released again if the land is altered, whether through deliberate actions like farming or accidental events like wildfires.

Examples

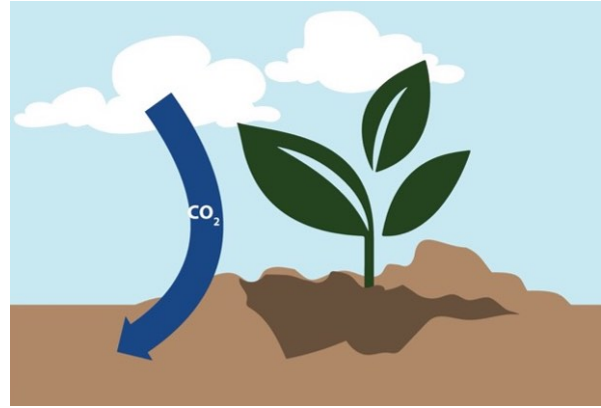
- Government policies, incentives, and funding to identify available land, plant trees, and manage forests.
- Business, land owner, and public support for large scale tree planting.
- Carbon markets that incentivise farmers to implement agricultural soil carbon sequestration practices such as cover cropping and crop rotation.
- Manufacturing and using biochar as a soil amendment.

Nature-Based Carbon Dioxide Removal Methods

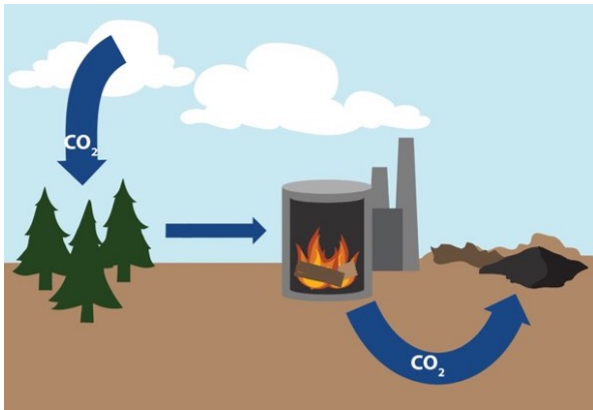
The following methods of nature-based CO₂ removal can be explored in the En-ROADS simulator:



Afforestation and reforestation. As trees grow, they draw carbon out of the air, which reduces the concentration of carbon dioxide. The CO_2 is then stored in living biomass.



Agricultural soil carbon sequestration involves using agricultural practices which enhance soil carbon (such as no-till agriculture and preventing overgrazing).



Biochar is biomass (e.g., from trees) that has been made into charcoal via pyrolysis, and is then buried to retain the carbon.

Big Messages

- Afforestation and reforestation have the potential to pull significant amounts of carbon dioxide out of the atmosphere, but land availability and other effects should be considered. It would take an immense amount of land to make a large impact on temperature change.
- Carbon stored in trees and soils is vulnerable to future release due to natural disturbances (e.g., wildfires) or changes in land management (e.g., overgrazing or deforestation).

Key Dynamics

- **Impact.** Growing more trees boosts global removal of CO₂ from the atmosphere, as photosynthesis pulls carbon into biomass and soils. Watch the temperature decrease modestly as a result.
- **Delay.** It takes decades for newly planted trees to remove enough carbon for it to be a significant source of carbon removals.
- **Reversibility.** Trees are susceptible to fire, insects, and weather-related damage, not to mention future harvests; all of which lead to carbon emissions as a result of combustion and decay.
- **Scale compared to emissions from energy.** The amount of carbon that additional trees can pull out of the atmosphere is overshadowed by the enormous amount of carbon dioxide released through fossil fuel combustion.
- **Land needed.** View the graphs “Land for Growing CO₂ Removal Biomass” and “Land for Farming with CO₂ Removal” and note the total amount of land area that all the approaches might require.

Potential Co-Benefits of Nature-Based Carbon Dioxide Removal

- New forests can create new ecosystems and protect existing wildlife habitats, biodiversity, and ecosystem services.
- Larger and healthier tree canopies in cities reduce urban heat island effects and energy needed for heating and cooling.
- Jobs are created in tree planting, care, and maintenance.
- Nature-based carbon removal approaches like agricultural soil carbon sequestration can help improve landholder and farmer profits in some cases through carbon markets.
- Some agricultural soil carbon sequestration methods such as cover crops, and amending soil with biochar, could improve soil health.

