En-ROADS User Guide

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

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

En-ROADS is being developed by Climate Interactive, Ventana Systems, UML Climate Change Initiative, and MIT Sloan.

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

In addition to this User Guide there is:

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

About En-ROADS

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

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

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

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

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

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

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

En-ROADS Tutorial

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

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

Graphs

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

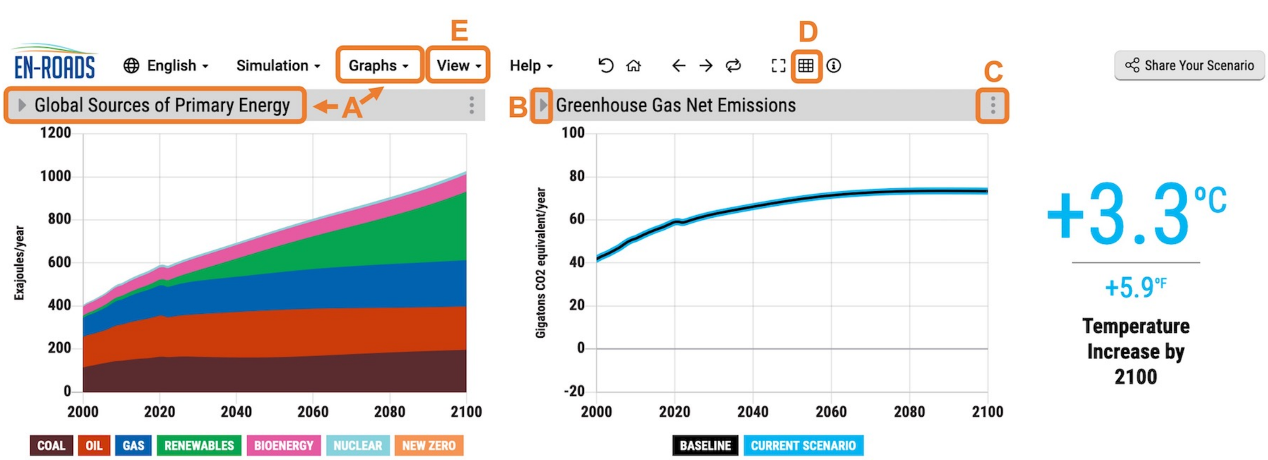
A. **Select graphs** – When you first open En-ROADS, you see the two default graphs. You can select from the full list of graphs by clicking the title of the left or right graph. You can also select from the Graphs menu in the top toolbar.

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

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

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

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



Sliders/Actions

There are 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:

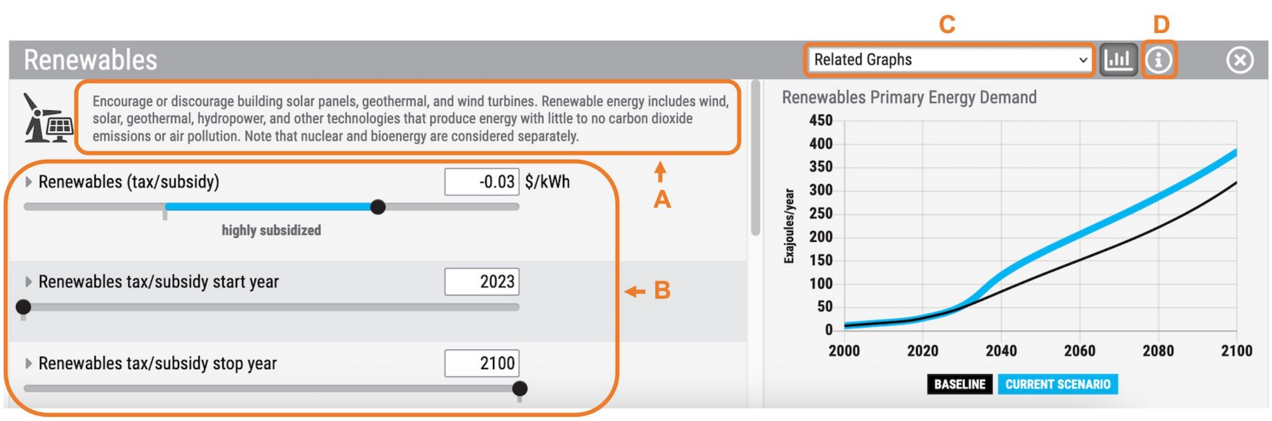
Here is what you will find in the detailed slider view:

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.

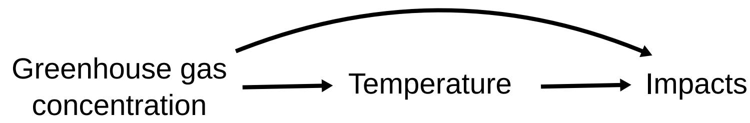
E. **Actions and Outcomes** [under the "View" menu] – This list summarizes the total actions and key climate outcomes from your scenario.

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.

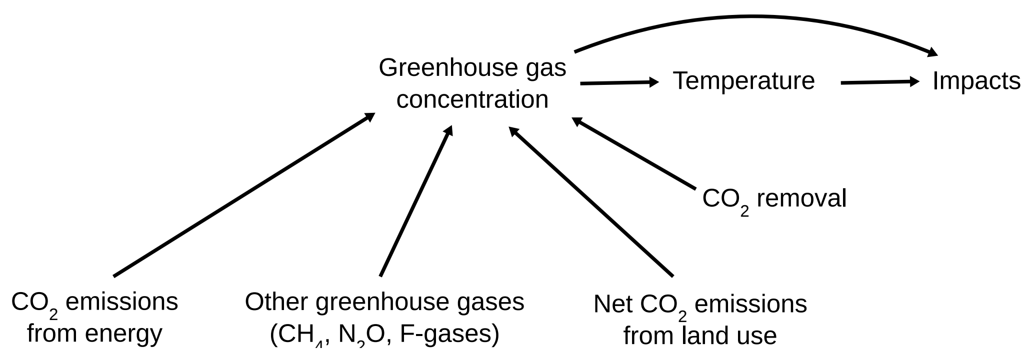
En-ROADS Structure

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:

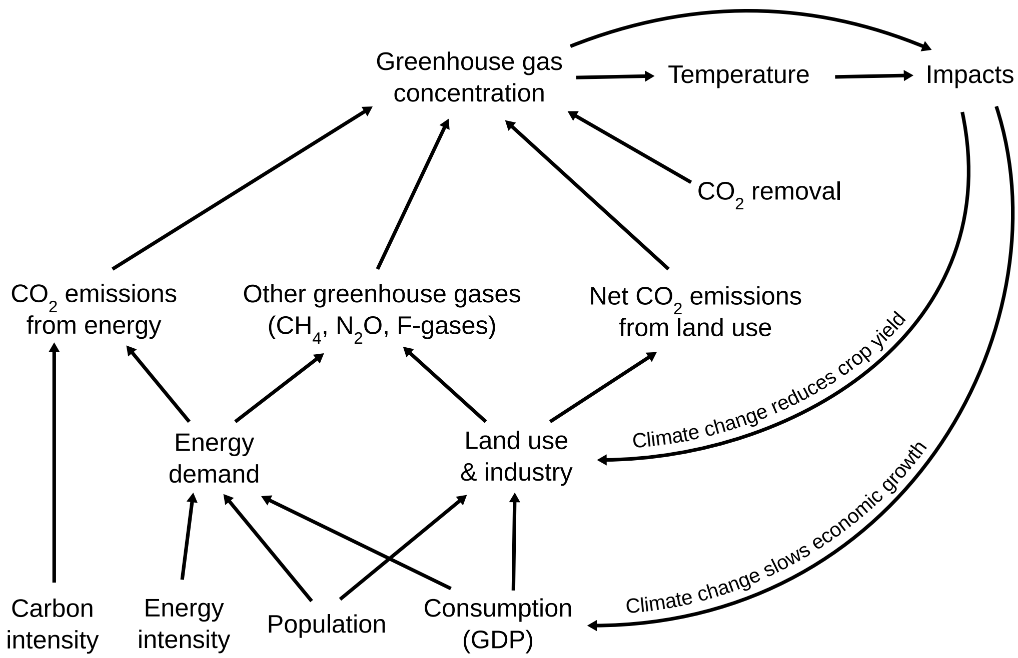
1. **Energy CO_2 Emissions** from burning coal, oil, gas, and biomass. CO_2 emissions from energy currently comprise about 67% of greenhouse gas emissions.
2. **Land Use CO_2 Emissions** such as forestry and land use change. CO_2 emissions from land use currently comprise about 7% of greenhouse gas emissions.
3. **Carbon Dioxide Removal** approaches that pull carbon dioxide out of the atmosphere and store it in plants, soils, or underground, leading to a decrease in CO_2 concentrations.
4. **Other Greenhouse Gas Emissions** such as methane, N_2O, and F-gases. Non-CO_2 emissions currently comprise about 26% of total greenhouse gas emissions.



Going further, CO_2 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 (CO_2 emissions per unit of energy) are all multiplied together and the result is overall energy CO_2 emissions. In this way, at a high level, reducing energy CO_2 emissions is about four things: fewer people, less consumption, more efficiency, and less high-carbon energy supplies.

Population and consumption (GDP/capita) growth also drive the emissions from the agricultural, land use, land use change, and forestry sectors, due to increased demand for things like food, wood products, and bioenergy feedstocks. This increases the CO_2 emissions from land use and other greenhouse gases, which reinforces temperature increase and climate change.

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



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

Videos

- En-ROADS Model Structure (with Professor John Sterman, MIT)
- How we use research and data in En-ROADS
- Comparison to data and others’ scenarios (Part 1)
- Comparison to data and others’ scenarios (Part 2)
- 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?

En-ROADS Baseline Scenario

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

What is included in the En-ROADS Baseline Scenario?

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

To learn more about the drivers of emissions in the Baseline Scenario, explore the Kaya graphs.

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

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

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

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

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

FAQs

- How does the En-ROADS Baseline Scenario compare to future scenarios from other models?

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

Kaya Graphs

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

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

Global Population × GDP per Capita × Energy Intensity of GDP × Carbon Intensity of Energy = CO_2 Emissions from Energy

Here is one way to understand its trends over time:

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

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

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

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

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

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

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En-ROADS Dynamics

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

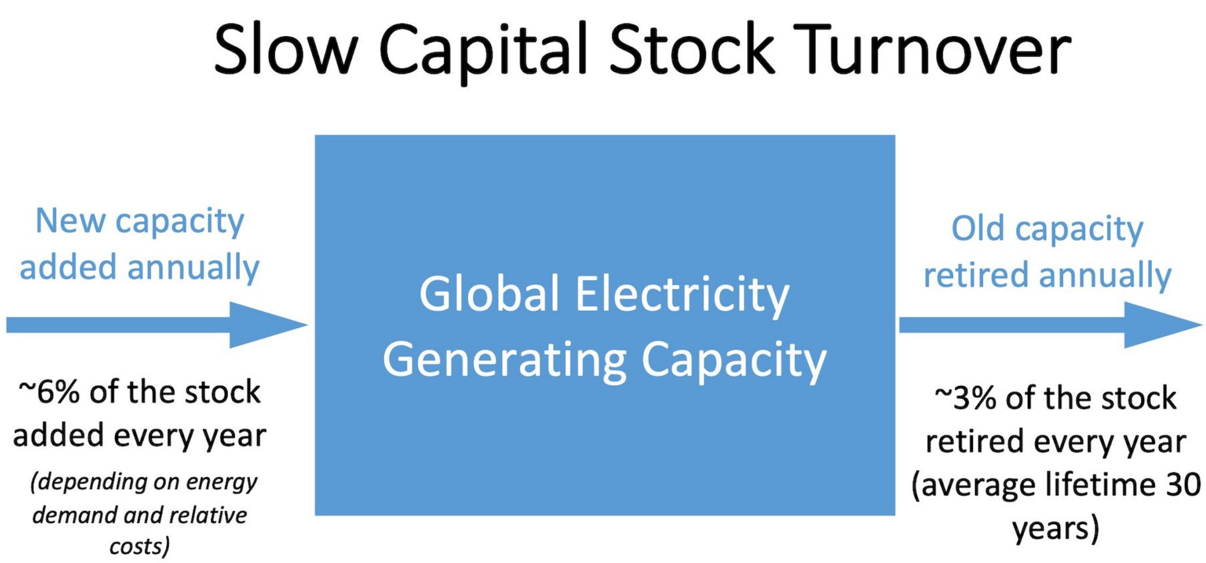
Most of the dynamics in En-ROADS can be answered by these explanations:

Complex Interactions Between Competing Energy Supplies and Demand

1. Delays and Capital Stock Turnover

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

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



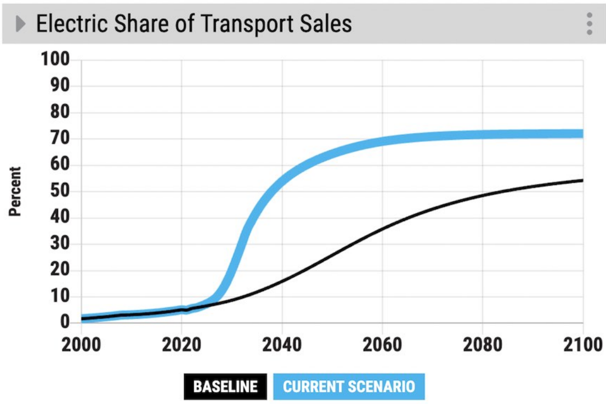
This addresses questions such as:

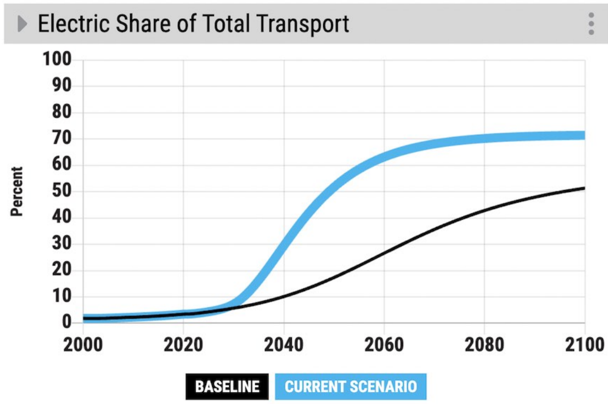
- "Why doesn't subsidizing renewables, nuclear, or a new zero-carbon energy source help avoid more warming?"

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

To illustrate this point: Move the Transport Electrification slider to be highly subsidized. Examine the "Electric Share of Total Transport" graph and notice that, even as the amount of electric transport grows, it takes several decades before it can reach over 50% of total transport. Compare this to the graph "Electric Share of Transport Sales" which rises much faster, as sales more immediately reflect the impact of the subsidy.

View this scenario in En-ROADS.





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

To learn more, view this video on Capital Stock Turnover.

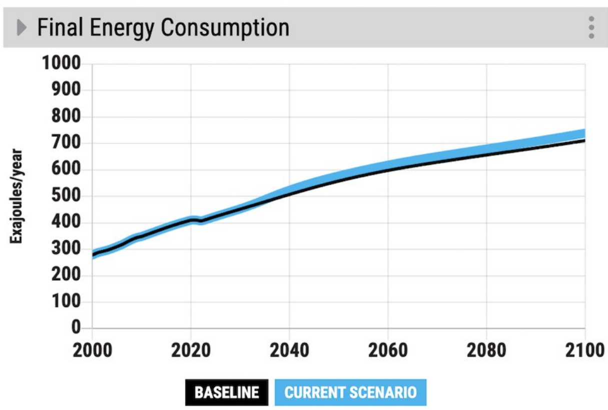
2. Price and Demand Effects

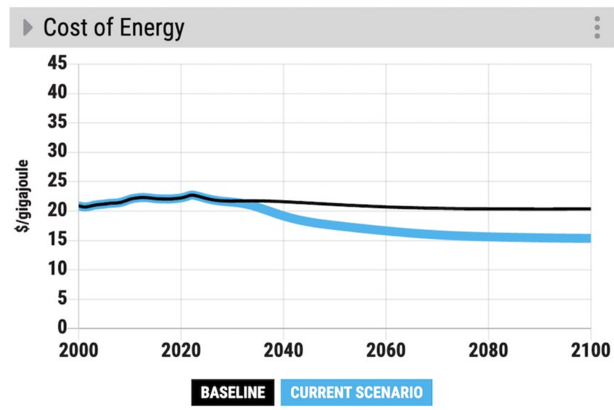
Energy demand falls if energy prices rise, and demand increases if prices fall. People and companies are more likely to take actions to conserve energy (such as turning off lights when they're not being used), or invest in energy efficiency (such as buying energy-efficient appliances or insulating buildings)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

When a high carbon price is set, for example, energy demand falls because energy prices increase. 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:

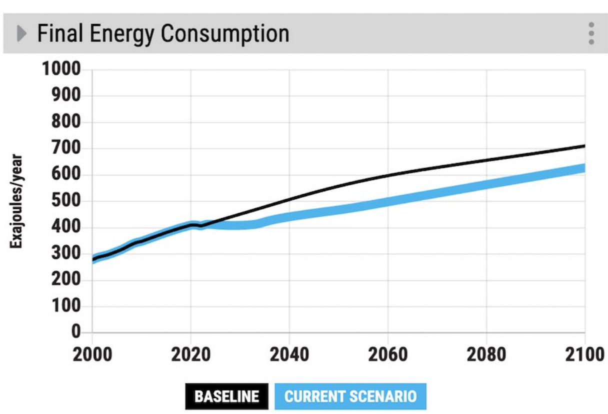
View this scenario in En-ROADS.

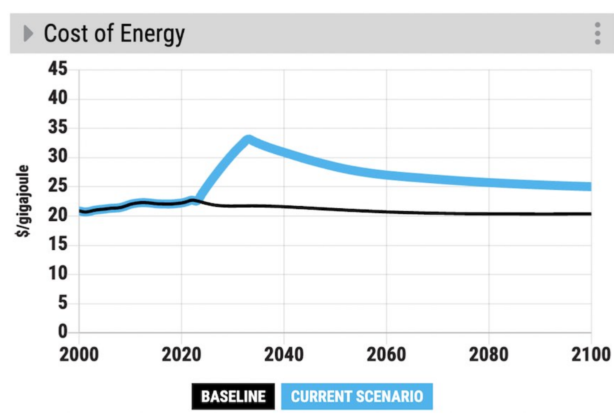




On the other hand, implementing a carbon price causes energy costs to increase and consumption to decrease:

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 CO_2 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 CO_2, 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.

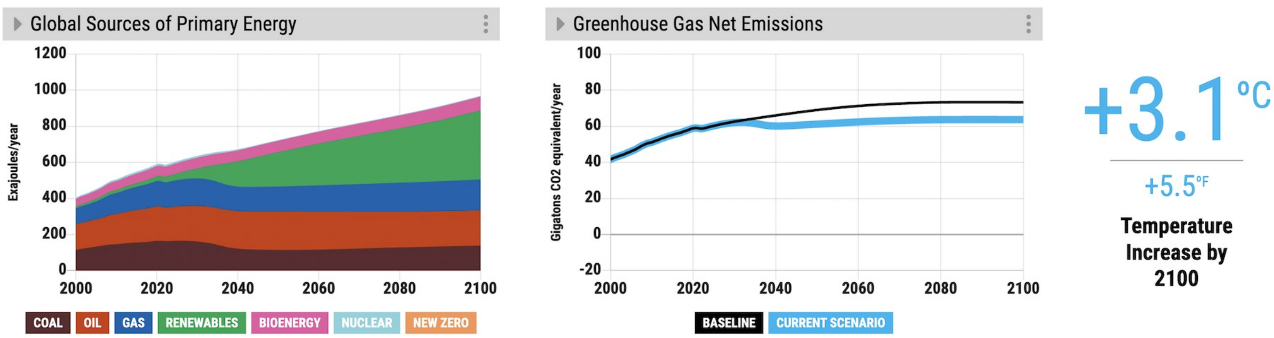
This addresses questions such as:

- “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.

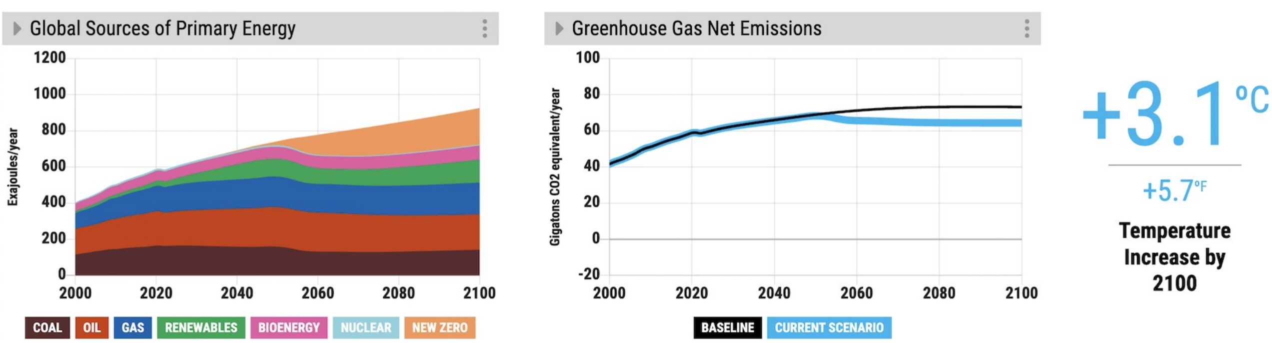
In the following scenario, a high Renewables subsidy leads to a 0.2°C (0.4°F) reduction in temperature from the Baseline:

View this scenario in En-ROADS.



