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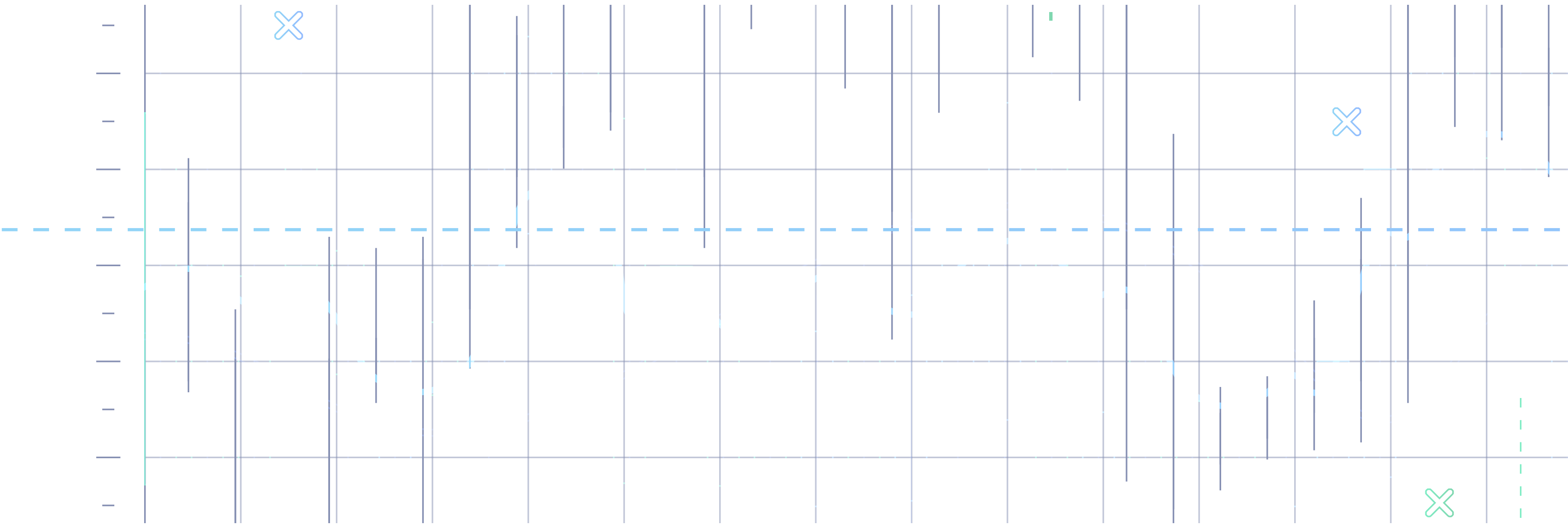

# Carbon Pricing: Necessary but not Sufficient

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# EXECUTIVE SUMMARY

Global carbon pricing has been recognized as one of the most efficient mechanisms that can be used to reduce CO2 emissions. Many countries and firms alike are currently reviewing and/or implementing carbon pricing as a method to reduce their emissions, but questions remain about the *magnitude* of the price and the *speed* of implementation.

Reports indicate significant variation in carbon prices across countries, while research is divided over what the global average carbon price should be in order to reach the Paris Climate Agreement goals of limiting global warming to 1.5–2°C by 2100 relative to pre-industrial levels. We examine this important issue by extending the Dynamic Integrated Climate and Economy (DICE) model to estimate global carbon prices to achieve various warming scenarios.

Similar to the conclusions of Cruz and Rossi-Hansberg, our analysis suggests that while carbon pricing can play a critical role in reducing greenhouse gas emissions and limiting global warming, it must be supported by other policy measures and innovations in order to reach the Paris Agreement targets.

In particular, we found there was no feasible carbon pricing scenario that was high enough to limit emissions sufficiently to achieve anything below 2.4°C warming on its own. Our findings indicate that a significant increase in the global average carbon price, which we estimate at $2.79 per tonne of CO2 emissions as of 2022, is necessary to achieve a target of 2.4°C by 2100.

Finally, we project significant differences in global *physical costs* due to climate change across various warming scenarios. Our projected physical damages under a 3°C scenario (approximately our current trajectory) are $480 trillion (all figures USD) by 2100. This figure is almost double that under a 2°C scenario ($264.69 trillion), and it is more than triple that under a 1.5°C scenario ($151.84 trillion), which confirms the importance of hitting the important targets set by the Paris Climate Agreement.

# 1. INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) 2018 report[1] suggests that the world is on track for a 3°C increase in global temperatures by the end of the century, while the United Nations Environmental Programme's (UNEP) Emissions Gap Report (2022)[2] estimates that current policies would lead to a 2.8°C increase in global temperatures. The IPCC states in its 2022 report that "the time for action is now," and that if immediate action is not taken, the world will miss the goal of limiting global warming to 1.5°C to 2°C above pre-industrial levels by 2100, which will have a significant impact on global biodiversity and the 3.3–3.6 billion people living in high-vulnerability hotspots, facing issues such as water and food scarcity, flood risks, and declining prosperity (IPCC, 2022) [3].

Our study focuses on the impact of a global carbon pricing policy to reduce CO2 emissions, as well as the cost of various warming scenarios. We analyze the carbon price required to achieve different warming outcomes by 2100, the physical costs of climate change associated with these outcomes, and the projected carbon revenues generated by the carbon price. This focus on carbon pricing provides critical information to guide the effective development of global policies.

