En-ROADS User Guide

Climate Interactive
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En-ROADS User Guide

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The En-ROADS Climate Solutions Simulator is a fast, powerful climate simulation 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 an extensive Reference Guide that covers model assumptions and structure, as well as references for data sources.

Please visit support.climateinteractive.org for additional inquiries and support.
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 EMF-27 suite. These larger disaggregated models are used for calibrating results in En-ROADS.

En-ROADS stands for “Energy-Rapid Overview and Decision-Support.” 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 model emphasizes the system-wide interactions of policies. Behind the simulation 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, 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 https://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.
There are 18 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 18 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 CO\(_2\) Emissions** from burning coal, oil, gas, and biomass. CO\(_2\) emissions from energy currently comprise about 67% of greenhouse gas emissions.
2. **Land Use CO\(_2\) Emissions** such as forestry and land use change. CO\(_2\) emissions from land use currently comprise about 5% 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 CO\(_2\) concentrations.
4. **Other Greenhouse Gas Emissions** such as methane, N\(_2\)O, and F-gases. Non-CO\(_2\) emissions currently comprise about 28% 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 CO₂ emissions is about four things: fewer people, less consumption, more efficiency, and less high-carbon energy supplies.

This is the simplest 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 technical Reference Guide.

**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)
- 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?
- What is the background and meaning of the En-ROADS Baseline scenario?
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:

\[
\text{Global Population} \times \text{GDP per Capita} \times \text{Energy Intensity of GDP} \times \text{Carbon Intensity of Energy} = \text{CO}_2 \text{ Emissions from Energy}
\]

Here is one way to understand its trends over time:

Global Population is growing—we are currently approaching 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.
Background on 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 away, and in the absence of other interventions, that amount is relatively small — approximately 3% per year.

   ![Slow Capital Stock Turnover](image)

   *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. However, energy-using capital, such as vehicles, buildings, and industry, has an average lifetime that is much shorter (10-15 years). One can promote increases to the energy efficiency of new cars immediately, for example, but the average energy efficiency of all the cars takes decades to improve since it takes time for all the old inefficient cars to be taken off the road.
To illustrate this point: Move the New Zero-Carbon slider to a huge breakthrough. Examine the “Global Sources of Primary Energy” graph and notice that, even as low-carbon sources grow, it takes several decades before enough fossil fuel capacity retires away to make much of an impact. Notice that coal, oil, and natural gas grow steadily through the 2020s and 2030s and it takes time for greenhouse gas emissions to depart from the Baseline scenario.

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. Thus, meeting climate goals also requires direct disincentives to building and using fossil fuel infrastructure.

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. 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.

While subsidizing low-carbon energy supplies such as Renewables, watch Final Energy Consumption increase. Inexpensive wind and solar spreading around the world decreases overall energy prices and boosts energy demand up:

*View this scenario in En-ROADS.*

On the other hand, implementing a carbon price causes energy costs to increase and consumption to decrease:

*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.

In the following scenario, a high Renewables subsidy leads to a 0.2 degree Celsius reduction in temperature from the Baseline:

View this scenario in En-ROADS.

A huge breakthrough in New Zero-Carbon also leads to a 0.2 degree Celsius reduction on its own:

View this scenario in En-ROADS.
When combined, instead of seeing an additive 0.4 degree Celsius reduction, we only see a 0.3 degree 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."

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 0.2 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.

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.
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”). 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.

![Renewables Primary Energy Demand Graph](image)

To learn more, view this video on Economies of Scale.
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. To learn more about this Baseline scenario, visit this FAQ: What is the background and meaning of the En-ROADS Baseline scenario?

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 steady growth in GDP. Recognizing this fact 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 Methane & Other Gases slider. Adjusting this 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 28% 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 Methane & Other Gases slider. See the scenario below – highly reducing Methane & Other Gases 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 stabilize (in red below) have flattened, 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.
Coal

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.

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 reduces energy demand (see graphs “Total Primary Energy” and “Cost of Energy”). 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.

<table>
<thead>
<tr>
<th>Change in price per ton of coal equivalent (tce)</th>
<th>very highly taxed</th>
<th>highly taxed</th>
<th>taxed</th>
<th>status quo</th>
<th>subsidized</th>
</tr>
</thead>
<tbody>
<tr>
<td>+$110 to +$40</td>
<td>+$40 to +$20</td>
<td>+$20 to +$6</td>
<td>$6 to -$6</td>
<td>-$6 to -$20</td>
<td></td>
</tr>
</tbody>
</table>

| 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 selecting the “Stop building new coal infrastructure” switch in the advanced view, and changing the “% Reduction in coal utilization” slider.

- **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.

- **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,” and how can I increase them?**

- **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


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 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 "Electric Share of Final Energy-Transport" 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 "Final Energy Consumption" and "Cost of Energy"). 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:

<table>
<thead>
<tr>
<th>Change in price per barrel of oil equivalent (boe)</th>
<th>very highly taxed</th>
<th>highly taxed</th>
<th>taxed</th>
<th>status quo</th>
<th>subsidized</th>
</tr>
</thead>
<tbody>
<tr>
<td>+$100 to +$30</td>
<td>+$30 to +$15</td>
<td>+$15 to +$5</td>
<td>+$5 to -5</td>
<td>-5 to -15</td>
<td></td>
</tr>
<tr>
<td>Cost increase or decrease</td>
<td>+200% to +60%</td>
<td>+60% to +30%</td>
<td>+30% to +10%</td>
<td>+10% to -10%</td>
<td>-10% to -30%</td>
</tr>
</tbody>
</table>

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 selecting the “Stop building new oil infrastructure” switch in the advanced view, and changing the “% Reduction in oil utilization” slider.