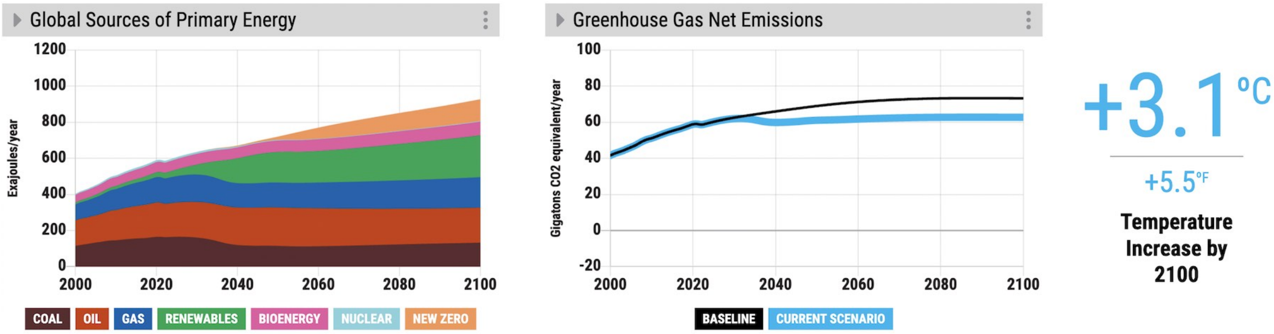
A huge breakthrough in New Zero-Carbon also leads to a 0.2°C (0.4°F) reduction on its own:

View this scenario in En-ROADS.



When combined, instead of seeing a total 0.4°C reduction, we only see a 0.2°C (0.4°F) reduction in temperature from the Baseline due to the energy supplies competing with each other for market share:

View this scenario in En-ROADS.

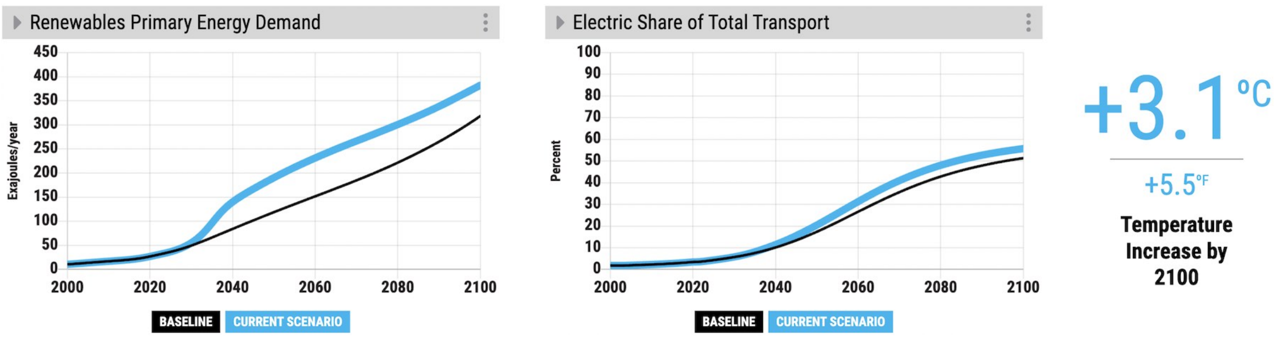


To learn more, view this video on "Crowding Out and Squeezing the Balloon."

4. Complementary Policies: Electrification

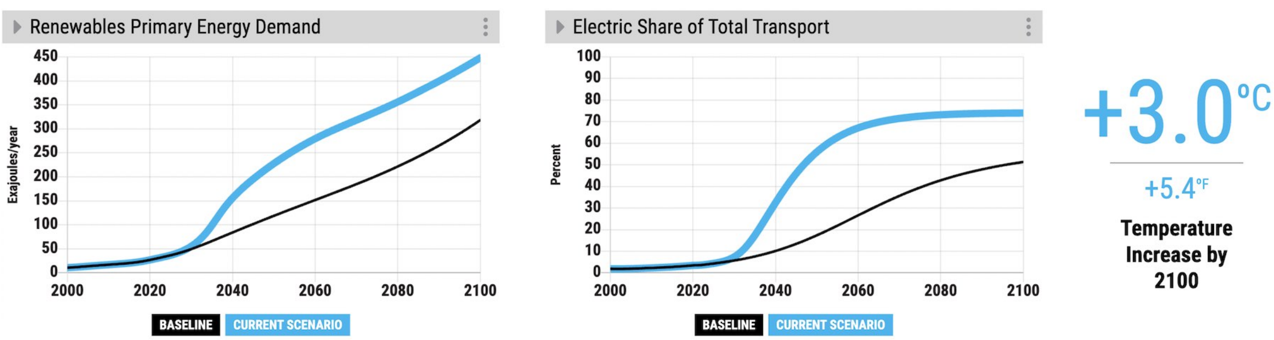
Renewables, nuclear, and new zero-carbon energy produce energy in the form of electricity in En-ROADS. Buildings, industry, and transportation need to be able to use electricity in order to use these cleaner sources of energy. Electrification of buildings and industry (for example, by switching to electric heat pumps) and transportation (switching from internal combustion engines to electric vehicles) is therefore essential for changing the energy mix. Notice in En-ROADS how significantly subsidizing Renewables leads to a 0.2 degree Celsius reduction in temperature:

View this scenario in En-ROADS.



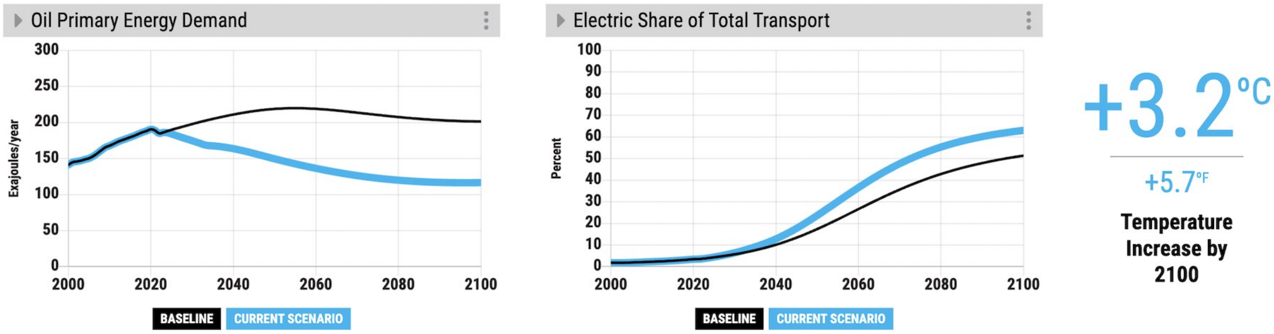
And then adding a policy to increase transport electrification lowers the temperature further and boosts demand for renewables:

View this scenario in En-ROADS.



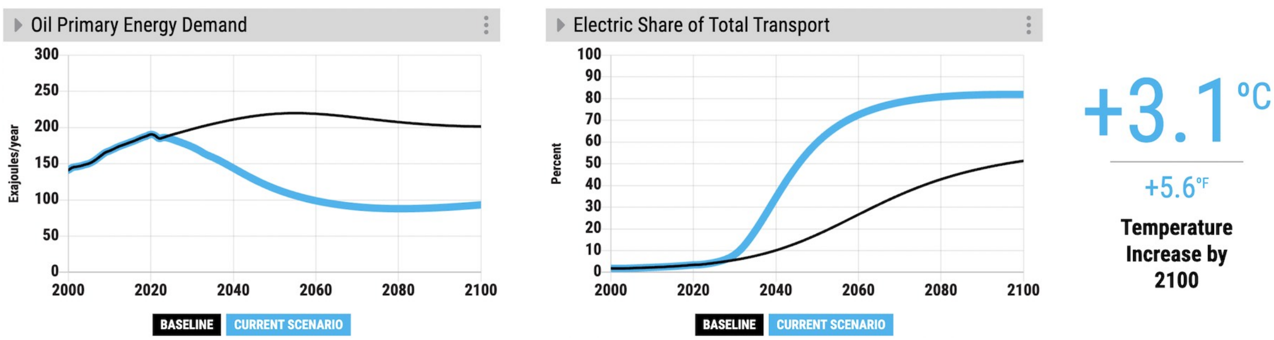
Similarly, in a different scenario, taxing oil is not enough to discourage use of this fuel:

View this scenario in En-ROADS.



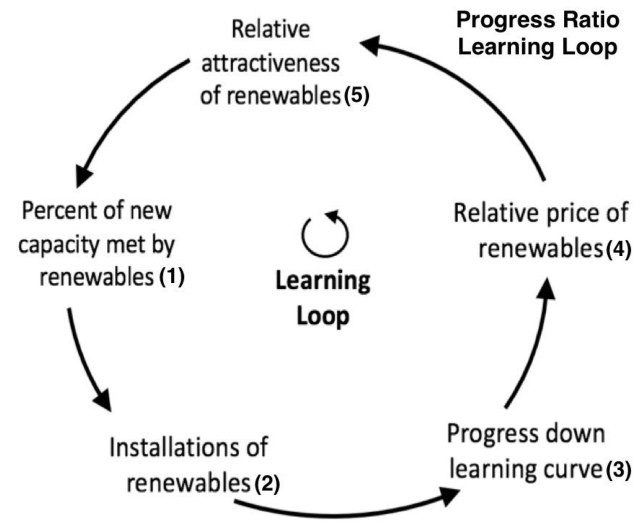
You must also add policies that encourage electrification, which enables things that were dependent on oil to use other sources of energy.

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"). In the graphic below, increasing the capacity (1) and installation (2) of new energy sources leads to increased learning (3), a decrease in price (4), increasing the attractiveness of renewables (5) and therefore even greater capacity and installations:



This addresses questions such as:

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

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

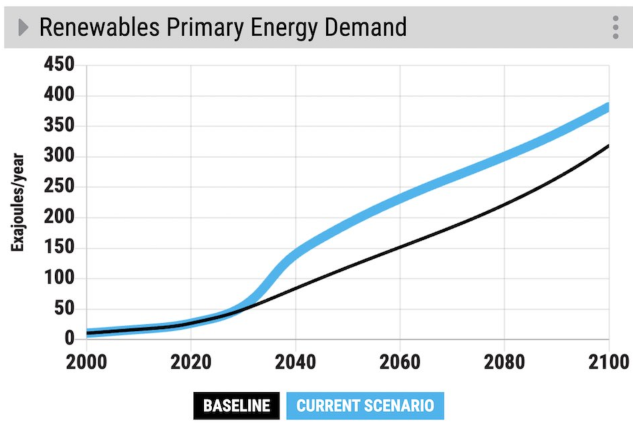
The progress ratio for renewables is 0.80, which is quite low compared to other sources of energy such as nuclear and coal (0.98). Remember, a progress ratio of 0.80 means that every doubling of cumulative installed capacity lowers costs 20%. For coal, every doubling of cumulative installed capacity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

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

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

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

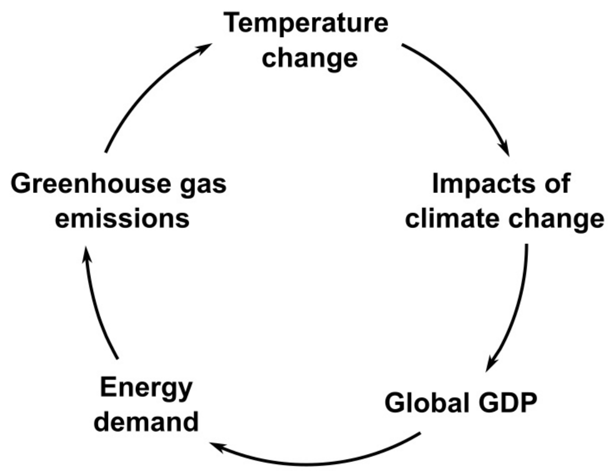
View this scenario in En-ROADS.



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

6. Economic Damage from Climate Change

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



This addresses questions such as:

- “Does En-ROADS account for the costs of climate change impacts?”
- “Why do Carbon Removal actions increase Energy Consumption or CO_2 Emissions from Energy?”
- “Why does action on Methane & Other Gases increase Energy Consumption?”

Here are the key points to remember about this dynamic:

1. This dynamic can be turned off with the “Climate change slows economic growth” switch under Simulation > Assumptions > Economy > "Economic impact of climate change." This results in the economy continuing to grow without being affected by climate change, causing more greenhouse gas pollution and more climate change. Note that changing the Assumptions in En-ROADS only affects the Current Scenario, and the economic impact of climate change will continue to be present in the Baseline Scenario. *View this scenario in En-ROADS, and turn ON and OFF the “Climate change slows economic growth” switch.*

2. Actions (e.g., Afforestation or Methane & Other Gases) that reduce temperature without affecting energy costs or energy efficiency will still cause energy consumption to increase. The temperature reduction caused by these actions reduces some of the economic impact of climate change, which leads to higher GDP growth and thus more Final Energy Consumption and greenhouse gas emissions.

   Note that if the only sources of energy available do not emit CO_2, then an increase in energy demand due to higher GDP growth would not have an effect on the climate.

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

To learn more, read the Explainer on the Economic Impact of Climate Change in En-ROADS.

Drivers of the Baseline Scenario

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

1. Drivers of Growth

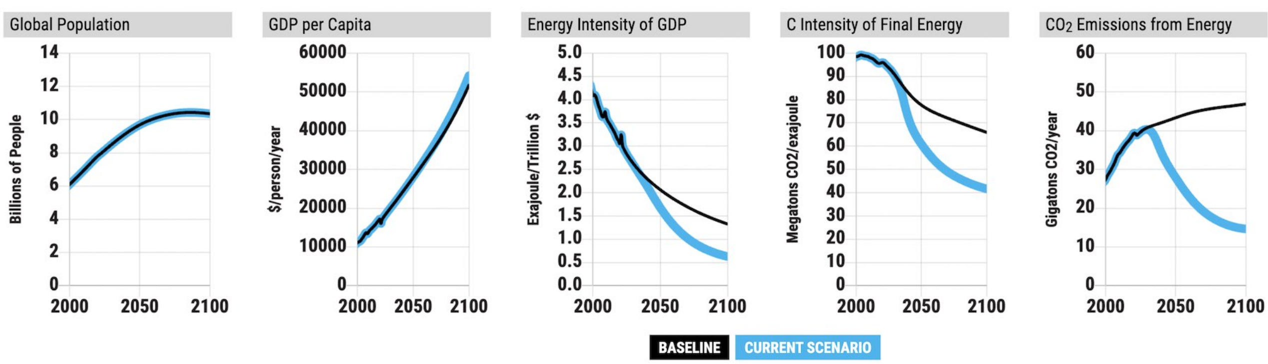
A challenge to limiting future warming in this simulation is the powerful growth in global GDP (Gross World Product). This is driven by the Population and Economic Growth sliders. More production and consumption of goods and services requires more energy. While energy efficiency and changes to the fuel mix can help reduce energy emissions, their success is dampened by the growth in GDP. Part of this growth is slowed down by climate change impacts such as lower crop yields, intensified natural disasters, sea level rise, and biodiversity loss. This impact on GDP is known as the "damage function" and slows the increase in consumption and energy demand. However, energy demand and CO_2 emissions from energy are still rising throughout the century, which leads many users to explore different futures for population (for example, by empowering women in developing countries, which could lower population growth) and economic growth measured in GDP per person (for example, by finding ways to meet economic needs without increasing consumption).

This addresses questions such as:

- *"We've done a lot in energy efficiency and clean energy – why haven't emissions reduced substantially enough?"*

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

View this scenario in En-ROADS.



To learn more, view this video on the Kaya graphs.

2. Non-CO_2 Emissions Affect Temperature Significantly

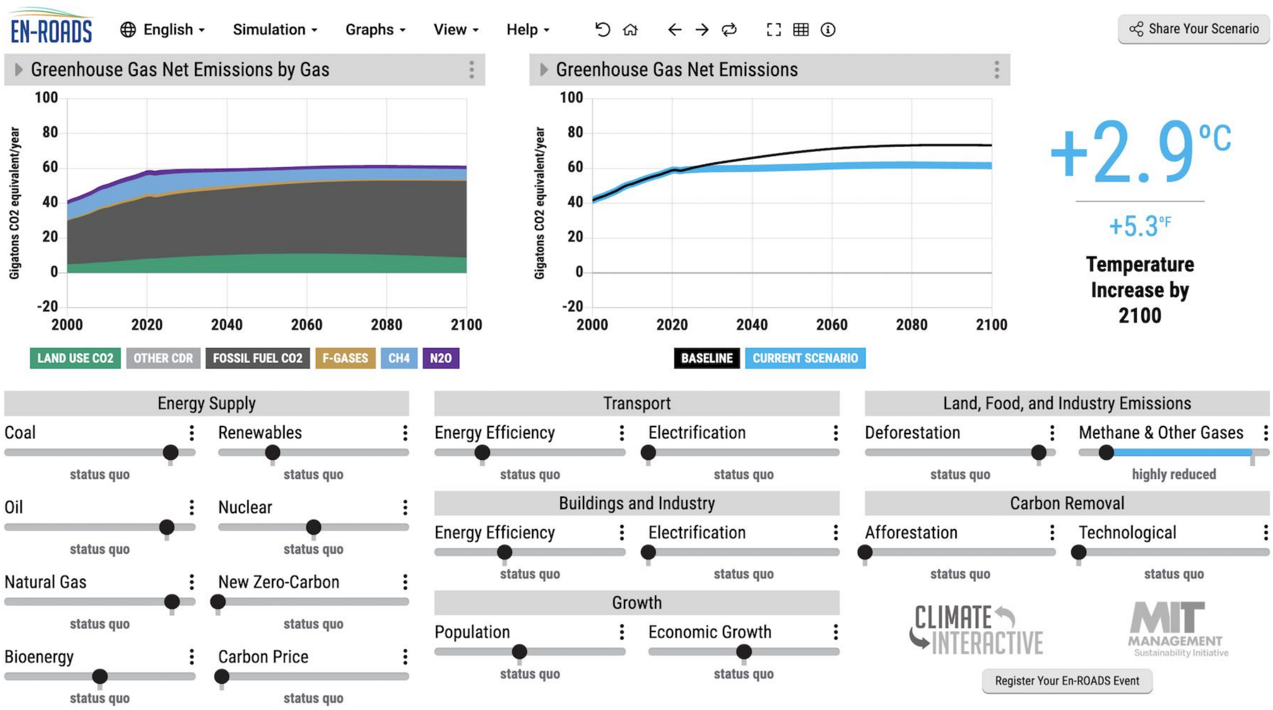
Methane (CH_4), N_2O, and the F-gases are controlled by the Methane & Other Gases slider. Adjusting this has a large impact on temperature. This implies significant changes in livestock management and consumption, waste management, fertilizer use, and industry. These emissions currently make up around 26% of total greenhouse gas emissions.

This addresses questions such as:

- "We've done a lot in energy – why haven't we solved the climate crisis?"

To illustrate this point: See the "Greenhouse Gas Net Emissions by Gas – Area" and "Greenhouse Gas Net Emissions" graphs and adjust the 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.

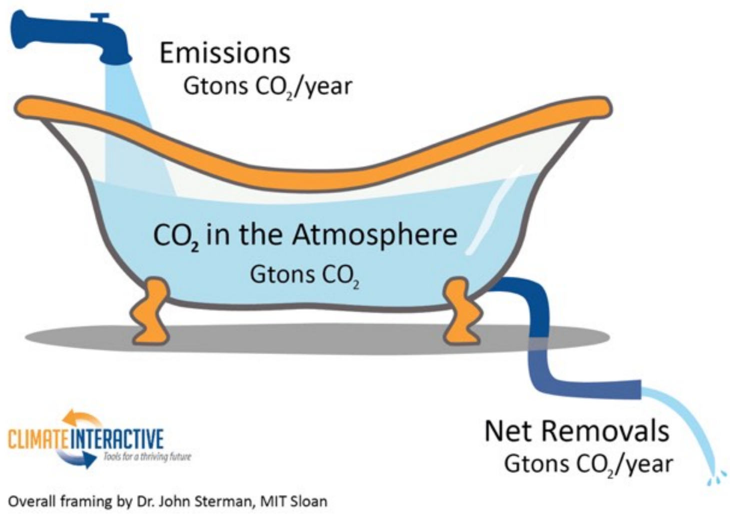


To learn more, read this article on the June 2023 Baseline Scenario.

System Dynamics of the Climate

1. Bathtub Dynamics - CO_2 Emissions Must Be Equal to or Lower than CO_2 Removals for Temperature to Stabilize

The metaphor of a bathtub helps explain the dynamics of rising CO_2 concentration in the atmosphere. If more CO_2 enters the atmosphere (like water flowing into a tub) than is removed (like water draining from the tub), then the amount of CO_2 in the atmosphere (the amount of water in the tub) will continue to increase. To flatten CO_2 concentration and therefore temperature, we need to bring CO_2 emissions down to equal removals. If your bathtub is overflowing, you turn off the tap first.

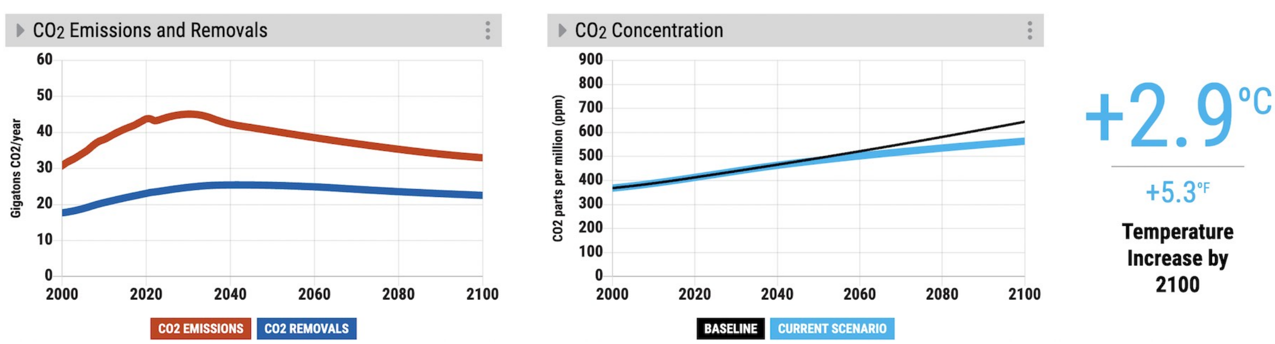


This addresses questions such as:

- "Emissions are stabilized, so why is temperature or CO_2 concentration still going up?"