There is a wide variation regarding the prices on CO2 emissions required to achieve the Paris Climate Agreement goals. IPCC (2018) suggests that global carbon prices ranging from $135 to $5,500/tCO2 by 2030 and from $245 to $13,000 in 2050 (2010 US dollars) would be needed to keep carbon emissions below the 1.5 °C limit. Nordhaus (2013)[4] suggested a global carbon price of approximately $31 to $271/tCO2 would reduce the temperature by 0.5°C by 2100. Cruz and Rossi-Hansberg (2022[5]) found that a carbon price in excess of $200/tCO2 is necessary to meet the Paris Climate Agreement goals. Similar to our findings, they also found that reaching this goal using a carbon price alone is not economically feasible.

Currently, the global uptake of carbon pricing initiatives is limited, with 68 initiatives in place in only 47 countries, accounting for only 23.1% of global Greenhouse Gas (GHG) emissions or 11.83 GTCO2 (Gigatonnes of CO2) (World Bank, 2023[6]).

Furthermore, these initiatives lack consistency (Ritchie and Rosado, 2022[7]), with significant disparities in carbon pricing levels, such as France's carbon price of $49 per tonne of CO2 compared to Japan's price of $2 per tonne.

We estimate the 2022 global average carbon price by identifying countries that have implemented carbon pricing policies and then determining their current CO2 pricing per tonne using data from Statista (2022[8]). We determine the contribution of each country to global CO2 emissions, and then calculate the weighted contribution of each country's carbon price based on its percentage of the global CO2 emissions. By summing up the total, we arrive at the *emissions-weighted* global average carbon price. Our analysis shows that the **global average carbon price is $2.79**, and the countries that have carbon pricing policies cover **14.47% of global CO2 emissions**. Our findings align with previous studies (Parry, 2019[9]; IMF, 2021[10]; IMF, 2022[11]) which estimate global average carbon prices of $2, $3, and $6 per tonne respectively. Our coverage of carbon pricing policies is also consistent with a World Bank (2020) report[12], which indicates that such policies cover around 13% of global emissions.

The broad range of estimates to date of the required price on carbon to meet climate targets suggests the need for an attempt at greater precision. We investigate the impact of a global carbon price using the Dynamic Integrated Climate and Economy (DICE) model, developed by the 2018 Nobel Laureate William Nordhaus. The DICE model is an integrated assessment model (IAM) that projects the relationship between CO2 emissions, GDP, and climate damages over time, based on various macroeconomic inputs. The DICE model projects the social cost of carbon (SCC), which we use as our carbon price. In an ideal policy design, the carbon price is equal to the SCC (Nordhaus, 2013).

The SCC is a dollar estimate of the damage caused by each additional ton of carbon emissions. It is useful to us because it is a standard estimate used when evaluating the benefits of actions taken to reduce emissions. For example, policymakers use the SCC to weigh the costs and benefits when assessing regulatory proposals (Rennert & Kingdon, 2022)[13]. Currently, the federal governments of the United States and Canada use the SCC when evaluating policy options (Government of Canada, 2022a)[14]. When carbon prices are set below the SCC, value is destroyed by not adequately accounting for the societal costs of climate change, including fires, floods, and numerous other consequences linked to rising temperatures (Mason, 2023)[15].

In calibrating the DICE model, we found that feasible carbon prices high enough to limit emissions sufficiently to achieve a 2°C scenario (or lower) were not possible, with a 2.4°C scenario being the lowest, economically feasible outcome.[i] Therefore, similar to Cruz and Rossi-Hansberg (2022), we recognize that while carbon pricing is an important piece of the puzzle, on its own, it is insufficient to mitigate climate change and achieve the Paris Agreement targets.

We tailor the carbon price in the DICE model to meet the different warming scenarios of 2.4°C, 3°C, 4°C, and 4.2°C (the "zero carbon price" scenario) by 2100. In addition to modelling the impact of the carbon price on emissions, we also use the DICE model to project the global economy's GDP and the fraction of GDP lost as a result of physical climate change damages. Our analysis generates a unique dataset of global economic outcomes for each temperature scenario from present day to 2100. Our climate damage projections indicate that annual damages increase in a relatively linear manner until 2030, before escalating, which highlights the importance of immediate policy planning and execution.

We determine that in order to achieve a 2.4°C warming scenario, a proactive global carbon policy must be implemented, starting at $223.31/TCO2 in 2023 and increasing to $435.55/TCO2 by 2045. A 3°C scenario requires a less aggressive carbon pricing policy, starting at $85.07/TCO2 and increasing to $357.64/TCO2, while a 4°C scenario requires a modest carbon price of $5.38/TCO2 in 2023, and only increasing to $39.77/TCO2 by 2100.

Our results indicate that the cost to the global economy by 2100, under different projected warming scenarios, compared to a 2.4°C warming scenario, range from $148.7 trillion under a 3°C scenario to $433.5 trillion under a 4.2°C (no carbon pricing) scenario.

The PV[ii] of the difference in physical costs between a 2.4°C and a 4.2°C scenario ranges from $21.4 trillion to $131.8 trillion when using discount rates ranging from 5.5% to 2%. Additionally, our results project losses of $16.61 trillion by 2050 under our 3°C scenario using a discount rate of 5.5%.

These findings align with projections estimating damages ranging from $15 trillion to $23 trillion using a 2.6–3.2°C scenario over the same timeframe (The Hill, 2021[16]; Swiss Re Institute, 2021[17]). Overall, the average carbon prices in our study over the examined timeframe align with studies projecting an increase to $185–$190 when using the same discount rate (EPA, 2022[18]; Mason, 2023; Rennert et al., 2022[19]).

