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ROUTES TO A CARBON-FREE WORLD

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YOUNG REVIEWERS:

ALEX
AGE: 14

CALEB
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MARCUS
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Humans need to cut CO_2 emissions rapidly to limit global warming and prevent dangerous climate change. Policies adopted so far in countries worldwide are not enough. The good news is that there are many things we can do. First, we can save energy by using the most energy-efficient technologies and by changing our lifestyles. Second, we can use CO_2-free energy sources, such as solar, wind, or hydropower. Third, we can invest in technologies that can remove CO_2 from the atmosphere. Finally, we can regrow forests all over the planet. Scientists imagine alternative future “scenarios” including different combinations of technology, energy, and lifestyle solutions. We know it is possible, but we need to act now to reduce CO_2 emissions, even if it means making hard choices.

THE WORLD NEEDS TO REDUCE GREENHOUSE GAS EMISSIONS

The world's climate is warming because of human activities, such as burning coal, oil, and natural gas to produce electricity, heat our homes, and fuel our cars (Figure 1A). In the **Paris Agreement** of 2015, countries worldwide promised to limit the increase in global average temperature to well below 2°C and to pursue efforts to stay below 1.5°C compared to temperatures before the Industrial Revolution, when humans started to use a lot of fossil fuels. These goals were chosen to prevent the potentially disastrous impacts of climate change. At the moment, Earth is already around 1.4°C warmer, and the impacts of climate change are becoming noticeable.

PARIS AGREEMENT

The international treaty adopted in December 2015 in Paris, France, in which countries agree to mitigate climate change by limiting global warming to well below 2 degrees Celsius above pre-industrial levels and pursue efforts to keep warming below 1.5 degrees.

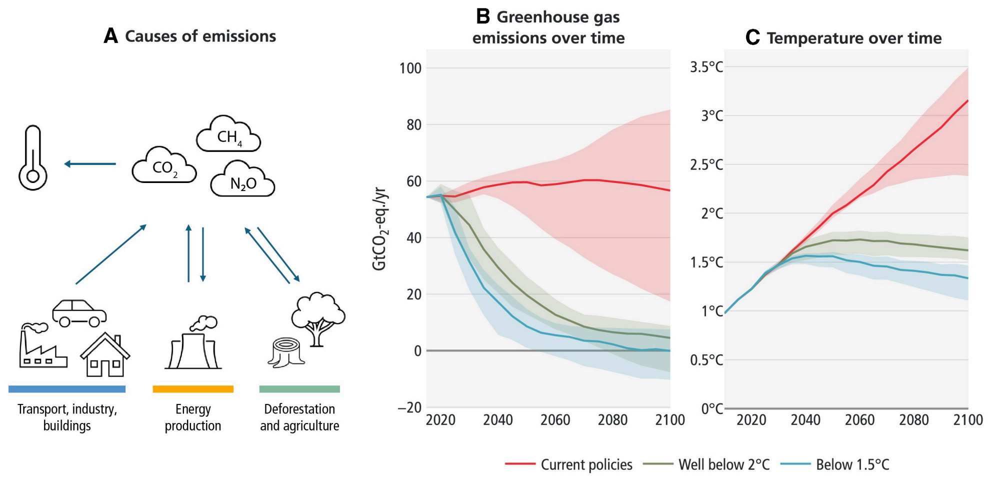

Figure 1

Figure 1

(A) Greenhouse gas emissions mostly result from burning fossil fuels in industry, houses, and transport; from producing electricity; and from cutting down forests and other emissions related to agriculture. **(B)** Based on current policies and trends, emissions are likely to stay constant, while for the goals of the Paris Climate Agreement emissions need to go down. **(C)** This means that the temperature projections stay above those of the Paris Climate Agreement (well below 2). Figure based on IPCC [1, 2].