To illustrate this point: See the "CO_2 Emissions and Removals" and "CO_2 Concentration" graphs in a scenario where CO_2 emissions stabilize. Even though CO_2 emissions (in red below) are declining, CO_2 concentration (in blue on the right below) continues to increase because emissions are greater than removals.

View this scenario in En-ROADS.



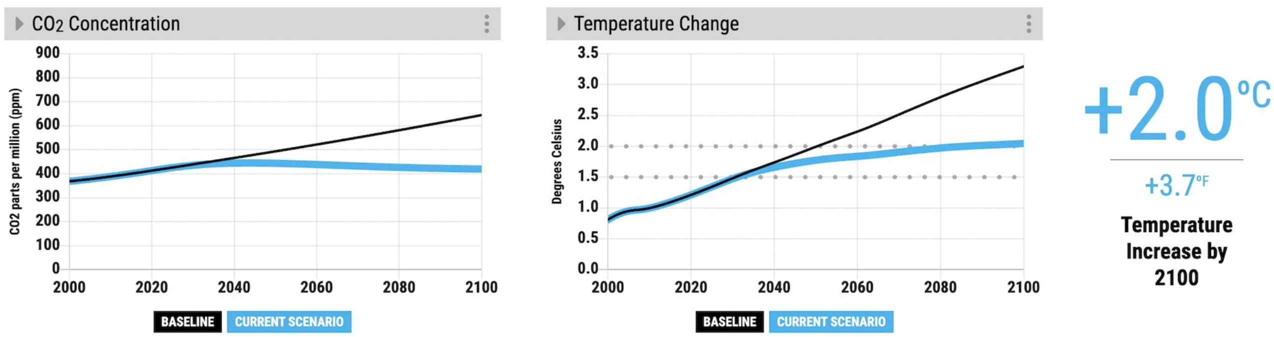
To learn more, view this video on the Carbon Dioxide Bathtub.

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 CO_2 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 CO_2 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. Carbon capture and storage (CCS) can capture some emissions from coal, but it is not yet used widely and faces barriers to deployment.

Examples

Discouraging coal:

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

Big Messages

- Discouraging coal is a high leverage strategy for reducing future temperature change. Coal emits more carbon dioxide when it is burned than either oil or natural gas (coal has the highest carbon intensity).

- Discouraging coal also improves public health and saves medical costs through improved air quality. Coal plants emit particulate matter and other forms of air pollution that lead to respiratory and cardiovascular diseases and premature deaths.[1]

Key Dynamics

- **Impact.** When coal is discouraged, watch the brown area of Coal go down in the "Global Sources of Primary Energy" graph. It is one of the most sensitive energy supplies to any increase in cost because unlike oil, coal can often be replaced by natural gas (for heating or electricity) or renewables (for electricity).

- **"Squeezing the Balloon."** When coal is taxed, notice what happens to natural gas in response. Unless there are restrictions on gas, its demand will go up in response to expensive coal. We call this the "squeezing the balloon" problem—reducing fossil fuel emissions in one area causes them to pop up in another. Renewables are also boosted slightly, but the impact on emissions from increased renewables is small. Solutions to the "squeezing the balloon" problem include taxing oil and natural gas as well, or adding a carbon price, which addresses all fossil fuels together.

- **Price-Demand Feedback.** Taxing coal also slightly reduces energy demand (see graphs "Total Primary Energy" and "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.

Slider Settings

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

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

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

Model Structure

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

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

Case Studies

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

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

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

FAQs

- **How can I directly force deeper reductions in coal use?** Consider changing the "Reduce new coal infrastructure," "% Reduction in coal utilization," and "Coal plant accelerated retirement" sliders in the advanced view.
- **How do I simulate reducing coal subsidies?** Current coal subsidies are included in the En-ROADS Baseline Scenario, and you can remove them by moving the coal slider to "taxed." Click here for more information.
- What's the difference between a carbon price and a tax on a fuel (coal, oil, natural gas, or bioenergy)?
- Why aren't coal and natural gas carbon capture and storage (CCS) technologies included under "Technological Carbon Removal"?
- Why are the slider ranges (min and max) what they are? How did you decide the range of the sliders?
- What happens to the revenue from taxes or a carbon price in En-ROADS?

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

Footnotes

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

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

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

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

Oil

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 "CO_2 Emissions from Energy 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.

Slider Settings

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

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

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

Model Structure

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

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

FAQs

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

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

Natural Gas

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

Examples

Discouraging natural gas:

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

Big Messages

- More natural gas is not an effective long-term strategy for the climate—it is less carbon intensive than coal, but it still emits carbon dioxide.

- Gas infrastructure has a long lifetime and it competes with the adoption of lower-carbon alternatives such as renewables as they scale up.

Key Dynamics

- **"Squeezing the Balloon."** If natural gas is taxed, in absence of other policies, primary energy demand for gas decreases, but carbon-intensive coal demand increases slightly. We call this the "squeezing the balloon" problem—reducing fossil fuel emissions in one area causes them to pop up in another. Adding a carbon price is a good solution to the "squeezing the balloon" problem, as it addresses all fossil fuels together.

- **Methane leakage.** When gas is discouraged, by taxing it, watch the blue line of the Current Scenario go down in the "CH_4 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.[5] [6]
- There have been cases where wealthy white communities have successfully resisted natural gas development and it has shifted to low-income communities predominantly inhabited by people of color. Low-income communities often have less ability to influence development.[7] [8]
- Limited data on the placements of fracking and power plant sites in developing countries exists, yet macro-level research shows that low-income communities and communities of color disproportionately experience the negative impacts of natural gas drilling and burning.[9]

Slider Settings

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

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

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

Model Structure

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

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

FAQs

- **How can I directly force deeper reductions in natural gas use?** Consider changing the “Reduce new gas infrastructure” and the “% Reduction in gas utilization” sliders in the advanced view.
- **How do I simulate reducing natural gas subsidies?** Current natural gas subsidies are included in the En-ROADS Baseline Scenario, and you can remove them by moving the natural gas slider to "taxed." Click here for more information.
- **How do I simulate fixing natural gas pipeline leaks?** Activate “Use detailed settings” in the Methane & Other Gases advanced view, and then set the "Adoption of best practices for energy, industry, and waste (CH_4, N_2O, & F-gases)" slider to 18%. 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"?

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

Footnotes

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

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

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

[4]: Carpenter, D. O. (2016). Hydraulic fracturing for natural gas: impact on health and environment. *Reviews on Environmental Health*, 31(1).

[5]: Clough, E. (2018). Environmental justice and fracking: A review. *Current Opinion in Environmental Science & Health*, 3, 14–18.

[6]: Bienkowski, B. (2016, February 17). Fracking's Costs Fall Disproportionately on the Poor and Minorities in South Texas. *Inside Climate News*.

[7]: Jula, M. (2018, April 17). Parents didn't want fracking near their school. So the oil company chose a poorer school, instead. *Mother Jones*.

[8]: Gislason, M., & Andersen, H. (2016). The Interacting Axes of Environmental, Health, and Social Justice Cumulative Impacts: A Case Study of the Blueberry River First Nations. *Healthcare*, 4(4), 78.

[9]: Perera, F. (2017). Pollution from Fossil-Fuel Combustion is the Leading Environmental Threat to Global Pediatric Health and Equity: Solutions Exist. *International Journal of Environmental Research and Public Health*, 15(1), 16.

Bioenergy

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

Examples

Discouraging bioenergy:

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

Encouraging bioenergy:

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

Big Messages

- Bioenergy is not a high leverage response to climate change – while it uses a potentially renewable resource, it still emits large amounts of carbon dioxide and faces supply constraints with scale up.
- Subsidizing bioenergy from wood increases temperature because it results in higher net CO_2 emissions.

Key Dynamics

- As bioenergy is subsidized or taxed, notice that the temperature changes very little and bioenergy's contribution to the mix of global sources of primary energy does not change much. The main constraint on bioenergy is the amount of biomass that is available each year to be turned into energy. This limitation means that there are only small changes to other energy sources, if bioenergy is subsidized.
- Subsidizing wood bioenergy increases CO_2 emissions (shown in the “CO_2 Gross Emissions from Forest Bioenergy” graph) and reduces the removal of CO_2 from the atmosphere (shown in the “CO_2 Removals from Land” graph). Together, the change in emissions and removals results in more CO_2 in the atmosphere, shown in the “CO_2 Net Emissions from Forest Bioenergy” graph. For an in-depth understanding of this dynamic, read the Bioenergy Explainer.

- Bioenergy is only zero-carbon if the biomass is regrown to account for the carbon emitted. This is not guaranteed, and in some areas, bioenergy is produced from trees, which take decades to regrow to make up for the carbon released when burned.

- Bioenergy carbon capture and storage (BECCS) is proposed as a 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.

Potential Co-Benefits of Discouraging Bioenergy

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

Equity Considerations

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

Slider Settings

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

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

Model Structure

- Bioenergy sources, known as “feedstocks,” are categorized into wood, crops, and waste/other. These feedstocks can be separately subsidized or taxed. Wood feedstocks result in net CO_2 emissions due to the delays in regrowing trees, while the other types of feedstocks do not result in net CO_2 emissions due to their faster regeneration times (e.g., bioenergy crops are regrown within a year).
- Subsidizing bioenergy drives more deforestation and forest degradation due to harvesting of wood as feedstock or clearing land to grow crops for bioenergy.
- This sector tracks several stages of bioenergy installations, or energy supply capacity including: capacity under development, under construction, and actually producing energy, as well as the delays between each stage.

FAQs and Explainers

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

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

Renewables

Encourage or discourage building solar panels, geothermal, and wind turbines. Renewable energy includes wind, solar, geothermal, hydropower, and other technologies that produce energy with little to no carbon dioxide emissions or air pollution. Note that nuclear and bioenergy are considered separately.

Examples

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

Big Messages

- Subsidizing renewable energy helps to limit coal and gas demand and reduce future temperature as it becomes the most affordable source of electricity.

- Renewable subsidies can more significantly displace coal, oil, and gas demand when complemented with other actions, particularly the electrification of transport, buildings, and industry.

- Achieving a high share of renewable energy for electricity requires energy storage and other solutions to balance the variability of wind and solar.

Key Dynamics

- **Impact.** As you encourage renewables, watch demand for Renewables (in green) grow and the demand for Coal (in brown) and Natural Gas (in blue) reduce in the “Global Sources of Primary Energy” graph. Renewable energy is already growing steadily in the Baseline Scenario, so the additional subsidies help reduce emissions but only so much.

- **Price-Demand Feedback.** Subsidies to renewables decrease energy costs, which increase energy demand over what it would have been otherwise (people use more energy when it is cheap). This feedback effect somewhat reduces the positive impact of encouraging renewable energy. View this dynamic with the graph “Final Energy Consumption.” Learn more.

- **Economies of Scale.** The Baseline Scenario already assumes a high growth of renewable energy based on historical trends in cost reductions and high adoption rates (see the “Marginal Cost of Solar Electricity History” and “Primary Energy Demand of Wind and Solar History” graphs in the “Model Comparison—Historical” section), and for more details on the dynamics read here.

- **Delays.** It takes time for the subsidies and encouragement of renewables to show up in installed capacity. New energy infrastructure is only added as demand grows or as the old infrastructure is retired and makes space for new infrastructure (this is known as “capital stock turnover delays”). The new infrastructure takes time to build. Subsidies and taxes are also phased in over 10 years, creating some of the delay in the speed at which actions make an impact.

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

Potential Co-Benefits of Encouraging Renewables

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

Equity Considerations

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

Slider Settings

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

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

Model Structure

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

The most important feedback loops in the renewables sector include:

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

Case Studies

United States: Scaling up wind and solar energy sources is estimated to have avoided 7,000 premature deaths and saved $87.6 billion in health costs and climate impacts from 2007-2015.[2]

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

Global: Increasing the share of renewable energy in the global energy supply to 65% could generate 6 million jobs and add $19 trillion to the world economy by 2050.[4]

FAQs

- **Why doesn't encouraging renewables with a big subsidy avoid much future warming alone?**
  - Renewables only reduce CO_2 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.
  - Adjust the "Hydrogen storage breakthrough cost reduction" and/or "Other storage breakthrough cost reduction" sliders to simulate a breakthrough that would lower the cost of the energy storage needed to accommodate the variability of wind and solar power.

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

- How do I simulate energy storage for wind and solar?

- How do I simulate innovations in wave energy and tidal energy?

- How do I simulate hydrogen use?

- Why are all renewable energy sources grouped together in En-ROADS?

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

Footnotes

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

[2]: Millstein, D., Wiser, R., Bolinger, M., & Barbose, G. (2017). The climate and air-quality benefits of wind and solar power in the United States. *Nature Energy*, 2(9).

[3]: Burney, J., Woltering, L., Burke, M., Naylor, R., & Pasternak, D. (2010). Solar-powered drip irrigation enhances food security in the Sudano–Sahel. *Proceedings of the National Academy of Sciences*, 107(5), 1848–1853.

[4]: IEA & IRENA. (2017). Perspectives for the Energy Transition – Investment Needs for a Low-carbon Energy System.

Nuclear

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.

Slider Settings

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

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

Model Structure

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

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

Footnotes

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

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

? New Zero-Carbon

Discover a brand-new cheap source of electricity that does not emit greenhouse gases. Some speculate that such a breakthrough could be nuclear fusion 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 CO_2 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.

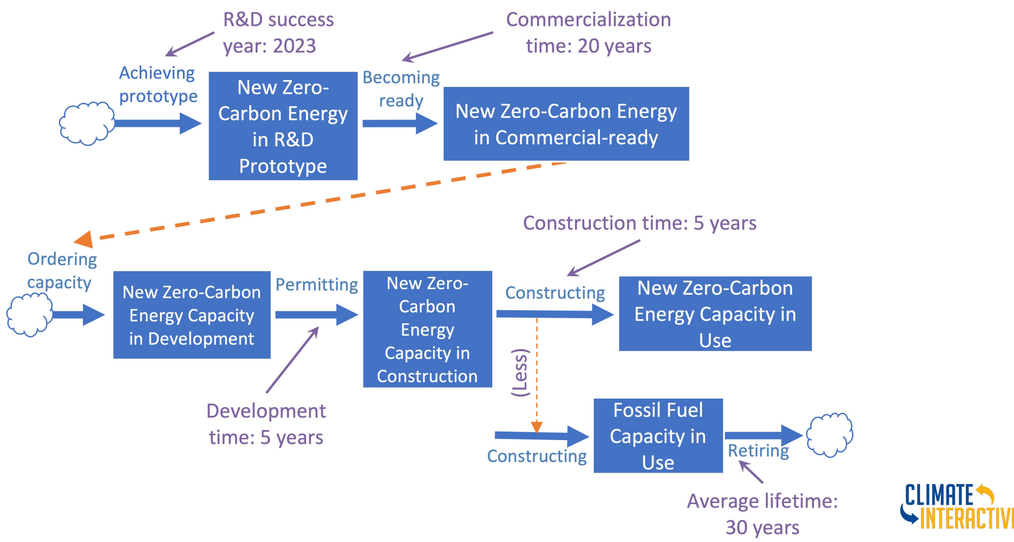
Big Messages

- 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 – 20 years to commercialize, several years to plan and build, and then growing only as existing coal and natural gas plants (which have a lifetime of 30 years) are retired. Watch how little Coal (brown area) and Natural Gas (dark blue area) go down before 2040. Because of this, very little carbon is kept underground during this critical period.
- **Price-Demand Feedback.** The reason the new zero-carbon technology grows quickly is that it is cheaper than all other energy supplies, so the abundance of inexpensive energy increases demand to higher than it would be otherwise. View this in the “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.

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



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

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

Equity Considerations

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

Slider Settings

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

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

Model Structure

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

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

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 CO_2 emissions from energy. To affect CO_2 emissions from land use, use the Deforestation and Afforestation sliders. To affect non-CO_2 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, it is not easily substituted for other energy sources (e.g., a diesel truck can’t be powered with solar). Bioenergy (in pink) increases as its relative cost makes it more attractive, unless you decide to apply the carbon price to bioenergy net emissions by turning on the “Carbon price applies to bioenergy emissions” switch in the advanced view. Renewables (in green) increases as the relative cost of wind and solar make them more attractive.

- **Price-Demand Feedback.** Just like taxing coal, a significant carbon price increases energy costs, which reduces energy demand. View this in the “Final Energy Consumption” graph, where a high carbon price Current Scenario (blue line) is lower than the Baseline Scenario (black line). Learn more.

- **Methane leakage.** When a carbon price is implemented, watch the blue line of the Current Scenario go down in the “CH_4 Emissions” graph. Natural gas is primarily composed of methane (CH_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.

Slider Settings

	status quo	low	medium	high	very high
Carbon price per ton of CO_2	**$ 0 to $5** *	$5 to $20	$20 to $60	$60 to $100	$100 to $250

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

Carbon price applies to bioenergy emissions

The switch “Carbon price applies to bioenergy emissions” in the Carbon Price advanced settings determines whether the CO_2 emissions from bioenergy are exempt from a carbon price. Many current policies exempt bioenergy from climate regulations or treat it as "net zero" even when it is not, so we default to the same for carbon pricing. If switched on, this will apply carbon prices to the net intensity of bioenergy the same as other sources of CO_2.

Carbon price encourages carbon capture and storage (CCS)

The switch “Carbon price encourages carbon capture and storage (CCS)” in the Carbon Price advanced settings determines whether CCS receives funding due to a carbon price. If turned off, CCS could only be encouraged by a Clean Electricity Standard.

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

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

Transport – Energy Efficiency

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

Examples

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

Big Messages

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

Key Dynamics

- **Impacts.**
    - Watch Oil (in red) decrease in the “Global Sources of Primary Energy” graph as the world increases the efficiency of its transport. Less oil is burned, and coal and gas fall as well, as electrified transport becomes more efficient.
    - View the “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.

Slider Settings

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

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

Model Structure

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

Case Studies

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

Barcelona, Spain: Replacing 20% of Barcelona's car trips with bikes could save 38 lives per year from decreased air pollution and increased physical activity, while also reducing 21,000 tons of CO_2 per year.[3]

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

Footnotes

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

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

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

Transport – Electrification

Increase 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

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

Key Dynamics

- **Efficiency.** Overall efficiency is greater for electrified transport than for internal combustion engines–in general, less fuel is used to power transport with electricity than oil.

- **Changes in the energy mix.** Oil, in the “Global Sources of Primary Energy” graph, goes down as we electrify transport. At the same time, primary energy demand for coal, renewables, and to a more limited extent, natural gas, all increase to power the rise in electric demand. For electrification to reduce emissions further, try subsidizing renewables, discouraging coal and natural gas, or adding a carbon price.

- **Renewables growth.** Electrification is necessary in order for transport to use renewables or other zero-carbon electricity. Notice how electrification enables Renewables Primary Energy Demand to grow much faster than in the Baseline Scenario.

- **Delays.** It takes decades for existing fuel-based vehicles to retire and be replaced by electric vehicles (this is known as “capital stock turnover delays”). As a result, the “Electric Share of Transport Sales” graph rises faster than the “Electric Share of Total Transport” graph.

Potential Co-Benefits of Encouraging Electrification

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

Equity Considerations

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

Slider Settings

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

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

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

Because it is more challenging technologically to electrify airplanes, boats, and ships, those forms of transport are in a separate "Air and Water" section of sliders in the advanced settings.

Model Structure

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

Note that the Baseline Scenario accounts for an increase in electrified transport over the century (see "Electric Share of Total Capital—Transport" graph).

FAQs and Explainers

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

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

Footnotes

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

Buildings and Industry – Energy Efficiency

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

Examples

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

Big Messages

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

Key Dynamics

- **Impact.** As less energy is used for buildings and industry, notice how all the energy sources decline in the "Global Sources of Primary Energy" graph—particularly coal and gas when they are the main sources of electricity. Less fossil fuels are burned so CO_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.

Slider Settings

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

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

Model Structure

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

Case Studies

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

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

FAQs

- How do I simulate reducing waste or inefficiency?
- How do I simulate recycling or reducing plastic?
- How do I simulate reducing emissions from cement production?

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

Footnotes

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

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

Buildings and Industry – Electrification

Increase the use of electricity, 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 Scenario.

- **Delays.** It takes decades for existing fuel-based equipment to retire and be replaced by electric equipment (this is known as "capital stock turnover delays"). As a result, the "Electric Share of Buildings & Industry Equipment Sales" graph rises faster than the "Electric Share of Total Buildings & Industry Equipment" graph.

Potential Co-Benefits of Encouraging Electrification

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

Equity Considerations

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

Slider Settings

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

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

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

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

Model Structure

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

FAQs and Explainers

- Explainer: Electrification in En-ROADS
- How do I simulate energy storage for wind and solar?

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

Footnotes

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

Population Growth

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

Examples

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

Big Messages

- Limiting population growth is not a silver bullet for addressing climate change.

- Decisions around population and family choice are personal decisions and efforts to shift these decisions have many ethical implications.

Key Dynamics

- **Impact.** Since energy demand depends on the number of people, watch all the sources of energy change as you change population growth. Use the Kaya graphs to understand how population growth affects emissions in your scenario.

