Do Not Drop the Hot Potato: Take Control with our Simulator

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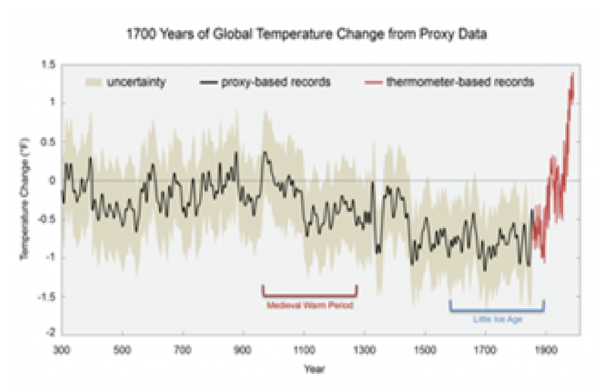
Scan this barcode to try our simulator!

BACKGROUND



Scientists studied the global temperature change from 300 AD until now and found that "the 2021 surface temperature was already 1.51 °F (0.84 °C) warmer than the twentieth-century average".

(1700 years of Temperature from Proxy Data, n.d.)

According to NASA "changes to Earth's climate are already having widespread effects ":

- glaciers and ice sheets are shrinking,
- river and lake ice is breaking up earlier,
- rising sea levels threatening coastal and island communities,
- many regions are seeing more hot days, heat waves, and increased drought,
- many regions are experiencing more severe and frequent storms,
- and so on.

GOAL

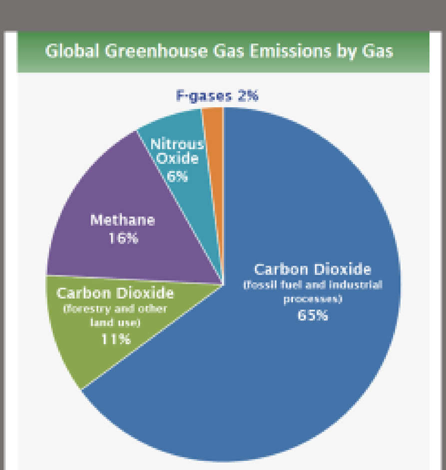
Design and create a user-friendly computer simulator that effectively visualizes the impact of carbon emissions on global temperature, to engage and educate the public on the impact of our carbon footprint on the environment.

Assessment Plan

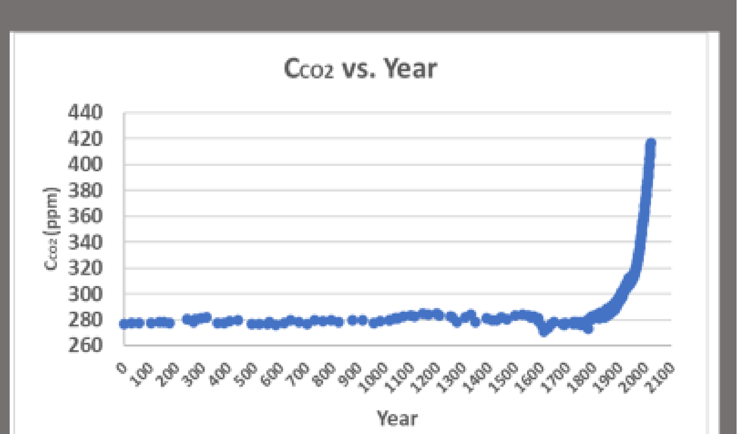
To gauge the effectiveness of our model and simulator, we compared our simulator results with the award-winning online policy simulator, C-ROADS, which was a collaborative outcome of the Climate Interactive, MIT, Ventana Systems, and UMass Lowell Climate Change. (Climate Interactive, n.d.)

THE ROLE OF CO_2

The Intergovernmental Panel on Climate Change (IPCC), the United Nations body for assessing the science related to climate change, pointed out that greenhouse gases from human activities are the most significant driver of observed climate change since the mid-twentieth century. Carbon dioxide (CO_2) accounts for most of the greenhouse gas emissions