- 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.

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 “CH4 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.
- Price-Demand Feedback. Taxing gas also reduces energy demand (see graphs “Final Energy Consumption” and “Cost of Energy”). 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.  
- 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. 
- 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. 

**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:

<table>
<thead>
<tr>
<th>Change in price per thousand cubic feet (Mcf)</th>
<th>very highly taxed</th>
<th>highly taxed</th>
<th>taxed</th>
<th>status quo</th>
<th>subsidized</th>
</tr>
</thead>
<tbody>
<tr>
<td>+$5.00 to +$2.00</td>
<td>+$2.00 to +$1.00</td>
<td>+$1.00 to +$0.30</td>
<td>+$0.30 to -$0.30</td>
<td>-$0.30 to -$1.00</td>
<td></td>
</tr>
</tbody>
</table>

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 selecting the “Stop building new natural gas infrastructure” switch in the advanced view, and changing the “% Reduction in gas utilization” slider.

- **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?** Activate “Use detailed settings” in the Methane & Other Gases advanced view, and then set the “Energy and industry emissions” slider to -25%. [Click here for more information.](#)

- **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,” and how can I increase them?**

Please visit [support.climateinteractive.org](http://support.climateinteractive.org) for additional inquiries and support.

Footnotes


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


Bioenergy

Discourage or encourage the use of trees, forest waste, and agricultural crops to create energy. Bioenergy is energy produced from the burning, or combustion, of living organic material as solids (e.g., wood pellets), liquids (e.g., ethanol), or gas (e.g., methane from decomposition). There are a variety of sources, some of which can be sustainable and others which can be worse than burning coal.

Examples

Discouraging bioenergy:

- 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.

Big Messages

- Bioenergy is not a high leverage response to climate change – while it uses a renewable resource, it still emits large amounts of carbon dioxide and faces supply constraints with scale up.

Key Dynamics

- As bioenergy is subsidized or taxed, notice that the temperature changes very little and demand does not change as much as other energy sources do. 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.
- 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 way to remove additional carbon from the atmosphere. For this to benefit the climate, 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. BECCS can be controlled under the “Technological Carbon Removal” sliders and assumptions.
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 deforestation 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:

<table>
<thead>
<tr>
<th></th>
<th>highly taxed</th>
<th>taxed</th>
<th>status quo</th>
<th>subsidized</th>
<th>highly subsidized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in price per barrel of oil equivalent (boe)</td>
<td>+$30 to +$15</td>
<td>+$15 to +$5</td>
<td>+$5 to -$5</td>
<td>-$5 to -$15</td>
<td>-$15 to -$30</td>
</tr>
<tr>
<td>Cost increase or decrease</td>
<td>+60% to +30%</td>
<td>+30% to +10%</td>
<td>+10% to -10%</td>
<td>-10% to -30%</td>
<td>-30% to -60%</td>
</tr>
</tbody>
</table>

Model Structure

- 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.
- Bioenergy with Carbon Capture and Storage (BECCS) is controlled separately under the Technological Carbon Removal slider. However, a large breakthrough cost reduction in bioenergy can result in BECCS increasing as it becomes cost competitive with other sources.
- Future modeling in this sector will add more refinement to the ways the bioenergy supply is characterized and include stronger links to the amount of available land.
FAQs

- 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 systems, and wind turbines.** Renewable energy includes wind, solar, geothermal, hydropower, and other technologies that produce energy with little to no carbon dioxide emissions. Note that nuclear and bioenergy are considered separately.

**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.

**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 "Final Energy Consumption." Learn more.

- **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:

<table>
<thead>
<tr>
<th></th>
<th>taxed</th>
<th>status quo</th>
<th>subsidized</th>
<th>highly subsidized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in price per kilowatt hour (kWh)</td>
<td>+$0.02 to +$0.01</td>
<td>+$0.01 to -$0.01</td>
<td>-$0.01 to -$0.02</td>
<td>-$0.02 to -$0.03</td>
</tr>
<tr>
<td>Cost increase or decrease</td>
<td>+30% to +10%</td>
<td>+10% to -10%</td>
<td>-10% to -30%</td>
<td>-30% to -60%</td>
</tr>
</tbody>
</table>

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 R&D 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.

- How do you handle the availability and cost of storage of electricity from renewables? The cost of storage for renewables is explicitly modeled in En-ROADS, and as renewables become a significant part of energy supply, storage must be cost effective to enable further expansion.

- How do I simulate innovation in energy storage?

- 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


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:

<table>
<thead>
<tr>
<th></th>
<th>highly taxed</th>
<th>taxed</th>
<th>status quo</th>
<th>subsidized</th>
<th>highly subsidized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Change in price per kilowatt hour (kWh)</td>
<td>+$0.07 to +$0.03</td>
<td>+$0.03 to +$0.01</td>
<td>+$0.01 to -$0.01</td>
<td>-$0.01 to -$0.03</td>
<td>-$0.03 to -$0.07</td>
</tr>
<tr>
<td>Cost increase or decrease</td>
<td>+60% to +30%</td>
<td>+30% to +10%</td>
<td>+10% to -10%</td>
<td>-10% to -30%</td>
<td>-30% to -60%</td>
</tr>
</tbody>
</table>

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.