- **Delay.** Lower population growth takes a long time to affect emissions because global population shifts do not occur quickly and instead play out over many decades.

Potential Co-Benefits of Lower Growth

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

Equity Considerations

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

Slider Settings

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

	lowest growth	low growth	status quo	high growth	highest growth
UN Scenario	low end of UN's 95% range		**middle of of UN's 95% range**		high end of UN's 95% range
Population in 2100	8.8 to 9.2 billion	9.2 to 10.0 billion	**10.0 to 10.9 billion**	10.9 to 11.9 billion	11.9 to 12.4 billion

Model Structure

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

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

Footnotes

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

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

[3]: United Nations. (2022). World Population Prospects 2022.

Economic Growth

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

Examples

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

Big Messages

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

Key Dynamics

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

Potential Co-Benefits of Lower Growth

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

Equity Considerations

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

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

Slider Settings

Economic Growth

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

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

Reduction in GDP from Climate Impacts

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

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

To learn more, visit the Economic Damage from Climate Change section of the En-ROADS Dynamics page.

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

Model Structure

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

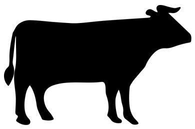
FAQs and Explainers

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

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

Footnotes

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



Methane & Other Gases

Decrease or increase greenhouse gas emissions from methane, nitrous oxide, and the F-gases. Methane (CH_4) is released from sources like cows, agriculture, oil and natural gas drilling, and waste. Nitrous oxide (N_2O) 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

- 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 for reducing emissions, although it requires many approaches across a diverse set of industries and more research and support is needed to scale them up.

Key Dynamics

- Methane, N_2O, and F-gas emissions comprise approximately 26% of current greenhouse gas emissions, and their reduction is key to addressing climate change.

- Plant-based diets that relate to methane emission reductions can be adjusted in the Deforestation advanced view, since demand for crops and grazing land is a primary driver of deforestation.

Potential Co-Benefits of Decreasing Methane & Other Gases

- 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 and good manure management can reduce water pollution, decrease eutrophication, and increase the health of aquatic ecosystems.

Equity Considerations

- 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.
- Adoption of practices to limit emissions in some industries requires technologies or methods that add costs to goods that can be passed on to consumers.

Slider Settings

The variable being changed is the percent reduction or percent increase of maximum possible action in methane and other greenhouse gases. 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.

	highly reduced	**moderately reduced**	**status quo**	**increased**
Percent reduction or increase of maximum action	-100% to -50%	-50% to -2%	**-2% to 0%**	0% to +10%

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_2 equivalency conversions. Greenhouse gases other than CO_2 that are reflected in graphs with the units CO_2e 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 throughout the model and in outputs like temperature change.

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

- Explainer: Food and Agriculture in En-ROADS

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

Footnotes

[1]: Castro, D. C., Samuels, M., & Harman, A. E. (2013). Growing Healthy Kids. *American Journal of Preventive Medicine*, 44(3).

Deforestation and Food

Decrease or increase the amount of forests and make changes to global food and agriculture choices. The main driver of deforestation is the need for cropland, which results in the permanent removal of forests. If the demand for additional cropland is avoided as a result of less food from animals, less food waste, or better crop yield then deforestation can be significantly reduced. Forest degradation is the temporary loss of forests due to harvesting for wood products or bioenergy.

Examples

- Government policy to preserve forested land and place restrictions on industries such as soybean and/or palm oil.
- Shifting from animal-based diets to more vegetarian and vegan diets.
- Improved supply chains that result in less food waste.
- Increased support for Indigenous land rights.
- Public support and campaigns to encourage land preservation.

Big Messages

- Reducing deforestation is part of a multi-pronged effort to address climate change. However, deforestation emissions are overshadowed by the enormous amount of carbon dioxide released through fossil fuel combustion.

- Protecting forests is helpful for many reasons other than climate action, including biodiversity conservation and protection of Indigenous peoples' lands.

Key Dynamics

- Highly reducing deforestation emissions reduces temperature less than most people would estimate. View the “Greenhouse Gas Net Emissions by Gas – Area” graph to see the role of land use, land use change, and forestry relative to all the other sources of emissions.

- As consumption grows, food waste and animal-based food demand increase the amount of cropland needed, which drives more deforestation.

- Drivers of forest degradation also include logging and harvesting forests for products like wood bioenergy (e.g., firewood and wood pellets), lumber, and paper products.

- Reducing deforestation and forest degradation reduces the net emissions from the land use sector. There is more carbon removal capacity from the forests if they are left to grow, and there are less gross emissions from carbon taken from forests through logging and harvesting. For an in-depth understanding of this dynamic, read the Land and Forests Explainer.

Potential Co-Benefits of Decreasing Deforestation

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

Equity Considerations

- Forest preservation efforts have sometimes restricted the land access of Indigenous people who have lived sustainably on the land for generations. Policies should be created with local stakeholder engagement.[1] [2]
- Many cultural values are attached to certain foods, meaning a change to more plant-based diets could require a large societal shift.

Slider Settings

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

Model Structure

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

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

FAQs and Explainers

- Explainer: Land and Forests in En-ROADS

- Explainer: Food and Agriculture in En-ROADS

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

Footnotes

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

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

Afforestation and Reforestation

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 CO_2 from the atmosphere, as photosynthesis pulls carbon into biomass and soils. Watch the temperature decrease modestly as a result.

- **Delay.** It takes decades for newly planted trees to remove enough carbon for it to be a significant source of carbon removals.

- **Reversibility.** Trees are susceptible to fire, insects, and weather-related damage, not to mention future harvests; all of which lead to carbon emissions as a result of combustion and decay.

- **Scale compared to emissions from energy.** The amount of carbon that additional trees can pull out of the atmosphere is overshadowed by the enormous amount of carbon dioxide released through fossil fuel combustion.

- **Land needed.** Explore the graph “Land for Growing CO_2 Removal Biomass.” The land area of India, represented by the dotted line, is approximately 329 million hectares.[1] 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.

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]

	status quo	low growth	medium growth	high growth
Percent available land for afforestation	**0% to +15%**	+15% to +40%	+40% to +70%	+70% to +100%

Model Structure

Forests are dynamic and result in both carbon removals and emissions. Notice in the "CO_2 Removal from Afforestation" graph that net CO_2 removals are lower than total removals due to the carbon loss from decay and forest fires in older or unhealthy forests.

Maximum amount of available land: For higher removals, one can adjust the "Max available land for afforestation" under 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.

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

- Why is planting trees (afforestation) not more impactful?

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

Footnotes

[1]: United Nations. (2020). Demographic Yearbook. Table 3.

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

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

Technological Carbon Dioxide Removal

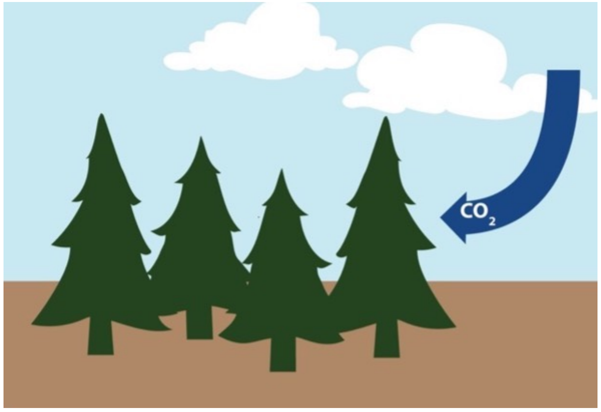
Carbon Dioxide Removal (CDR) technologies pull carbon out of the atmosphere by manually sequestering and storing carbon, or enhancing natural removals. CDR technologies include: direct air capture, enhanced mineralization, agricultural soil carbon, and biochar. CDR approaches face significant barriers to scale up and deployment.

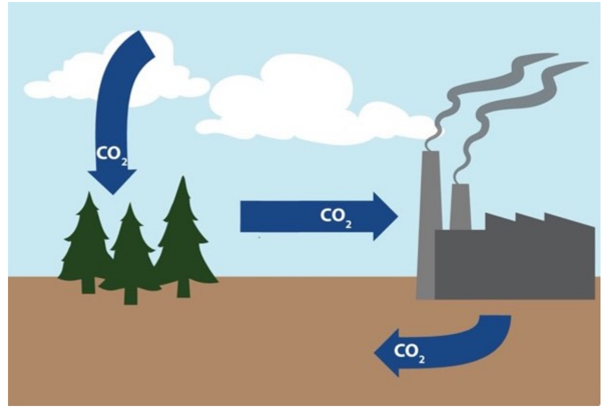
Examples

- 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

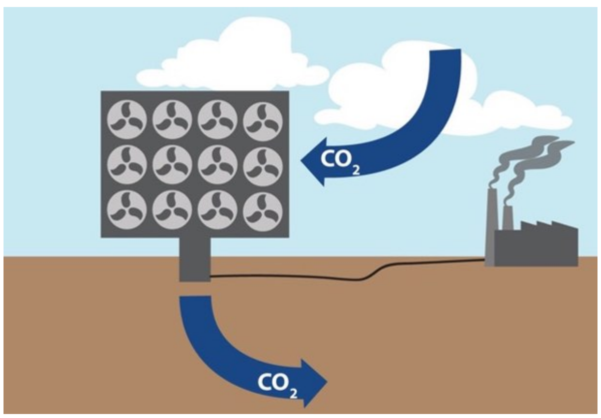
The following methods of CO_2 removal can be explored in the En-ROADS simulator:

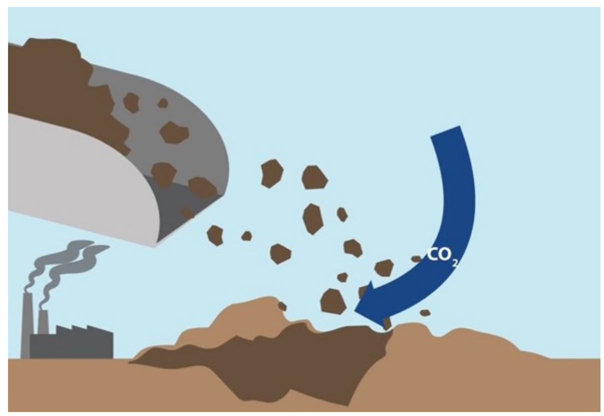




Afforestation and reforestation. As trees grow, they draw carbon out of the air, which reduces the concentration of carbon dioxide. The CO_2 is then stored in living biomass.

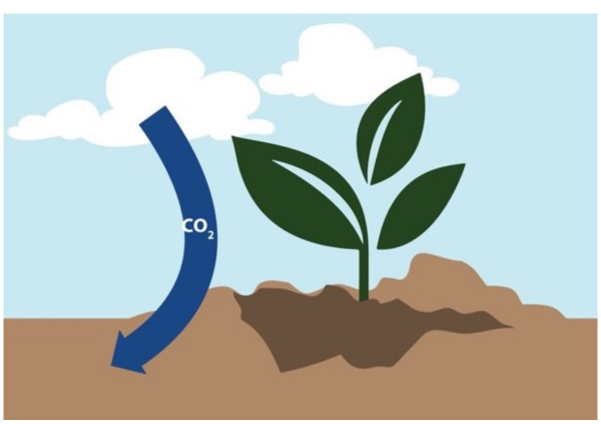
Bioenergy with carbon capture and storage (BECCS) entails burning biomass for energy, capturing the CO_2 emissions, storing the emissions long-term, and successfully re-growing any used biomass. *(Coming back soon in a future update.)*

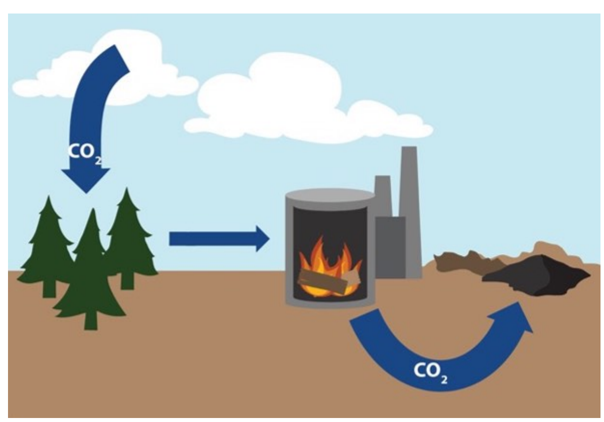




Direct air carbon capture and storage (DACCS) is an emerging technology that pulls CO_2 out of the air, where it is then stored in geological reserves. To get a net removal benefit, the captured carbon must be stored long term.

Enhanced mineralization entails mining specific rocks—like basalt—that can absorb CO_2 from the air and converting it to rock for long-term carbon storage.





Agricultural soil carbon sequestration involves using agricultural practices which enhance soil carbon (such as no-till agriculture and preventing overgrazing).	**Biochar** is biomass (e.g., from trees) that has been made into charcoal via pyrolysis, and is then buried to retain the carbon.

Big Messages

- 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 CO_2-Removal Biomass" and "Land for Farming with CO_2 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 carbon 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 carbon capture and storage 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.

Slider Settings

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

Model Structure

The methods of CO_2 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

- **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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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:

- Global Carbon Project: Friedlingstein, P., et al. (2022). Global carbon budget 2022. *Earth System Science Data, 14,* 4811–4900. [CO_2 energy emissions only]
- IEA. (2020a). *Evolution of solar PV module cost by data source, 1970-2020.*
- IEA. (2020b). *Global average LCOEs and auction results for utility-scale PV by commissioning date.*
- IEA WEO: IEA. (2022). *World Energy Outlook 2022.*
- IEA World Energy Statistics & Balances: IEA. (2022). *World Energy Statistics & Balances.*
- IRENA. (2020). *Renewable Power Generation Costs in 2019.*
- Lazard. (2021). *Lazard's Levelized Cost of Energy Analysis - Version 15.0.*
- LUH2: Hurtt, G. C., et al. (2020). Harmonization of global land-use change and management for the period 850-2100 (LUH2) for CMIP6. *Geoscientific Model Development, 13*(11), 5425–5464.
- Met Office Hadley Centre HadCRUT5: Morice, C. P., et al. (2022). An updated assessment of near-surface temperature change from 1850: the HadCRUT5 dataset. *Journal of Geophysical Research: Atmospheres, 126,* e2019JD032361. Data available at https://www.metoffice.gov.uk/hadobs/hadcrut5/data/current/download.html.
- NASA GISS. (2022). *GISS Surface Temperature Analysis (GISTEMP), version 4.* NASA Goddard Institute for Space Studies.
- NOAA AGGI: NOAA. (2022). *Annual Greenhouse Gas Index.*
- NOAA ESRL: NOAA. (2022). *Trends in Atmospheric Carbon Dioxide.*
- PRIMAP: Gütschow, J., Günther, A., & Pflüger, M. (2021). *The PRIMAP-hist national historical emissions time series (1850-2018). v2.3.1.* [Non-CO_2 greenhouse gas emissions only]

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 Bioenergy
- Primary Energy from Nuclear

Global primary energy demand of energy sources for the En-ROADS Baseline Scenario compared to IEA historical data. This is measured in exajoules per year (joules x 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).

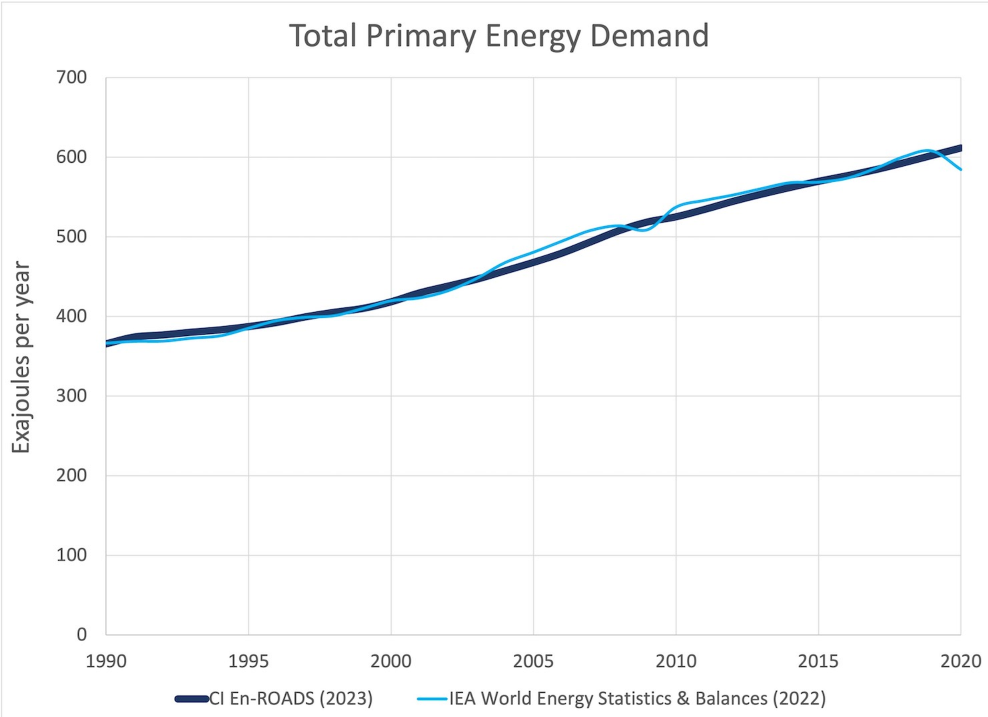
Statistical fit

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

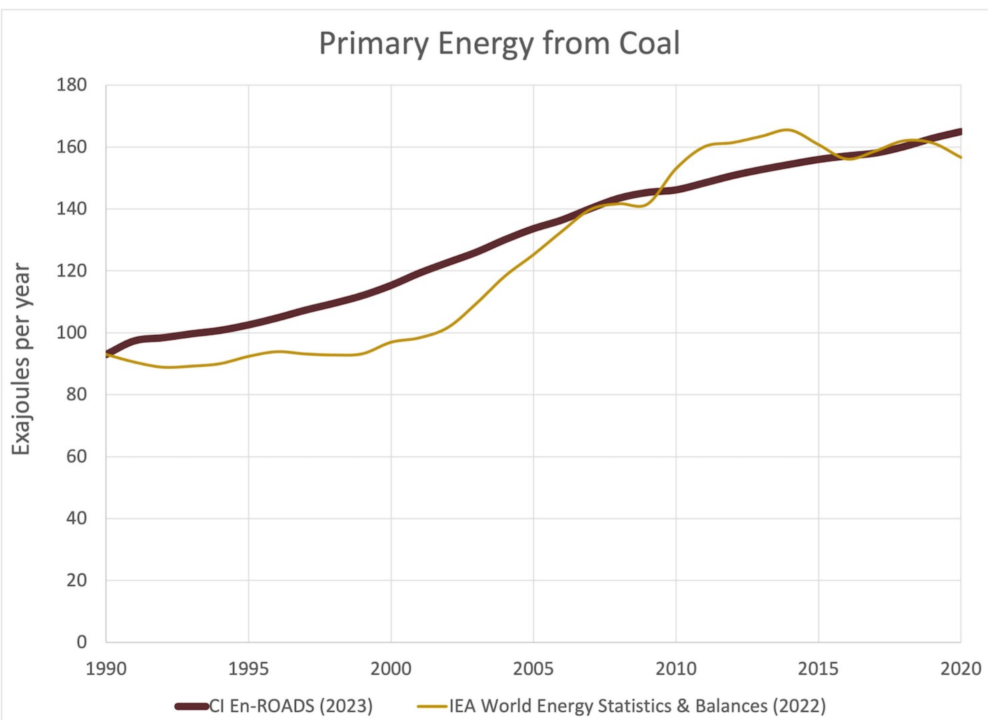
Sources of historical data

- IEA World Energy Statistics & Balances: IEA. (2022). *World Energy Statistics & Balances.*

