En-ROADS Guide Documentation

Climate Interactive

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Contents:

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

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

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

In addition to this User Guide, there is an extensive Reference Guide that covers model assumptions and structure, as well as references for data sources.

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

CHAPTER 1

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1.1 About En-ROADS

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

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

Relative to many global energy and climate system models, En-ROADS returns results in a few seconds, is transparent in its mathematical logic, and allows you to interactively test hundreds of factors. En-ROADS complements the other, more disaggregated models addressing similar questions, for example, those in the EMF-22 suite. These larger disaggregated models are used for data and calibrating results in En-ROADS.

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

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

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

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1.2 En-ROADS Tutorial

En-ROADS is designed to be easy to use. You can watch this 20-minute introductory video tour of En-ROADS. We encourage you to explore all the features of En-ROADS by clicking around. Here are some key features of En-ROADS:

1.2.1 Graphs

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

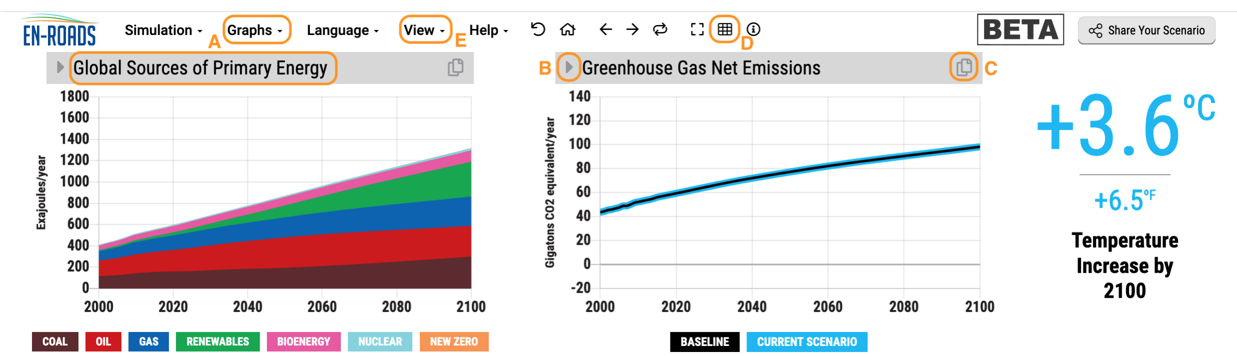
A. **Select graphs** – When you first open En-ROADS, you see the two default graphs. You can select from the full list of graphs by clicking the title of the left or right graph. You can also select from the Graphs menu from the top toolbar.

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 using the copy icon on the top right side of a graph.

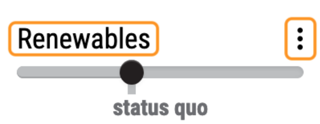
D. **Shortcut to popular graphs** – You can quickly jump to a selection of the most commonly used graphs from the "Show miniature graphs" icon on the top toolbar. You can click any of these miniature graphs to switch to that graph in the main graph view.

E. **View larger graphs** – If you want to expand one of the graphs into a separate window, you can access our "Large Left Graph" or "Large Right Graph" feature from the View menu in the top toolbar.



1.2.2 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:



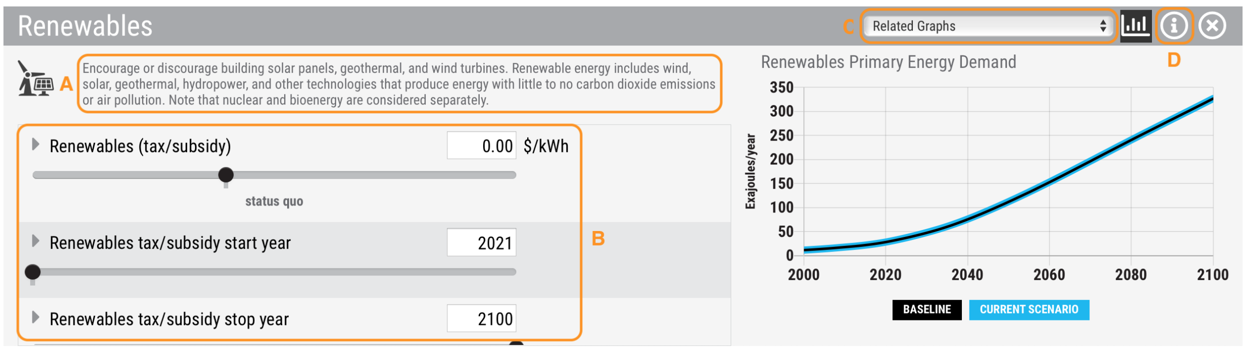
Here is what you will find in the detailed slider view:

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.



1.2.3 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 to others. Others can open your En-ROADS scenario with all the settings you have chosen and the last main graphs you viewed. You can then share your scenario to social media channels. Grabbing the link from your browser's URL bar will also work, however, 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.

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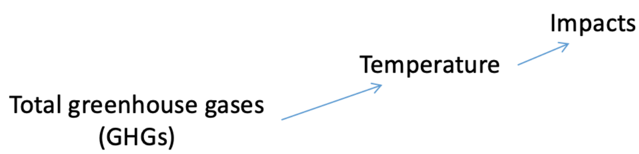
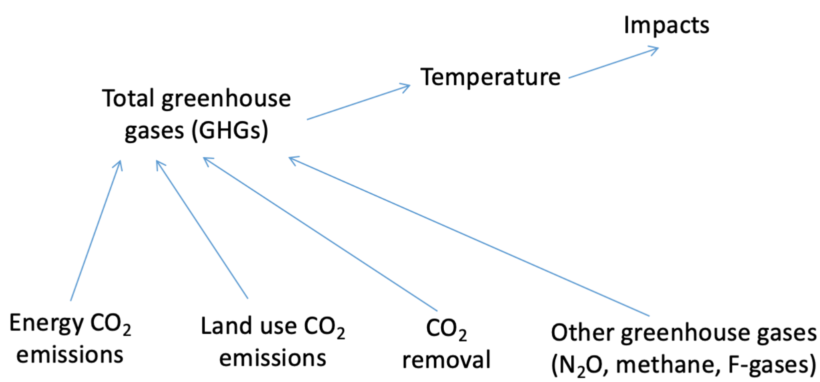
1.3 En-ROADS Structure

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

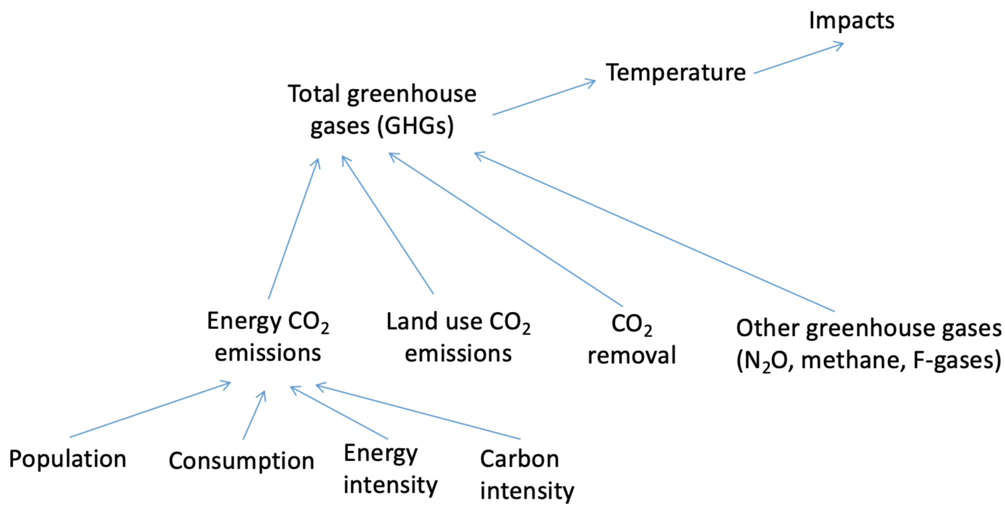


The concentration of greenhouse gases in the atmosphere is driven by four main sources:

1. **Energy CO2 Emissions** from burning coal, oil, gas, and biomass. CO_2 emissions from energy currently comprise about 65% of greenhouse gas emissions.
2. **Land Use CO2 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 28% 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 CO_2 emissions is about four things: fewer people, less consumption, more efficiency, and less high-carbon energy supplies.



1.4 Kaya Graphs

This view shows the drivers of growth in carbon dioxide emissions from energy, which reflects about two-thirds of all greenhouse gas emissions.

It is called the "Kaya" view because of the equation below, created by Yoichi Kaya:

Global Population x GDP per Capita x Energy Intensity of GDP x 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 approaching 8 billion people—and anticipate growth to 11 billion by the end of the century, according to UN projections. The rate of growth is slowing over time as people have smaller families.

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

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

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

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

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

1.5 Background on En-ROADS Dynamics

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

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

1.5.1 1. 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.