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

Footnotes

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 or thorium-based nuclear fission. 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 or nuclear fusion.

**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 – 10 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 “Final Energy Consumption” 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.
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

<table>
<thead>
<tr>
<th></th>
<th>status quo</th>
<th>breakthrough</th>
<th>huge breakthrough</th>
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</thead>
<tbody>
<tr>
<td>Breakthrough year</td>
<td>no breakthrough</td>
<td>2022</td>
<td>2022</td>
</tr>
<tr>
<td>Time to commercialize</td>
<td>10 years</td>
<td>10 years</td>
<td></td>
</tr>
<tr>
<td>Initial cost relative to coal</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
Model Structure

The path to deployment will take some time after the success of the technology in the laboratory: commercialization (set at 10 years, roughly the same amount of time that uranium-based fission took), planning (2 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.
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. To affect CO₂ emissions from land use, use the Deforestation and Afforestation sliders. To affect non-CO₂ emissions, use the Methane & Other Gases slider.

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, because it is not easily substituted for other energy sources (e.g. can't power a diesel truck with wind power). Bioenergy (in pink) decreases because the carbon price in En-ROADS applies to all energy sources that release CO₂, including bioenergy. 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 "Final Energy Consumption" graph, noting that the high carbon price Current Scenario (blue line) is lower than Baseline (black line). Learn more.
• **Methane leakage.** When a carbon price is implemented, watch the blue line of the Current Scenario go down in the "CH\textsubscript{4} Emissions" graph. Natural gas is primarily composed of methane (CH\textsubscript{4}), 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.
- 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**

<table>
<thead>
<tr>
<th>status quo</th>
<th>low</th>
<th>medium</th>
<th>high</th>
<th>very high</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon price per ton</td>
<td>no carbon price</td>
<td>$0 to $20</td>
<td>$20 to $60</td>
<td>$60 to $100</td>
</tr>
</tbody>
</table>

*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 CO$_2$ 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 CO$_2$ per TJ energy), followed by oil (66 tons CO$_2$/TJ), and then natural gas (51 tons CO$_2$/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**

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 (red area) 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 “Final Energy Consumption” graph to see the fall in energy demand.
  - To see another benefit, look at the “Cost of Energy” 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.

<table>
<thead>
<tr>
<th>Annual rate</th>
<th>discouraged</th>
<th>status quo</th>
<th>increased</th>
<th>highly increased</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-1% to 0%</td>
<td>0% to +1%</td>
<td>+1% to +3%</td>
<td>+3% to +5%</td>
</tr>
</tbody>
</table>

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.


Transport – Electrification

Increase purchases of new electric cars, trucks, buses, trains, and possibly even ships and airplanes. Using electric motors for transport helps reduce greenhouse gas emissions and air pollution if the electricity 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

- If the world is dependent on coal and natural gas for electric power, the net effect of electrification is only a slight change in emissions and temperature.
- Switching to electric modes of transport makes the biggest impact for the climate when electrical energy sources are low-carbon.

Key Dynamics

- 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.

- 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.

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**

*Electrication*

**Slider Settings**

The main Transport Electrification slider adds a policy mandating the minimum percentage of new road and rail transport (cars, trucks, buses, and trains) that must be powered by electricity rather than fuels.

Note that the slider's electrification target is the minimum for the scenario. The Baseline scenario assumptions and other actions can lead to higher levels of electrification than this minimum.

With the “Electrification of new transport – air and water” slider in the advanced settings, you can set the percentage of new electric airplanes, ships, boats, etc. that use air or water to get around. Currently, electric airplanes and long-range electric ships are only available as prototypes and face significant technological challenges due to the limitations of energy storage, so the default assumption is that they do not scale up. If the slider is moved, then the electrification action would begin in 2030 and take 70 years to reach the specified percentage.

<table>
<thead>
<tr>
<th>Minimum percentage of new transport</th>
<th>status quo</th>
<th>incentivized</th>
<th>highly incentivized</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% to 9%</td>
<td>10% to 49%</td>
<td>50% to 100%</td>
<td></td>
</tr>
</tbody>
</table>

**Model Structure**

This input directly forces growth of electrification up to a minimum percentage, unlike the inputs for energy sources, which change the financial attractiveness to drive future behavior.

**FAQs**

- How do I simulate innovation in energy storage?
- How do I simulate hydrogen use?

Please visit [support.climateinteractive.org](http://support.climateinteractive.org) for additional inquiries and support.

**Footnotes**

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 CO\textsubscript{2} 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 “Final Energy Consumption” 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.

<table>
<thead>
<tr>
<th>Annual rate</th>
<th>discouraged</th>
<th>status quo</th>
<th>increased</th>
<th>highly increased</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1% to 0%</td>
<td>0% to +1.5%</td>
<td>+1.5% to +3%</td>
<td>+3% to +5%</td>
<td></td>
</tr>
</tbody>
</table>

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

Buildings and Industry – Electrification

Increase the use of electricity, instead of fuels like oil or gas, in buildings, appliances, heating systems, and other machines. Using electric motors only helps reduce emissions if the electricity 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.