Our findings demonstrate that relying solely on carbon pricing policies **will not be sufficient** to limit warming to 1.5–2°C by 2100. This will require complementary actions. A few examples might include, expanding the green-fixed income market, regulations and incentives to decarbonize our transportation system by expanding the use of electric vehicles, setting green standards and incentivizing building retrofits and making new buildings zero-emissions. These are relatively low-cost ways to reduce greenhouse gas emissions (Martin and Riordan, 2020[20]; UNEP, 2022, Government of Canada, 2019[21]). Other activities, like industrial processes, need to be improved by incentivizing zero-emissions steel and cement. While these are all investments that require varying amounts of capital and time, some action can be taken immediately through ceasing current activities, such as avoiding fossil fuel subsidies and building any new CO2 intensive industrial infrastructure like new gas connections for buildings (UNEP, 2022).

Again, a carbon tax is an efficient mechanism to incentivise efficiency and investment in climate solutions, and an important tool in the climate policy toolkit. As this paper demonstrates, high enough carbon taxes have the power to significantly reduce greenhouse gas emissions. But as our model shows, on a global basis we are currently nowhere near those levels, and carbon pricing alone will not result in the dramatic emissions reductions we need to see.

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[i] Our projections indicate that the theoretical maximum carbon price of $523, which would reduce emissions to zero immediately, would result in a temperature of 2.1°C by 2100. This increase in carbon price is almost 200x the current global average and provides only 0.3°C in temperature reduction by 2100.

[ii] Present Value (PV): We use rates of return to determine the current value of future sums. In this case, we apply PV to quantify climate change damages from the present to 2100 in 2023 dollars.

# 2. RESEARCH DESIGN AND RESULTS

The DICE model is an IAM that projects temperature scenarios based on CO2 emissions, which are determined by a number of factors, such as productivity and carbon pricing. As CO2 concentrations increase over time, the radiative forcings increase, leading to higher global temperatures. The increased global temperatures translate into greater physical damages through the loss of biodiversity, flooding, and degradation of physical assets. The model uses a variety of equations to compute economic impacts from these ecological changes.

This study uses carbon pricing to curb CO2 emissions, which slows the growth of radiative forcings, thereby slowing the temperature increase. We project carbon prices that would lead to 2.4°C, 3°C, 4°C, and 4.2°C global warming scenarios by the year 2100. From these scenarios we can project the economic cost due to physical damages, as well as year-over-year global CO2 emissions, and the revenue generated from carbon prices from present day to 2100. The technical details of our application of the model can be found in the Appendix.

## 2.1 CARBON PRICING ESTIMATES

Table 1 provides our 2022 global average carbon price estimates, which we determine by identifying countries that have implemented carbon pricing policies and then determining their current CO2 pricing per tonne using data from the World Bank (2023)[22]. We then evaluate the contribution of each country to global CO2 emissions, and calculate the weighted contribution of each country's carbon price based on its percentage of the global CO2 emissions. By summing up the total, we arrive at the emissions-weighted global average carbon price. Our analysis shows that the global average carbon price is $2.79, and the countries that have carbon pricing policies cover 14.47% of global CO2 emissions.

**TABLE 1**

Carbon Pricing Rates worldwide as of 2022, in US$ per ton of CO2

| Country | Emissions GTCO2 (% of global) | GDP in trillions USD (% of global) | Carbon Price (Y/N) | Carbon Price ($USD) | Other (i.e., Emissions Trading System) |
|---|---|---|---|---|---|
| Argentina | 176,509,560 (0.49%) | 630,698,000 (0.62%) | Y | 5 | No ETS |
| Belgium | 84,079,882 (0.23%) | 589,491,000 (0.58%) | N | 0 | Emissions Trading System |
| Canada | 542,787,422 (1.51%) | 2,200,352,000 (2.17%) | Y | 40 | Sub-national Emissions Trading System |
| Chile | 84,555,971 (0.24%) | 310,866,000 (0.31%) | Y | 5 | Sub-national Emissions Trading System |
| China | 11,680,416,049 (32.48%) | 18,321,197,000 (18.04%) | N | 0 | Sub-national Emissions Trading System |
| Columbia | 90,252,425 (0.25%) | 342,919,000 (0.34%) | Y | 5 | No ETS |
| Denmark | 25,707,552 (0.07%) | 386,724,000 (0.38%) | Y | 27 | Emissions Trading System |
| Finland | 40,704,439 (0.11%) | 281,411,000 (0.28%) | Y | 85 | Emissions Trading System |
| France | 279,990,676 (0.78%) | 2,778,090,000 (2.74%) | Y | 49 | Emissions Trading System |
| Germany | 636,876,464 (1.77%) | 4,031,149,000 (3.97%) | N | 0 | Emissions Trading System |
| Iceland | 3,169,293 (0.01%) | 27,702,000 (0.03%) | Y | 34 | Emissions Trading System |