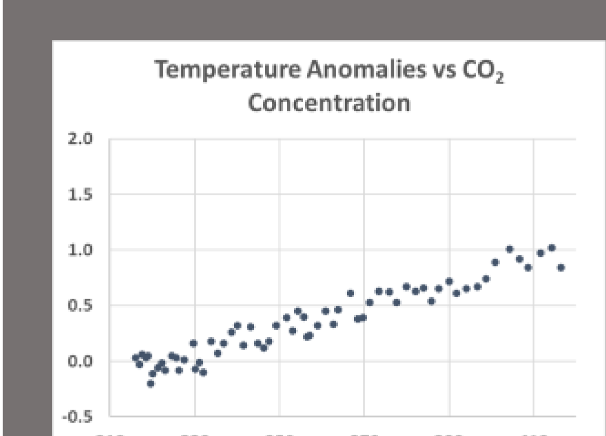


https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data



C_{CO2} from year 1 to year 2021. Data sources: Climate Change Indicators: Atmospheric Concentrations of Greenhouse Gases, n.d. from EPA for before 1959 and NOAA for 1959-2021.

ΔT vs. CO_2 CONCENTRATION



Correlations		C_{CO2} (ppm)	ΔT (°C)
C_{CO2} (ppm)	Pearson Correlation	1	.961**
	Sig. (2-tailed)		0.000
ΔT (°C)	Pearson Correlation	.961**	1
	Sig. (2-tailed)	0.000	

**. Correlation is significant at the 0.01 level (2-tailed).

According to the IPCC, "The temperature response to increasing CO_2 concentration is logarithmic" (Scenario Consistency and Reporting, n.d.). Indeed, it is well-established (Climate Sensitivity, n.d.; Gregory & Andrews, 2016; Huang & Bani Shahabadi, 2014; Myhre et al., 1998; Romps et al, 2022) that:

$$\Delta T = \lambda \ln(C_{CO2}/280)$$

where λ is within the range of 2.164 to 6.492. We tested λ in the range of 2.15 to 6.50 at a step of 0.05. λ = 2.75 resulted in R^2 of 0.9238 and similar prediction outcomes compared with the C-ROADS simulator. (Climate Interactive, n.d.)

To predict future ΔT, we need future C_{CO2}!

THE CARBON CYCLE-BASED BOX MODEL

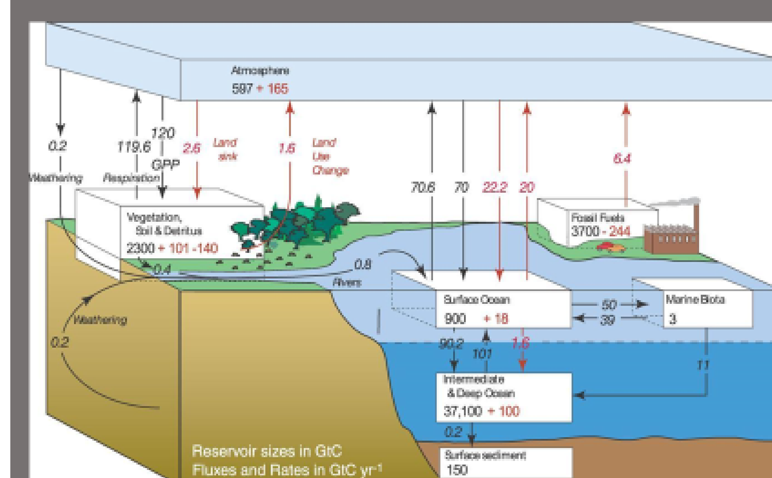


Figure from United Nations The Intergovernmental Panel on Climate Change, 2007a

dC/dt = Fa+Fe -Fr

where C = $v_a \times C_{CO2}$ is the mass of atmospheric CO_2 and Raupach et al. (2008) gave v_a = 2.13 PgC ppm-1, Fa represents anthropogenic emissions, Fe represents environmental (oceanic + terrestrial) emissions, Fr represents environmental uptake, and dC/dt is the growth rate of atmospheric CO_2.

119.6 (flux in due to respiration)-120 (flux out due to annual gross (terrestrial) primary production) + 70.6 (flux in due to exchange with ocean) - 70 (flux out from due to exchange with ocean) - 0.2 (flux out due to weathering) = 0 GtC yr^{-1}.

dCss/dt = Fe(ss)-Fr(ss)=0

d(C-Css)/dt = Fa+ΔFe-ΔFr

WHAT AFFECTS C_{CO2}

d(C-Css)/dt = Fa+ΔFe-ΔFr

Where ΔF_e and ΔF_r are the disturbances from the steady state.