Equity Considerations

- Afforestation entails shifting large areas of land to forest. This can sometimes result in monocultures of trees that are all the same age, which does not contribute to healthy biodiversity as much as natural forests.
- Large shifts in land can compromise historical land access, so involving low-income and minority communities, including Indigenous peoples, in the process of policy development and implementation is essential.
- Harvesting feedstocks for biochar production may compete with other uses, such as food production or habitat preservation, and could have negative environmental or social impacts if not managed sustainably.

Slider Settings

Moving the main Nature-Based Carbon Dioxide Removal slider changes the amount of carbon removed by three methods: afforestation and reforestation, agricultural soil carbon sequestration, and biochar.

	status quo	low growth	medium growth	high growth
Percent of max potential	0% to +15%	+15% to +40%	+40% to +70%	+70% to +100%

Afforestation and reforestation: The “Percent available land used for afforestation and reforestation” slider changes the amount of available land that is used to grow new forests. 100% would mean that 550 million hectares (Mha) of land is covered in forests. 550 Mha represents approximately 16% of current grassland area, 6% of all land (including desert and tundra) that is not currently forest, and about 80% of the difference in forest area back in 1850 until now (i.e., there is 680 Mha less forest area today than in 1850).¹

Agricultural soil carbon sequestration and biochar: The default settings for the maximum potential of agricultural soil carbon sequestration and biochar (“% of max potential”) are sourced from the midpoint of the ranges of the [2018 "Greenhouse gas removal" report by the Royal Society](#) (Table 2, Chapter 2). For example, moving the simulator’s biochar slider to “100% of max potential” increases removals up to 3.5 Gton/year, which was taken from the report’s range of 2-5 Gtons/year. For higher removal, one can adjust the “Carbon dioxide removal maximum” settings within the Assumptions view, up to the highest end of the range sourced from the report. For example, the biochar maximum can be increased to 5 Gtons/year.

Model Structure

The methods of nature-based CO₂ removal included are modeled independently. They each vary in their maximum sequestration potential, the year they might start to scale up, how long it takes them to store carbon, and the carbon leakage rate over time (stored carbon is not always permanent).

Afforestation and reforestation: Forests are dynamic and result in both carbon removals and emissions. Notice in the “CO₂ Removals from Afforestation and Reforestation” graph that net CO₂ removals are lower than total removals due to the carbon loss from decay and forest fires in older or unhealthy forests. For higher removals, one can adjust the “Max available land for afforestation and reforestation” under the “Afforestation and reforestation” settings within the Assumptions view. For example, to explore planting a trillion trees, increase the slider “Max available land for afforestation and reforestation” to 900 Mha (with an average tree spacing consistent with the midpoint value from [Russell \(2020\)](#)).

Case Studies

New York City, USA: Increasing urban tree density by 343 trees per square kilometer was shown to reduce the rate of childhood asthma by 29% in New York City.²

FAQs

- [Why is planting trees \(afforestation and reforestation\) not more impactful?](#)
- **Where can I learn more about the different Nature-Based CDR types?** Follow the links to find detailed fact sheets on these CDR types:
 - [Forestation](#)
 - [Biochar](#)
 - [Agricultural Soil Carbon Sequestration](#)
- **Why isn’t BECCS included under Nature-Based CDR?** Bioenergy with carbon capture and storage (BECCS) is both a possible source of energy and a carbon dioxide removal (CDR) method. For consistency with coal and gas CCS, it appears in the advanced view of its respective energy source slider (Bioenergy), rather than under Nature-Based CDR.

Please visit support.climateinteractive.org for additional inquiries and support.

Footnotes

[1]: Hurtt, G. C., L. Chini, R. Sahajpal, S. Frolking, B. L. Boudirsky, K. Calvin, J. C. Doelman, J. Fisk, S. Fujimori, K. K. Goldewijk, T. Hasegawa, P. Havlik, A. Heinemann, F. Humpeöder, J. Jungclaus, Jed Kaplan, J. Kennedy, T. Kristzin, D. Lawrence, P. Lawrence, L. Ma, O. Mertz, J. Pongratz, A. Popp, B. Poulter, K. Riahi, E. Shevliakova, E. Stehfest, P. Thornton, F. N. Tubiello, D. P. van Vuuren, X. Zhang (2020). [Harmonization of Global Land-Use Change and Management for the Period 850-2100 \(LUH2\) for CMIP6](#). *Geoscientific Model Development Discussions*.