| Country | Emissions GTCO2 (% of global) | GDP in trillions USD (% of global) | Carbon Price (Y/N) | Carbon Price ($USD) | Other (i.e., Emissions Trading System) |
|---|---|---|---|---|---|
| Italy | 297,351,815 (0.83%) | 1,996,934,000 (1.97%) | N | 0 | Emissions Trading System |
| India | 2,411,732,890 (6.71%) | 3,468,566,000 (3.42%) | N | 0 | No ETS |
| Iran | 690,240,852 (1.92%) | 1,973,738,000 (1.94%) | N | 0 | No ETS |
| Ireland | 32,647,974 (0.09%) | 519,776,000 (0.51%) | Y | 45 | Emissions Trading System |
| Japan | 1,061,774,366 (2.95%) | 4,300,621,000 (4.23%) | Y | 2 | No ETS |
| Latvia | 7,445,899 (0.02%) | 40,588,000 (0.04%) | Y | 17 | Emissions Trading System |
| Liechtenstein | 3,900,000 (0.01%) | 6,114,000 (0.01%) | Y | 130 | Emissions Trading System |
| Luxembourg | 7,997,937 (0.02%) | 82,154,000 (0.08%) | | | Emissions Trading System |
| Mexico | 407,695,112 (1.13%) | 1,424,533,000 (1.40%) | Y | 3.7 | No ETS |
| Netherlands | 144,694,864 (0.4%) | 990,583,000 (0.98%) | N | 46 | Emissions Trading System |
| Norway | 42,181,691 (0.12%) | 504,703,000 (0.50%) | Y | 88 | Emissions Trading System |
| Poland | 292,562,425 (0.81%) | 716,305,000 (0.71%) | Y | 1 | Emissions Trading System |
| Portugal | 40,432,854 (0.11%) | 255,854,000 (0.25%) | Y | 26 | Emissions Trading System |
| Russia | 1,674,228,016 (4.66%) | 2,133,092,000 (2.10%) | N | 0 | No ETS |
| Singapore | 56,107,637 (0.16%) | 423,632,000 (0.42%) | Y | 4 | Emissions Trading System |
| Slovenia | 13,782,058 (0.04%) | 62,191,000 (0.06%) | Y | 19 | Emissions Trading System |
| South Africa | 435,126,911 (1.21%) | 411,480,000 (0.41%) | Y | 10 | No ETS |
| Spain | 214,846,722 (0.6%) | 1,389,927,000 (1.37%) | Y | 17 | Emissions Trading System |
| Sweden | 42,296,678 (0.12%) | 603,922,000 (0.59%) | Y | 130 | Emissions Trading System |
| Switzerland | 35,299,423 (0.01%) | 807,418,000 (0.80%) | Y | 130 | Emissions Trading System |
| Ukraine | 189,304,801 (0.53%) | 199,719,000 (0.20%) | Y | 1 | No ETS |
| United Kingdom | 313,728,861 (0.87%) | 3,198,470,000 (3.15%) | Y | 24 | Emissions Trading System |
| United States | 4,535,301,085 (12.61%) | 25,035,164,000 (24.65%) | N | 0 | Sub-national Emissions Trading System |
| Uruguay | 5,878,158 (0.02%) | 71,161,000 (0.07%) | Y | 137 | No ETS |

This table displays the emissions (in GTCO2), GDP (in trillions $USD), and their carbon price status and amounts. We also include details on other pricing mechanisms, such emissions trading systems (ETS). We determine the global average carbon price by weighting the carbon prices of countries that have implemented carbon pricing policies by their contribution to global CO2 emissions. Our estimates show a global weighted average carbon price of $2.79 for 2022.

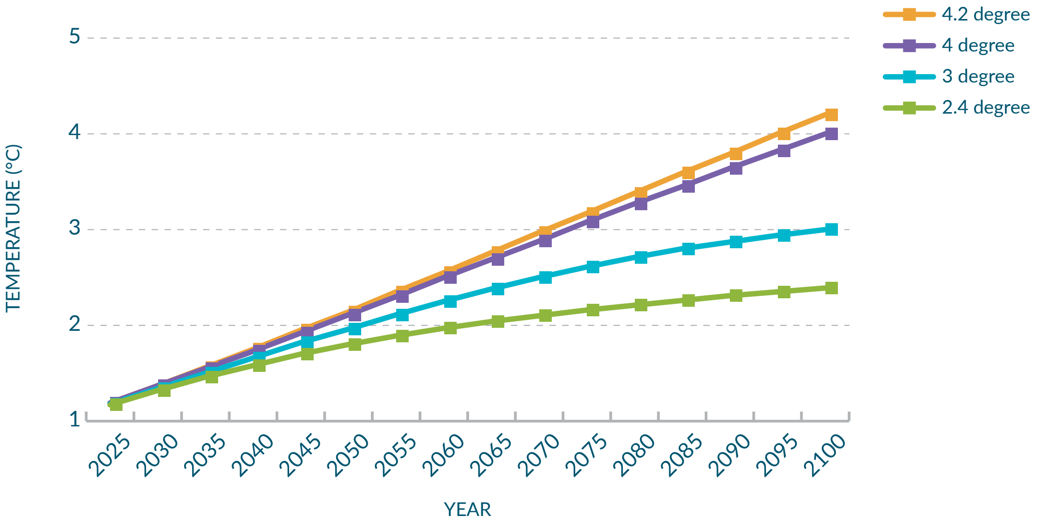
These findings align with a 2021 IMF study, which suggests that the global average carbon pricing is $3 per tonne (IMF, 2021). However, it is worth noting that there is some variation in global carbon price estimates. For example, the 2022 IMF study referenced above projects a current global carbon price of $6 per tonne (IMF, 2022); whereas other studies have indicated that the price may be as low as $2 per tonne (Parry, 2019). Our coverage of carbon pricing policies is also consistent with World Bank (2022[23]) report, which indicates that such policies cover around 13% of global emissions.

The DICE model generates scenarios by adjusting the carbon price, which reduces the global temperature by decreasing CO2 emissions. An increase in carbon prices decreases the CO2 emissions by making them more costly, thereby lowering the radiative forcings (in W/m2) (in Equation 1 of the Appendix). We adjust the carbon prices to achieve each warming scenario by 2100. Table 2 displays the carbon price for each scenario, while Figure 1 shows the yearly temperature projections for each scenario.