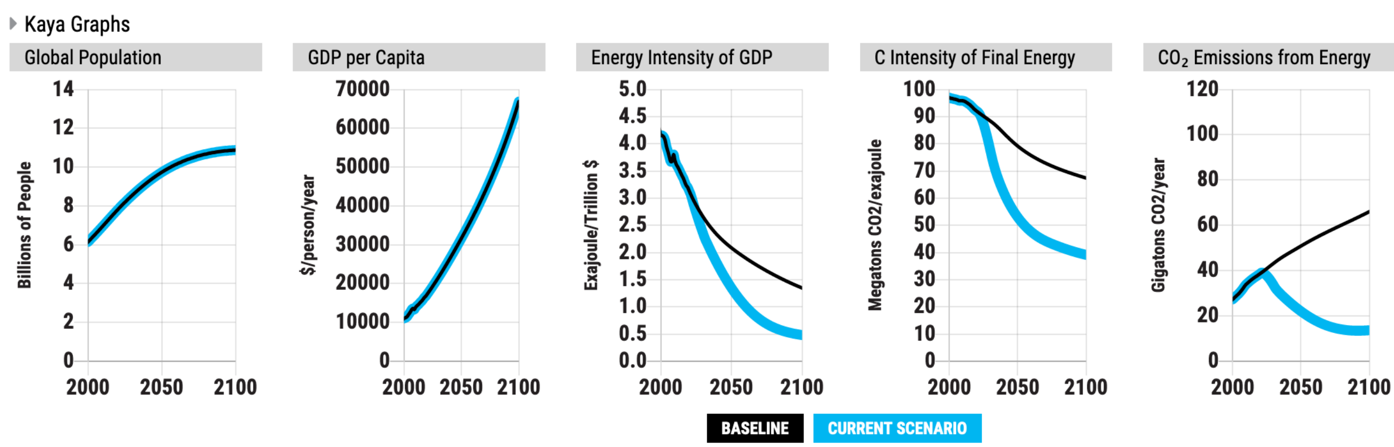
Drivers of Growth

A challenge to limiting future warming in this simulation is the powerful growth in global GDP, which is population multiplied by GDP per person. Energy efficiency and changes to the fuel mix can help reduce energy emissions, but their success is dampened by the steady growth in GDP. Recognizing this fact leads many participants 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.



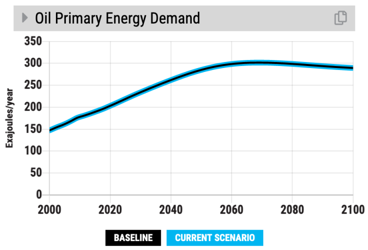
Long-Term Limits to Fossil Fuels

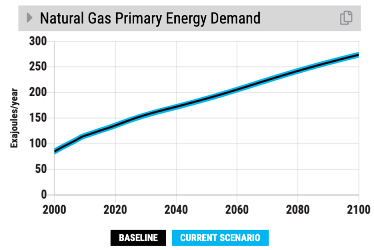
Rising costs due to the scarcity of oil and gas supplies limits the pace of growth for those energy sources. This creates a balancing effect that is evident in the 2060s-2080s for oil and gas in the Baseline scenario when they begin to level off. Oil peaks and falls, while the growth rate of natural gas begins decreasing.

This addresses questions such as:

- "Why do the curves for gas and oil level out?"

To illustrate this point: See the "Primary Energy Demand" graphs for Oil and Natural Gas. Supplies of oil and gas are becoming scarce, pushing up their prices and curtailing investment in new capacity.





Assumptions for available reserves of coal, oil, and gas can be reviewed and adjusted in the "Assumptions" view.

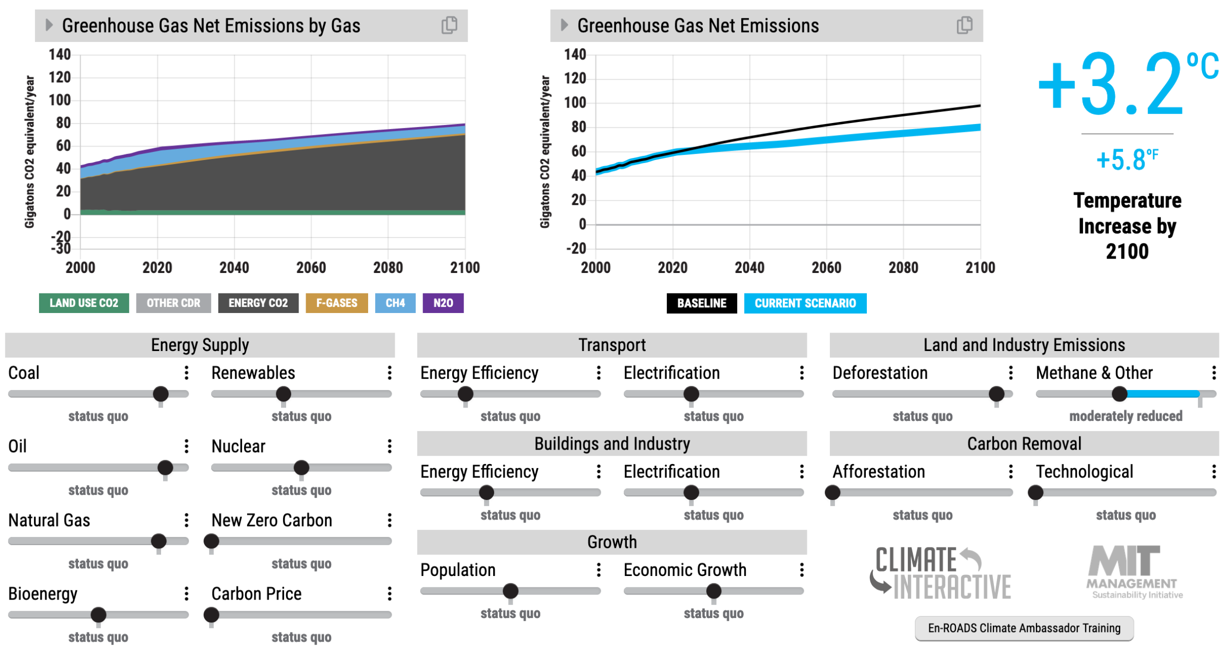
Non-CO2 Emissions Affect Temperature Significantly

Methane, N_2O, and the F-gases are controlled by the Methane & Other slider. Adjusting this has a large impact on temperature. This implies significant changes in livestock management and consumption, waste management, fertilizer use, and industry. These emissions currently make up around 28% of total greenhouse gas emissions.

Addresses questions such as:

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

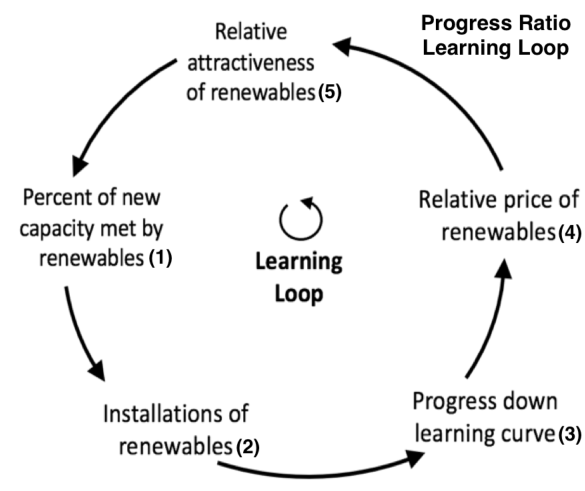
To illustrate this point: See the "Greenhouse Gas Net Emissions by Gas – Area" and "Greenhouse Gas Net Emissions" graphs and adjust the Methane & Other slider. See the scenario below – moderately reducing Methane & Other emissions achieves a large reduction in 2100 temperature.



1.5.2 2. Complex Interactions Between Competing Energy Supplies and Demand

Economies of Scale and Learning

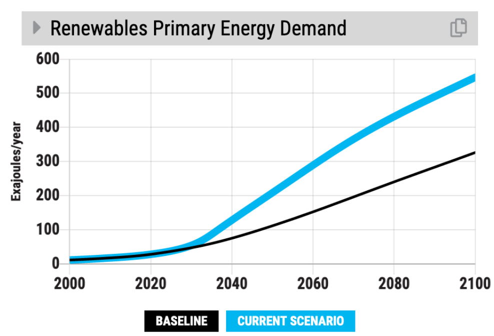
Costs of energy supplies such as renewables fall as cumulative experience is gained through a learning feedback loop, also known as "economies of scale." Every doubling of cumulative installed capacity of renewables reduces costs by around 20%, creating a reinforcing loop (this is known as the "progress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



This addresses questions such as:

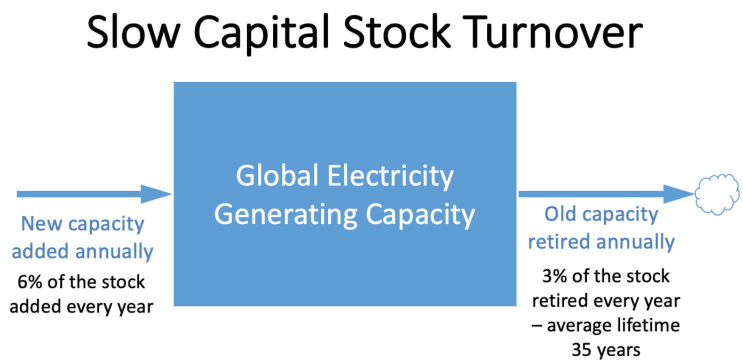
- "Why should we have hope?"
- "How can we afford a transition to a low carbon economy?"
- "Aren't the costs of renewables prohibitive?"