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
**Slides Settings**

The Buildings & Industry Electrification slider adds a policy mandating the minimum percentage of new building construction, industry, and appliances that must be powered by electricity rather than fuels.

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

<table>
<thead>
<tr>
<th>Minimum percentage of new buildings and industry</th>
<th>status quo</th>
<th>incentivized</th>
<th>highly incentivized</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% to 39%</td>
<td>40% to 69%</td>
<td>70% to 100%</td>
<td></td>
</tr>
</tbody>
</table>

**Model Structure**

This input directly forces growth of electrification up to a minimum percentage, unlike the inputs for energy sources, which change the financial attractiveness to drive future behavior.

This input affects climate outcomes through two pathways:

1. Changing energy demand. The efficiency for electrified energy use is generally greater than for the direct burning of coal, oil, and gas.
2. Changing fuel mix. Increased electrification decreases use of oil but then increases use of coal, natural gas, and renewables in electricity generation.

**FAQs**

- How do I simulate innovation in energy storage?

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

**Footnotes**

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. The variable being changed reflects the global population by 2100, in billions of people.

<table>
<thead>
<tr>
<th>UN Scenario</th>
<th>lowest growth</th>
<th>low growth</th>
<th>status quo</th>
<th>high growth</th>
<th>highest growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>low end of UN's 95% range</td>
<td>low end of UN's 95% range</td>
<td>middle of UNs 95% range</td>
<td>high end of UN's 95% range</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Population in 2100</td>
<td>9.1 to 9.5 billion</td>
<td>9.5 to 10.5 billion</td>
<td>10.5 to 11.4 billion</td>
<td>11.4 to 12.8 billion</td>
<td>12.8 to 13.2 billion</td>
</tr>
</tbody>
</table>

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


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.

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.

- As you increase the economic damage caused by climate change (in the Assumptions settings), notice how this reduces the emissions, but cannot halt the temperature increase even under extreme assumptions where the world's GDP plummets.

Potential Co-Benets 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. Reference or note for the austerity measures and their implications.
Videos

- Population & Economic Growth

Slider Settings

Economic Growth

<table>
<thead>
<tr>
<th></th>
<th>low growth</th>
<th>status quo</th>
<th>high growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long-term economic growth</td>
<td>0.5% to 1.2%</td>
<td><strong>1.2% to 1.9%</strong></td>
<td>1.9% to 2.5%</td>
</tr>
<tr>
<td>Near-term economic growth</td>
<td>1.7% to 2.1%</td>
<td><strong>2.2% to 2.9%</strong></td>
<td>3.0% to 3.7%</td>
</tr>
</tbody>
</table>

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

The two sliders “Reduction in GDP at 2°C from climate impacts” and “Maximum reduction in GDP” (located in the Assumptions menu under “Economic impact of climate change”) enable the user to explore the strength of the feedback between climate impacts and economic growth. These two sliders are displayed on a single line since they are related to each other. Maximum reduction in GDP cannot be smaller than Reduction in GDP at 2°C, hence they move together if a user tries to move them past each other. To see the dynamics as you adjust these sliders, view the graph “Reduction in GDP vs Temperature.”

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. Several economists formulated this impact, known as the “damage function,” as a percentage reduction on global GDP, and estimated it as a function of temperature change. The four main functions in the literature are from Nordhaus (2017), Weitzman (2012), Dietz & Stern (2015), and Burke et al. (2015). You can see their estimates for economic damage in the “Reduction in GDP vs Temperature” graph, and replicate them in En-ROADS by entering the following values for the two sliders, or by selecting the function in the "Preset" menu:

<table>
<thead>
<tr>
<th>En-ROADS Slider</th>
<th>Nordhaus</th>
<th>Weitzman</th>
<th>Dietz &amp; Stern</th>
<th>Burke</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduction in GDP at 2°C</td>
<td>0.9%</td>
<td>1.3%</td>
<td>2.6%</td>
<td>13%</td>
</tr>
<tr>
<td>Maximum reduction in GDP</td>
<td>22%</td>
<td>97%</td>
<td>98%</td>
<td>20%</td>
</tr>
</tbody>
</table>
Model Structure

In the real world, there would be multiple feedbacks to economic growth from energy prices, and various taxes. En-ROADS does not model the economic costs and/or benefits of sliders, so GDP will not be affected when sliders are moved. However, the model does feature the feedback from climate impacts to GDP. This setting must be initiated by the user in the Assumptions menu under “Economic impact of climate change.” Due to the lack of scientific consensus about the extent of economic impact on GDP, we have left the decision to the user. The user can explore other feedback by changing economic growth projections with the sliders manually.

FAQs

- Are the financial or economic costs or benefits of actions modeled in En-ROADS?
- Does En-ROADS account for the economic impact of climate change?
- What is the mathematical formulation behind the economic impact of climate change in En-ROADS?
- Why doesn't En-ROADS fully match the damage functions from scientific literature if I use the preset damage functions?

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

Footnotes

Methane & Other Gases

Decrease or increase greenhouse gas emissions from methane, nitrous oxide, and the F-gases. Methane (CH₄) is released from sources like cows, agriculture, oil and natural gas drilling, and waste. Nitrous oxide (N₂O) mainly comes from fertilizers. Fluorinated gases, or F-gases, include HFCs, PFCs, and others that are used in industry and consumer goods like air conditioners.