The temperature scenario projections in Figure 1 are similar until 2035, around which time the lines depicting the 2.4°C and 3°C scenarios begin to level off. The 3°C scenario shows a slight deviation from the 4°C and 4.2°C scenarios starting in 2035, and this difference becomes more pronounced over time, reaching a wide gap around 2070. Under all carbon pricing projections, we reach 1.5°C above pre-industrial by 2040 or earlier.

**FIGURE 1**

## Temperature Warming Scenarios



This figure displays the projected temperatures in degrees Celsius from 2023 to 2100 based on the DICE model. The carbon prices per tonne of CO2 were altered to change the industrial CO2 emissions in each scenario, leading to the varying warming temperatures by 2100. The annual temperature is determined using Equation 1.

Table 2 displays our carbon prices from 2025 to 2100 for each global climate scenario. For each scenario, we set the initial carbon price value in 2023 and allow them to grow over time using the DICE model growth rate. As mentioned previously, we conducted trials for a carbon price scenario that aims to restrict global temperatures to 2°C by 2100, but no feasible prices were sufficient to limit emissions to that extent. Additionally, even at a carbon price of $0, the model does not project global temperatures higher than 4.2°C globally by 2100.

**TABLE 2**

## Carbon Prices (per TCO2, $, USD)

| Year | 2.4°C | 3°C | 4°C | 4.2°C |
|---|---|---|---|---|
| 2025 | 238.22 | 90.75 | 6.38 | 0.00 |
| 2030 | 280.05 | 106.69 | 7.50 | 0.00 |
| 2035 | 326.71 | 124.46 | 8.75 | 0.00 |
| 2040 | 378.46 | 144.18 | 10.14 | 0.00 |
| 2045 | 435.55 | 165.93 | 11.67 | 0.00 |
| 2050 | 460.68 | 189.81 | 13.35 | 0.00 |
| 2055 | 449.16 | 215.92 | 15.18 | 0.00 |
| 2060 | 437.93 | 244.35 | 17.18 | 0.00 |
| 2065 | 426.98 | 275.20 | 19.35 | 0.00 |
| 2070 | 416.31 | 308.55 | 21.69 | 0.00 |
| 2075 | 405.90 | 344.48 | 24.22 | 0.00 |
| 2080 | 395.75 | 383.09 | 26.94 | 0.00 |
| 2085 | 385.86 | 385.86 | 29.84 | 0.00 |
| 2090 | 376.21 | 376.21 | 32.95 | 0.00 |
| 2095 | 366.81 | 366.81 | 36.26 | 0.00 |
| 2100 | 357.64 | 357.64 | 39.77 | 0.00 |

This table displays the carbon prices for each warming scenario from 2023 to 2100 in five-year increments, in $ per tonne of CO2.

Figure 2 illustrates the total CO2 emissions (in GTCO2) projected (using Equation 4 of the Appendix), which are industrial plus land emissions. Industrial emissions are emissions produced from industrial activities such as electricity generation or waste management (Nordhaus, 2013; European Environmental Bureau, 2018[24]). In contrast, land emissions are emissions generated from land use activities and natural disturbances, such as deforestation, forest fires, and volcanic activity (Nordhaus, 2013, Government of Canada, 2022b[25]).

The results indicate that higher carbon prices lead to a significant decrease in CO2 emissions. The introduction of carbon prices results in an immediate reduction in year-over-year emissions under the 2.4°C scenario. Despite this, emissions under the 3°C scenario continue to increase until 2035, before declining. Meanwhile, emissions under the 4°C and 4.2°C scenarios continue to grow until 2070[iii]. Notably, the data shows that the slowing of CO2 emissions growth in the 4°C and 4.2°C scenarios is mainly attributed to the reduction in land emissions rather than industrial emissions as land emissions decline in all scenarios due to the reduced land used for activities like farming and timber harvesting which contribute to our yearly total emissions (IPCC, 2013[26]). Under the 2.4°C and 3°C scenarios, industrial emissions reach zero by 2050 and 2085 respectively,[iv] while they never reach zero under the 4°C and 4.2°C scenarios. The 4.2°C scenario experiences continuous emissions growth over the entire time period, while the 4°C scenario shows emissions declining starting in 2085.

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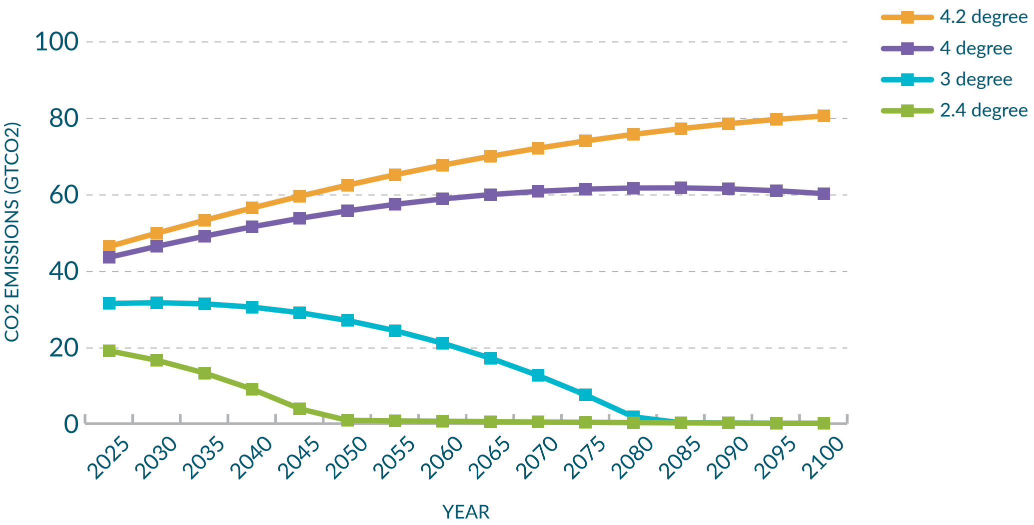
[iii] The initial GHG emissions rate in each scenario graphed in Figure 2 (Y axis) relies on a different CO2 pricing regime. For example, in the 2.4 scenario we anticipate north of $220 US per tonne, while in the 4.0 degree scenario we anticipate less than $6 US. The rates and initial values change based on the introduction of these prices as if done in real time, so the change in emissions is assumed to be instantaneous and appears that way on the graph.