[2]: Lovasi, G. S., Quinn, J. W., Neckerman, K. M., Perzanowski, M. S., & Rundle, A. (2008). [Children living in areas with more street trees have lower prevalence of asthma](#). *Journal of Epidemiology & Community Health*, 62(7), 647–649.



Technological Carbon Dioxide Removal

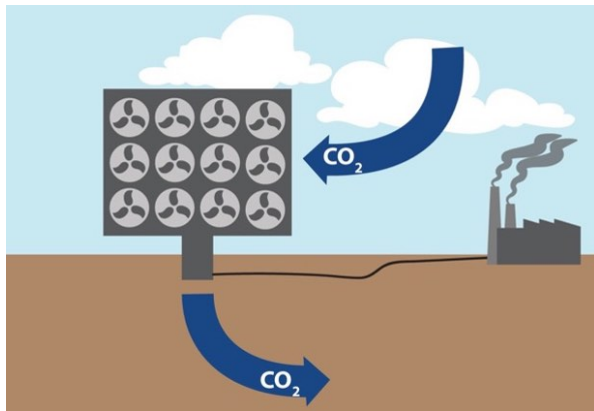
Promote the use of carbon dioxide removal technologies like direct air capture and enhanced mineralization. These methods rely on heavy industry to directly remove carbon dioxide from the atmosphere. While these technologies offer promising solutions for reducing atmospheric carbon, they require substantial energy and investment to implement on a large scale.

Examples

- Advancements in various CDR technologies through research and development and government policies.
- Support from businesses, land owners, and the general public to implement such technologies.

Carbon Dioxide Removal Methods

The following methods of technological CO₂ removal can be explored in the En-ROADS simulator:



Direct air carbon capture and storage (DACCS) is an emerging technology that pulls CO₂ out of the air, where it is then stored in geological reserves. To get a net removal benefit, the captured carbon must be stored long term.



Enhanced mineralization entails mining specific rocks—like basalt—that can absorb CO₂ from the air and converting it to rock for long-term carbon storage.

Big Messages

- Technological Carbon Removal has the potential to pull significant amounts of carbon dioxide out of the atmosphere.
- Most of these technologies are still undergoing pilot testing, and do not exist at the level needed to deploy at a large scale.
- To be successful, these technologies must store carbon (usually underground) for the indefinite future without leaking back into the atmosphere.

Key Dynamics

- **Industry scale.** View the graph “Bulk Material for Mineralization” to see the scale of industrial production these approaches entail.
- **Carbon bathtub.** CO₂ concentration in the atmosphere will continue to increase as long as CO₂ emissions exceed CO₂ removals, just as the level of water in a bathtub will continue to increase as long as the water entering the tub exceeds the water draining out. [Learn more here](#).

Potential Co-Benefits of CDR Growth

- The scale up of many carbon removal approaches would result in vast new industries and businesses, which would create jobs.
- Enhanced mineralization can benefit soil by reducing its acidity.

Equity Considerations

- Methods like direct air carbon capture and storage would demand large amounts of energy. View the graph “Energy Used to Capture and Store Carbon” to see the energy usage that DACCS and CCS entail.
- Many of the technological carbon removal approaches have not been developed at scale yet and pose unknown risks and consequences to the communities they are situated within.

Videos

[Afforestation & Technological CO₂ Removal](#)

Slider Settings

	status quo	low growth	medium growth	high growth
Percent of maximum potential	0% to +10%	+10% to +40%	+40% to +70%	+70% to +100%

DACCS: The main Technological Carbon Dioxide Removal slider (or the “Direct air carbon capture and storage (DACCS) subsidy” slider in the advanced view) controls the amount of subsidy a DACCS facility could receive per ton of CO₂ captured. The amount of carbon dioxide removals (CDR) achieved depends on the economics. Default assumptions are set so that a maximum slider setting of \$1000/ton CO₂ captured results in removals consistent with the [2018 ‘Greenhouse gas removal’ report by the Royal Society](#) (Table 2, Chapter 2). Different outcomes can be explored by adjusting the settings in the Assumptions view under the “Carbon capture and removals” section.

Model Structure

The methods of CO₂ removal included are modeled independently. They each vary in their maximum sequestration potential, the year they might start to scale up, how long it takes them to be phased in, and the carbon leakage rate over time (stored carbon is not always permanent).