Examples

- Decreased meat consumption, which reduces emissions from livestock and the fertilizers used to produce livestock feed.
- Modified agricultural practices such as better processing of manure and decreasing fertilizer use.
- Decreased methane leakage from oil and gas industries, for example by reducing venting and flaring of methane from oil and gas wells and properly sealing old wells.
- Increased capturing of gases emitted from landfills.
- Research and development into substitutions for F-gases in industrial processes and consumer appliances.

Big Messages

- Reducing methane, nitrous oxide, and the F-gases is high leverage, although many approaches to reducing these emissions need more research and support to scale up.

Key Dynamics

- Methane, N₂O, and F-gas emissions comprise approximately 30% of current greenhouse gas emissions, and their reduction is key to addressing climate change.

Potential Co-Benefits of Decreasing Methane & Other Gases

- Plant-based diets have been shown to be healthier for individuals and have less impact on ecosystems.
- Sustainable and plant-based agriculture produces more food with fewer resources, which increases food security.
- Reducing methane leakage from natural gas systems can save money.
- Less nitrogen-rich fertilizer runoff can reduce water pollution, decrease eutrophication, and increase the health of ocean ecosystems.

Equity Considerations

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

The variable being changed is the percent reduction or percent increase of maximum possible action. The model limits how much these emissions can be reduced—so 100% max reduction is not a 100% total emissions reduction—since some emissions are considered unavoidable, particularly a minimum amount of emissions from agriculture, landfills, and wastewater. The lower limit is approximated from the agriculture and waste emissions in IPCC scenarios for RF 1.9 levels for land use.

<table>
<thead>
<tr>
<th>Percent reduction or increase of maximum action</th>
<th>highly reduced</th>
<th>moderately reduced</th>
<th>status quo</th>
<th>increased</th>
</tr>
</thead>
<tbody>
<tr>
<td>-100% to -50%</td>
<td></td>
<td></td>
<td></td>
<td>+10%</td>
</tr>
<tr>
<td>-50% to -2%</td>
<td></td>
<td></td>
<td>-2% to 0%</td>
<td></td>
</tr>
<tr>
<td>0% to +10%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Slider settings for modeling food system changes in En-ROADS:**

To test out changes to the food and agriculture system in En-ROADS, use a combination of three sliders according to the table below. The “Agricultural and waste emissions” slider, located in the advanced settings of Methane & Other Gases, adjusts the direct emissions from livestock and fertilizer use. The food system is linked to other sectors, so also adjust the Transport Energy Efficiency (representing reduced need for farm machinery, transport, etc.) and Deforestation sliders (representing decreased demand for grazing land). **Pick only one Livestock or Diet column—these are alternative choices, they do not add together.**

The Improved Crop System settings can be used alone or in combination with any of the other options. These represent agricultural practices that grow food with less land and emissions, including improved seed quality or crop varieties, crop rotation, efficient methods of fertilization, and irrigation.

Add the settings to your current scenario. Note that the Agricultural & Waste and Deforestation slider values are negative (lower emissions) while the Transportation slider is positive (more progress). For more information, see “How to talk about food in En-ROADS.”

These slider settings are based on the UN Food and Agriculture Organization (FAO) report *Tackling Climate Change with Livestock* (2013).

<table>
<thead>
<tr>
<th>Slider</th>
<th>Baseline</th>
<th>Efficient Livestock or More Plant-based (a)</th>
<th>Mostly Vegetarian or “Lancet” diet (b)</th>
<th>Improved Crop System (a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agriculture and Waste (under “Methane &amp; Other Gases”)</td>
<td>0</td>
<td>-10</td>
<td>-20</td>
<td>-5</td>
</tr>
<tr>
<td>Transportation Efficiency</td>
<td>0.5</td>
<td>+0.5</td>
<td>+0.5</td>
<td>+0.7</td>
</tr>
<tr>
<td>Deforestation</td>
<td>0</td>
<td>-1.5</td>
<td>-1.5</td>
<td>-1.5</td>
</tr>
</tbody>
</table>
Assumptions behind these settings:

(a): 1/3 reduction of each category of associated emissions
(b): 1/3 of energy and deforestation emissions plus 2/3 of direct emissions

Model Structure

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 CO\textsubscript{2} equivalency conversions. Greenhouse gases other than CO\textsubscript{2} that are reflected in graphs with the units CO\textsubscript{2}e do use GWP100 to enable comparison and reporting of all greenhouse gases together. This means that the short-lived, but high impact, nature of greenhouse gases like methane is captured.

Case Studies

Carrboro, NC, USA: Participation in a community gardening program in Carrboro, NC showed improvements in childhood obesity levels and resulted in families with children in the program eating one-third more fruits and vegetables every day. ¹

FAQs

- How do I simulate plant-based, vegetarian, or vegan diets?

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

Footnotes

Deforestation

**Decrease or increase the loss of forests for agricultural and wood product uses.** Deforestation often entails burning and removing forests to clear land for crops like soybeans, corn, or palm oil. Forest protection efforts increase biodiversity and can support community resilience.

**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**

- Efforts to reduce deforestation are relatively low leverage for the climate, because the influence from energy CO₂ emissions is so dominant, but stopping deforestation is still part of a multi-pronged effort to address climate change.
- 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 (deforestation) CO₂ relative to all the other sources of emissions.