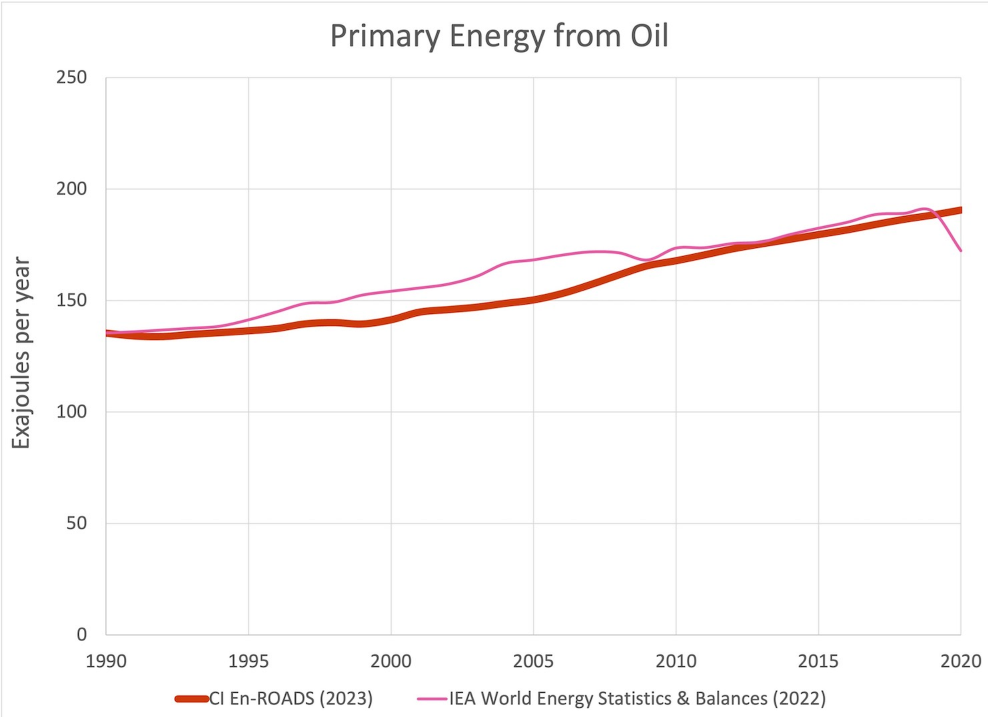
Total Primary Energy Demand



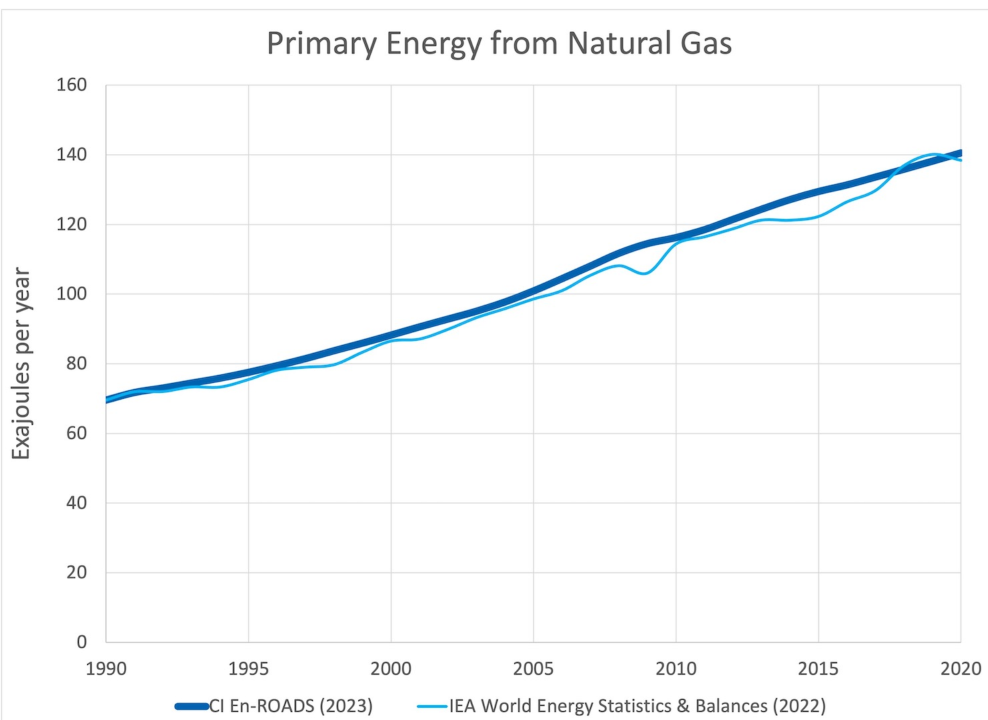
Primary Energy from Coal



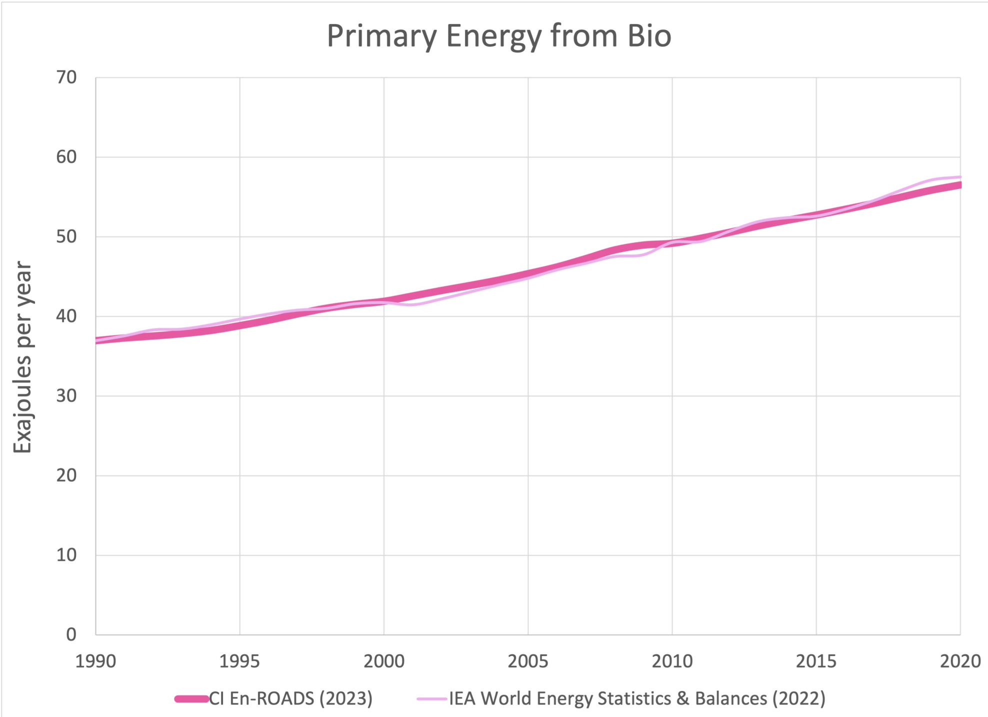
Primary Energy from Oil



Primary Energy from Natural Gas

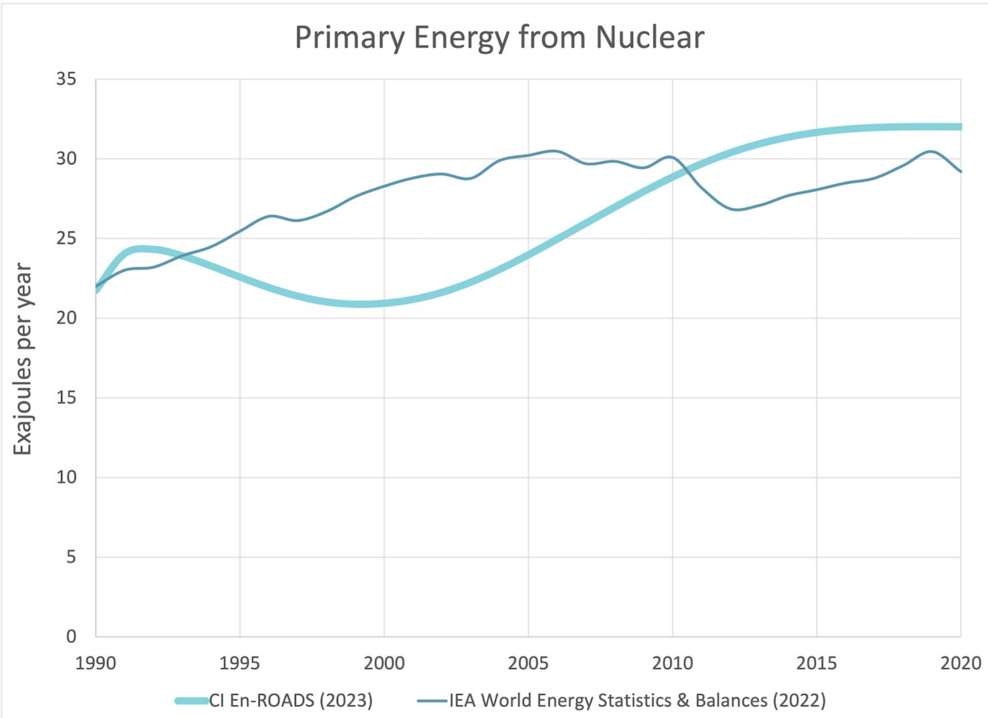


Primary Energy from Bioenergy



Primary Energy from Nuclear

En-ROADS, as well as many other sources, assumes that nuclear energy has an efficiency of 100% conversion of primary energy into electricity generated. Some sources, like the IEA WEO, assume that the primary energy equivalent from the electricity generation has an efficiency of 33%. To compare En-ROADS output to the IEA WEO, we multiply the primary energy in En-ROADS by 3.



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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 Scenario 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.

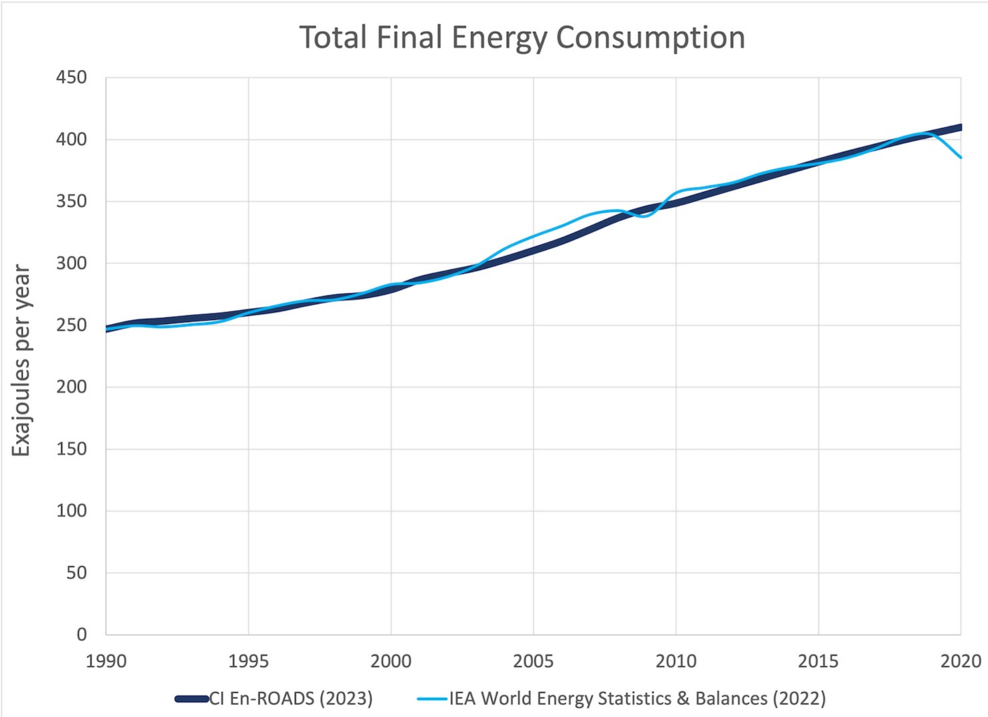
Statistical fit

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

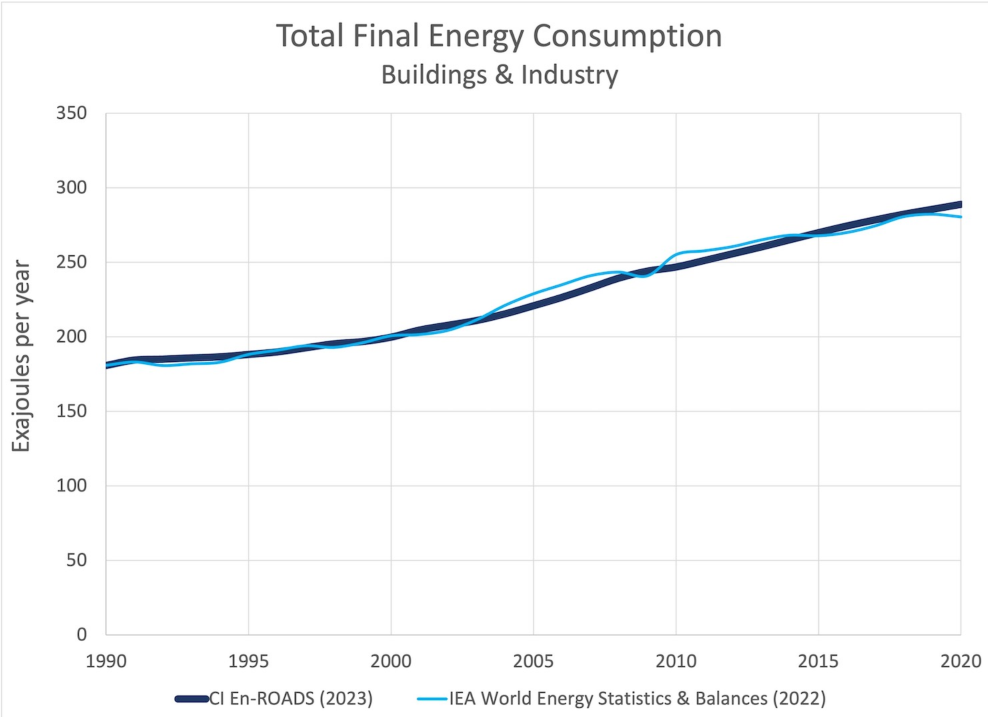
Sources of historical data

- IEA World Energy Statistics & Balances: IEA. (2022). *World Energy Statistics & Balances.*

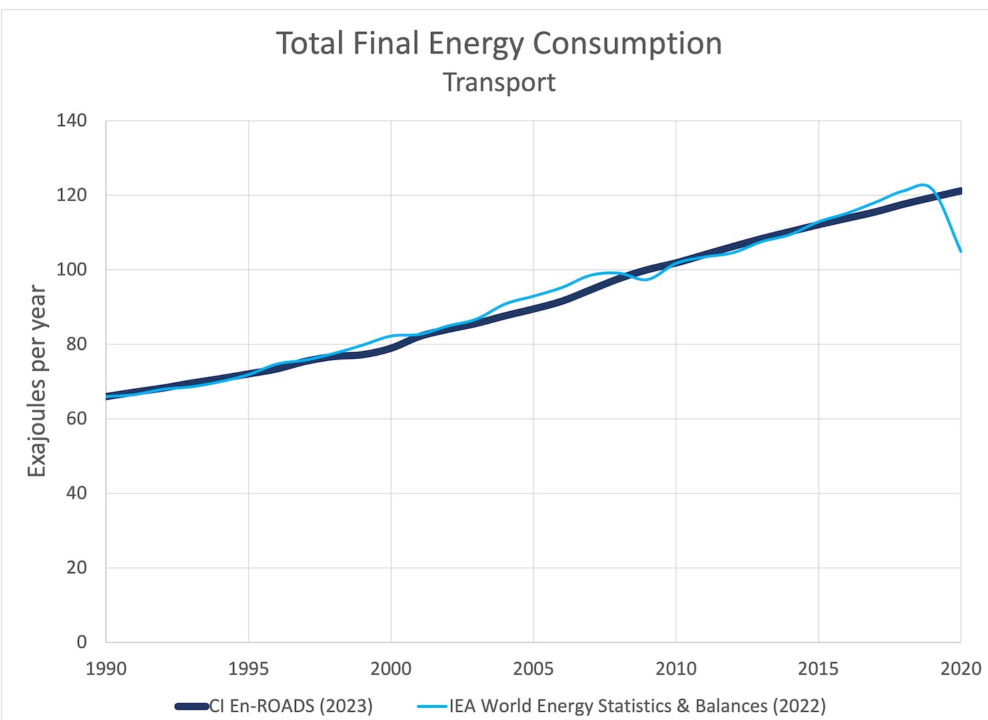
Total Final Energy Consumption



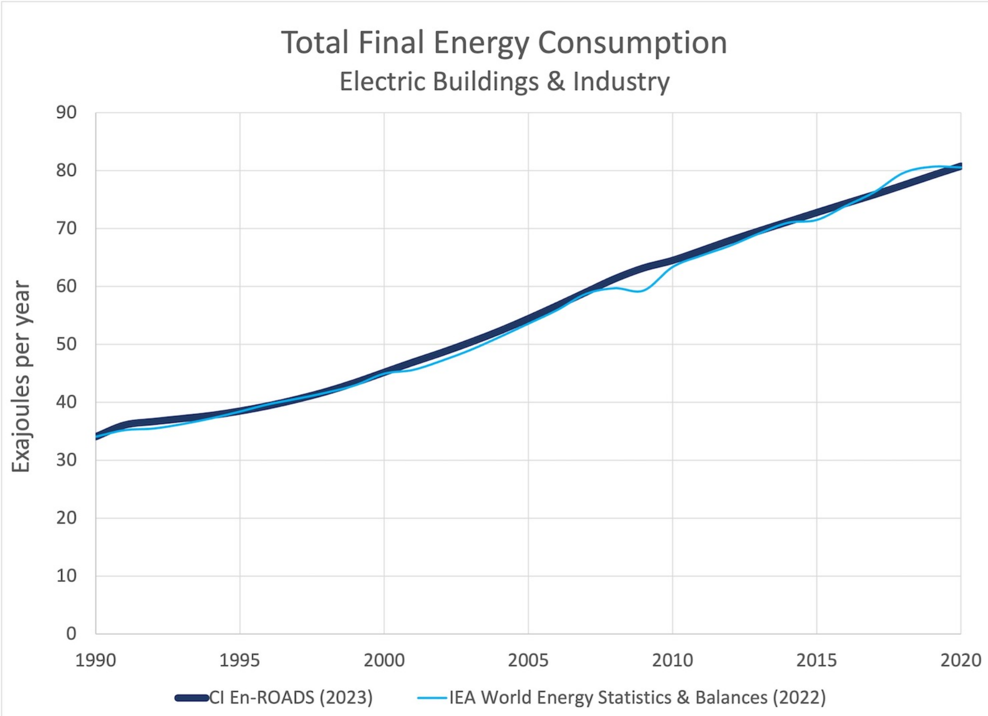
Total Final Energy Consumption – Buildings & Industry



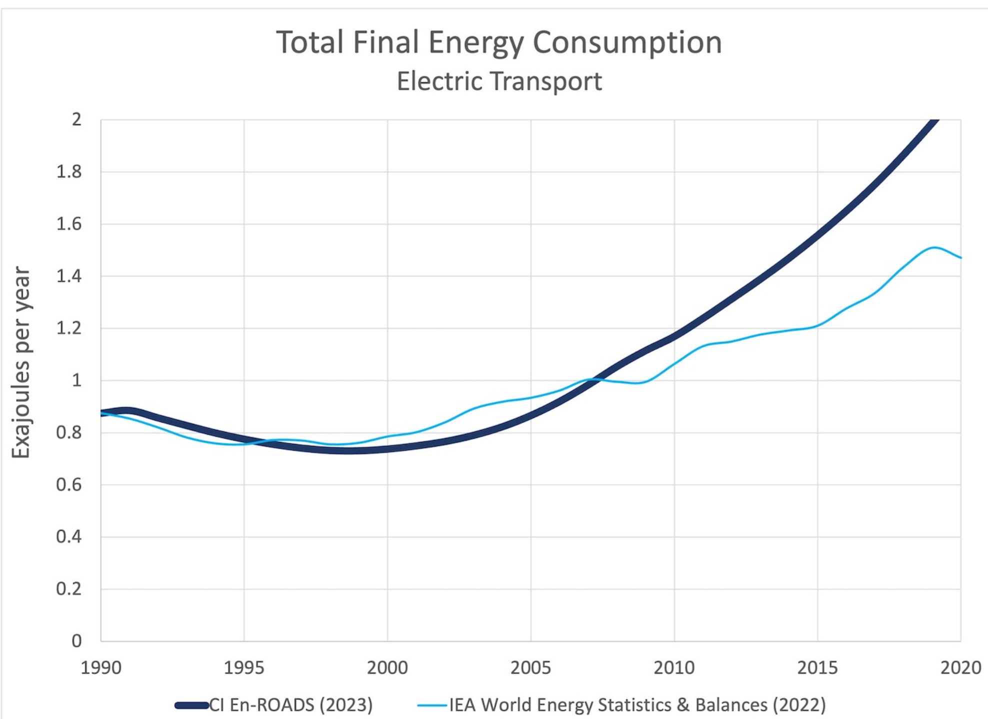
Total Final Energy Consumption – Transport



Total Final Energy Consumption – Electric Buildings & Industry



Total Final Energy Consumption – Electric Transport



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Electricity Generated by Energy Source History

- Electricity Generated by Coal
- Electricity Generated by Oil
- 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 Scenario compared to historical data.