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



Delays and Capital Stock Turnover

New energy sources (e.g., renewables and new zero-carbon technology) take decades (not years) to scale up to sufficiently 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 turnover and be retired. The climate is only helped when coal, oil, and gas is retired away, and in the absence of other interventions, that amount is relatively small – approximately 3% per year.

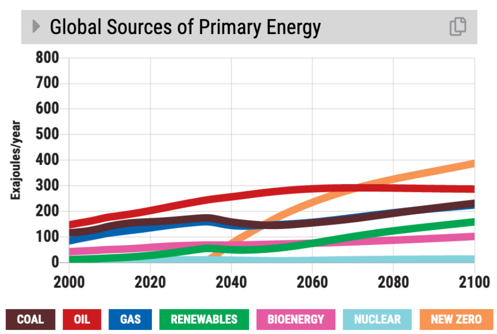


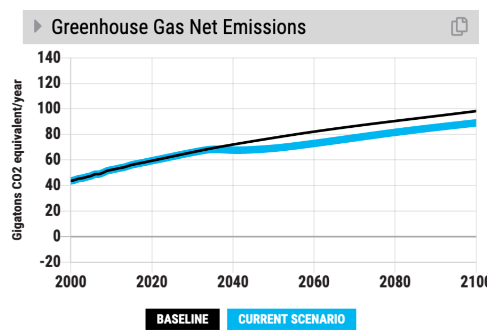
This addresses questions such as:

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

This dynamic is also relevant to increasing energy efficiency, however, energy-using capital such as vehicles, buildings, and industry, has an average lifetime that is much shorter (10-15 years). One can promote increases to energy efficiency of new cars immediately, for example, but the average energy efficiency of all the cars takes decades to improve since it takes time for all the old inefficient cars to be taken off the road.

To illustrate this point: Move the New Zero-Carbon slider to huge breakthrough. Examine the "Global Sources of Primary Energy" graph and notice that, even as low-carbon sources grow, it takes several decades before enough fossil fuel capacity retires away to make much of an impact. Notice that coal, oil, and natural gas grow steadily through the 2020s and 2030s and it takes time for greenhouse gas emissions to depart from the Baseline scenario.



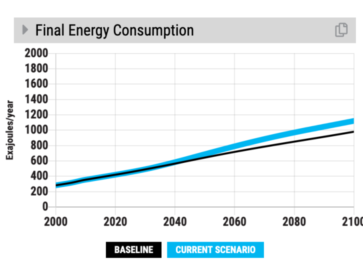


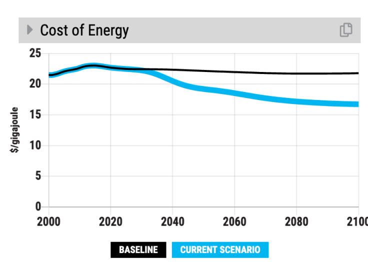
Implications of this dynamic: Policies that merely promote alternatives to fossil fuels take several decades to reduce carbon dioxide emissions – the existing infrastructure takes a long time to retire away. Thus, meeting climate goals also requires direct disincentives to building and using fossil fuel infrastructure.

Price and Demand Effects

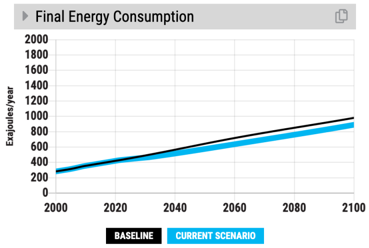
Energy demand falls if energy prices rise, and demand increases if prices fall. The first dynamic is evident when carbon prices increase. The second, known as the rebound effect, is when zero-carbon energy such as renewables or a new technology are either subsidized or experience a breakthrough in cost improvement.

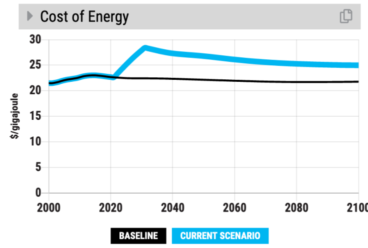
While subsidizing low carbon energy supplies such as Renewables, watch Final Energy Consumption increase. Inexpensive wind and solar spreading around the world decreases overall energy prices and boosts energy demand up:





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





Crowding Out or Squeezing the Balloon

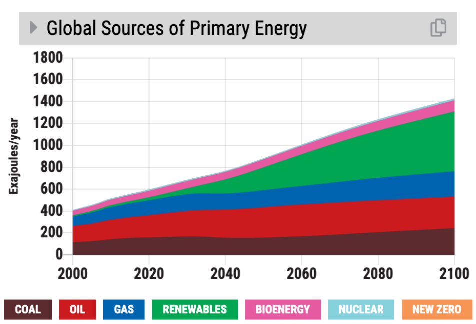
Many assume that if the world promoted several long term zero-carbon energy sources such as nuclear, wind, and solar, their contribution to carbon mitigation would be additive. Instead, they actually compete. More of one, less of the other.

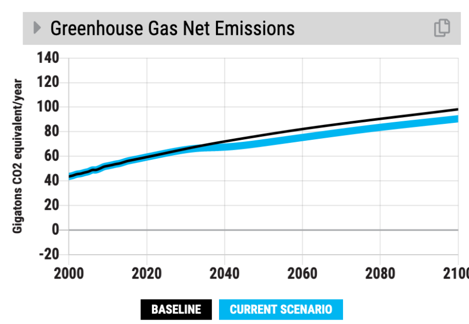
This addresses questions such as:

- "Why didn't it help to have a breakthrough in a new zero-carbon energy supply in this renewable-dominant scenario?"

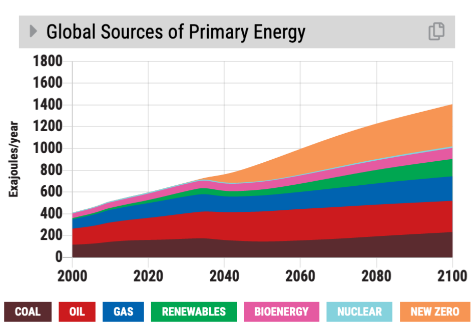
To illustrate this point: See the "Global Sources of Primary Energy" graph in the three scenarios below. In the first graph, we subsidize renewables alone; in the second, there is a breakthrough in new zero-carbon technologies; in the third graph, we see both a renewables subsidy and a new zero-carbon breakthrough.

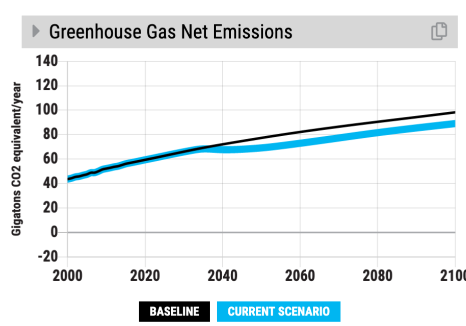
In the following scenario, a high Renewables subsidy leads to a 0.1 degree Celsius reduction in temperature:



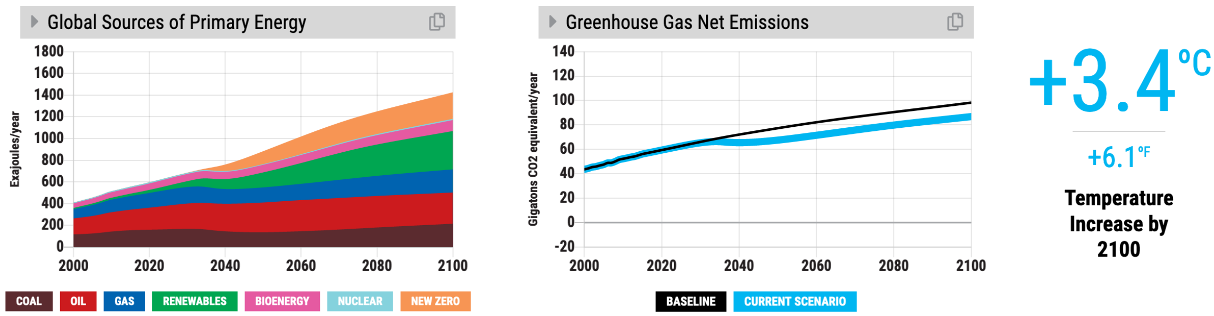


A huge breakthrough in New Zero-Carbon also leads to a 0.2 degrees Celsius reduction on its own:





When combined, instead of seeing an additive 0.3 degree Celsius reduction, we only see a 0.2 degree reduction in temperature due to the energy supplies competing with each other for market share:



1.5.3 3. System Dynamics of the Climate

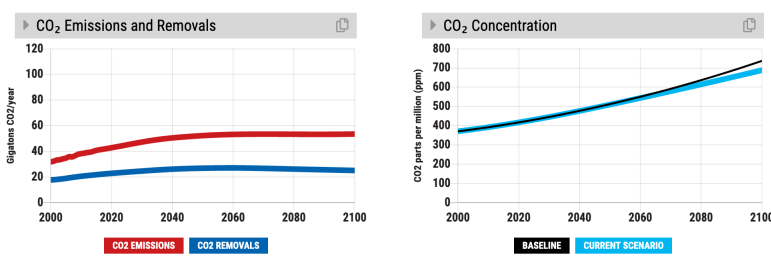
Bathtub Dynamics - Temperature and CO2 Concentrations Seem Weakly Responsive to CO2 Emissions

Emissions must fall significantly just to change the growth in temperature and CO_2 concentrations slightly. This counterintuitive dynamic is an important feature of the carbon and climate system. A short explanation for this dynamic would include the fact that the momentum in the carbon cycle and the climate lead to long delays between emissions and temperature.