DACCS: En-ROADS represents both the economics and physics of DACCS. As an emerging technology, many parameters remain uncertain. The maximum deployment potential of DACCS is determined by the DACCS subsidy and various parameters within the Assumptions view. These parameters include the time required to complete DACCS infrastructure, from planning through construction, the energy needed to operate DACCS (and how that might improve with technological advances), and the transport and storage of the captured CO₂. It also considers the supply curve—how much DACCS would be built if its cost were matched by revenue from markets or subsidies—as well as factors affecting cost, such as learning, siting limitations, and distance to storage sites. Users can adjust all these parameters in the Assumptions view.

Enhanced mineralization: En-ROADS represents the time it takes for the practice of enhanced mineralization to be adopted and the infrastructure to be built. After adoption, the gross amount of CO₂ removed by mineralization is a function of the land area the ground rock is applied to, the amount of rock per area, and the absorption potential of the type of rock. The net CO₂ captured is the gross amount of CO₂ removed minus the emissions from energy used to grind and spread the rock. Users can adjust all these parameters in the Assumptions view.

FAQs

- [Explainer: Direct air carbon capture and storage \(DACCS\) in En-ROADS](#)
- **Where can I learn more about the different Technological CDR types?** Follow the links to find detailed fact sheets on these CDR types:
 - [Direct Air Capture](#)
 - [Enhanced Mineralization](#)

Please visit support.climateinteractive.org for additional inquiries and support.

Glossary

afforestation: Starting a forest or stand of trees in an area where there was no forest before.

AIM/CGE: An Integrated Assessment Model maintained by the National Institute for Environmental Studies, Japan.

anthropogenic: Caused by human activity

AR5: IPCC Fifth Assessment Report on Climate Change (2014)

AR6: IPCC Sixth Assessment Report on Climate Change (2021 and 2022)

BECCS: Bioenergy with carbon capture and storage. An experimental method of energy generation and technological carbon dioxide removal. BECCS entails burning biomass for energy, capturing the CO₂ emissions, storing the emissions long-term, and successfully re-growing any used biomass to result in a process that stores more carbon than it releases. BECCS relies on the success of emerging technologies and availability of sustainable sources of biomass.

biochar: A form of charcoal produced from plant matter and added to soil as a means of removing carbon dioxide from the atmosphere and adding nutrients for growing plants. Biochar operations would need to be scaled massively from current levels and steps taken to ensure biochar permanently stores carbon in the ground for it to make a significant impact on global CO₂.

biomass: Organic (carbon-based) material that comes from living organisms such as plants and can be used as fuel. Examples include wood, corn, or crop residues such as the stalks left after harvesting.

BOE (barrel of oil equivalent): A unit of energy approximately equivalent to the amount of energy generated by burning 1 barrel of oil (159 liters) or 6.12 gigajoules (GJ) of energy.

capital stock turnover: The time it takes for physical energy infrastructure (such as power plants or cars) to be retired and replaced by new, often more efficient, infrastructure.

carbon intensity: The amount of carbon dioxide emitted per amount of energy. E.g., grams of CO₂ emitted per megajoule of energy produced. Coal has the highest carbon intensity of the fossil fuels, followed by oil, then natural gas.

CCS: Carbon capture and storage. A process where CO₂ emissions, say from fossil fuel energy generation, are captured at the source and then stored in a location where the carbon will not leak into the atmosphere, such as deep underground. CCS technology is not yet commercially viable in most settings.

CDR: Carbon dioxide removal. Pulling carbon dioxide out of the atmosphere with technology (e.g., direct air capture) or via plants through photosynthesis (e.g., afforestation).

CH₄: Methane. A greenhouse gas. Methane is released from sources like cows, agriculture, natural gas drilling, and waste.

climate change: Refers to any long-term changes in Earth's weather patterns (rain, temperature, sunshine, storms, etc.) Scientists have been studying changes in the Earth's climate over millions of years, and the data show that the weather patterns have been changing dramatically recently.

climate change adaptation: Changes made by people or plants and animals in the way things are usually done in order to respond or react to change in climate. For example, seawalls and levees are being built in many low-lying coastal cities to keep out rising tides and increased storm surge as a result of climate change.

climate sensitivity: The amount that the global surface temperature will increase in response to a doubling of CO₂ in the atmosphere.

CO₂: Carbon dioxide. A greenhouse gas that can be naturally made by living things and used by plants for photosynthesis or produced by burning fuel (gas, wood, coal, oil, etc.).

co-benefit: A positive effect of climate action that does not directly relate to climate. For example, a co-benefit of shutting down coal plants is improved air quality.