[iv] Due to the aforementioned land emissions, we would still surpass the 1.5°C and 2°C warming levels by 2100. Emissions from activities such as wild fires, deforestation, and volcanic activity produce roughly 3 GTCO2 per year (IPCC, 2013). Despite the comparatively low contribution, because we will have warmed to 1.8°C by 2050, the land emissions will be sufficient to reach 2.4°C by 2100.

**FIGURE 2**

CO2 Emissions (in GTCO2)



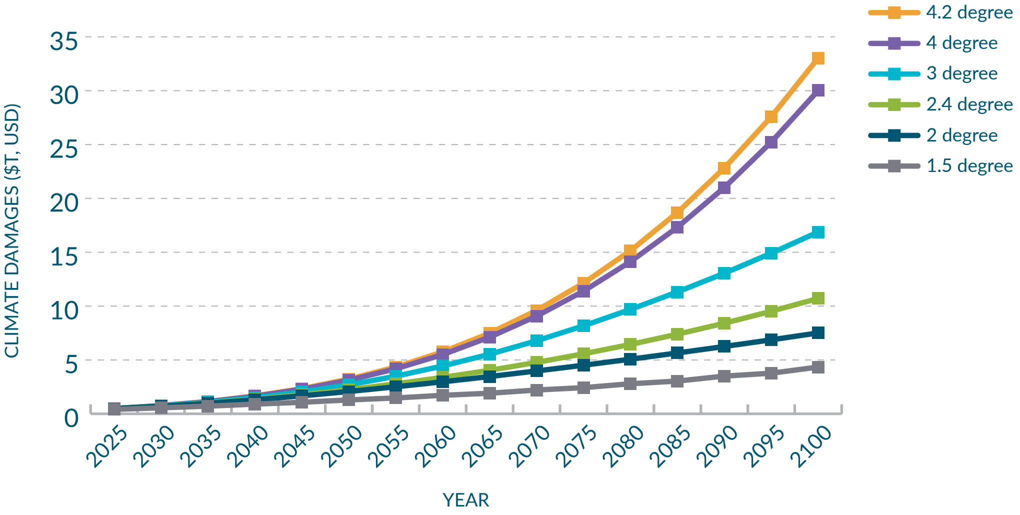
This figure displays the projected yearly, total (industrial + land) CO2 emissions in GTCO2 from 2023 to 2100. The carbon price within the DICE model is altered, resulting in changes to the yearly industrial CO2 emissions in each scenario.

## 2.2 GLOBAL DAMAGE PROJECTIONS

Figure 3 displays projections of climate damage calculated using the DICE model, and also includes cost estimates for the Paris Agreement target 1.5°C and 2°C warming scenarios, even though as discussed earlier, carbon pricing alone cannot lead to these scenarios. The results demonstrate that physical climate damage values significantly increase under higher temperature scenarios. According to IPCC (2018), 2050 and 2070 are considered two critical dates where action must have already been taken; otherwise, we will begin to incur substantial climate-related costs. The costs grow gradually until 2050, when there is a noticeable surge in year-over-year damages for all scenarios. The 4°C and 4.2°C scenarios show an exponential increase in damages around 2070, whereas the 3°C scenario shows a slower but significant increase in damages. The 1.5°C, 2°C and 2.4°C warming scenarios all demonstrate more steady and modest increases.

**FIGURE 3**

## Climate Related Damages



This figure displays the projected physical damages related to climate change based on the DICE model, according to each warming scenario. The results are cumulative damages over time, starting in 2023 and ending in 2100.

Table 3 presents estimated capital losses due to climate change for each temperature scenario from 2025 to 2100, in five-year increments. It is interesting to note that total damages even under the 2.4°C scenario at $331.18 trillion are 25% higher than under the 2°C scenario ($264.69 trillion) and are more than double (i.e., 118% higher) than under a 1.5°C scenario ($151.84 trillion), which confirms the importance of hitting these targets. The total difference in costs under the other scenarios are dramatically higher. In particular, the total costs under the 3°C scenario of $479.90 trillion are more than three times those under the 1.5°C scenario, while the total costs under the 4°C and 4.2°C scenarios of $711.77 trillion and $764.63 trillion respectively are just under and just over five times those under the 1.5°C scenario.