The most important action we can take to limit global warming is to stop releasing CO_2 (the main greenhouse gas), as well as other greenhouse gases, such as methane (CH_4) and nitrous oxide (N_2O), into the atmosphere. There is a direct relationship between the amount of CO_2 we put in the atmosphere and the level of global warming. Based on this, climate scientists often refer to the remaining **carbon budget**, which is the maximum amount of CO_2 that can be emitted before global warming passes a temperature goal. To stay below 1.5°C, we cannot release more than about 250 billion tons of CO_2 from today onward, while also reducing **emissions** of other greenhouse gases. This is only about 6 times the CO_2 emissions released in 2023 alone [1]. To stay below 1.5°C, CO_2 emissions need to be deeply reduced now and reach **net zero emissions** around 2050 (Figure 1B). To stay well below 2°C, emissions need to be reduced rapidly as well, reaching net zero around 2070 [1]. While these years might sound far away, they actually imply that immediate action is needed. Clearly, it will be much more difficult to limit warming to 1.5°C than well-below 2°C, but if we do so the damage of climate change will be much less.

CARBON BUDGET

The amount of CO_2 that still can be emitted into the atmosphere given a selected goal for limiting global warming.

EMISSIONS

The release of greenhouse gases into the atmosphere due to human activities such as burning fossil fuels.

Some countries are already reducing emissions, but in others emissions continue to grow. Overall, greenhouse gas emissions have been increasing. Taking into account the current actions and policies that countries are implementing, temperatures will likely increase to around 2.5°C–3.5°C of warming by the end of this century, with negative consequences for all life on Earth (Figure 1C) [1–4].

CO_2 emissions mostly come from burning fossil fuels and deforestation. It will not be easy to reach net zero. Fossil fuels are used all across society. For example, think about the boilers installed in homes for heating purposes, the coal and gas power plants that provide electricity, and the oil used in cars and planes. How fast can we shift away from these technologies and adopt new ones? What are the main changes we need to make to stop global warming? These are the topics we discuss in this article.

NET ZERO EMISSIONS

Balancing the amount of greenhouse gases released and removed from the atmosphere to stop adding to climate change.

COMPUTER MODELS

Computer simulations of systems that determine future climate change, such as energy use and production, agriculture, nature, the climate system itself, and possible consequences, such as sea level rise. Models are used to explore possible scenarios or pathways for future climate change.

SCENARIOS

Descriptions of possible future developments based on a consistent set of assumptions (such as population growth or technology development). Scenarios help in understanding the potential consequences of different actions.

REACHING NET ZERO EMISSIONS

To find out what changes can help us get to net zero, scientists collect data on possible technological and social changes. They then use **computer models** to develop **scenarios**, which are possible choices or action plans that the world could follow to stay within the remaining carbon budget [5]. Next, we will describe four types of actions that people could take to limit greenhouse gas emissions.

Reducing Energy Use in Buildings, Transport, and Industry

We use energy in our daily lives for heating, cooling, and lighting our homes, schools, and offices, and for cooking and other daily tasks. Industries need energy to manufacture products like clothing. Energy is also used to transport goods and passengers in cars, ships, and airplanes. Today, most of this energy comes from fossil fuels. There are several ways that we could reduce our overall use of energy for these purposes. For example, we can insulate our buildings better, keep the temperature to a comfortable level (not too cool or too warm), and switch to more efficient heating systems, like heat pumps. Together, such changes could reduce emissions by 40%–70% in 2050. Using less energy overall will also make it much cheaper and quicker to move away from fossil fuels, because we will not have to produce as many windmills, solar panels, and other renewable sources.

Replacing Fossil Fuels With Renewable Energy Sources

Renewable energy sources, like wind and solar power, have become cheaper over the last decade. This makes them good alternatives to fossil fuels for generating electricity without creating greenhouse gas emissions. However, sun and wind cannot always supply all our energy—sometimes the sun does not shine and the wind does not blow and for some purposes, electricity is not an alternative. Therefore, additional solutions are needed, such as powerful batteries to store energy, large energy grids to move electricity around, or **bioenergy**, in which sustainably grown crops or trees are used for energy. We could also continue to use fossil fuels in combination with removing the CO_2 from the fume gases and store it underground, called **CO_2 capture and storage**, or we could use nuclear power. Still, some emissions are very difficult to reduce.

BIO-ENERGY

Energy generated from burning products generated from plants or trees. This can be wood, but also fuels (like biodiesel) created from crops.