C-ROADS: Climate-Rapid Overview and Decision Support simulator created by Climate Interactive. Focuses on specific emission reduction pledges from different countries and world regions (e.g., to meet the goals of the Paris Agreement).

crop yield: The amount of food or animal feed produced per hectare of farmland, measured in kilograms/year/hectare. In En-ROADS, the crop yield is the global average productivity on land.

damage function: The estimated effect of temperature change on global economic growth. Learn more about the economic damage function and how it is modeled in En-ROADS [here](#).

deforestation: The clearing of trees, transforming a forest into cleared land, often through burning and removing forests to make land available for crops like soybeans, corn, or palm oil.

direct air carbon capture and storage (DACCS): An experimental method of technological carbon dioxide removal where CO₂ is captured from the air with machines and stored permanently (e.g., underground). DACCS is a new industrial process that is still in development. To get a net removal benefit, the captured carbon must be stored long-term and the DACCS facility must be powered by low-carbon energy.

EIA: U.S. Energy Information Administration

EMF: Stanford Energy Modeling Forum

emissions: Making and giving off something (for example: giving off carbon dioxide gas)

En-ROADS: Energy Rapid Overview and Decision-Support climate change solutions simulator created by Climate Interactive

equity: A way of creating the conditions that enable a just and fair inclusion of everyone into a society in which all can participate, prosper, and reach their full potential. (Definition courtesy of the Partnership for Southern Equity).

exajoule: A measure of energy equal to 10¹⁸ joules

F-gases: Fluorinated gases. Synthetic (created by humans) gases that are used in industrial applications (like refrigeration, air conditioning, aerosols, foams, and manufacturing microchips) and are powerful greenhouse gases. Include HFCs, PFCs, SF₆, and Montreal gases (ozone-depleting substances controlled by the Montreal Protocol).

feedstock: Raw material used for an energy or industrial process. For bioenergy, these can be wood, waste, crops, algae, etc.

final consumption of energy sources: Total energy consumed to meet the demand of all final energy uses plus the use of feedstocks for products like plastics. For example, how much electricity a lightbulb uses or how much fuel a truck burns are measures of final energy consumption. It does not include energy lost through transmission and distribution (T&D) or inefficiencies, which, in contrast, is accounted for in primary energy.

fossil fuels: Coal, oil, and natural gas. Fuel derived from the remains of ancient plants and animals.

GCAM: An Integrated Assessment Model (IAM) maintained by the Pacific Northwest National Laboratory (PNNL) and Joint Global Change Research Institute (JGCRI).

GDP: Gross Domestic Product. The total value (money) of goods produced and services provided in a country during one year.

gigajoule: A measure of energy equal to 10^9 joules.

GISTEMP: GISS Surface Temperature Analysis created by NASA. An estimate of global surface temperature change.

greenhouse gas: Any gas that absorbs radiation (heat energy) from the Earth's surface and thus traps heat and makes the planet warmer. Anthropogenic (caused by human activity) greenhouse gases include CO_2 , CH_4 , N_2O , and F-gases.

Gtons: A measure of mass. Metric gigatons (10^9 tons or 10^{12} kg).

GWP: Global warming potential. The heat absorbed by a greenhouse gas in the atmosphere over a period of time as compared to the heat absorbed by an equivalent amount of CO_2 .

HadCRUT5: A global dataset of historical surface temperature anomalies. Maintained by the Met Office Hadley Centre for Climate Change.

HFCs: Hydrofluorocarbons. A type of F-gas used in refrigeration and air conditioning.

HVAC: Heating, ventilation, and air conditioning

IAM: Integrated Assessment Model. A type of computer model that links economic activities with biological and geophysical dynamics to better understand how people can affect things like climate change.

IEA: International Energy Agency

IMAGE: An Integrated Assessment Model (IAM) maintained by the PBL Netherlands Environmental Assessment Agency.

IPCC: Intergovernmental Panel on Climate Change

joule: A measure of energy. Lifting an apple one meter takes about 1 joule of energy, and a liter of gasoline contains 31,536,000 joules of energy ([source](#)).