- Css = 2.13× 280 = 596.4 PgC
- ΔFe ∝ β_T ΔT, β_T is the sensitivity coefficient and ~ 3.5±0.6 PgC $y^{-1}C^{-1}$ (Adams and Piovesan, 2005; Wang et al., 2013; Wang and Nemani, 2014)
- ΔFr ∝ $k_s(C–C_{ss})$, k_s is the yearly CO_2 sink rate and is an adjustable model parameter to optimize the model fit to the existing data (following Spencer (2022)). A previous study has shown that ks typically ranged from 0.01/y to 0.05/y from 1959 to 2013. (Raupach et al., 2014) In this project, we tried using different k_s from 0.01/y to 0.05/y at a step of 0.005 and the ks=0.04/y gave us the best fit with the existing data.

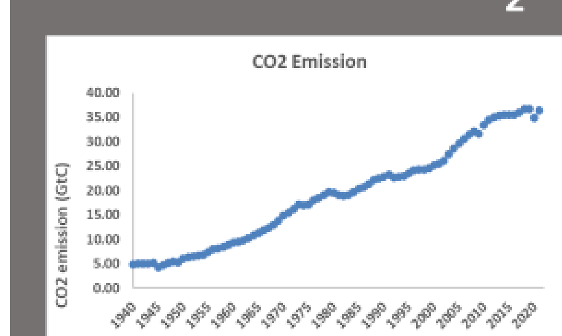
$$d(v_a C_{CO2}-596.4\ PgC)/dt = Fa + \beta_T \Delta T - k_s(v_a C_{CO2}-596.4\ PgC)$$

- where Css = 2.13× 280 = 596.4 PgC
- βT=3.5 PgC y-1C-1
- ks=0.04/y
- $\Delta T = \lambda \ln(C_{CO2}/280)$

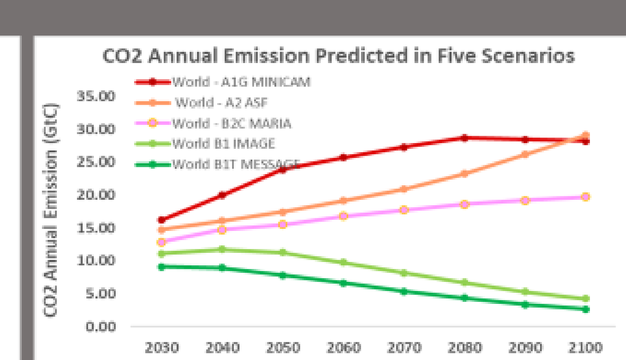
$$d(v_a C_{CO2}-596.4\ PgC)/dt = Fa + \beta_T \lambda \ln(C_{CO2}/280) - k_s(v_a C_{CO2}-596.4\ PgC)$$

Only need current C_{CO2} and future Fa!

CO_2 EMISSION



Annual CO_2 emission from 1940 to 2021. (Data source: Tiseo, 2007)



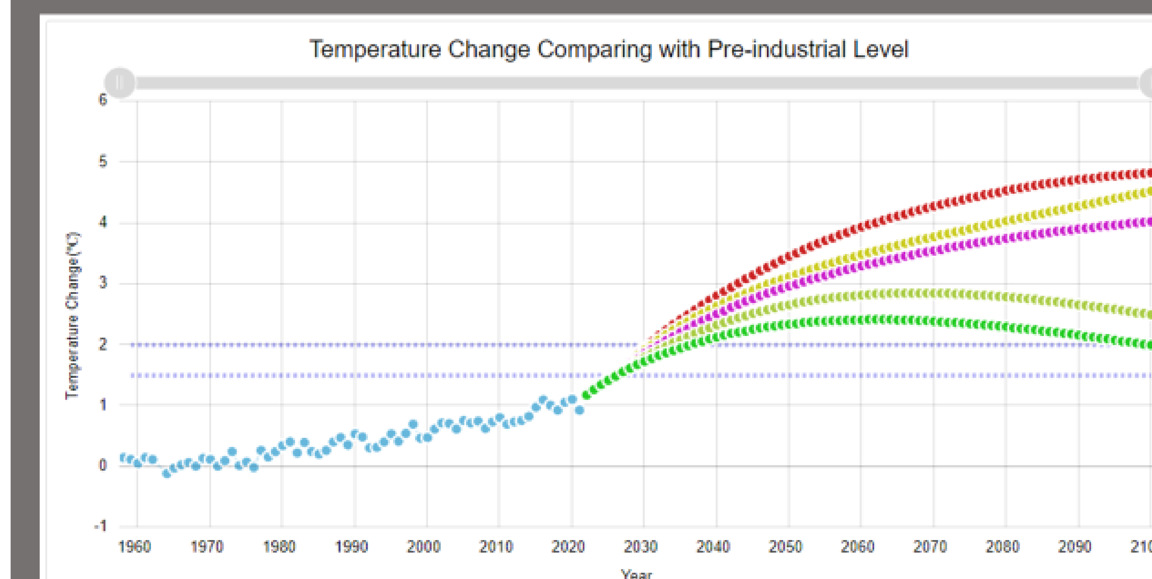
Annual CO_2 emission (future Fa) in five selected future scenarios from the Special Report on Emissions Scenarios (SRES). (Data source: The United Nations The Intergovernmental Panel on Climate Change, 2000.)