**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.
Videos
Deforestation

Slider Settings

<table>
<thead>
<tr>
<th>Percent per year reduction or increase</th>
<th>highly reduced</th>
<th>moderately reduced</th>
<th>status quo</th>
<th>increased</th>
</tr>
</thead>
<tbody>
<tr>
<td>10% to -4%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-4% to -1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-1% to 0%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0% to +1%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Model Structure

Emissions from deforestation stay level in the Baseline scenario to reflect trends that indicate deforestation continues to be insufficiently addressed worldwide.

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

Footnotes


Afforestation

Plant new forests and restore old forests. As trees grow, they draw carbon out of the air, which reduces the concentration of carbon dioxide. However, without care, large-scale afforestation can compromise biodiversity and historical land rights.

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.

Big Messages

- Afforestation has 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.

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 or more for newly planted trees to become large enough to remove significant amounts of carbon from the atmosphere.

- **Reversibility.** Trees do not live forever, and when they die or are cut down, their stored carbon eventually returns to the atmosphere.

- **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.** Explore the graph “Land for Growing CO₂ Removal Biomass.” The land area of India, represented by the dotted line, is approximately 329 million hectares. Even if we were to forest an area of that size, we would still not see much change in temperature.

Potential Co-Benefits of Increasing Afforestation

- 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.
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.

Videos

Afforestation & Technological CO₂ Removal

Slider Settings

The Afforestation slider changes the percentage of available land that is used to grow new forests. 100% would mean that 700 million hectares (Mha) of land is covered in forests. 700 Mha represents approximately 21% of current grassland area, 8% of all land (including desert and tundra) that is not currently forest, and just over the difference in forest area back in 1850 until now (i.e., there is 680 Mha less forest area today than in 1850).²

<table>
<thead>
<tr>
<th>Percent available land for afforestation</th>
<th>status quo</th>
<th>low growth</th>
<th>medium growth</th>
<th>high growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% to +15%</td>
<td>+15% to +40%</td>
<td>+40% to +70%</td>
<td>+70% to +100%</td>
<td></td>
</tr>
</tbody>
</table>

Model Structure

The carbon sequestration of forests changes over time as the forest matures. Notice that net carbon removals are different than total removals due to carbon loss in older or unhealthy forests.

Maximum amount of available land: With a growing time of 80 years for new forests and 2%/year in total forest carbon loss, 700 Mha achieves an annual removal consistent with the mid-point of estimates of afforestation potential from the 2018 'Greenhouse gas removal' report by the Royal Society (range of 3-20 Gtons CO₂/year).

For higher removals, one can adjust the "Afforestation settings" within the Assumptions view. For example, to explore the assumptions of the 2019 paper by Bastin et al., increase the slider "Max available land for afforestation" to 900 Mha under Assumptions.

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.³
FAQs

- How do I simulate plant-based, vegetarian, or vegan diets?
- Why is planting trees (afforestation) not more impactful?

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

Footnotes


Technological Carbon Dioxide Removal

Pull carbon dioxide out of the air with new technologies that enhance natural removals or manually sequester and store carbon. Carbon Dioxide Removal (CDR) technologies include: direct air capture, bioenergy with carbon capture and storage (BECCS), biochar, and others (but not including coal or gas CCS). CDR is not yet used widely, and most approaches face significant barriers to deployment.

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

All of the following methods of CO$_2$ removal can be explored in the En-ROADS simulator:
<table>
<thead>
<tr>
<th><strong>Afforestation and reforestation.</strong> 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.</th>
<th><strong>Bioenergy with carbon capture and storage (BECCS)</strong> entails burning biomass for energy, capturing the CO$_2$ emissions, storing the emissions long-term, and successfully re-growing any used biomass.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Direct air capture</strong> is an emerging technology that pulls CO$_2$ 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.</td>
<td><strong>Enhanced mineralization</strong> entails mining specific rocks—like basalt—that can absorb CO$_2$ from the air and converting it to rock for long-term carbon storage.</td>
</tr>
<tr>
<td><strong>Agricultural soil carbon sequestration</strong> involves using</td>
<td><strong>Biochar</strong> is biomass (e.g. from trees) that has been</td>
</tr>
</tbody>
</table>
agricultural practices which enhance soil carbon (such as no-till agriculture and preventing overgrazing). The carbon is made into charcoal via pyrolysis, and is then buried to retain the carbon.

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

- **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.
- **Industry scale.** View the graph “Bulk Material for Mineralization” to see the scale of industrial production these approaches entail.

Potential Co-Benefits of CDR Growth

- Nature-based carbon removal approaches like agricultural soil sequestration can help improve landholder and farmer profits in some cases.
- Some carbon removal methods could provide energy (like BECCS) or improve soil health (like agricultural soil carbon sequestration).
- The scale up of many carbon removal approaches would result in vast new industries and businesses, which would create jobs.

Equity Considerations

- Approaches like BECCS require large areas of land that in some cases could otherwise be used for food production.
- Methods like direct air capture and enhanced mineralization would demand large amounts of energy.
- 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

<table>
<thead>
<tr>
<th>Percent of maximum potential</th>
<th>status quo</th>
<th>low growth</th>
<th>medium growth</th>
<th>high growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% to +10%</td>
<td>+10% to +40%</td>
<td>+40% to +70%</td>
<td>+70% to +100%</td>
<td></td>
</tr>
</tbody>
</table>

Model Structure

The five 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).