Kaya graphs: Show the drivers of growth in carbon dioxide emissions. Yoichi Kaya created the equation behind the graphs: $\text{Global Population} \times \text{GDP per Capita} \times \text{Energy Intensity of GDP} \times \text{Carbon Intensity of Energy} = \text{CO}_2 \text{ Emissions from Energy}$.

kWh: Kilowatt hour. A measure of energy. Equals one hour of electricity use at 1 kW power.

mature forest degradation: The harvesting of older forests for wood bioenergy or other forest products. Although the trees may not be permanently or completely lost, this disturbs the forest, releasing part of the carbon locked in the trees and soils, and reducing its capacity to remove additional carbon.

MCF: Thousand cubic feet. A unit for measuring the volume of natural gas, often used for energy measurements. Burning a thousand cubic feet of natural gas generates approximately 1.1 GJ of energy. The “M” in “MCF” is the Roman numeral for thousand.

MESSAGE-GLOBIOM: An Integrated Assessment Model (IAM) maintained by the International Institute for Applied Systems Analysis (IIASA).

multisolving: When people work together across sectors to address multiple problems with one policy or investment.

MWh: Megawatt hour. A measure of energy. Equals 1000 kWh.

N₂O: Nitrous oxide. A greenhouse gas.

NF₃: Nitrogen trifluoride. An F-gas.

NGFS: Network for Greening the Financial System. An international consortium of central banks and financial institutions. They partner with climate and economic modeling groups to create a set of climate scenarios, which were included in the recent IPCC Assessment Report (AR6 2022). Three different integrated assessment modeling teams contributed to the NGFS scenarios: PIK REMIND-MAGPIE, PNNL/JGCRI GCAM, and IIASA MESSAGEix-GLOBIOM.

Paris Agreement: [International treaty](#) signed in 2015 by 196 countries with the aim of limiting global warming “to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels.”

PFCs: Perfluorinated chemicals. A family of F-gases.

PM_{2.5}: Particulate matter (tiny particles that can be inhaled) in the air of 2.5 micrometers or less in diameter. This is a category of air pollution that is associated with significant health impacts and is responsible for millions of deaths worldwide each year.

ppm: Parts per million. A common measure of CO₂ concentration in the atmosphere.

primary energy demand: Primary energy is the total energy contained in a raw energy source before it is converted into consumable energy or used as a feedstock for products like plastics. For example, primary oil energy demand refers to the energy content of crude oil before it is refined into fuel or used in industrial applications. Primary energy is greater than final energy consumption because it accounts for inefficiencies in fuel processing, thermal conversion, and transmission and distribution (T&D).

progress ratio: The relative amount of cost reduction per doubling of cumulative production of a technology. In the case of renewable energy, the progress ratio is thought to be 20%, i.e. for every doubling of production, costs decrease by 20%. Costs come down as supply chains, business models, and production industries grow. Also known as the learning effect or learning/experience curve.

RCP: Representative concentration pathway. A greenhouse gas concentration (not emissions) pathway used by the IPCC. Shared socioeconomic pathways (SSPs) are a successor to the RCPs.

REMIND-MagPIE: An Integrated Assessment Model (IAM) maintained by the Potsdam Institute for Climate Impact and Research (PIK).

radiative forcing (RF): The difference between energy absorbed by the Earth and energy radiated back into space. Incoming energy minus outgoing energy. When incoming energy is greater than outgoing energy, RF is positive and the planet will warm. Measured in W/m^2 .

SF₆: Sulfur hexafluoride, an F-gas.

SSPs: Shared Socioeconomic Pathways. A set of five narratives about future social, political and economic conditions in the world that are used to create and compare climate scenarios. [Learn more](#).

terajoule: A measure of energy equal to 10^{12} joules.

thorium: A chemical element that can be used as fuel for nuclear fission, similar to uranium. Thorium fission is an experimental technology that has yet to be used in a large-scale nuclear reactor. Its use at a large scale could be modeled in En-ROADS using the New Zero-Carbon slider.

TOE (ton of oil equivalent): A unit of energy equivalent to 29.3 gigajoules (GJ). This is the amount of energy generated by burning 1 metric ton of coal.

WEO: World Energy Outlook. A yearly publication by the International Energy Agency (IEA).

WITCH-GLOBIOM: An Integrated Assessment Model maintained by the European Institute on Economics and the Environment (EIEE)



These materials are licensed under a [Creative Commons Attribution 4.0 International License](https://creativecommons.org/licenses/by/4.0/). This license lets you remix, adapt, and build upon Climate Interactive's work, even commercially, as long as you give Climate Interactive credit for the original creation of the materials.