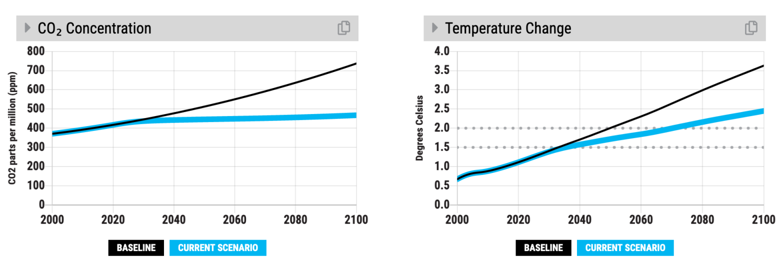
Addresses questions such as:

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

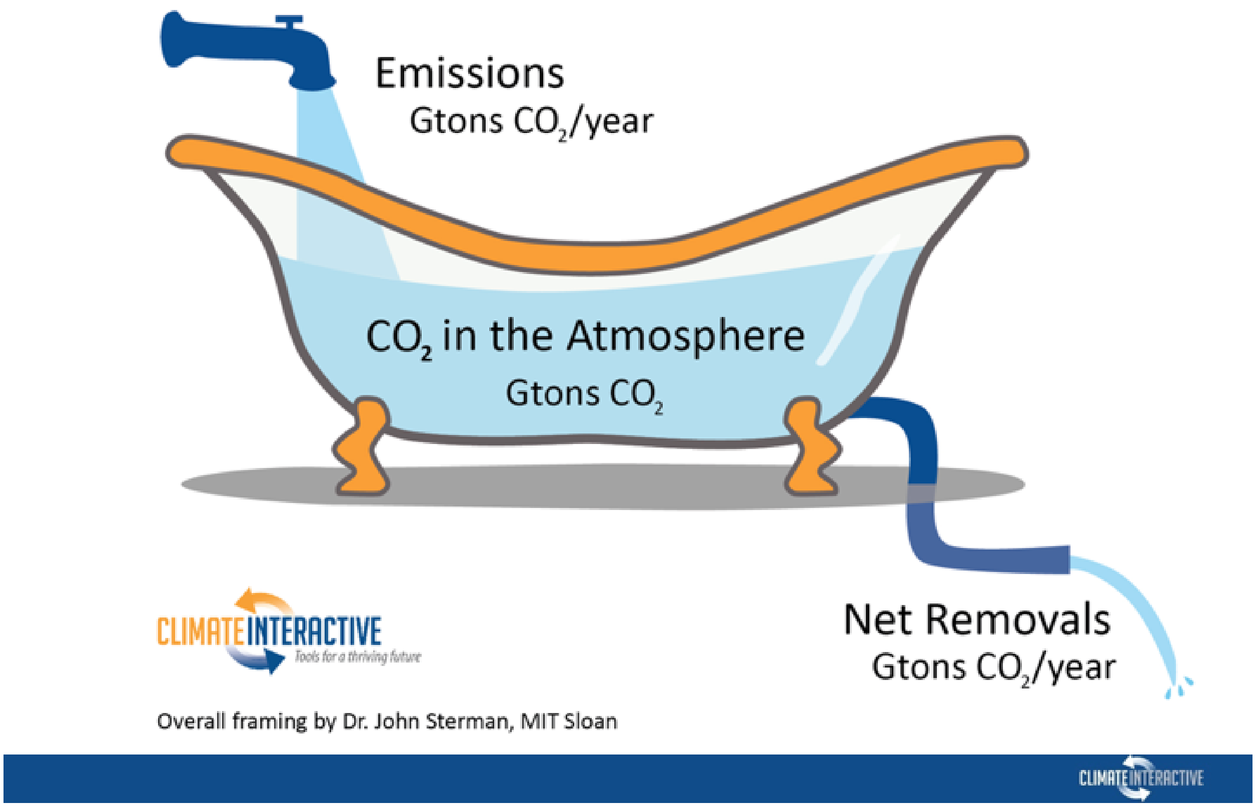
To illustrate this point: See the "CO_2 Emissions and Removals" and "CO_2 Concentration" graphs in a scenario where CO_2 emissions stabilize. Even though CO_2 emissions (in red below) have flattened, CO_2 concentrations (in blue on the right below) continue to increase:



Similarly, in a much more stringent scenario where CO_2 concentration stabilizes, temperature change continues to increase:



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



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1.6 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.

1.6.1 Examples

- 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 capital for new coal mining, refining, and power plant infrastructure.

1.6.2 Big Messages

- Discouraging coal is a high leverage strategy for reducing future temperature change. It keeps coal in the ground, increases the cost of energy, and reduces energy demand.

- Discouraging coal also improves public health and saves medical costs through improved air quality.

1.6.3 Key Dynamics

- When coal is discouraged, by taxing it, watch the brown area of Coal go down in the "Sources of Primary Energy" graph. It is one of the most sensitive energy supplies to any increase in cost. Unlike oil, it can often be substituted for natural gas and renewables.
- Taxing coal 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 harmfully impacted by high energy prices.

1.6.4 Potential Co-Benefits of Discouraging Coal

- Reduced air pollutants from coal burning improves air quality and health outcomes for surrounding communities.
- Less coal mining reduces heavy metal drainage and waste from mine sites which improves water quality and helps protect wildlife habitats, biodiversity, and ecosystem services.

1.6.5 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.

1.6.6 Slider Settings

The following table highlights the numerical ranges for the labelled input levels of the Coal slider. Each of the energy supply sliders is set to reflect a similar percentage cost increase or decrease for each input level.

	very highly taxed	highly taxed	taxed	**status quo**	subsidized
Change in price per ton of coal equivalent (tce)	+$110 to +$40	+$40 to +$20	+$20 to +$6	**+$6 to -$6**	-$6 to -$20
Cost increase or decrease	+200% to +60%	+60% to +30%	+30% to +10%	**+10% to -10%**	-10% to -30%

1.6.7 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).

1.6.8 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.[1]

United States: The total cost of reliance on coal to the US economy is estimated to be $344 billon per year. Of that cost, $187B is from air pollution, $74.6B is from public health affects in Appalachia, and $61.7B from climate damages.[2]

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.[3]

1.6.9 FAQs

How can I directly force deeper reductions in coal use? Consider selecting the "Stop building new coal infrastructure" switch in the advanced view, and changing the "% Reduction in coal utilization" slider.

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

1.7 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.

1.7.1 Examples

- 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.

1.7.2 Big Message

- 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 any large reduction of temperature.

1.7.3 Key Dynamics

- When oil is discouraged, by taxing it, watch the red area of Oil go down in the "Global Sources of Primary Energy" graph.

[1] 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. http://dx.doi.org/10.1016/j.rser.2017.05.119

[2] 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. https://doi.org/10.1111/j.1749-6632.2010.05890.x

[3] Barrows, G., Garg, T., & Jha, A. (2019). The Health Costs of Coal-Fired Power Plants in India. SSRN. http://dx.doi.org/10.2139/ssrn.3281904

- 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 "squeeze the balloon" problem – depressing fossil fuel emissions in one area causes them to pop up in another. Renewables are also boosted slightly, but the impact is negligible. Adding a carbon price is a good solution to the "squeeze the balloon" problem, as it addresses all fossil fuels together.
- 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.

1.7.4 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.

1.7.5 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.

1.7.6 Slider Settings

The following table highlights the numerical ranges for the labelled input levels of the Oil slider. Each of the energy supply sliders is set to reflect a similar percentage cost increase or decrease for each input level.

	very highly taxed	highly taxed	taxed	status quo	subsi-dized
Change in price per barrel of oil equivalent (boe)	+$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%

1.7.7 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).

1.7.8 FAQs

How can I directly force deeper reductions in oil use? Consider selecting the "Stop building new oil infrastructure" switch in the advanced view, and changing the "% Reduction in oil utilization" slider.

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

1.8 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 carbon dioxide (although less than coal and oil) and, if leaked into the air, it contains high amounts of methane. Natural gas drilling uses large amounts of water and can cause contamination.

1.8.1 Examples

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

1.8.2 Big Message

- More natural gas is not an effective long-term strategy for the climate – it is less carbon intensive than coal, but its infrastructure has a long life so it competes with the adoption of lower-carbon alternatives as they scale up.