**TABLE 3**

## Climate Damages ($ Trillions, USD)

| Year | 1.5°C | 2°C | 2.4°C | 3°C | 4°C | 4.2°C | 3°C – 2.4°C | 4°C – 2.4°C | 4.2°C – 2.4°C |
|---|---|---|---|---|---|---|---|---|---|
| 2025 | 0.41 | 0.48 | 0.48 | 0.49 | 0.49 | 0.49 | 0.01 | 0.01 | 0.02 |
| 2030 | 0.56 | 0.70 | 0.71 | 0.74 | 0.76 | 0.77 | 0.03 | 0.05 | 0.06 |
| 2035 | 0.71 | 0.97 | 1.00 | 1.07 | 1.13 | 1.14 | 0.07 | 0.13 | 0.15 |
| 2040 | 0.90 | 1.30 | 1.35 | 1.49 | 1.63 | 1.66 | 0.14 | 0.28 | 0.31 |
| 2045 | 1.07 | 1.67 | 1.77 | 2.03 | 2.28 | 2.34 | 0.26 | 0.51 | 0.57 |
| 2050 | 1.29 | 2.07 | 2.24 | 2.69 | 3.12 | 3.22 | 0.45 | 0.88 | 0.97 |
| 2055 | 1.47 | 2.51 | 2.78 | 3.49 | 4.18 | 4.34 | 0.71 | 1.40 | 1.56 |
| 2060 | 1.72 | 2.97 | 3.38 | 4.44 | 5.50 | 5.75 | 1.06 | 2.12 | 2.37 |
| 2065 | 1.91 | 3.46 | 4.04 | 5.53 | 7.12 | 7.48 | 1.49 | 3.08 | 3.44 |
| 2070 | 2.21 | 3.98 | 4.77 | 6.78 | 9.07 | 9.59 | 2.01 | 4.30 | 4.82 |
| 2075 | 2.43 | 4.51 | 5.57 | 8.17 | 11.39 | 12.13 | 2.60 | 5.82 | 6.56 |
| 2080 | 2.79 | 5.07 | 6.44 | 9.69 | 14.13 | 15.14 | 3.25 | 7.69 | 8.70 |
| 2085 | 3.04 | 5.65 | 7.39 | 11.31 | 17.32 | 18.69 | 3.93 | 9.94 | 11.30 |
| 2090 | 3.50 | 6.25 | 8.41 | 13.05 | 21.01 | 22.82 | 4.64 | 12.60 | 14.40 |
| 2095 | 3.77 | 6.87 | 9.52 | 14.91 | 25.23 | 27.58 | 5.39 | 15.71 | 18.06 |
| 2100 | 4.34 | 7.51 | 10.71 | 16.88 | 30.02 | 33.03 | 6.17 | 19.31 | 22.32 |
| **Total** | **151.84** | **264.69** | **331.18** | **479.90** | **711.77** | **764.63** | **148.72** | **380.59** | **433.46** |
| **Upper Bound** | **171.65** | **307.87** | **376.78** | **571.91** | **890.25** | **961.84** | **195.13** | **513.47** | **585.06** |
| **Lower Bound** | **134.75** | **239.22** | **291.95** | **406.10** | **576.19** | **615.38** | **114.15** | **284.24** | **323.43** |
| **Disc 5.5%** | **18.12** | **28.09** | **31.54** | **39.90** | **50.52** | **52.95** | **8.37** | **18.99** | **21.41** |
| **Disc 3.75%** | **30.67** | **49.73** | **57.75** | **76.72** | **102.57** | **108.48** | **18.97** | **44.82** | **50.72** |
| **Disc 2.0%** | **59.58** | **100.51** | **121.03** | **168.24** | **237.07** | **252.77** | **47.21** | **116.04** | **131.75** |

This table displays the value of capital output lost due to climate change from 2023 to 2100 in five-year increments, in $ trillions. Columns 2 to 7 show the climate damage for respective year. Columns 8 to 10 present the differences in climate damages for each global temperature increase (3°C, 4°C, or 4.2°C) compared to a 2.4°C temperature increase by 2100.

Comparing the differences at the key dates specified by the IPCC (2018) report, we observe distinct differences in climate-related damages. In 2030, the differences between the 3°C, 4°C, and 4.2°C scenarios when compared to the 2.4°C scenario are $0.03 trillion, $0.05 trillion, and $0.06 trillion respectively. By 2050, the differences are $0.45 trillion, $0.88 trillion, and $0.97 trillion, and by 2070, the differences are $2.01 trillion, $4.30 trillion, and $4.82 trillion respectively.

To examine our projections, we conducted a sensitivity analysis and created ranges for our estimates. To do this, we project climate damages for each climate scenario by modifying the equations in the DICE model for estimating Total Factor Productivity ($TFP_n$) and the Abatement Cost Factor (ACF). Total Factor Productivity (TFP) represents the ratio of aggregate output (such as GDP) to aggregate inputs (Sickles and Zelenyuk, 2019[27]), while the ACF represents the marginal abatement costs as a function of emissions reduction compared to current energy costs. Within these equations, we calibrate the growth rate of technology ($ga_n$) and the industrial energy costs decline rate ($CDR$).[v] By increasing $ga_n$, we increase the technological growth rate, creating greater efficiency in turning inputs into outputs, increasing TFP. This action positively influences industrial emissions, therefore higher $ga_n$ values lead to higher projected climate costs for each temperature scenario. Similarly, by increasing the $CDR$, energy costs within the model become lower over time, delaying migration to emission-free energy sources and keeping emissions and costs high. For our upper bound estimate, we increase both $ga_n$ by 10% and $CDR$ by 25%. Similarly, the lower bound estimate is created by decreasing both variables by 10% and 25%, respectively.

The magnitude of variation in both variables is reasonable given market studies and the timeframe (2023–2100). The Bureau of Labor Statistics (2023[28]) published a study on TFP, which showed significant gains in TFP from 2007–2022, but some years, such as 2020 and 2008, experienced significant losses. Considering the volatility of the global economy, the impact of technological innovation, and our time horizon, a 10% difference in either direction is reasonable, considering that annual changes tend to be within the range of -1% to 4% (Bureau of Labor Statistics, 2023). Additionally, a 25% fluctuation in industrial energy price growth over this time horizon is also reasonable. The Energy Information Administration (EIA) published data values for the last decade, indicating that from 2013 to 2022, industrial energy costs rose from 6.89 to 8.45 cents per kilowatt-hour, representing a 22% increase (EIA, 2023). Similar to TFP, volatility in industrial energy prices is likely due to technological innovations, efficiency advancements, and shifts in energy pricing policies.