The default settings for the maximum potential of technological carbon removal ("% 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 same report. For example, the biochar maximum can be increased to 5 Gtons/year.

FAQs

- Why aren't coal and gas carbon capture and storage (CCS) included here, and how can I increase them? We think of coal and gas CCS as reducing CO₂ emissions from coal and gas, not actually as removing CO₂ from the atmosphere. Both can be changed in the Advanced Views that support the Coal and Natural Gas sliders.

- Where can I learn more about the different CDR types? Follow the links to find detailed fact sheets on these CDR types:
  - Agroforestry
  - Forestation
  - BECCS
  - Biochar
  - Direct Air Capture
  - Enhanced Mineralization
  - Agricultural Soil Carbon Sequestration

Please visit support.climateinteractive.org for additional inquiries and support.
Model Comparison – Historical

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1. Primary Energy Demand History
2. Final Energy Consumption History
3. Electricity Generated by Energy Source History
4. Marginal Cost of Wind, Solar, and Geothermal Electricity History
5. Emissions History
6. Atmospheric Concentrations History
7. Radiative Forcing History
8. Temperature History

The purpose of this section of the En-ROADS User Guide is to supplement the historical comparison graphs in the En-ROADS application by sharing multiple comparisons of En-ROADS model behavior compared against measured historical data.

En-ROADS uses historical data for two purposes: initialization of the simulation and calibration. Certain variables in En-ROADS are initialized with their measured historical values from 1990, and then the model runs. We compare the model output from 1990 through present day to measured historical data to identify opportunities for model improvement.

The graphs below compare the En-ROADS Baseline scenario to measured historical data for select variables. Not all variables and comparisons to history are included here. The historical data are derived from the following sources:

Five historical comparison graphs are also included in the En-ROADS app under Graphs > Model Comparison - Historical and are included and disaggregated here:

- Greenhouse Gas Net Emissions History
- Primary Energy Demand of Coal, Oil, and Gas History
- Primary Energy Demand of Wind and Solar History
- Marginal Cost of Solar Electricity History
- Temperature History
Primary Energy Demand History

- Total Primary Energy Demand
- Primary Energy from Coal
- Primary Energy from Oil
- Primary Energy from Natural Gas
- Primary Energy from Nuclear

Global primary energy demand of energy sources for the En-ROADS Baseline compared to IEA historical data. This is measured in exajoules per year (joules $\times 10^{18}$/year) for electric and nonelectric sources combined.

Primary energy refers to the total energy from a raw energy source that is converted into consumable energy. For example, primary coal energy demand refers to the total energy in coal that is mined, processed, and consumed. Primary energy is greater than final energy consumption because it accounts for inefficiencies in fuel processing, thermal conversion, and transmission and distribution (T&D).

Statistical fit

Click here for descriptive statistics of En-ROADS fit to historical data.

Sources of historical data

Primary Energy from Oil

Primary Energy from Natural Gas
Final Energy Consumption History

- Total Final Energy Consumption
- Total Final Energy Consumption - Buildings & Industry
- Total Final Energy Consumption - Transport
- Total Final Energy Consumption - Electric Buildings & Industry
- Total Final Energy Consumption - Electric Transport

Global total final energy consumption of energy sources in exajoules/year (joules x 10^{18}/year) for electric and nonelectric sources combined in the En-ROADS Baseline compared to historical data.

Final energy consumption is the total energy consumed to meet the demand of all final end uses. 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 demand.

Final energy consumption is divided into two end uses: stationary (buildings and industry) and transport.

**Statistical fit**

Click here for descriptive statistics of En-ROADS fit to historical data.

**Sources of historical data**

Total Final Energy Consumption

The graph illustrates the Total Final Energy Consumption from 1990 to 2020, showing the trend of energy consumption over time.

- The graph includes a line for In-ROADS (2021) and another for IEA WEO (2020).
- The energy consumption is measured in Exajoules per year.

From the graph, it can be observed that energy consumption has generally increased over the years.
Electricity Generated by Energy Source History

- Electricity Generated by Coal
- Electricity Generated by Natural Gas
- Electricity Generated by Nuclear
- Electricity Generated by Bioenergy
- Electricity Generated by Hydro
- Electricity Generated by Solar
- Electricity Generated by Wind
- Electricity Generated by Geothermal
- Electricity Generated by Other Renewables

The electricity generated by energy sources in the En-ROADS Baseline compared to historical data.

Statistical fit

Click here for descriptive statistics of En-ROADS fit to historical data.

Sources of historical data

Electricity Generated by Coal

Electricity Generated by Natural Gas
Electricity Generated by Hydro

[Graph showing the trend of electricity generated by hydro over the years.]
Marginal Cost of Wind, Solar, and Geothermal Electricity History

- Marginal Cost of Wind
- Marginal Cost of Solar
- Marginal Cost of Geothermal

The marginal cost of electricity production from wind, solar, and geothermal energy in dollars (US 2017) per kilowatt hour (kWh) in the En-ROADS Baseline compared to historical data. This is the marginal cost for energy producers to make electricity from a new solar, wind, or geothermal installation. The cost factors in how much it costs to build new energy generation facilities (the levelized capital costs) and how much it costs to operate and maintain new facilities (O&M).