1.8.3 Key Dynamics

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

1.8.4 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][5]

[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. https://doi.org/10.2190/NS.22.1.e

[2] Ridlington, E., & Rumpler, J. (2013). Fracking by the Numbers: Key Impacts of Dirty Drilling at the State and National Level. *Environment America*. Retrieved from https://environmentamerica.org/sites/environment/files/reports/EA_FrackingNumbers_scrn.pdf

[3] Good, K. (2015, February 12). These 4 Countries Have Banned Fracking … Why Can't the U.S. Get On Board? Retrieved from https://www.onegreenplanet.org/environment/countries-except-united-states-that-have-banned-fracking/

[4] Food & Water Watch. (2019, August 12). Local Resolutions Against Fracking. Retrieved from https://www.foodandwaterwatch.org/insight/local-resolutions-against-fracking

[5] Carpenter, D. O. (2016). Hydraulic fracturing for natural gas: impact on health and environment. *Reviews on Environmental Health*, 31(1). https://doi.org/10.1515/reveh-2015-0055

1.8.5 Equity Considerations

- Generally speaking, natural gas production in developed countries is disproportionately located near low-income and minority communities.[6][7]
- 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.[8][9]
- 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.[10]

1.8.6 Slider Settings

The following table highlights the numerical ranges for the labelled input levels of the Natural Gas slider. Each of the energy supply sliders is set to reflect a similar percentage cost increase or decrease for each input level.

	very highly taxed	highly taxed	taxed	status quo	subsidized
Change in price per thousand cubic feet (Mcf)	+$5.00 to +$2.00	+$2.00 to +$1.00	+$1.00 to +$0.30	**+$0.30 to -$0.30**	-$0.30 to -$1.00
Cost increase or decrease	+200% to +60%	+60% to +30%	+30% to +10%	**+10% to -10%**	-10% to -30%

1.8.7 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).

1.8.8 FAQs

How can I directly force deeper reductions in natural gas use? Consider selecting the "Stop building new natural gas infrastructure" switch in the advanced view, and changing the "% Reduction in gas utilization" slider.

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

[6] Clough, E. (2018). Environmental justice and fracking: A review. *Current Opinion in Environmental Science & Health*, 3, 14–18. https://doi.org/10.1016/j.coesh.2018.02.005

[7] Bienkowski, B. (2016, February 17). Fracking's Costs Fall Disproportionately on the Poor and Minorities in South Texas. *Inside Climate News*. https://insideclimatenews.org/news/10022016/poor-minorities-carry-burden-fracking-waste-south-texas-eagle-ford-shale

[8] Jula, M. (2018, April 17). Parents didn't want fracking near their school. So the oil company chose a poorer school, instead. *Mother Jones*. https://www.motherjones.com/environment/2018/04/an-oil-company-faced-pushback-about-fracking-near-a-charter-so-it-moved-next-to-a-low-income-public-school/

[9] 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. https://doi.org/10.3390/healthcare4040078

[10] 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. https://doi.org/10.3390/ijerph15010016

1.9 Bioenergy

Discourage or encourage the use of trees, forest waste, and agricultural crops to create energy. Bioenergy is energy produced from the burning, or combustion, of living organic material such as wood, algae, or agricultural crops. There are a variety of bioenergy sources, some of which can be sustainable and others which can be worse than burning coal.

1.9.1 Examples

- Government incentives and/or targets to convert land into growing biofuel feedstocks and drive bioenergy development.
- 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.

1.9.2 Big Message

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

1.9.3 Key Dynamics

- As bioenergy is subsidized or taxed, notice that the temperature changes very little. Changes in bioenergy shift the amount of other energy sources, which can mean things like more coal if bioenergy is taxed or less renewables if bioenergy is subsidized.
- Bioenergy is only zero-carbon if the feedstock is regrown to account for the carbon emitted. In some areas, trees are being used for bioenergy, which will take decades to regrow to make up for the carbon released when burned.

1.9.4 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, like forests, intact enables biodiversity to be preserved.
- A reduction in biomass burning can improve indoor and outdoor air quality from reduced soot and particulates.
- Bioenergy can accelerate deforestation through dependence on wood for fuels or through the expansion of bioenergy crops, particularly in the tropics. Less deforestation has many benefits including additional carbon sequestration.

1.9.5 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.

1.9.6 Slider Settings

The following table highlights the numerical ranges for the labelled input levels of the Bioenergy slider. Each of the energy supply sliders is set to reflect a similar percentage cost increase or decrease for each input level.

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

1.9.7 Model Structure

- This sector tracks several stages of bioenergy installations, or energy supply capacity including: capacity under development, under construction, and actually producing energy, as well as the delays between each stage.
- Future modeling in this sector will add more refinement to the ways the bioenergy supply is characterized and include stronger links to the amount of available land.

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

1.10 Renewables

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

1.10.1 Examples

- Governments offering tax incentives to families installing solar panels on their roofs.
- Farmers and land owners allowing the installment 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.

1.10.2 Big Message

- Subsidizing renewable energy helps to limit coal and gas demand and reduce future temperature. Without other actions, however, it isn't enough to keep fossil fuels in the ground.

1.10.3 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.

- **Rebound effect.** Additionally, 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 rebound effect somewhat reduces the positive impact of encouraging renewable energy. View this dynamic with the graph "Final Energy Consumption."
- **Delays.** It takes time for the subsidies and encouragement of renewables to show up in installed capacity. Subsidies are phased in over 10 years so note in the "Renewable Final Energy Consumption" graph that the Current Scenario does not immediately differ from the Baseline.

1.10.4 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.

1.10.5 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.

1.10.6 Slider Settings

The following table highlights the numerical ranges for the labelled input levels of the Renewables slider. Each of the energy supply sliders is set to reflect a similar percentage cost increase or decrease for each input level.

	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 -$0.03
Cost increase or decrease	+30% to +10%	**+10% to -10%**	-10% to -30%	-30% to -60%

1.10.7 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.

[1] Eisenberg, A. (2018). Just Transitions. *Southern California Law Review*, Vol. 92, No. 101, 2019. https://ssrn.com/abstract=3281846

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.

1.10.8 Case Studies

United States: Scaling up wind and solar energy sources is estimated to have avoided 7,000 premature deaths and saved $87.6 B 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]

1.10.9 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.
- Second, there is a rebound 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 coal and oil 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.

How do you handle the availability and cost of storage of electricity from renewables?

- The cost of storage for renewables is explicitly modeled in En-ROADS, and as renewables become a significant part of energy supply, storage must be cost effective to enable further expansion.

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

1.11 Nuclear

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

[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). https://doi.org/10.1038/nenergy.2017.134

[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. https://doi.org/10.1073/pnas.0909678107

[4] IEA/IRENA. (2017) Perspectives for the Energy Transition – Investment Needs for a Low-carbon Energy System. Paris/Abu Dhabi: IEA/IRENA. https://www.irena.org/DocumentDownloads/Publications/Perspectives_for_the_Energy_Transition_2017.pdf

1.11.1 Examples

Discouraging

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

Encouraging

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

1.11.2 Big Message

- Nuclear is not a huge driver of future temperature and competes with the growth of renewables and new zero-carbon technology.
- It could be part of a suite of climate action if one is willing to accept the environmental costs – e.g., handling waste materials and the risk of radiation damage near the plants.

1.11.3 Key Dynamics

- As you subsidize nuclear, watch Nuclear (light blue area) grow, and Coal (brown area) and Natural Gas (dark blue area) 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.
- Nuclear competes with all energy sources available, so notice also what happens to Renewables (green area) when nuclear is incentivized —it decreases too.

1.11.4 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.

1.11.5 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.

[1] Union of Concerned Scientists. (2013, July). How it Works: Water for Nuclear. https://www.ucsusa.org/resources/water-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. https://doi.org/10.3390/ijerph13070700

1.11.6 Slider Settings

The following table highlights the numerical ranges for the labelled input levels of the Nuclear slider. Each of the energy supply sliders is set to reflect a similar percentage cost increase or decrease for each input level.

	highly taxed	taxed	status quo	subsidized	highly subsidized
Change in price per kilowatt hour (kWh)	+$0.07 to +$0.03	+$0.03 to +$0.01	**+$0.01 to -$0.01**	-$0.01 to -$0.03	-$0.03 to -$0.07
Cost increase or decrease	+60% to +30%	+30% to +10%	**+10% to -10%**	-10% to -30%	-30% to -60%

1.11.7 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 inquires and support.

1.12 ? 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.

1.12.1 Examples

- Research and development, or other investment into new sources of energy supply such as thorium fission or nuclear fusion.
- Note, this does not include new technologies in CO_2 removal, transportation, electrification, or energy efficiency.

1.12.2 Big Message

- 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.

1.12.3 Key Dynamics

- 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. There are two reasons why:
  - First, notice it takes a long time for the new technology to grow and become a large part of the global energy mix. There is a long delay between discovery of the zero-carbon energy technology and its dominance in the market – 10 years to commercialize, several years to plan and build, and then growing only as existing coal and natural gas plants (which have a lifetime of 30 years) are retired. Watch how little Coal (brown

area) and Natural Gas (dark blue area) go down before 2040. Because of this, very little carbon is kept underground during this critical period.

– Second, look at the "Final Energy Consumption" graph. 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.

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

- A breakthrough in a new energy sources 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.

1.12.5 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.

1.12.6 Slider Settings

	status quo	breakthrough	huge breakthrough
Breakthrough year	no breakthrough	2022	2022
Time to commercialize		10 years	10 years
Initial cost relative to coal		2	1

1.12.7 Model Structure

The path to deployment will take some time after the success of the technology in the laboratory: commercialization (set at 10 years, roughly the same amount of time that Uranium-based fission took), planning (2 years), and construction (5 years). Then the new energy source must compete with other energy sources.

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

1.13 Carbon Price

Set a global carbon price that makes coal, oil, and gas more expensive depending on how much carbon dioxide they release. Energy producers frequently pass additional costs to their customers, so policy must be designed to minimize the impacts on the poorest.