Reducing Emissions in Difficult Sectors

Some emissions are especially difficult to reduce, such as emissions from cement and steel production, long airplane flights, and meat and dairy farming (scientists call them "hard to abate"). Why are these difficult sectors? The main reason is that right now we have limited technologies to help reduce emissions in these sectors. For example, wind and solar power cannot be used to power airplanes because current batteries are too heavy and do not store enough electricity to keep a plane flying for a long time. Researchers think that hydrogen produced from renewable energy sources—so-called green hydrogen—could be used in steel-producing furnaces, but we do not currently produce much green hydrogen, so it tends to be very expensive. Livestock is another challenge: cows and sheep produce methane emissions when they fart and burp. There may be some technologies to reduce such emissions, but it is likely that we will not be able to stop them completely.

CO_2 CAPTURE AND STORAGE

Removing CO_2, mostly from fume gases but possibly from the atmosphere and storing it in reservoirs like empty natural gas fields.

Due to the difficulty in reducing emissions from these sources, it is important to consider alternatives. For example, people could make lifestyle changes like eating less meat or flying less. Nonetheless, scientists think that to stabilize global temperatures we will also need to remove some CO_2 out of the atmosphere to compensate for these hard-to-abate emissions. We also may want to remove some of the CO_2 emissions we have put in the atmosphere later. Captured CO_2 can be stored for long periods of time in trees, other plants, soils, rocks or underground in reservoirs (see this Frontiers for Young Minds article for more information).

Stop Cutting Down Forests—Plant Forests Instead

When trees and other natural vegetation are cut down and burned, they produce a lot of carbon emissions. Trees are usually cut down to create new areas to produce food. How do we prevent this? First, we could protect existing forests and we could plant new ones, which is called **reforestation**. Second, we could improve food production on current farms in a sustainable way, so that we can meet the growing demand for food without using more land. And lastly, we can reduce food waste and change what we eat. Shifting toward diets with less meat, especially in countries with high meat consumption, can decrease the amount of land needed to produce our food. Shifting diets not only helps the environment but could also improve human health.

REFORESTATION

The planting of forests on lands which have, historically, previously contained forests.

COMBINING ELEMENTS INTO PATHWAYS

Scenarios can help us learn more about possible solutions for reducing emissions: How much renewable energy do we need? How can we reduce energy use? From all the scenarios found in the scientific literature, a report from a group of experts called the **Intergovernmental Panel on Climate Change (IPCC)** presents a few choices [1–4]. These are called the illustrative mitigation **pathways**. All of them meet the goals of the Paris Agreement and limit temperature increase close to 1.5°C, but their implications and risks are different (Figure 2).

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC)

The international organization consisting of scientists with the task to assess scientific knowledge on climate change and its impacts.

PATHWAYS

Equivalent to the word scenarios.

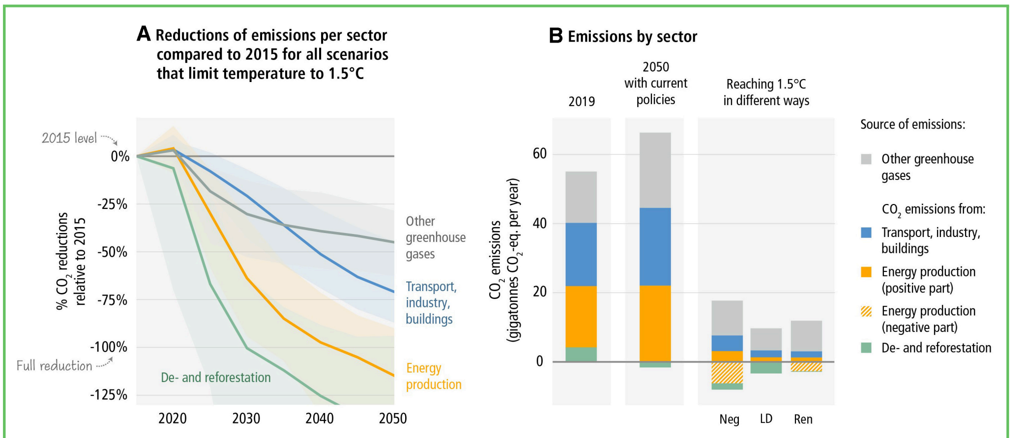

Figure 2

Figure 2

(A) To limit warming to 1.5°C, emissions must be reduced in multiple sectors, including CO_2 emissions from transport/industry/buildings, CO_2 emissions from energy and electricity production, net CO_2 emissions from de- and afforestation and other greenhouse gases (mostly from agriculture and energy production). **(B)** Examples of pathways to reach net zero CO_2 emissions. Emissions can be negative if CO_2 is taken from the atmosphere (e.g., due to regrowing trees). The graph on the right shows three scenarios to stay below 1.5°C: the negative emissions pathway (neg), the low-demand pathway (LD), and the renewable energy pathway (ren). The first column shows emissions in 2019 and the second column shows what will happen in 2050 following current policies [3]. Figure based on IPCC [1, 2].