SERS Scenarios selection criteria:

1. The predicted cumulative CO_2 emission between 1990 and 2020 is within ±115% of the reported global cumulative CO_2 emission of the same period (Nakicenovic et al, 2000; Tiseo, 2022).
2. Select scenarios to ensure coverage of a broad spectrum of future emission scenarios. Scenarios with similar long-term projections were not selected.

World B1T MESSAGE: Immediate decrease in CO_2 emission;
World B1 IMAGE: CO_2 emission peaks in 2040;
World - B2C MARIA, business as usual;
World - A2 ASF, relatively rapid CO_2 emission growth;
World - A1G MINICAM: Rapid CO_2 emission growth peaks in 2080.

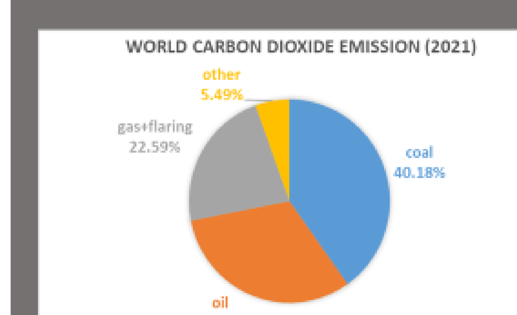
IMPLEMENT THE MODEL



Model predicted average land-ocean temperature change.

- **Bright green:** Immediate decrease in CO_2 emission (B1T MESSAGE);
- **Chartreuse:** CO_2 emission peaks in 2040 (B1 IMAGE);
- **Violet:** Business as usual (B2C Maria);
- Yellow: Relatively rapid CO_2 emission growth (A2 ASF);
- **Red:** Rapid CO_2 emission growth peaks in 2080 (A1G MINICAM).

SELECT A USER INPUT



World CO_2 emission by fuel in 2021 (newest data we were able to find, Ritchie & Roser, n.d.)

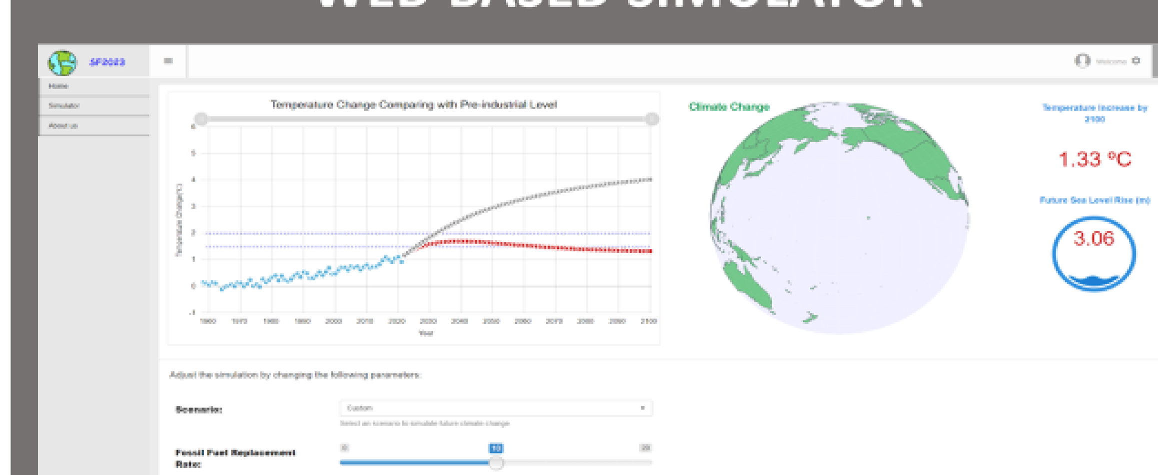
- **Yearly fossil fuel replacement rate**, i.e. the percentage of fossil fuel being replaced by renewables, as the user input: helps the user to directly relate the reduction in global warming with actionable measures.
- **Emission reduction rate**: requires the users to have an understanding of what action items may contribute to the reduction of emission.
- Fa from the **SRES Business-as-Usual scenario** is used as the baseline for the simulator.