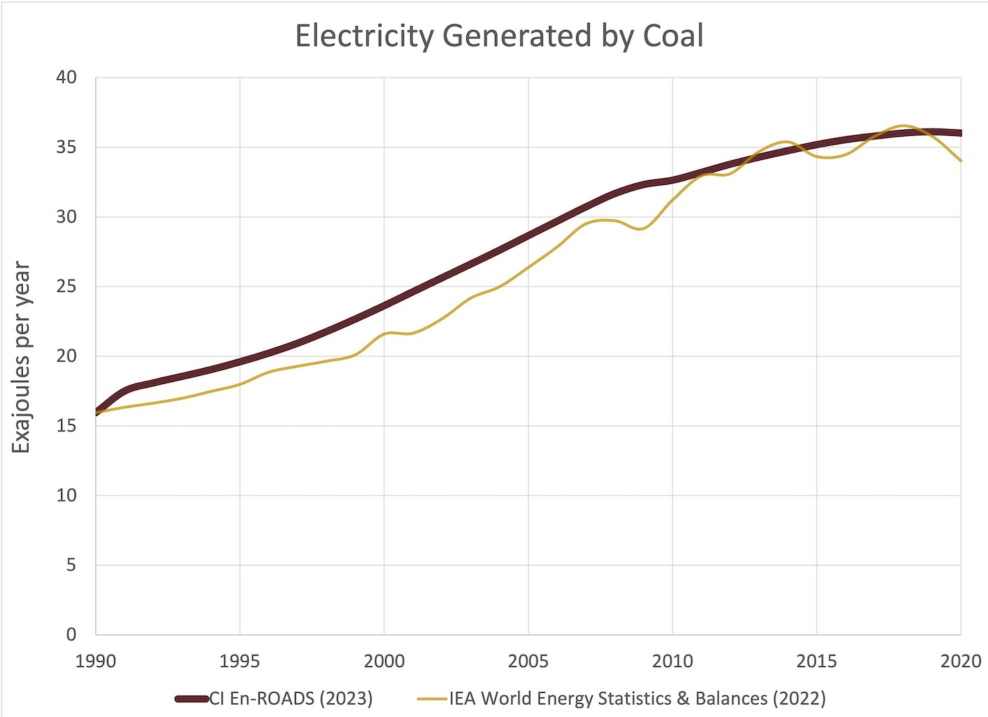
Statistical fit

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

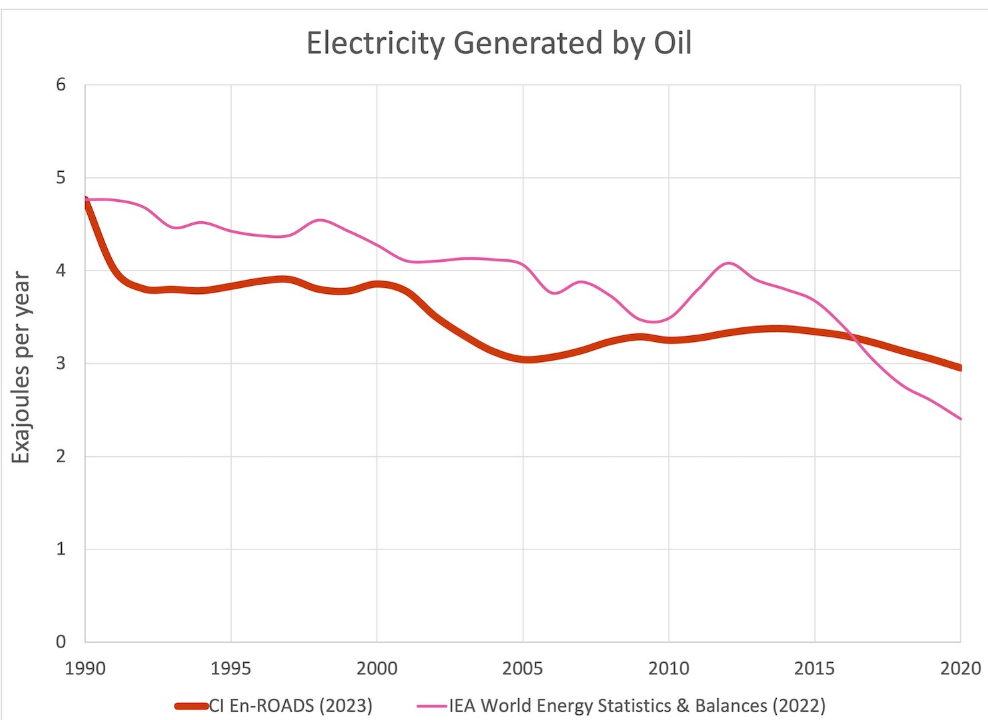
Sources of historical data

- IEA World Energy Statistics & Balances: IEA. (2022). *World Energy Statistics & Balances.*