1.13.1 Examples

- Countries and regions implementing carbon taxes.
- Grassroots campaigns generating public support for carbon pricing.

1.13.2 Big Message

- Pricing carbon is a high leverage strategy, as it both reduces the carbon intensity of the energy supply and reduces the overall energy demand.

1.13.3 Key Dynamics

- When the carbon price is increased, notice that Coal (brown area) 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 (dark blue area) decreases as well, although more modestly. Oil (red area) decreases only slightly, even though it is more carbon intensive than gas, because it is not easily substituted for other energy sources (e.g. can't power a diesel truck with wind power). Renewables (green area) increases as the relative cost of wind and solar make them more attractive.
- Just like taxing coal, a significant carbon price increases energy costs, which reduces energy demand. View this in the "Final Energy Consumption" graph, noting that the high carbon price Current Scenario (blue line) is lower than Baseline (black line).

1.13.4 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.
- Revenue from carbon pricing can be allocated to social programs that can be shared with everyone.

1.13.5 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 loop holes or exemptions.

1.13.6 Slider Settings

	status quo	low	medium	high	very high
Carbon price per ton	**no carbon price**	$0 to $20	$20 to $60	$60 to $100	$100 to $250

1.13.7 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]

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

[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. https://doi.org/10.1080/10962247.2016.1192071

1.14 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.

1.14.1 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.

1.14.2 Key Dynamics

- Watch Oil (red area) decrease in the "Global Sources of Primary Energy" graph as the world increases the efficiency of its transport. Less oil is burned, and coal and gas fall as well as electrified transport becomes more efficient.
- View the "Final Energy Consumption" graph to see the fall in energy demand.
- To see another benefit, look at the "Cost of Energy" graph. Less demand for energy means prices are lower.

1.14.3 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 sizeable health savings.

1.14.4 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.

[1] Lusk, A. (2019, August 23). Stop Designing Bike-Friendly Cities Only for Wealthy White Cyclists. *City Lab*. https://www.citylab.com/transportation/2019/02/bike-friendly-cities-should-be-designed-everyone/582409/

1.14.5 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%

1.14.6 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. 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). The model structure tracks overall efficiency, which includes retrofitting of existing capital.

1.14.7 Case Studies

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

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

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

1.15 Transport – Electrification

Increase or decrease purchases of new electric cars, trucks, buses, trains, and ships. 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.

1.15.1 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.

[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. https://doi.org/10.2105/AJPH.2014.301868

[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. https://doi.org/10.1016/j.envint.2012.08.009

1.15.2 Big Message

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

1.15.3 Key Dynamics

- As you increase Transport Electrification, there are two main forces that affect future temperature:
  - Overall efficiency is greater for electrified transport than for internal combustion engines – in general, less fuel is used to power transport with electricity than oil.
  - Oil, in the "Global Sources of Primary Energy" graph, goes down as we electrify transport. At the same time, primary energy demand for coal, renewables, and to a more limited extent, natural gas, all increase to power the rise in electrical demand.

1.15.4 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.

1.15.5 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.

1.15.6 Slider Settings

The variable being changed is the annual growth rate of electricity used in new transport capital such as vehicles, trains, and ships.

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

1.15.7 Model Structure

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

This input affects climate outcomes through two pathways:

[1] Lombrana, L. M. (2019, June 11). Saving the Planet With Electric Cars Means Strangling This Desert. *Bloomberg Green*. https://www.bloomberg.com/news/features/2019-06-11/saving-the-planet-with-electric-cars-means-strangling-this-desert

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

1.15.8 Case Studies

United States: Increasing fuel economy standards in the United States could save consumers tens of billions of dollars per year, reduce gas consumption by tens of billions of gallons per year, and create over 300,000 jobs by 2030 while also reducing greenhouse gas emissions by millions of tons per year.[2]

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

1.16 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.

1.16.1 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.

1.16.2 Big Message

- 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.

1.16.3 Key Dynamics

- 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.
- 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).

[2] Bezdek, R. H., & Wendling, R. M. (2005). Potential long-term impacts of changes in US vehicle fuel efficiency standards. *Energy Policy*, 33(3), 407–419. https://doi.org/10.1016/j.enpol.2003.08.015

1.16.4 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.

1.16.5 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.

1.16.6 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%

1.16.7 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, which is delayed from this intervention because improvement only come to new things and many buildings and industrial facilities last decades.

1.16.8 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]

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

[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. https://doi.org/10.1038/s41370-017-0014-9

[2] Rosenow, J., Eyre, N., Sorrell, S., & Guertler, P. (2017). Unlocking Britain's First Fuel: The potential for energy savings in UK housing. Retrieved from https://www.e3g.org/docs/17_9_6_UKERC_CIED_briefing_final.pdf

1.17 Buildings and Industry - Electrification

Increase or decrease 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.

1.17.1 Examples

- Increase in public interest for replacing oil and gas heating 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.

1.17.2 Big Message

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

1.17.3 Key Dynamics

- When there is more efficient electrical systems powering building and industries, notice that Natural Gas (dark blue area) and Coal (brown area) move down in the "Global Sources of Primary Energy" graph.

1.17.4 Potential Co-Benefits of Encouraging Electrification

- Improved air quality at the 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.

1.17.5 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]

[1] World Health Organization. (2018, May 7). Household air pollution: Health impacts. https://www.who.int/airpollution/household/health-impacts/en/

1.17.6 Slider Settings

The variable being changed is the annual growth rate of electricity used in buildings and industry.

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

1.17.7 Model Structure

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

This input affects climate outcomes through two pathways:

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

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1.18 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.

1.18.1 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.

1.18.2 Big Message

- Contrary to some people's beliefs, population growth is not a silver bullet for addressing climate change.
- Decisions around population and family choice are very personal decisions and efforts to shift these decisions have ethical implications in many cultures.

1.18.3 Key Dynamics

- Watch all the sources of energy change as you change population growth.

1.18.4 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.

1.18.5 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][3][4]

1.18.6 Slider Settings

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

	lowest growth	low growth	**status quo**	high growth	highest growth
UN Scenario	low end of UN's 95% range		**middle of of UN's 95% range**		high end of UN's 95% range
Population in 2100	9.1 to 9.5 billion	9.5 to 10.5 billion	**10.5 to 11.4 billion**	11.4 to 12.8 billion	12.8 to 13.2 billion

1.18.7 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 inquires and support.

1.19 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.

[1] Bi, S. (2015). Forced Sterilizations of HIV-Positive Women: A Global Ethics and Policy Failure. *AMA Journal of Ethics*, 17(10), 952–957. doi: 10.1001/journalofethics.2015.17.10.pfor2-1510

[2] White, H. (2014, May 28). African women fight back against forced, coerced sterilizations. https://www.lifesitenews.com/news/african-women-fight-back-against-forced-coerced-sterilizations

[3] Nittle, N. K. (2020, January 9). U.S. Government's Role in Sterilizing Women of Color. https://www.thoughtco.com/u-s-governments-role-sterilizing-women-of-color-2834600

[4] Blakemore, E. (2016, August 25). The Little-Known History of the Forced Sterilization of Native American Women. *JSTOR Daily*. https://daily.jstor.org/the-little-known-history-of-the-forced-sterilization-of-native-american-women/

1.19.1 Examples

- Global efforts to reduce overconsumption and embrace voluntary simplicity.
- Possible impacts on economic growth from the effects of climate change.

1.19.2 Big Message

- 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.

1.19.3 Key Dynamics

- Population gets multiplied with GDP per capita to equal total global GDP, or Gross World Product. Increases in this variable accelerate the exponential growth of GDP, arguably the most important driver of future carbon dioxide emissions.
- Watch all the sources of energy change as you change economic growth.
- As you increase the economic damage caused by climate change, notice how this reduces the emissions, but cannot halt the temperature increase even under extreme assumptions where the world's GDP plummets.

1.19.4 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.

1.19.5 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]

1.19.6 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"

[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. https://doi.org/10.1016/j.socscimed.2017.03.029

slider. This slider sets the initial global average growth in GDP per person. The slider “Transition time” is available to change the amount of time it takes for the “Near-term economic growth” level to reach the “long-term economic growth” level.

Reduction in GDP from Climate Impacts

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

Climate change is expected to have multiple adverse effects on the economy, such as decreased investment in goods and services due to the cost of responding to changes in extreme weather events, sea level rise, desertification, crop yield decreases, flooding, and resulting migration. Several economists formulated this impact, known as the “damage function,” as a percentage reduction on global GDP, and estimated it as a function of temperature change. The four main functions in the literature are from Nordhaus (2017), Weitzman (2012), Dietz & Stern (2015) and Burke et al. (2015). You can see their estimates for economic damage in the “Reduction in GDP vs Temperature” graph, and replicate them in En-ROADS by entering the following values for the two sliders, or by selecting the function in the ‘Preset’ menu:

En-ROADS Slider	Nordhaus	Weitzman	Dietz & Stern	Burke
Reduction in GDP at 2ºC	0.9%	1.3%	2.6%	13%
Maximum reduction in GDP	22%	97%	98%	20%

1.19.7 Model Structure

In the real world, there would be multiple feedbacks to economic growth from energy prices, and various taxes, however, the model only features the feedback from climate impacts to GDP. The user can explore the other feedbacks by changing economic growth projections with the sliders manually.