- Studies show that the carbon emissions of renewable sources typically is about 1/15 of the carbon emissions of fossil fuels for the same amount of energy. (Emissions, 2011).
- User input, x, is defined as percentage of yearly fossil fuel replacement rate by renewables starting in 2023.
- Fa^{new} is calculated using:

$$Fa^{new} = Fa \times \left\{P_r + P_f \times (1-x)^{year-2022} + \frac{1}{15} P_f \times [1-(1-x)^{year-2022}]\right\}$$

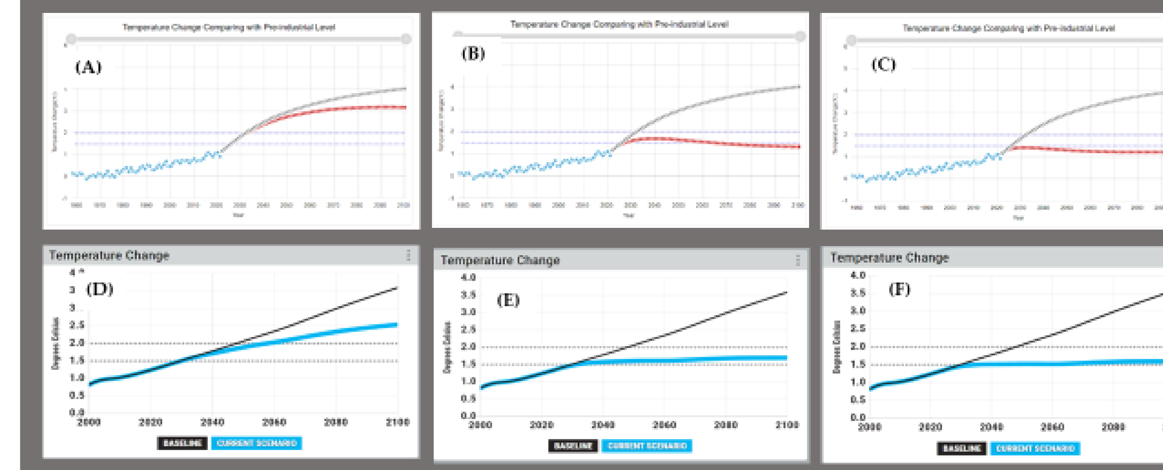
Where Fa is the SERS Business as Usual data set, P_r is the percentage of emission from non-fossil fuels in 2021, P_f is the percentage of emission from fossil fuels in 2021.

WEB-BASED SIMULATOR



- Web technologies including HTML5, JavaScript, and JQuery were used;
- Simulator was Implemented in JavaScript;
- amCharts was employed as the main charting library;
- A LineChart was used to render historical and future temperature increases. The IPCC goals of limiting global warming to less than 1.5 °C or 2°C are highlighted on the chart;
- A MapChart was used to create a globe with color change according to the predicted ΔT by 2100.
- A liquid fill gauge was used to indicate eventual sea level rise based on the predicted temperature change. The conversion rate used for this calculation was based on a sea level rise of around 2.3 meters for every degree (°C) that climate change warms the planet. (The Ocean Portal Team, n.d.)

COMPARE WITH C-ROADS



Starting in 2023 (A) 1% yearly replacement rate of fossil fuels by renewables in our simulator ; (B) 10% in our simulator; (C) 20% in our simulator; (D) 1% annual emission reduction rate in C-ROADS; (E) 10% in C-ROADS; (F) 20% in C-ROADS. (Climate Interactive, n.d.)