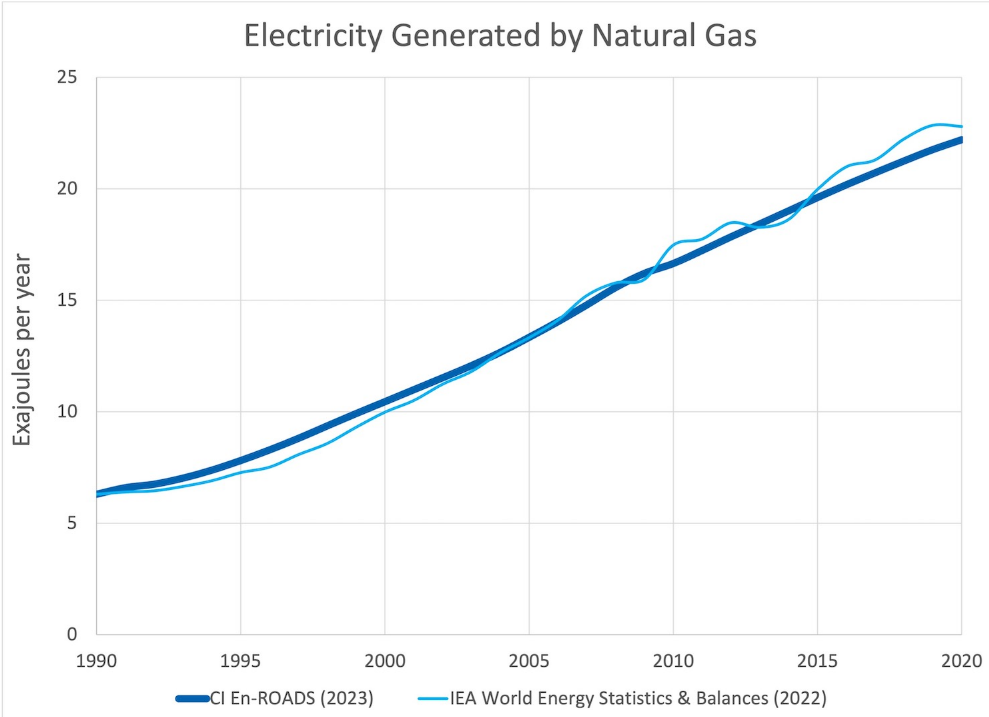
Electricity Generated by Coal



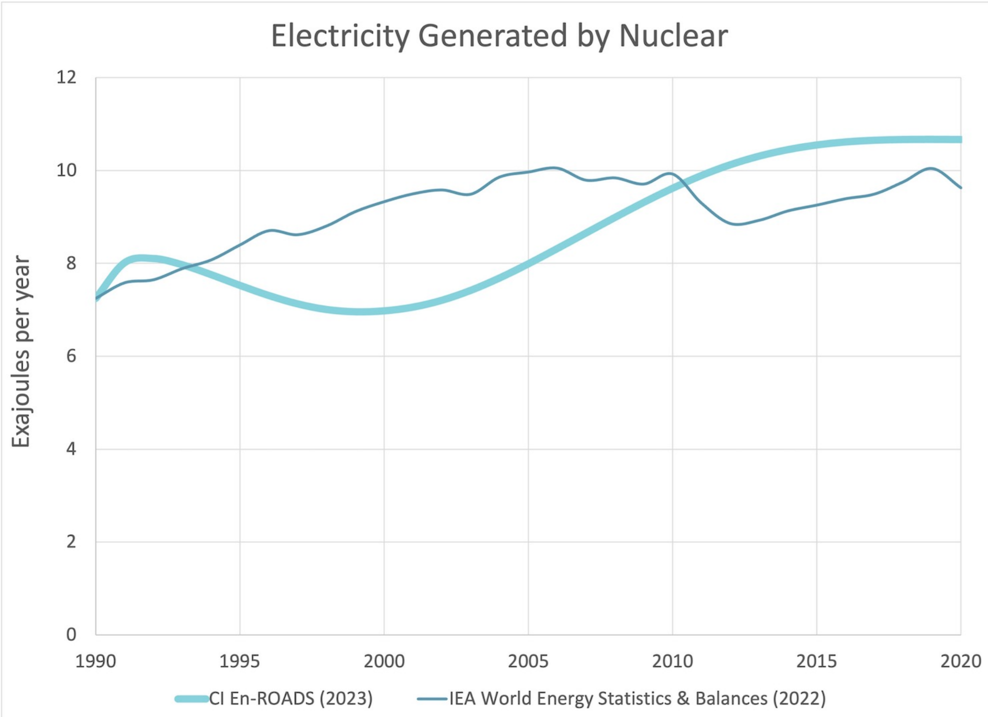
Electricity Generated by Oil



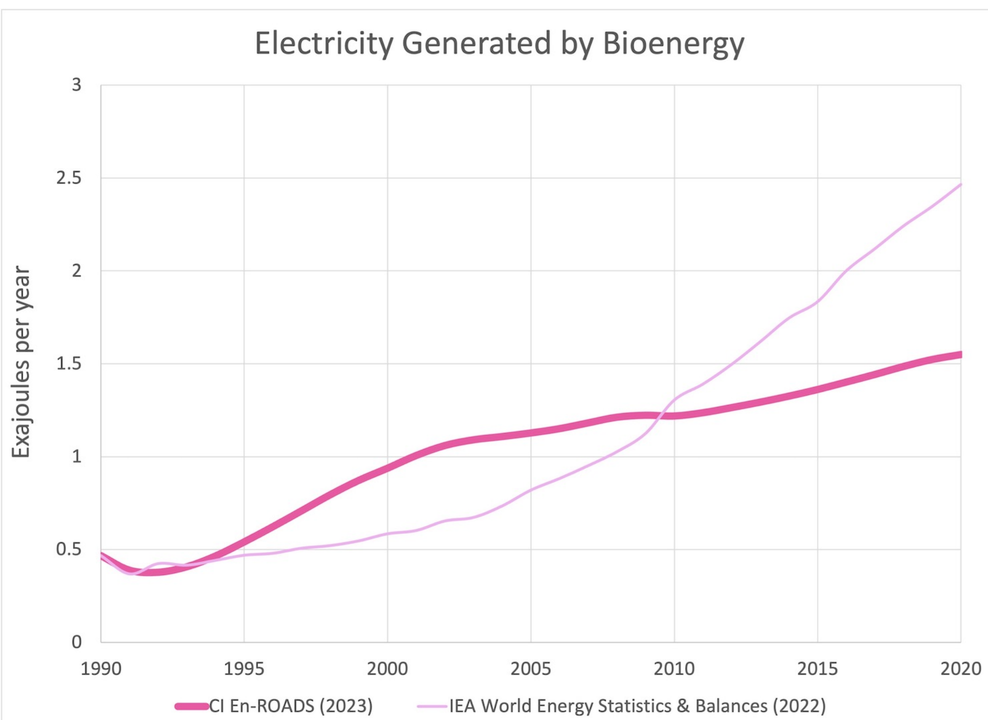
Electricity Generated by Natural Gas



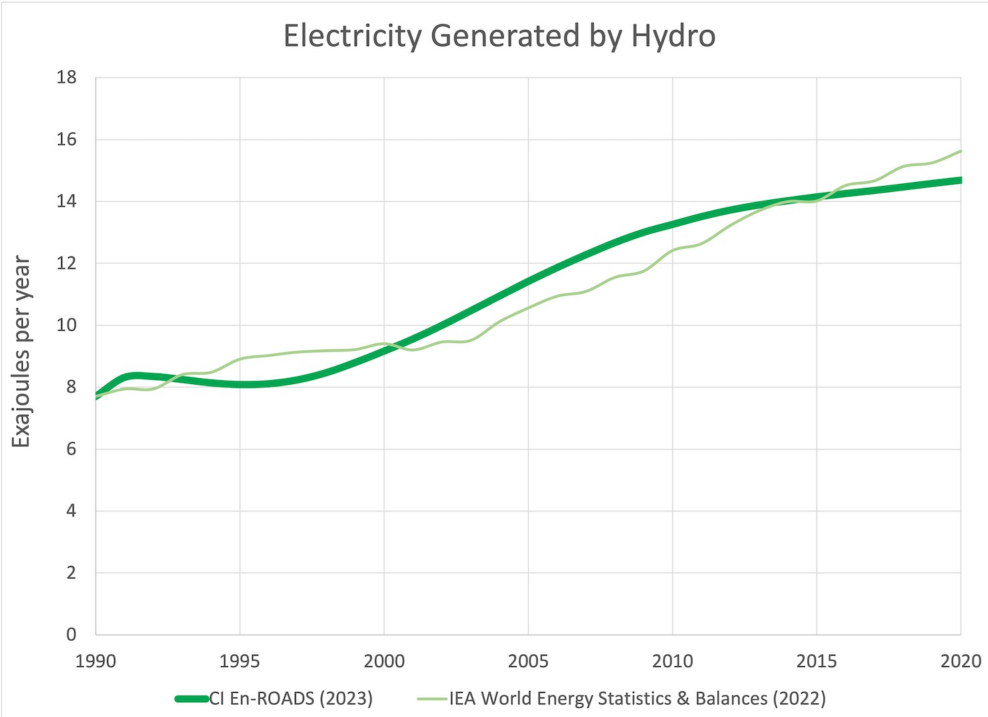
Electricity Generated by Nuclear



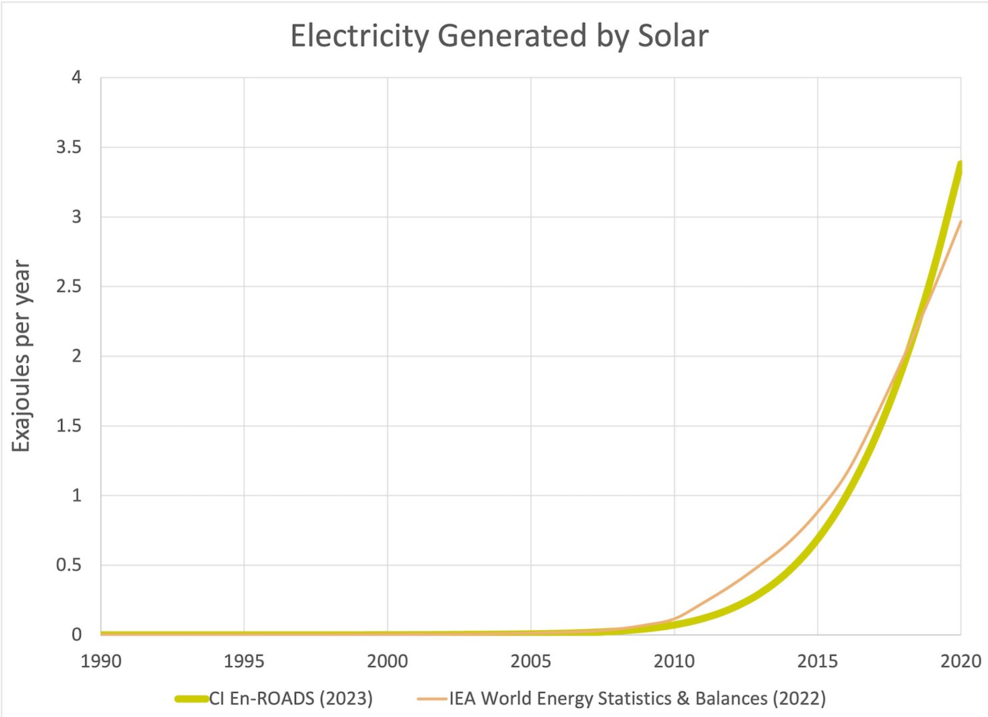
Electricity Generated by Bioenergy



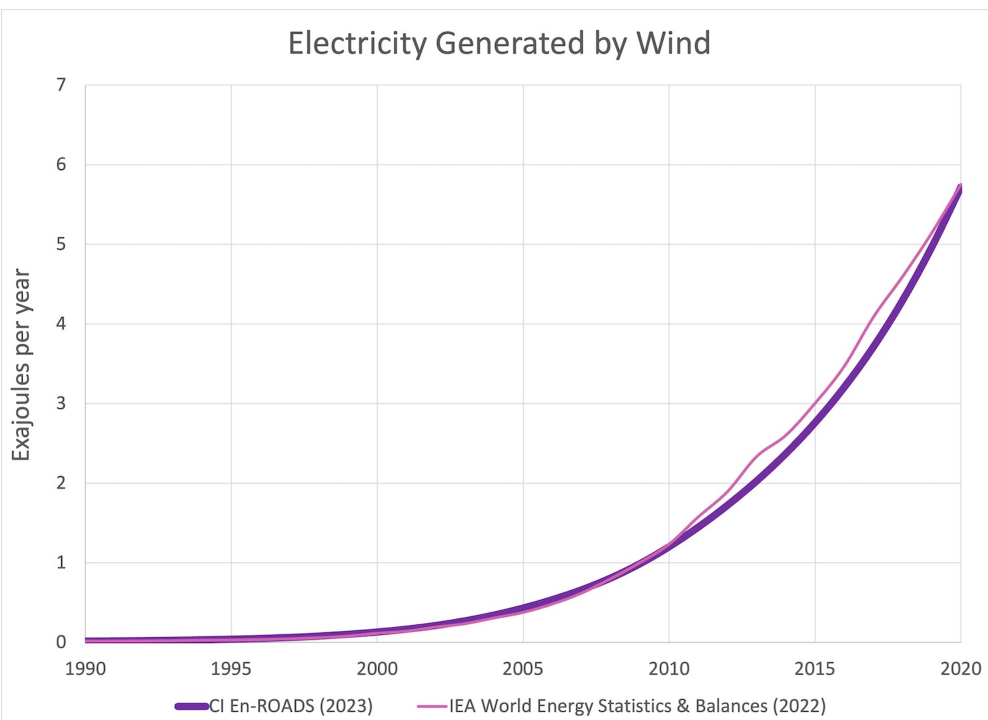
Electricity Generated by Hydro



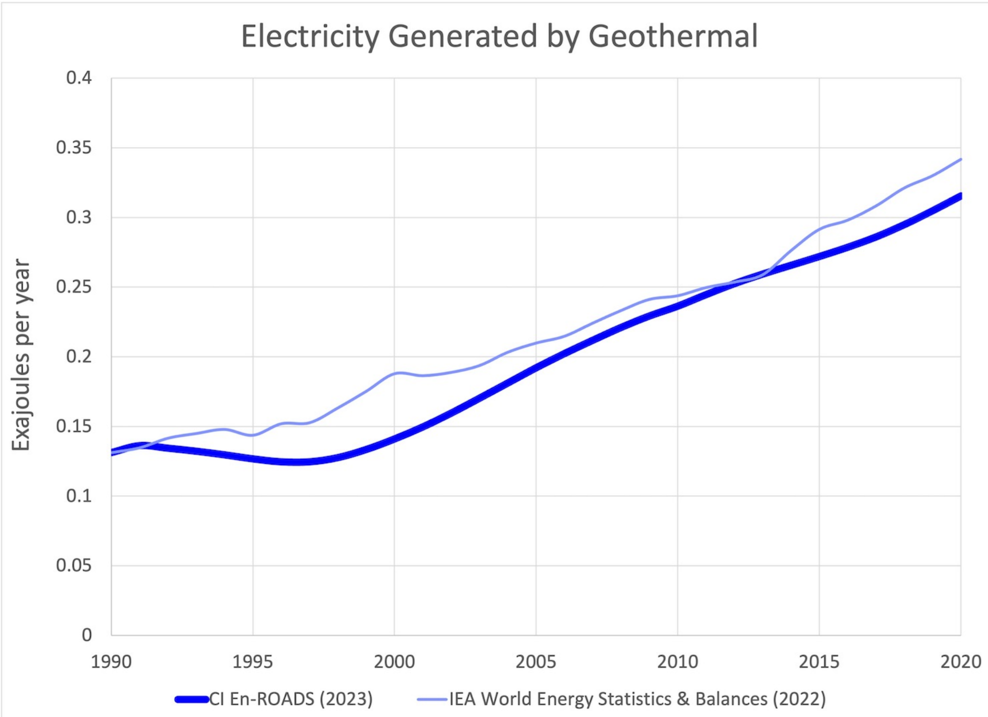
Electricity Generated by Solar



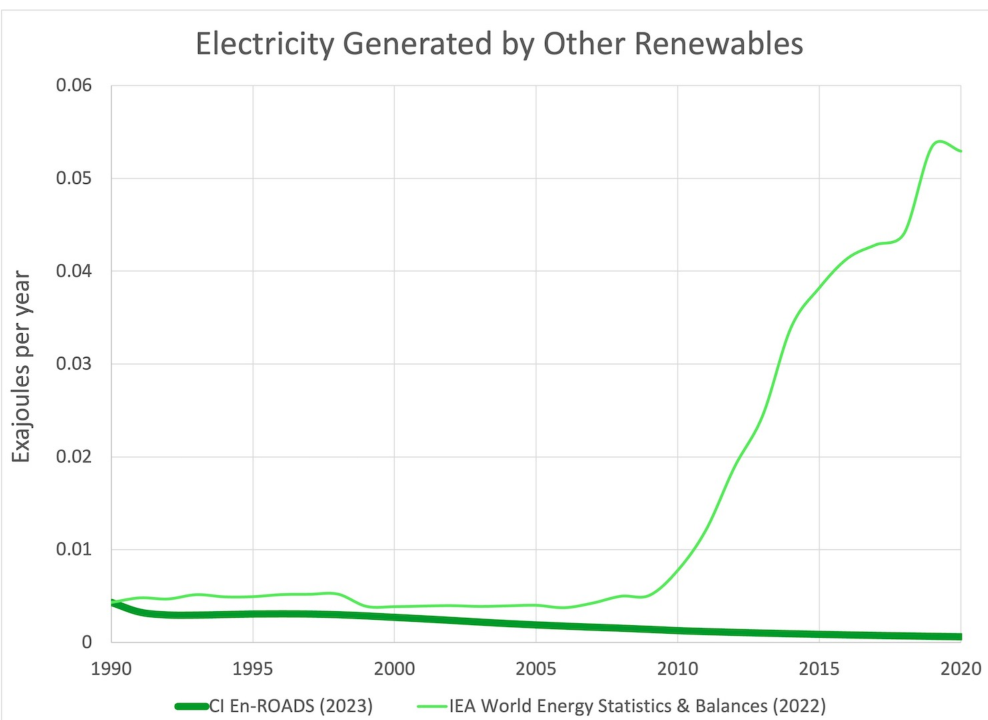
Electricity Generated by Wind



Electricity Generated by Geothermal



Electricity Generated by Other Renewables



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

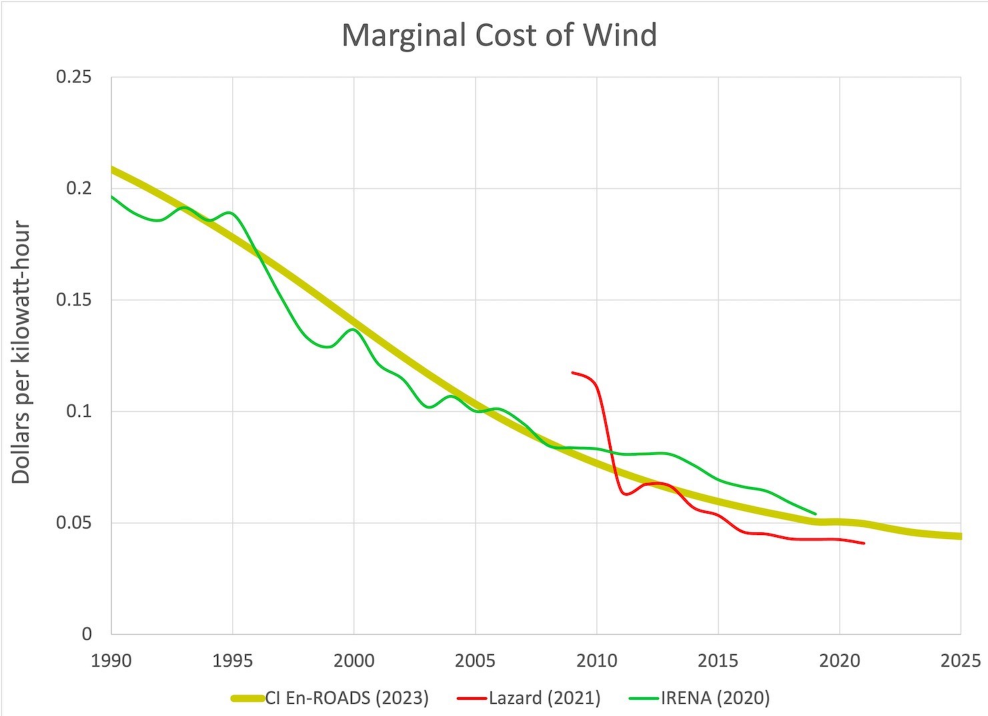
Statistical fit

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

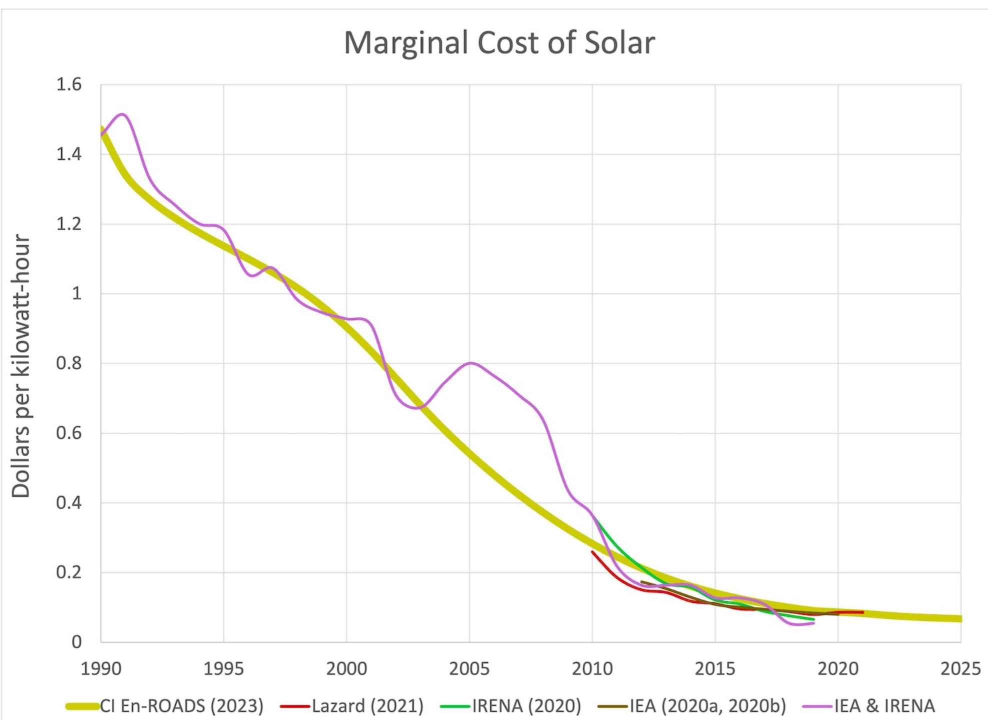
Sources of historical data

- IEA. (2020a). *Evolution of solar PV module cost by data source, 1970-2020.*
- IEA. (2020b). *Global average LCOEs and auction results for utility-scale PV by commissioning date.*
- IRENA. (2020). *Renewable Power Generation Costs in 2019.*
- Lazard. (2021). *Lazard's Levelized Cost of Energy Analysis - Version 15.0.*

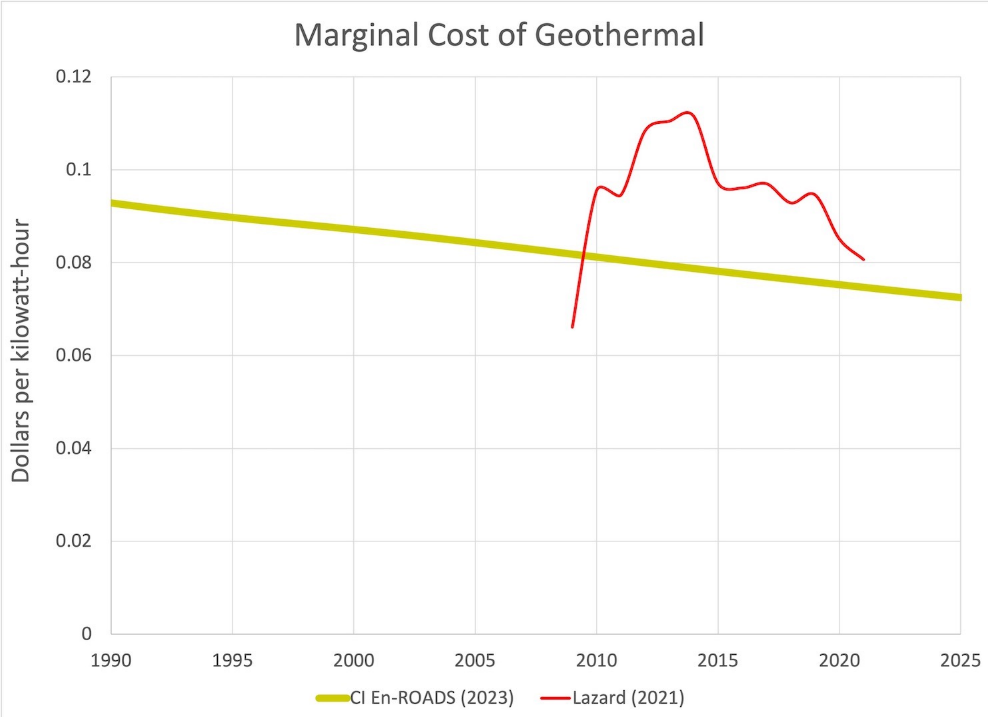
Marginal Cost of Wind



Marginal Cost of Solar



Marginal Cost of Geothermal



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Emissions History

- Greenhouse Gas Net Emissions
- CO_2 Net Emissions
- CO_2 Emissions from Fossil Fuels
- CH_4 Emissions
- N_2O Emissions
- F-Gas Emissions

Global greenhouse gas emissions (GHGs) in the En-ROADS Baseline Scenario and historical data, in gigatons of CO_2 or CO_2 equivalents per year. CO_2 equivalents are used to standardize the effect of all greenhouse gases in terms of CO_2.

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 (CO_2), nitrous oxide (N_2O), methane (CH_4), and the F-gases (PFCs, SF_6 and HFCs).

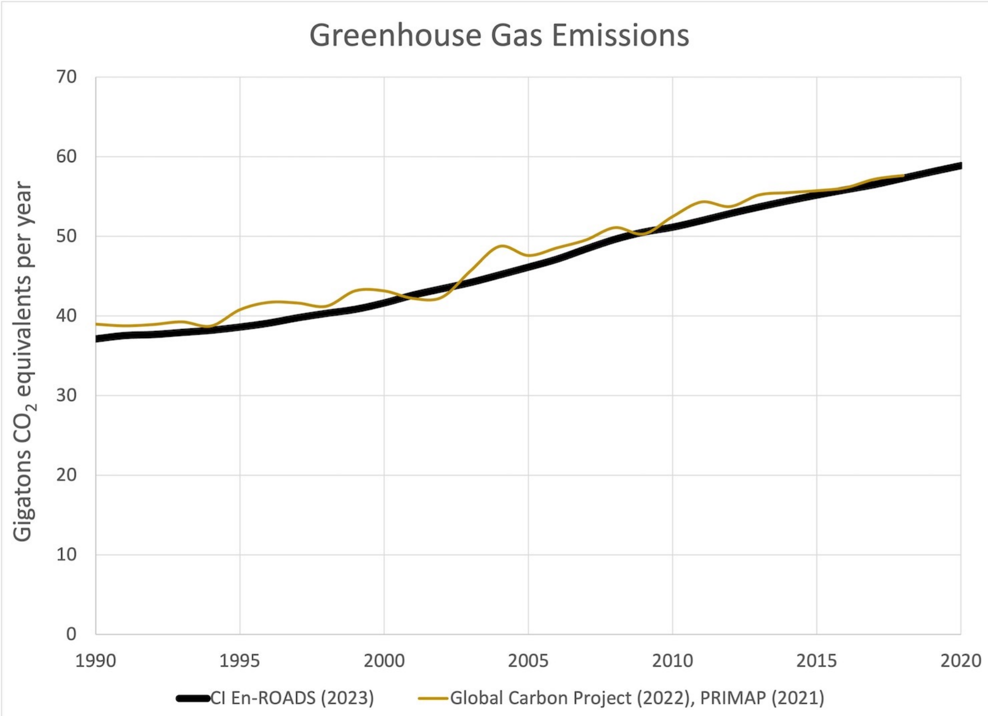
Statistical fit

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

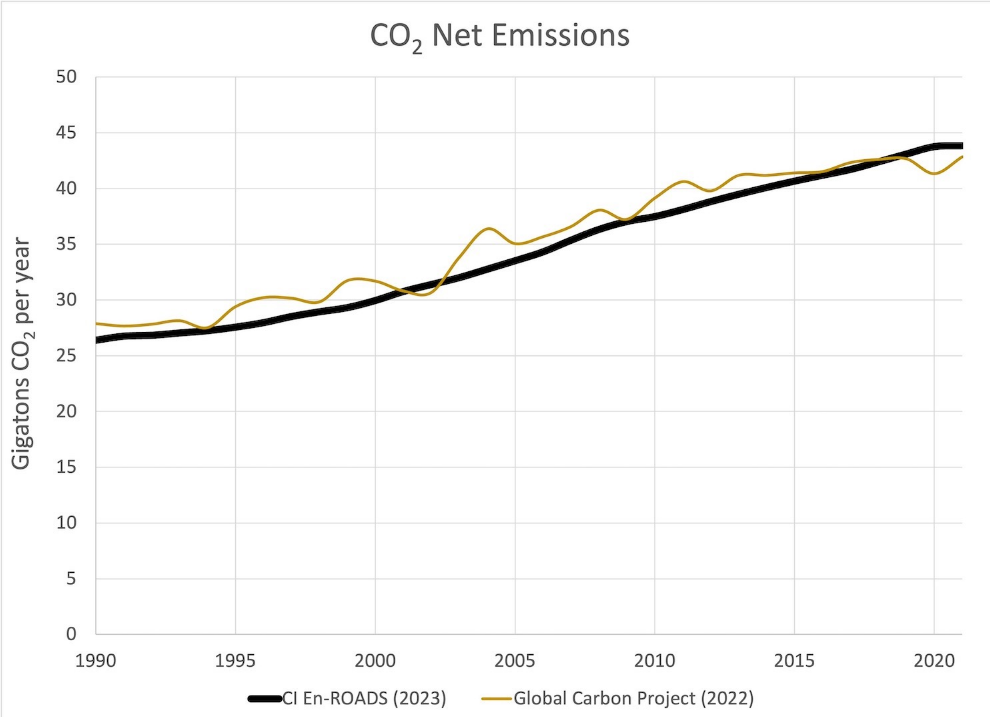
Sources of historical data

- Global Carbon Project: Friedlingstein, P., et al. (2022). Global carbon budget 2022. *Earth System Science Data, 14,* 4811–4900. [CO_2 energy emissions only]
- IEA WEO: IEA. (2022). *World Energy Outlook 2022.*
- PRIMAP: Gütschow, J., Günther, A., & Pflüger, M. (2021). *The PRIMAP-hist national historical emissions time series (1850-2018). v2.3.1.* [Non-CO_2 greenhouse gas emissions only]

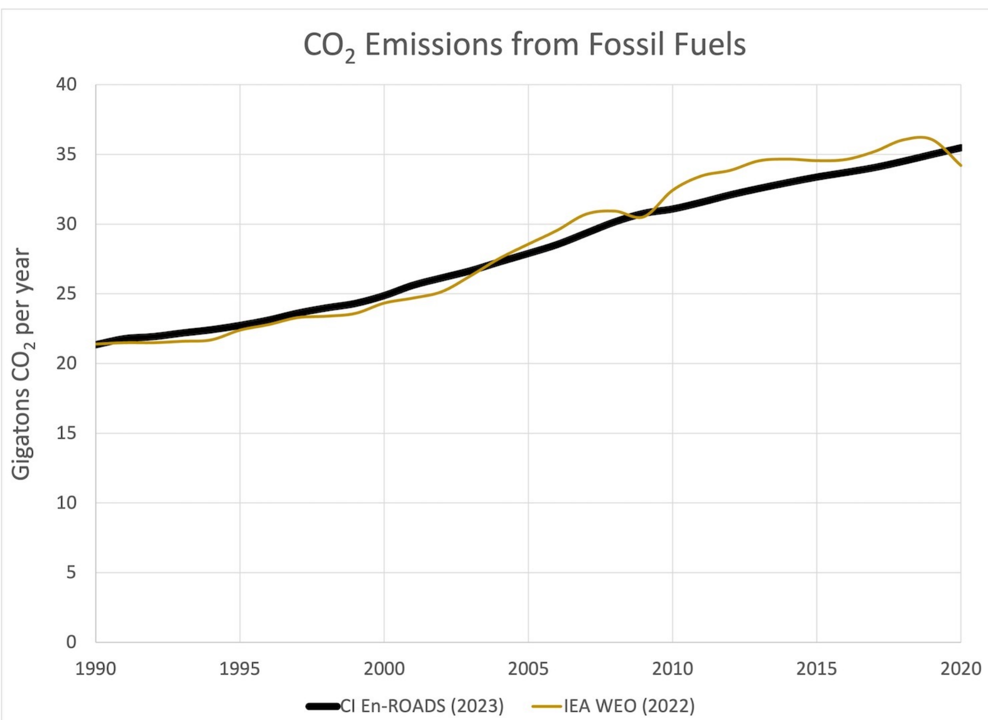
Greenhouse Gas Net Emissions



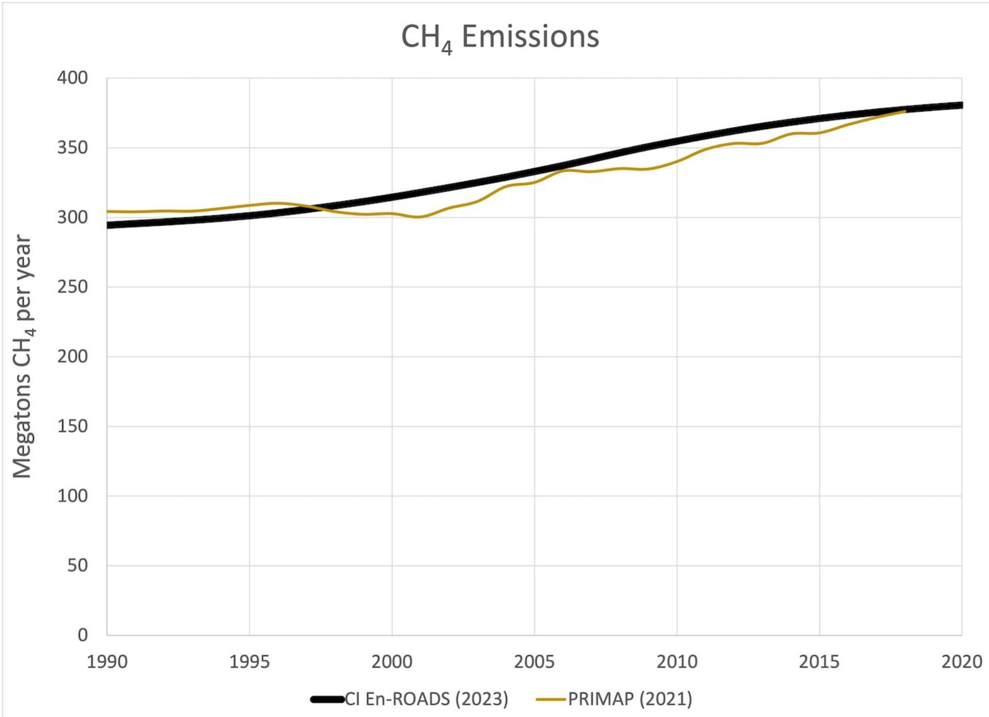
CO_2 Net Emissions



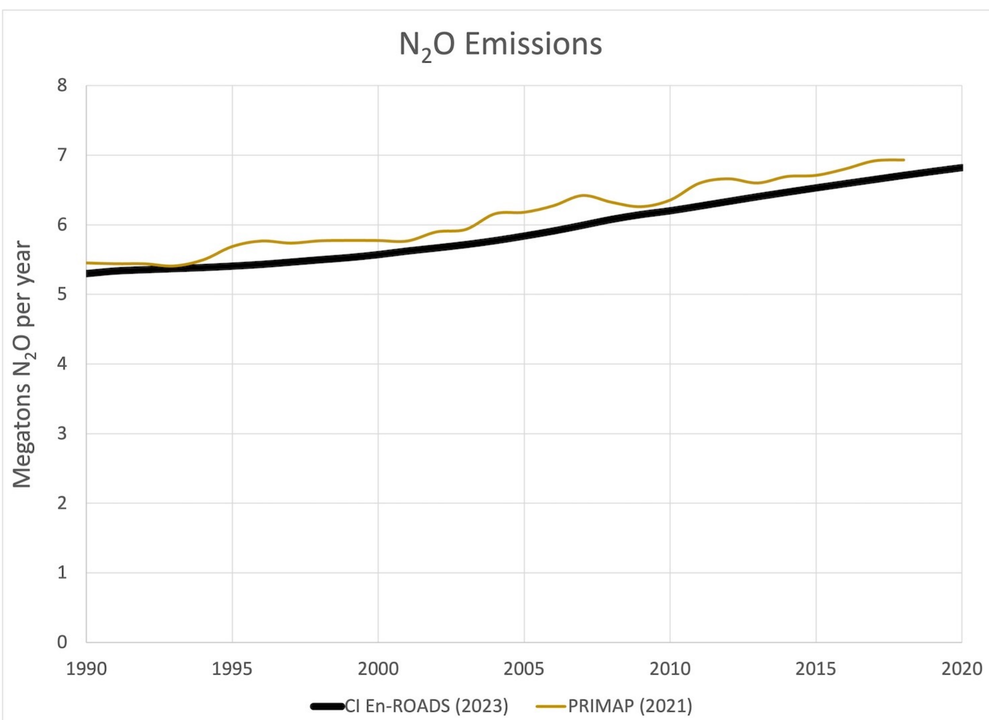
CO_2 Emissions from Fossil Fuels



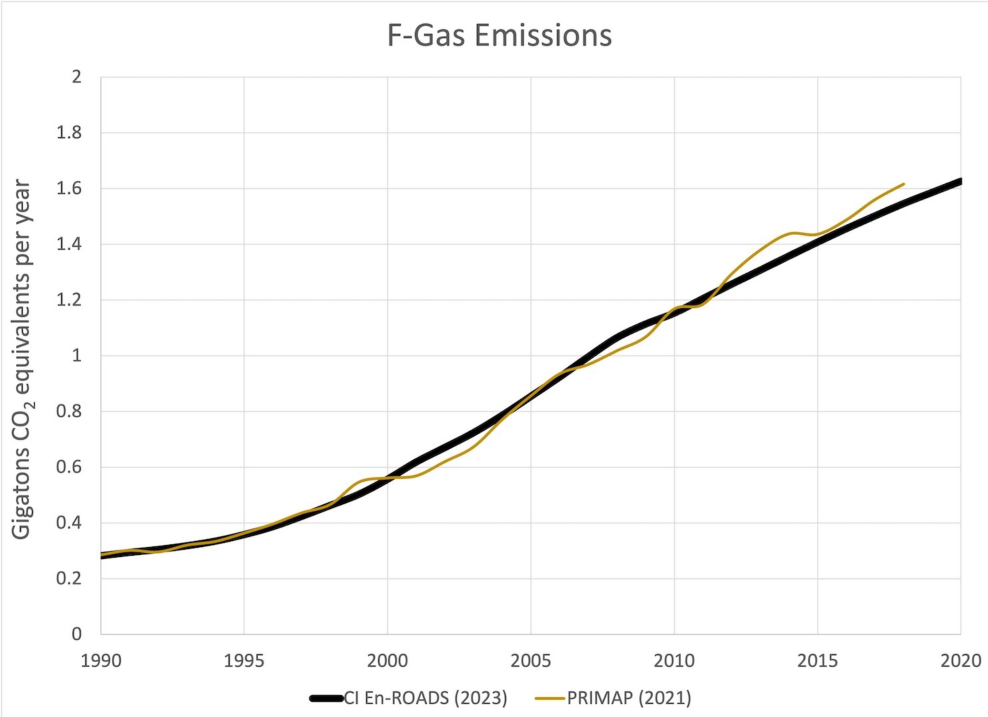
CH_4 Emissions



N_2O Emissions



F-Gas Emissions



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Atmospheric Concentrations History

- CO_2 Concentration in the Atmosphere
- CH_4 Concentration in the Atmosphere
- N_2O Concentration in the Atmosphere

The total concentration of CO_2, CH_4, and N_2O in parts per million (ppm) of CO_2 equivalents in the atmosphere in the En-ROADS Baseline Scenario compared to historical data.