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

1.20 Methane & Other Gases

Decrease or increase greenhouse gas emissions from methane, nitrous oxide, and the F-gases. Methane is released from sources like cows, agriculture, natural gas drilling, and waste. Nitrous oxide comes from fertilizers. The f-gases, includes HFCs, PFCs, and others that are used in industry and consumer goods like air conditioners.

1.20.1 Examples

- Decreased meat consumption.
- Modified agricultural practices such as increasing digestion of manure and decreasing fertilizer use.
- Decreased methane leakage from oil and gas industries.
- Increased capturing of gases emitted from landfills.
- Research and development into substitutions for F-gases in industrial processes.

1.20.2 Big Message

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

1.20.3 Key Dynamics

- Methane, N_2O, and F-gas emissions comprise 30% of current greenhouse gas emissions and are key in reducing to address climate change.

1.20.4 Potential Co-Benefits of Decreasing Methane & Other Gases

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

1.20.5 Equity Considerations

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

1.20.6 Slider Settings

The variable being changed is the percent reduction or increase of total maximum action. The model limits how much these emissions can be reduced–so 100% max reduction is not a 100% total emissions reduction–since some are considered unavoidable, particularly those 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%

1.20.7 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.

1.20.8 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]

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

1.21 Deforestation

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

1.21.1 Examples

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

1.21.2 Big Messages

- Efforts to reduce deforestation are relatively low leverage for the climate, because the influence from energy CO_2 emissions is so dominant, but stopping deforestation is still part of a multi-pronged effort to address climate change.
- Protecting forests is helpful for many reasons other than climate action, including biodiversity conservation and protection of native peoples' lands.

1.21.3 Key Dynamics

- Highly reducing deforestation emissions reduces temperature less than most people would estimate. View the "Greenhouse Gas Net Emissions by Gas – Area" graph to see the role of land use (deforestation) CO_2 relative to all the other sources of emissions.

1.21.4 Potential Co-Benefits of Decreasing Deforestation

- Forests protect biodiversity and provide ecosystem services and food sources.
- Forest preservation reduces erosion and prevents soil loss.
- 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.

[1] Castro, D. C., Samuels, M., & Harman, A. E. (2013). Growing Healthy Kids. *American Journal of Preventive Medicine*, 44(3). https://doi.org/10.1016/j.amepre.2012.11.024

1.21.5 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]

1.21.6 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%

1.21.7 Model Structure

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

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

1.22 Afforestation

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

1.22.1 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.

1.22.2 Big Message

- 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.

1.22.3 Key Dynamics

- 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.
- Explore the graph "Land for Carbon Dioxide Removal." The land area of India is 300 million hectares, so if we were to forest an area of that size we would still not see much change in temperature.

[1] Salopek, P. (2019, May 16). Millions of indigenous people face eviction from their forest homes. *National Geographic*. https://www.nationalgeographic.com/culture/2019/05/millions-india-indigenous-people-face-eviction-from-forests/

[2] Mwijuke, G. (2018, January 12). Batwa of Uganda mired in extreme poverty. *Chwezitraveller*. https://www.chwezitraveller.com/featured/batwa-ugandas-conservation-refugees-mired-in-extreme-poverty/

1.22.4 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.

1.22.5 Equity Considerations

- Afforestation entails shifting large areas of land into forests. 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 historic land access, so involving low-income and minority communities, including Indigenous peoples, in the process of policy development and implementation is essential.

1.22.6 Slider Settings

The Afforestation slider changes the percentage of available land that is used to grow new forests. 100% would mean that 700 Mha of land are covered in forests. 700 Mha represents approximately 25% of current grassland area, nearly 10% of all land that is not currently forest, and just over the difference in forest area back in 1850 until now (i.e., there is 630 Mha less forest area today than in 1850).

	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%

1.22.7 Model Structure

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

Maximum amount of available land: With a growing time of 80 years for new forests and 2%/year in total forest carbon loss, 700 Mha achieves an annual removal consistent with the mid-point of estimates of afforestation potential from the 2018 'Greenhouse gas removal' report by the Royal Society (range of 3-20 in CO2 GtonsCO2/year).

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

1.22.8 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.[1]

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

[1] 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. http://dx.doi.org/10.1136/jech.2007.071894

1.23 Technological Carbon Dioxide Removal

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

1.23.1 Examples

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

1.23.2 Big Message

- 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.

1.23.3 Key Dynamics

- View the graph "Land for Carbon Dioxide Removal" and note the total amount of land area that all the approaches might require.
- View the graph "Bulk Material for Mineralization" to see the scale of industrial production these approaches entail.

1.23.4 Potential Co-Benefits of CDR Growth

- Nature-based carbon removal approaches like agricultural soil sequestration can help improve land holder and farmer profits in some cases.
- The scale up of many carbon removal approaches would result in vast new industries and businesses which would create jobs.

1.23.5 Equity Considerations

- Approaches like BECCS require large areas of land that in some cases could otherwise be used for food production.
- 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.

1.23.6 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%

1.23.7 Model Structure

The five 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 low range 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 2 Gton/yr, which was taken from the report's range of 2-5 Gton/yr. 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 Gton/yr.

1.23.8 FAQs

Why aren't coal and gas carbon capture and storage (CCS) included here, and how can I increase them? We think of coal and gas CCS as reducing CO_2 emissions from coal and gas, not actually as removing CO_2 from the atmosphere. Both can be changed in the Advanced View that supports the Coal and Natural Gas sliders.

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

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

1.24 En-ROADS Model Version History

1.24.1 March 2021 Release

Model Upgrade

Updated

- En-ROADS model to version 2.7.37
- Added model structure for economic impact of climate change on GDP.

Interface Changes

Fixed

- Improved the colors on the "Renewables Capacity — Area" graph to make the plots easier to distinguish.

- Changed the Simulation > Assumptions > Climate sensitivity > "Sea level rise from ice sheet melting" slider label to "Additional sea level rise from ice sheet melt" and edited its associated description text for greater clarity.

New

- **Translation into Italian:** En-ROADS is now available in Italian.
- **New slider for Economic impact of climate change:** A new slider type with two input "handles" has been added to the Assumptions menu: Economic impact of climate change. The two handles control "Reduction in GDP at 2ºC from climate impacts" and "Maximum reduction in GDP."
- Two new "Climate impact on GDP" related graphs have been added under the Impacts header: "Reduction in GDP vs Temperature" and "Reduction in GDP from Climate Impacts."
- Read more in our blog post about the economic impact of climate change in En-ROADS.
- Added an Assumptions slider for the progress ratio of electrifying transport, buildings, and industry under Simulation > Assumptions > Progress ratio > Electric carrier.

1.24.2 February 2021 Release

Model Upgrade

Updated

- En-ROADS model to version 2.7.36
- Updated temperature change data and reference years using new temperature data update in HADCRUT5 dataset from December 2020.
- Modified En-ROADS to use baseline data from C-ROADS that is fed into the En-ROADS data model for initialization.
- Updated profitability effects to avoid getting too large with extremes that were leading to drastic and unrealistic swings that could be seen in capacity, utilization, and pricing.
- PRIMAP 2.1 data (2019) of historic GHG emissions were used to update initial fractions of each non-CO_2 GHG emissions from agriculture, waste, extracted fuel supply, demand capital, and non-CO_2 GHG emissions from energy use) and to improve calibration.
- Improved and simplified CH_4 concentration calibration to avoid unnecessarily introducing more uncertainty in response to CH_4 concentration effects on uptake and to include updated PRIMAP data.

Fixed

- Resolved unexpected bioenergy demand spikes that had appeared in the previous release for some scenarios.

Interface Changes

New

- **Four new translations**: New translations added for simplified Chinese, traditional Chinese, German, and Bulgarian. More languages on the way in March!

- **New graphs**: New graphs added related to enhanced mineralization and other carbon removal approaches: "Land for Growing CO_2-Removal Biomass," "Land for Farming with CO_2 Removal," and "Bulk Material for Mineralization." For more details about the carbon removal approaches displayed in these new graphs see this related blog post.
- Added new assumptions specific to enhanced mineralization (found in Assumptions > Mineralization settings).
- Relocated the Language menu to the first menu position and included a globe icon as an indicator for the menu.

Fixed

- Changed terminology from "mid-19th century" to 1850.
- Adjusted some graph and slider labels for better fit in translations.

1.24.3 January 2021 Release

Interface Changes

New

- **Translation into Turkish**: We have a new translation into Turkish this release. Check it out under the Language menu.
- **New graph**: Added a new graph, "% Electricity Consumption from Low-Carbon Sources". Find it under "Final Energy Consumption Types" under the Graphs menu.
- Corrected all references to Purchasing Power Parity to $US 2017. Other various text edits.

1.24.4 December 2020 Release

Read more details about the update.

Watch a video overview of the details of the update.

Model Upgrade

New

- **Updated Baseline**: Several model adjustments related to renewable energy sources, pre-industrial temperature benchmarking, and modeling of non-greenhouse gas forcings have lowered the baseline temperature in 2100 to 3.6°C/6.5°F.
- Renewables are now disaggregated and explicitly modeled for solar, wind, geothermal, and other renewables.
- We also account for the historical subsidies for renewables and the "soft costs" associated with each renewable type. These soft costs have declined as experience was gained.
- The temperature change reported is now relative to the 19th century.
- Initial heat is now calculated from historic temperature change in 1990, taken from temperature anomaly relative to 19th century from GISS (2020) and Hadley (2020) and adjusted to be relative to 18th century mean.
- Other forcings taken from Meinshausen (2011) to reflect those relative to 18th century. Natural forcings easier to subtract to obtain anthropogenic forcings for Equivalent CO_2 concentration.