For solar, the En-ROADS Baseline is shown relative to historical data from Lazard, IRENA, and IEA. The IEA & IRENA curve is calculated from IEA (2020) capital costs per GW from 1990-2019 relative to its 2010 value, and multiplied by IRENA’s 2010 levelized cost of energy (LCOE) (2020).

For wind, the En-ROADS Baseline is shown relative to historical data from Lazard and IRENA. For geothermal, the En-ROADS Baseline is shown relative to historical data from Lazard.

Statistical fit

Click here for descriptive statistics of En-ROADS fit to historical data.

Sources of historical data

Marginal Cost of Geothermal

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Emissions History

- Greenhouse Gas Net Emissions
- CO₂ Emissions from Energy
- CO₂ Emissions from Fossil Fuels
- CH₄ Emissions
- N₂O Emissions
- F-Gas Emissions

Global greenhouse gas emissions (GHGs) in the En-ROADS Baseline and historical data, in Gigatons of CO₂ or CO₂ equivalents per year. CO₂ equivalents are used to standardize the effect of all greenhouse gases in terms of CO₂.

The Greenhouse Gas Net Emissions graph measures the total gross greenhouse gas emissions minus the total net anthropogenic carbon dioxide removal (CDR). Contributions to gross GHGs are from carbon dioxide (CO₂), nitrous oxide (N₂O), methane (CH₄), and the F-gases (PFCs, SF₆ and HFCs).


Statistical fit

Click here for descriptive statistics of En-ROADS fit to historical data.

Sources of historical data

Greenhouse Gas Net Emissions

Greenhouse Gas Emissions

Gigatons CO₂ equivalent per year

- En-ROADS (2021)
CO₂ Emissions from Energy

CO₂ Emissions from Fossil Fuels
F-Gas Emissions

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Atmospheric Concentrations History

- CO₂ Concentration in the Atmosphere
- CH₄ Concentration in the Atmosphere
- N₂O Concentration in the Atmosphere

The total concentration of CO₂, CH₄, and N₂O in parts per million (ppm) of CO₂ equivalents in the atmosphere in the En-ROADS Baseline compared to historical data.

Carbon dioxide equivalents (CO₂e) are calculated from the 100-year global warming potential of each gas (IPCC AR5) for reporting purposes. Note the radiative forcing of each gas is modeled explicitly as a function of its atmospheric cycle and radiative efficiency.

Statistical fit

Click here for descriptive statistics of En-ROADS fit to historical data.

Sources of historical data

CO₂ Concentration in the Atmosphere

CH₄ Concentration in the Atmosphere
N₂O Concentration in the Atmosphere

N₂O parts per billion (ppb)

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Radiative Forcing History

- CO₂ Radiative Forcing
- CH₄ Radiative Forcing
- N₂O Radiative Forcing
- Halocarbon Radiative Forcing

The radiative forcing due to CO₂, CH₄, N₂O, and halocarbons in the atmosphere, in Watts per meter squared (W/m²), in the En-ROADS Baseline compared to historical data. Halocarbons refer to F-gases (PFCs, SF₆, and HFCs) and Montreal Protocol gases.

Greenhouse gases absorb infrared radiation and re-radiate it back, causing an increase in surface temperature. Radiative forcing measures the difference between energy absorbed by the Earth and energy radiated back into space. When incoming energy is greater than outgoing energy, RF is positive and the planet will warm.

Statistical fit

Click here for descriptive statistics of En-ROADS fit to historical data.

Sources of historical data

**CO₂ Radiative Forcing**

![Graph showing CO₂ Radiative Forcing](image)

**CH₄ Radiative Forcing**

![Graph showing CH₄ Radiative Forcing](image)
**N₂O Radiative Forcing**

![N₂O Radiative Forcing Graph](image)

**Halocarbon Radiative Forcing**

![Halocarbon Radiative Forcing Graph](image)

[Return to Table of Contents]
Temperature History

Temperature change from 1850 in the En-ROADS Baseline compared to historical data, in degrees Celsius. NASA GISS (GISTEMP v4) includes the average and the lower and upper 95% confidence intervals. Met Office Hadley Centre produced the HADCRUT5 data.

Statistical fit

Click here for descriptive statistics of En-ROADS fit to historical data.

Sources of historical data


Temperature Change

Return to Table of Contents
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 \( \text{CO}_2 \) in the atmosphere.

\( \text{CO}_2 \): 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.).

cobenefit: A positive effect of climate action that does not directly relate to climate. For example, a cobenefit 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).

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 capture (DAC): An experimental method of technological carbon dioxide removal where \( \text{CO}_2 \) is captured from the air with machines and stored permanently (e.g. underground). DAC 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 DAC 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 \( 10^{18} \) joules

F-gases: Fluorinated gases. Synthetic (created by humans) gases that are used in industrial applications (like refrigeration and manufacturing microchips) and are powerful greenhouse gases. Include HFCs, PFCs, and SF\(_6\).

final energy consumption: Total energy consumed to meet the demand of all final end uses. 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 demand.

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 Pacific Northwest National Laboratory (PNNL).

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$_2$O, 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: Global Population x GDP per Capita x Energy Intensity of GDP x Carbon Intensity of Energy = CO$_2$ Emissions from Energy.

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

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.


**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.

**PM2.5:** 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 refers to the total energy from a raw energy source that is converted into consumable energy. For example, primary oil energy demand refers to the total amount of energy of crude oil that is then extracted, refined, and consumed. 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/m².

**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 10¹² 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)
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