Carbon dioxide equivalents (CO_2e) 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.

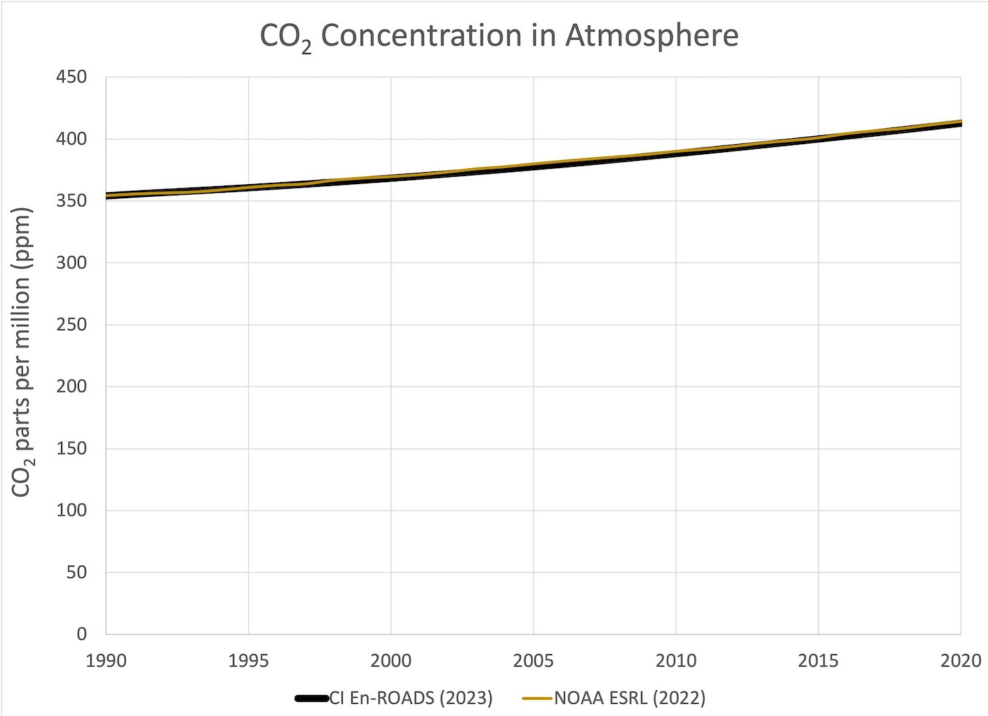
Statistical fit

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

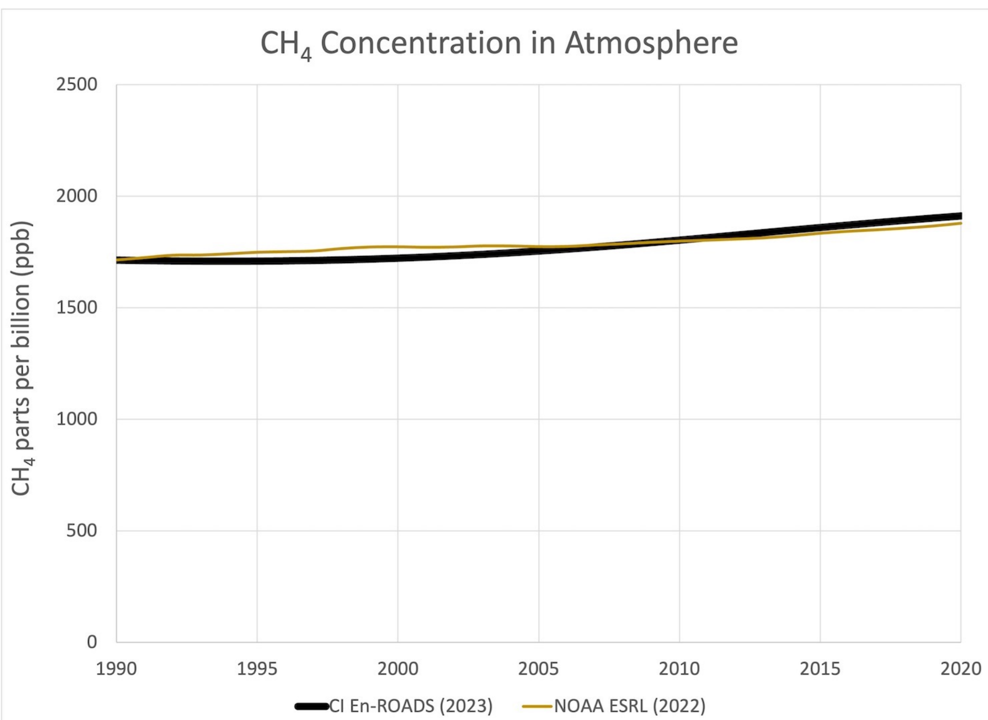
Sources of historical data

- NASA GISS. (2022). *GISS Surface Temperature Analysis (GISTEMP), version 4.* NASA Goddard Institute for Space Studies.
- NOAA ESRL: NOAA. (2022). *Trends in Atmospheric Carbon Dioxide.*

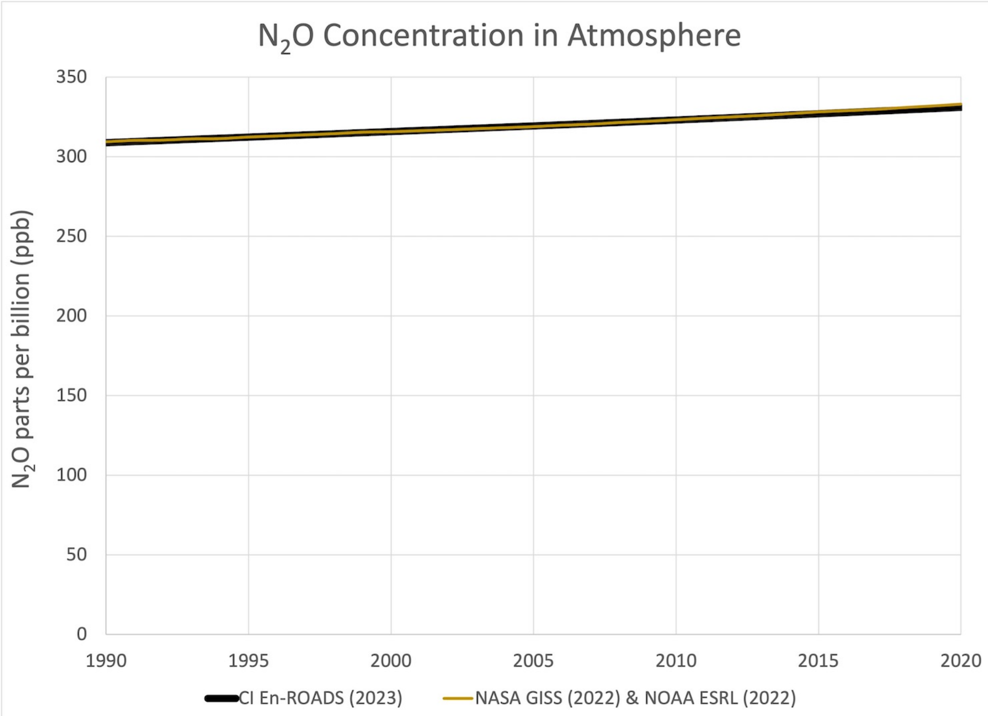
CO_2 Concentration in the Atmosphere



CH_4 Concentration in the Atmosphere



N_2O Concentration in the Atmosphere



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Radiative Forcing History

- CO_2 Radiative Forcing
- CH_4 Radiative Forcing
- N_2O Radiative Forcing
- Halocarbon Radiative Forcing

The radiative forcing due to CO_2, CH_4, N_2O, and halocarbons in the atmosphere, in watts per meter squared (W/m^2), in the En-ROADS Baseline Scenario compared to historical data. Halocarbons refer to F-gases (PFCs, SF_6, 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.

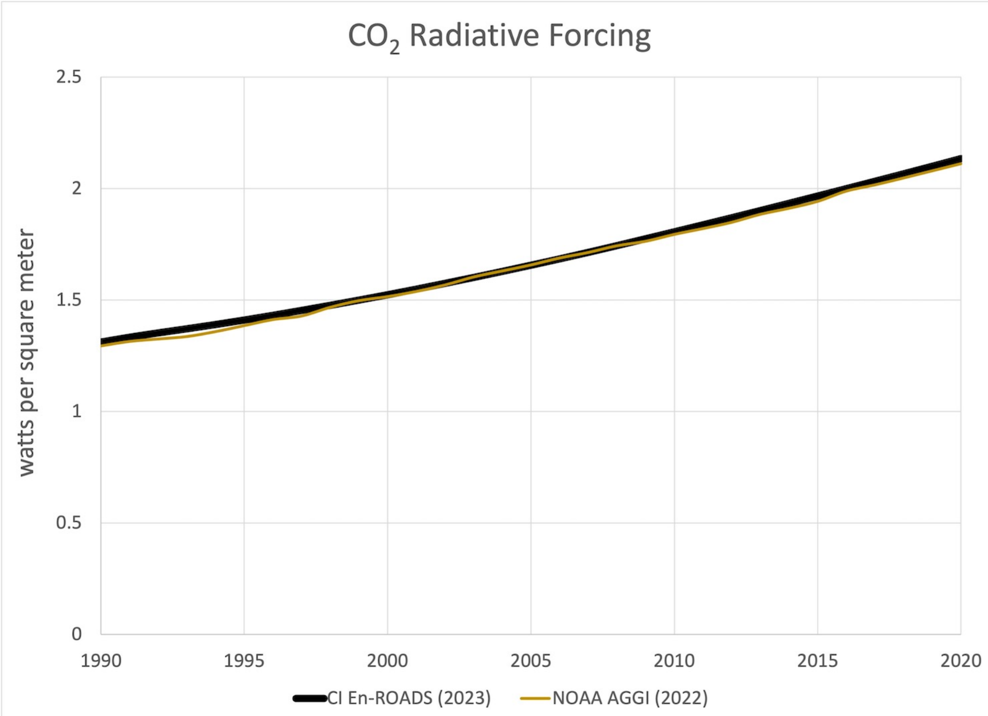
Statistical fit

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

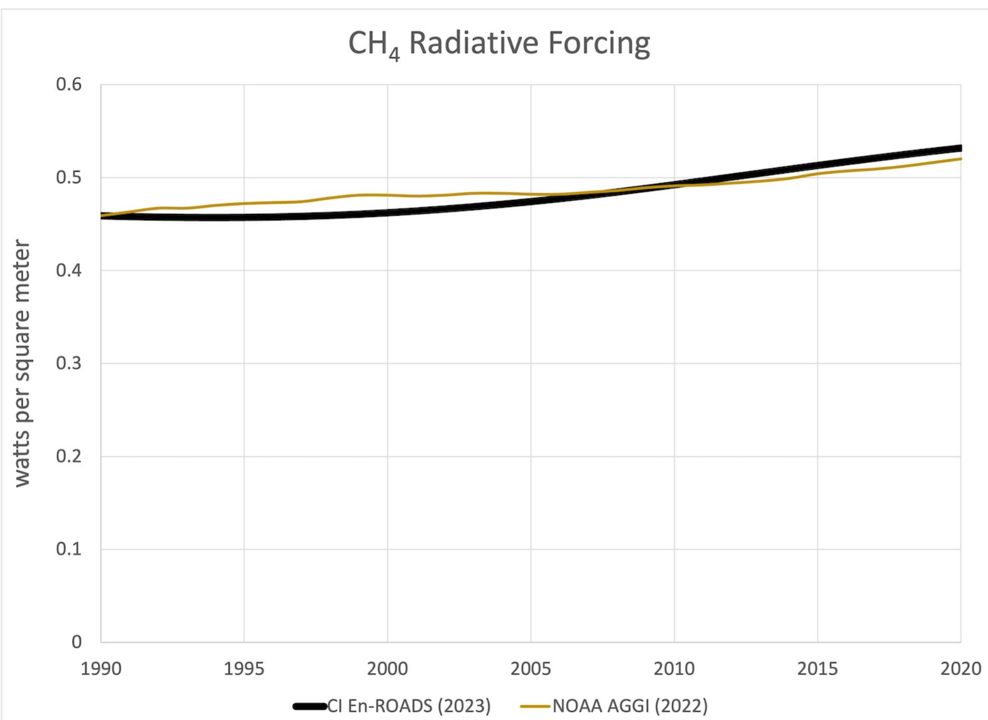
Sources of historical data

- NOAA AGGI: NOAA. (2022). *Annual Greenhouse Gas Index.*

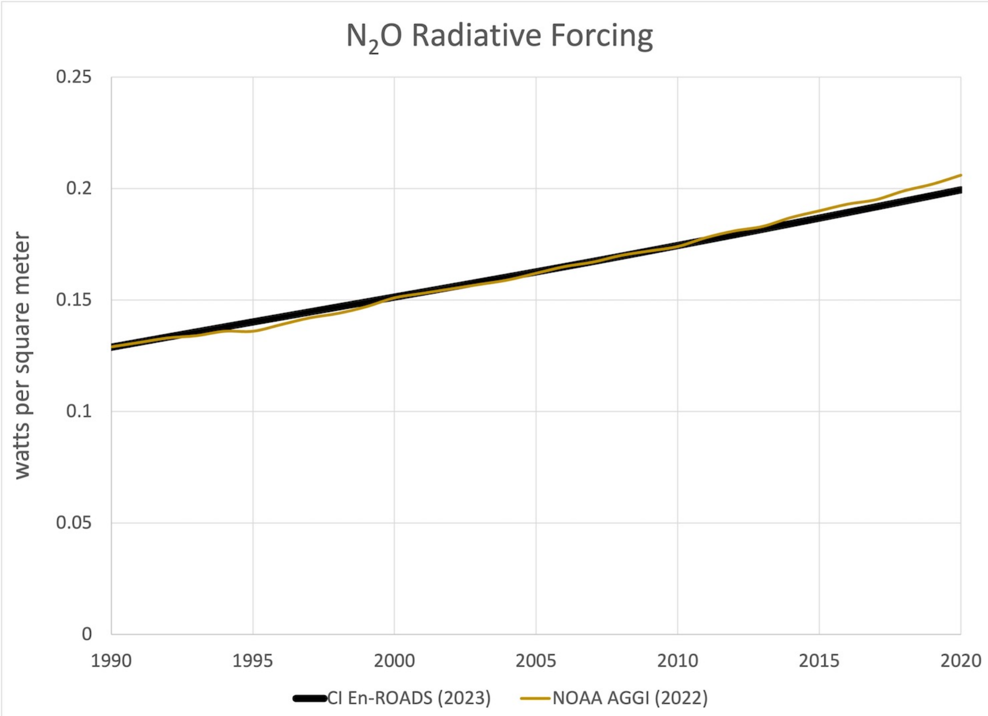
CO_2 Radiative Forcing



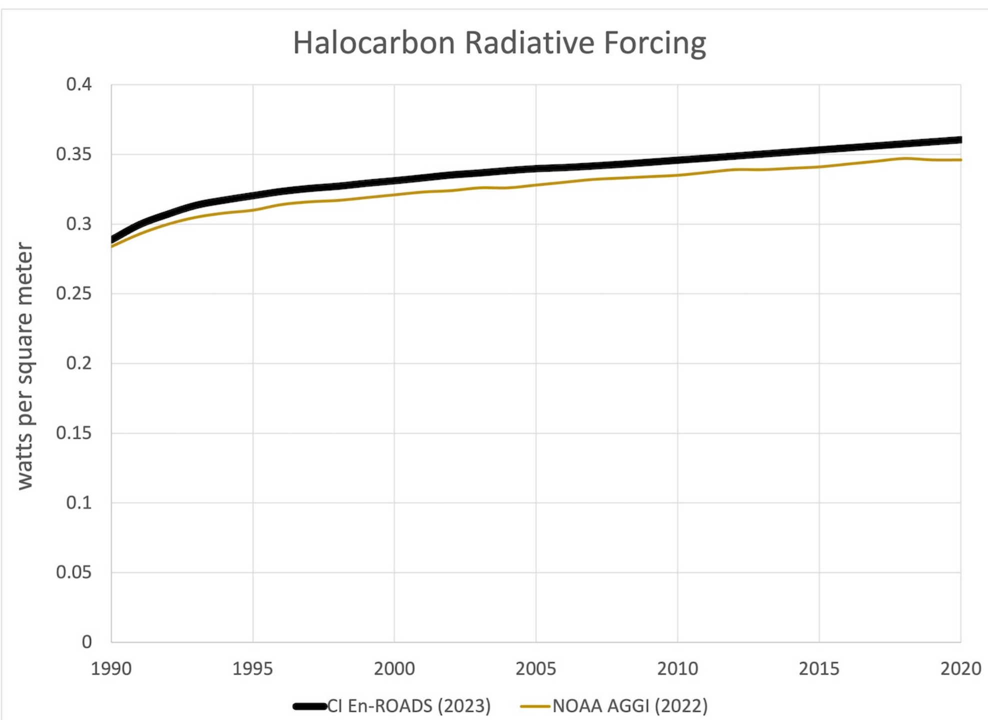
CH_4 Radiative Forcing



N_2O Radiative Forcing



Halocarbon Radiative Forcing



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Temperature History

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

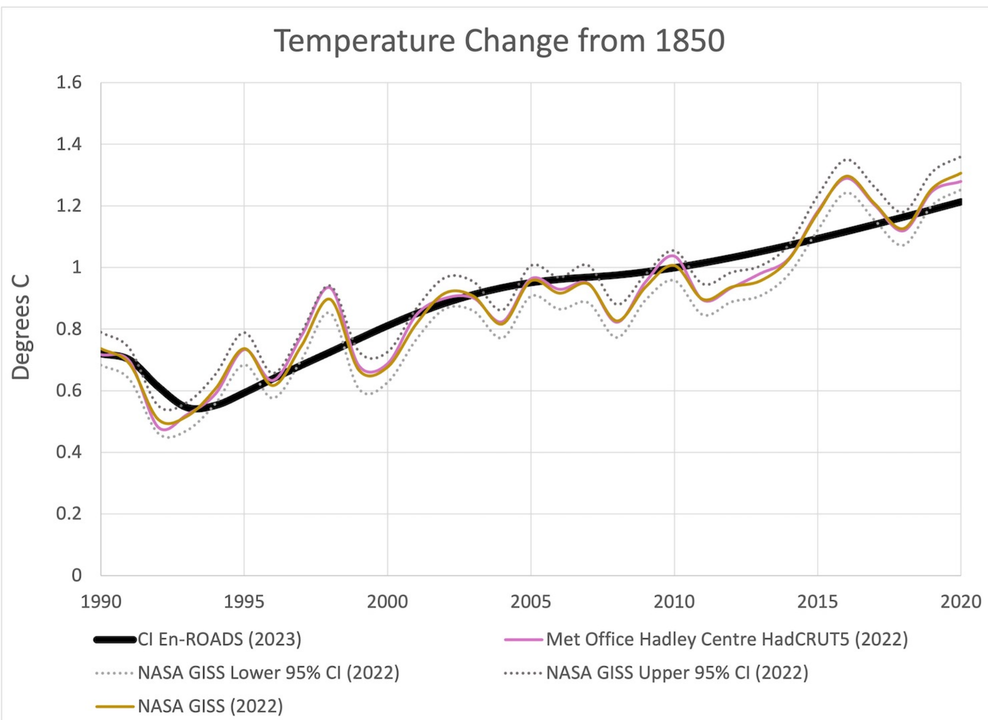
Statistical fit

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

Sources of historical data

- NASA GISS. (2022). *GISS Surface Temperature Analysis (GISTEMP), version 4.* NASA Goddard Institute for Space Studies.
- Met Office Hadley Centre HadCRUT5: Morice, C. P., et al. (2022). An updated assessment of near-surface temperature change from 1850: the HadCRUT5 dataset. *Journal of Geophysical Research: Atmospheres, 126,* e2019JD032361. Data available at https://www.metoffice.gov.uk/hadobs/hadcrut5/data/current/download.html.

Temperature Change



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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 CO_2 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 CO_2.

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 CO_2 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 CO_2 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).

CH_4: 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 CO_2 in the atmosphere.

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.).

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

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

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

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

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

direct air carbon capture and storage (DACCS): An experimental method of technological carbon dioxide removal where CO_2 is captured from the air with machines and stored permanently (e.g., underground). DACCS is a new industrial process that is still in development. To get a net removal benefit, the captured carbon must be stored long-term and the DACCS facility must be powered by low-carbon energy.

EIA: U.S. Energy Information Administration

EMF: Stanford Energy Modeling Forum

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

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

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

exajoule: A measure of energy equal to 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.

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

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 the Pacific Northwest National Laboratory (PNNL) and Joint Global Change Research Institute (JGCRI).

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

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

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

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

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

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

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

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

HVAC: Heating, ventilation, and air conditioning

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

IEA: International Energy Agency

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

IPCC: Intergovernmental Panel on Climate Change

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

Kaya graphs: Show the drivers of growth in carbon dioxide emissions. Yoichi Kaya created the equation behind the graphs: 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.

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

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

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

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

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

N_2O: Nitrous oxide. A greenhouse gas.

NF_3: Nitrogen trifluoride. An F-gas.

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

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

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

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 CO_2 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/m^2.

SF_6: Sulfur hexafluoride, an F-gas.

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

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

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

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

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

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