- Initial CO_2, CH_4, and N_2O updated to reflect actual data from GISS instead of C-ROADS 1990 values.
- Decrease in extraction overheating sensitivity and profitability effects on retirement rates of supply sources to dampen rapid changes in bioenergy demand.

Updated

- En-ROADS model to version 2.7.35c

Interface Changes

New

- **New default graphs**: Changed the default graphs from "Global Sources of Primary Energy" and "Temperature Change" to "Global Sources of Primary Energy — Area" and "Greenhouse Gas Net Emissions".
- Added several graphs related to renewable energy:
  - "Low Carbon Average Cost of Electricity Production by Source",
  - "Low Carbon Marginal Cost of Electricity Production by Source", and
  - "Renewables Capacity — Area".
- Changed the phrase "Business as usual" and "BAU" to "Baseline" across the interface, graphs, legends and descriptions.
- Renamed "New Technology" Energy Supply to "New Zero Carbon" Energy Supply throughout En-ROADS interface.
- Changed the population input slider to display "billion people in 2100" instead of the -1 to +1 index range.
- Expanded the inputs for Economic Growth from a single input to now include "Long-term economic growth", "Near-term economic growth" and a "Transition time" for the "Near-term economic growth" to converge on the "Long-term economic growth" rate.

Fixed

- Changed the start year for input sliders to 2021.
- The ranges for Tax/Subsidy sliders have been updated.
- Some graph descriptions have been edited for clarity.
- Adjusted the Y-axis maximum on some graphs to display the data better over different input configurations.

1.24.5 October 2020 Release

Model Upgrade

Updated

- En-ROADS model to version 2.7.29b
- Corrected the "New Tech" plot in the "Marginal Cost of Electricity Production" graph when the "New Technology" advanced sliders are adjusted.

Interface Changes

Fixed

- Added a short description at the top of the Assumptions panel to clarify how the sliders behave relative to the "Current" and "Business as Usual" scenarios.
- Fixed descriptions of transport electrification sliders to remove mention of ships and airplanes.

1.24.6 September 2020 Release

In addition to the details listed below, we've made a video highlighting the important new features.

Check it out: September 2020 Release Video

Interface Changes

New

- **Spanish**: En-ROADS is now available in Spanish! We're working to bring En-ROADS to even more languages too.
- **Air Pollution graphs**: There are two new graphs in the "Graphs > Impacts" menu showing Air Pollution (PM2.5 Emissions) from the energy sector. Additionally, sliders were added in the "Assumptions" panel to allow for adjusting the emission factor assumptions.

Model Upgrade

Updated

- En-ROADS model to version 2.7.29

Control Slider Related Changes

Updated

- Changed the population slider units to be on -1 to 1 indexed scale with "status quo" equal to zero.
- Fixed the units of the Carbon Price slider to read "\$/ton CO_2" instead of "\$/ton".

Other Interface Changes

Updated

- Fixed the Kaya view to show "Carbon Intensity of Final Energy" instead of "Carbon Intensity of Primary Energy".
- Fixed the menu bar to make it easier to select sub-menu items on iPad.
- Fixed tooltips on iPad so that they disappear automatically.
- Fixed alignment of slider handles on iPad.

- Fixed full screen layout on iPad so that the menu bar is not obscured by the Safari-provided controls.
- Fixed the large graph window to display in the current language (instead of defaulting to English).
- Fixed the x-axis labels on Kaya graphs to not overlap on large screens.
- Fixed graphs to not show tooltips for years outside the displayed range.
- Removed calibration graphs (these will be replaced by improved graphs in an upcoming release).

1.24.7 August 2020 Release

Interface Changes

New

- **Portuguese**: En-ROADS is now available in Portuguese! Localization to more languages is in progress, and we hope to come to your native language soon.
- **Initial iPad Support**: You can now run En-ROADS on your iPad (in Safari or your preferred browser)! In this release, the user experience is better on iPad models released in the last 3 years. In upcoming releases, we will be working to improve performance and refine the user experience across all iPad models.

Updated

- Improved performance in a number of areas, so sliders should feel smoother and more responsive (and further improvements are in the works).
- When sharing a scenario, the user's preference for Metric vs U.S. Units is captured and remembered in the URL.

Control Slider Related Changes

Fixed

- Updated the "Carbon Price" slider description to include bioenergy in the list of impacts.
- Removed accidental mention of deforestation in the "Other greenhouse gases start year" slider description under "Methane & Other Gases".

1.24.8 July 2020 Release

Graphs

Fixed

- Corrected the y-axis of the "Marginal Cost of Electricity Production" graph to adjust dynamically to keep graph lines in view.
- Corrected the "Renewables Primary Energy Demand" graph to reflect hydro in addition to renewables.

Control Slider Related Changes

Fixed

- Improved descriptions for the "Year to stop building new infrastructure" sliders for coal, oil, and natural gas.

Other Interface Changes

Updated

- Improved email sharing of scenarios by showing a preview of the message to be sent, and allowing for a custom note to be included with the shared scenario.
- Changed the welcome screen to direct feedback and questions to support.climateinteractive.org.
- Changed the "General FAQs" link under the Help menu to direct to the Knowledge Base on the support site.

1.24.9 May 2020 Release

Model Upgrade

Updated

- En-ROADS model to version 2.7.19
- Add email sharing of your current scenario to "Share Scenario" menu button.
- Update GDP with 2018 World Bank data.

Fixed

- Minor edits to description texts

1.24.10 April 2020 Release

Model Upgrade

Updated

- En-ROADS model to version 2.7.14
- Added link to "Uses for En-ROADS" under the Help menu
- Add menu control for "Reset Policies" sliders and "Reset Assumptions" sliders under "Simulation" menu; changed wording of "Reset" to "Reset Policies & Assumptions."

Graphs

- When switching from Metric Units to U.S. Units, the "Land for Carbon Dioxide Removal" graph switches from "Million hectares" to "Million acres".

Fixed

- Improved location of icons in the top toolbar to help avoid accidental clicks on the "Reset Policies & Assumptions" icon (formerly, "Reset sliders" tool tip).
- Correcting Large graph feature so graphs are sized correctly in the remote window.
- Edits to description texts for "Coal carbon capture & storage (CCS) (tax/subsidy)" slider, "Gas carbon capture & storage (CCS) (tax/subsidy)" slider and the overall description for Nuclear in the advanced views.

1.24.11 March 2020 Release

Along with the details listed below, we've made a cool video highlighting the important feature additions and changes to model behavior.

Check it out: March 2020 Release Video

Model Upgrade

Updated

- En-ROADS model to version 2.7.11
- Updated the equation for the Energy Intensity of New Capital to better respond to price effects
- BAU improvement rate in emission intensity and Annual improvement rate of emission intensity for F-gases were adjusted to reflect SSP2 baseline trajectories
- The settings for CH_4 and N_2O emissions from agriculture and waste have also been slightly updated

Graphs

Fixed

- Add "Hydro" data to "Average Cost of Electricity Production" graph and correct the name of "Renew/Hydro" to Renewables"
- Corrected several missing Related Graphs in some advanced views
- Corrected the variable in "Marginal Cost of Renewables" graph
- Corrected typo in descriptions for N_2O and CH_4 graphs (Megatons was corrected to $1x10^6$)
- The y-axis label in graph "CO_2 Emissions" was corrected to Gigatons CO_2/year

Updated

- Edited the description for "CH_4 Emissions" graph and corrected the plotted variable to display anthropogenic CH_4 emissions
- Edited "Storage Costs" graph description for clarity
- Edited the description for "Cumulative CO_2 Emissions" graph
- Changed the graph name from "Fuel Production Cost" to "Fuel Production Cost by Source" to make it consistent with the titles of the other graphs in the Financial category that are broken out by energy source

- Added "Greenhouse Gas Net Emissions by Gas—Area" to related graphs for Deforestation

Control Slider Related Changes

Fixed

- Updated New Tech slider description to match what the slider settings do
- Added back a missing description for slider, "Coal CCS R&D breakthrough cost reduction"
- Edit description for slider, "% Reduction in Coal Utilization"

Updated

- **Edit slider names referring to final carbon price, removing the word "target" so it is now:**
  - Final carbon price (previously, Final Carbon price final target)
  - Year to start achieving final carbon price (previously, Year to start achieving final carbon price target)
  - Years to achieve final carbon price (previously, Years to achieve final carbon price target)
- Added back assumptions sliders for "Methane emissions from biological activity", "Effect of temperature on methane emissions from permafrost and clathrates", and "Temperature threshold for permafrost and clathrates"

Other Interface Changes

New

- You can create a large copy of any of the graphs to use on additional screens or monitors. The graph outputs in the copies remain connected to changes in the control input sliders. These graphs are accessed under the View menu, as "Large Left Graph and "Large Right graph". You may select multiple copies of left or right graphs.

Coming Soon

- Localization to many languages is in process! We hope to come to your native language soon!

CHAPTER 2

Indices and tables

- genindex
- modindex
- search