1. The yearly replacement rate of fossil fuels by renewable is **NOT** the same as the annual emission reduction. 1% of replacement results in less than 1% emission reduction.
2. Our NASA ΔT data was 0.84°C in 2021 while the C-ROADS used 1.27°C as ΔT in 2021.
3. C-ROADS model most likely used different data sources and a different set of assumptions.
4. C-ROADS is a much more granular model of multiple-year efforts of a large interdisciplinary expert team.
5. C-ROADS probably took into consideration of many different factors that have been ignored in our simple model, such as the influence of water vapor or greenhouse gases other than CO_2. Thus, we should only compare the predicted trends not exact numbers. It is obvious that the trends predicted by our simple model reveal the same insights as the C-ROADS.

INSIGHTS GAINED

Summary of Our Simulator Predictions

Yearly Fossil Fuel Replacement Rate	1%	2%	5%	10%	20%
ΔT Peak Year		2069	2047	2037	2030
Peak ΔT (°C)		2.71	2.09	1.70	1.43
ΔT in 2100 (°C)	3.18	2.56	1.66	1.33	1.22

1. Even a small annual reduction in carbon emission such as 1% would significantly reduce global warming in the long run. However, a large enough effort (replacement rate >=10%) is needed to reach the IPCC goal of 1.5 °C.

2. The table here shows that a yearly replacement rate of

- 2% results in **ΔT** peaking in year 2069 and decreasing slightly from the peak by 2100.
- 10% results in the **ΔT** peaking at 1.70 °C in 2037 and decreasing to 1.33 °C in 2100.
- 20% results in the **ΔT** starting to level out at about 1.43 °C in 2030.

Similar trends have been observed in the C-ROADS with temperature peaking and turning points in years close to what's summarized in our table.

This observation tells us that reduction in carbon emission is the key to control the global temperature increase to be below 2 °C and the steeper the reduction, the sooner the global temperature change will level off.

3. Both our simulator and the C-ROADS show that a larger than 10% annual replacement or reduction rate results in the global temperature change by 2100 approaching a steady-state. It makes sense that the large replacement and reduction rate result in the leveling of the global temperature change at a steady level in both models since this temperature increase is largely dependent on the total amount of existing greenhouse gases and the current emission level. To reduce the temperature increase to below this steady level, we need to implement methods to remove existing greenhouse gases from the atmosphere.

CONCLUSIONS

- We have successfully created a web-based simulator that is straightforward and easy to use. In this simulator, users can select the yearly replacement rate of fossil fuels by the renewables and receive immediate visual response of the predicted mean global temperature change.
- Our model has large uncertainty due to the many assumptions we made to simplify the problem, such as ignoring many relevant factors including the land-use change emissions, other greenhouse gases, aerosol response, extraordinary weather conditions, volcanic events, etc. However, the trends predicted by our models are useful in guiding our actions to address the global warming issue.
- Going forward, we hope to take feedback from users to help us improve our simulator and eventually publish this simulator on the internet for general public to use.

Comparing Our Simulator to the C-ROADS Simulator

Simulator	C-ROADS	Our Simulator
Type of activity	Roleplaying game	Web-based interactive simulator
Focus	International climate negotiations about countries' emissions reduction pledges	Public awareness of carbon emissions and their impact on climate change
Stakeholder groups	Country/regional delegates	Students
	Climate event attendees	General public
	Climate Activists	
	Fossil Fuel Lobbyists,	
	United States Climate Alliance,	
	Press Corps	
	Others	
Length of time to play	1-3 hours. Breakdown of different timelines available here	1-5 minutes
Facilitator experience required	Fairly limited. One-hour training webinar plus additional preparation and familiarizing yourself with the C-ROADS simulator.	None. Brief instructions and explanations on the webpage.

ACKNOWLEDGEMENT

We want to thank Mrs. Patricia Shepherd for guiding and supporting us in pursuing this project.

REFERENCES

In-text citations have been included in this poster and corresponding references can be located in the References list of our final report.

Our article includes a list of references cited in the article.
Following is a list of references or links for figures in the title page and the C-ROADS website:

1. Scharping, N. (2021, February 15). *How Hot Will Climate Change Make the Earth By the Year 2100?* Discover Magazine. Retrieved March 2, 2023, from https://www.discovermagazine.com/environment/how-hot-will-climate-change-make-the-earth-by-the-year-2100
2. https://trendincite.com/wp-content/uploads/2020/07/Hand-holding-glass-world-with-green-leaf-sustainabilty.jpg
3. Climate Interactive. (n.d.). The C-ROADS Climate Change Policy Simulator. Retrieved February 28, 2023, from https://www.climateinteractive.org/c-roads/