The *Negative Emissions Pathway* relies heavily on CO_2 removal technologies. These include reforestation, the use of bioenergy combined with CO_2 storage underground, or direct capture of CO_2 from the atmosphere. This scenario might allow us a slightly slower transition now, but it heavily relies on future generations to invest in these removal technologies. There may be a risk that the technologies do not work, and many of them require land, which could compete with food production.

The *Low-Demand Pathway* relies heavily on reducing energy demand by efficiency and lifestyle changes. It imagines that we can avoid using products that we do not need, and that we can buy products that last longer, eat less meat and dairy, and live in smaller but more efficient homes. However, the question is how quickly and easily such changes can be adopted.

The *Renewable Pathway* relies heavily on renewable energy sources, assuming that we can support these technologies with energy storage solutions and well-connected electricity grids. This scenario also has a shift toward using more electricity for transport and buildings, like electric cars and heat pumps. This could be attractive, but it will require significant investments in renewable energy and power infrastructure starting now, which will increase demand for certain materials needed for these technologies (while also decreasing demand for fossil fuel materials).

MEETING THE PARIS AGREEMENT CLIMATE GOALS

Moving forward through any of these pathways will be challenging but the pathways show that it can be done! This is a major conclusion of the most recent IPCC report: we know how to meet the objectives of the Paris Agreement. However, meeting the objectives to limit global warming will require society to move toward a very different type of path, giving up our addiction to fossil fuels for the good of all life on Earth.

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REFERENCES

1. IPCC, 2022. "Climate Change 2022: Mitigation of Climate Change", in *Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,* eds. P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, et al. (Cambridge, UK and New York, NY, USA: Cambridge University Press). doi: 10.1017/9781009157926
2. IPCC, 2023. "Climate Change 2023: Synthesis Report", in *Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,* eds. Core Writing Team, H. Lee and J. Romero (Geneva, Switzerland: IPCC). p. 35–115. doi: 10.59327/IPCC/AR6-9789291691647
3. IPCC, 2022. "Climate Change 2022: Impacts, Adaptation, and Vulnerability", in *Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,* eds. H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, et al. (Cambridge, UK and New York, NY, USA: Cambridge University Press). p. 3056. doi: 10.1017/9781009325844
4. IPCC, 2021. "Climate Change 2021: The Physical Science Basis", in *Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change,* eds. V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, et al. (Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press). p. 2391. doi: 10.1017/9781009157896
5. Riahi, K., Van Vuuren, D. P., Kriegler, E., Edmonds, J., O'neill, B. C., Fujimori, S., et al. 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. *Global Environ. Change* 42:153–168. doi: 10.1016/j.gloenvcha.2016.05.009

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CONFLICT OF INTEREST: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

YOUNG REVIEWERS

ALEX, AGE: 14
Alex is an 8th grader who likes science, math, history, and English. He enjoys playing video games, role-playing Dungeons and Dragons, and playing Texas Hold'em (and winning).

CALEB, AGE: 11
Caleb enjoys all things science, animals, reading, exploring the outdoors, playing the violin, and curling. When he grows up, Caleb wants to be an architect focusing on eco-friendly and animal oriented buildings. He has tried four sports and is always up for trying something new. Caleb's favorite foods are macaroni and cheese or lasagna. He enjoys traveling and would like to go to an animal reserve.

ESTHER, AGE: 14
My name is Esther, and I am 14 years old. I enjoy playing the flute and drawing and painting in my free time.

MARCUS, AGE: 14
Marcus is a supporter of STEM. He is in 8th grade as of writing this review. He spends his time researching a wide variety of topics, especially sciences such as biology and physics. He is involved with mock trial, welding, and more.

MOMO, AGE: 12
Momo loves to travel the world and see new places. Even so, she is a self-proclaimed couch potato when she is at home. The two extremes can coexist in one person! Her favorite couchmate is her fuzzy and affectionate dog, Lita.

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