The two rows following the total projected damages ("Total") represent the upper and lower bounds for the total climate damages for each temperature scenario. We observe that the projected range of damages increases as the temperature at 2100 increases. For example, under the 1.5°C scenario, our bounds are between $134.75 trillion and $171.65 trillion, which is a difference of 11% and 13% from our projected loss, respectively. Under our 2.4°C scenario, the bounds are between $239.22 trillion and $307.87 trillion, a difference of 10% and 16% from our projected loss, respectively. Under a 4°C scenario, the bounds are between $576.19 trillion and $890.25 trillion, a difference of 19% and 25% from our projected loss, respectively. Our bounds grow further apart as the warming scenario temperature increases. This showcases the uncertainty in economic impact due to the more volatile relationship between the climate and our economic activity.

The last three rows in Table 3 present the climate damage estimates discounted to 2023 using discount rates of 5.5%, 3.75% and 2%. The choice of the 5.5% discount rate was based on the one used in The Economist (2015[29]) report, as well as evidence that most governments use discount rates of 5% or higher for climate policy and global health analysis (Haacker, Hallett, & Atun, 2020[30]). However, research from the London School of Economics (2018[31]) suggests that a 2% discount rate may be more appropriate, so we also use it. Finally, we also include PV estimates using the mid-point of these two discount rates (i.e., 3.75%). As such, we note that our results using the 5.5% discount rate can be viewed as conservative estimates of climate damages in today's dollars.

We project PV damage estimates of $31.54 trillion to $121.03 trillion for a 2.4°C scenario, $39.90 trillion to $168.24 trillion for a 3°C scenario, which grow to $50.52 trillion to $237.07 trillion for a 4°C scenario and $52.95 trillion to $252.77 trillion for a 4.2°C scenario. Significant differences in damages are observed between the warming scenarios, indicating that an increase in warming from 2.4°C to 3°C results in additional cumulative physical damages by 2100 with a PV of $8.37 trillion to $47.21 trillion. The difference in the PV of damages escalates to $18.99 trillion to $116.04 trillion under a 4°C scenario, and to $21.41 trillion to $131.75 trillion under a 4.2°C scenario.

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[v] Both of these variables are affected by technological development and innovation, which drives energy prices down and improves productivity. The rate of technological growth has a lot of variability over our time horizon (IPCC, 2013), as a result, this is a good factor to vary when constructing our scenario analysis.

## 2.3 RESULTING CARBON PRICE REVENUES

Table 4 displays the annual revenues generated from carbon pricing under each warming scenario in five-year intervals. The annual revenue is calculated by multiplying the carbon price by the corresponding industrial carbon emissions for a particular year. The fourth-to-last row of Table 5 displays the total carbon revenues for the period from 2023 to 2100. It is evident that carbon revenues are the second-highest under the 2.4°C scenario at $82.51 trillion, which is significantly lower than the revenue of $222.84 trillion in the 3°C scenario. The revenue generated under the 4°C scenario is $88.92 trillion, which is similar to the 2.4°C scenario revenues; although it has a significantly lower carbon price throughout the period to 2100.[vi]

**TABLE 4**

Carbon Price Revenue ($t, USD)

| Year | 2.4°C | 3°C | 4°C | 4.2°C |
|---|---|---|---|---|
| 2025 | 4.11 | 2.69 | 0.27 | 0.00 |
| 2030 | 4.20 | 3.21 | 0.34 | 0.00 |
| 2035 | 3.88 | 3.73 | 0.42 | 0.00 |
| 2040 | 2.97 | 4.22 | 0.51 | 0.00 |
| 2045 | 1.25 | 4.65 | 0.61 | 0.00 |
| 2050 | 0.00 | 4.95 | 0.73 | 0.00 |
| 2055 | 0.00 | 5.09 | 0.86 | 0.00 |
| 2060 | 0.00 | 4.98 | 1.00 | 0.00 |
| 2065 | 0.00 | 4.57 | 1.15 | 0.00 |
| 2070 | 0.00 | 3.76 | 1.31 | 0.00 |
| 2075 | 0.00 | 2.46 | 1.48 | 0.00 |
| 2080 | 0.00 | 0.58 | 1.65 | 0.00 |
| 2085 | 0.00 | 0.00 | 1.83 | 0.00 |
| 2090 | 0.00 | 0.00 | 2.02 | 0.00 |
| 2095 | 0.00 | 0.00 | 2.20 | 0.00 |
| 2100 | 0.00 | 0.00 | 2.39 | 0.00 |
| Total | 82.51 | 222.84 | 88.92 | 0.00 |
| Disc 5.5% | 51.19 | 67.26 | 10.69 | 0.00 |
| Disc 3.75% | 58.71 | 92.24 | 18.04 | 0.00 |
| Disc 2.0% | 68.25 | 134.41 | 34.97 | 0.00 |

This table presents the revenue generated from carbon pricing in $ trillions for each warming scenario from the time period 2023 to 2100 in five-year increments. The revenue is calculated by multiplying the carbon prices presented in Table 1 with the industrial CO2 emissions in GTCO2 shown in Table 3.

The last three rows show the carbon pricing revenues from Table 4 in discounted terms. It is noteworthy that even when discounted to 2023, the highest carbon price revenue remains in the 3°C scenario at $67.26 trillion to $134.41 trillion, while the 2.4°C scenario generates $51.19 trillion to $68.25 trillion. The 4°C scenario provides the least revenue in PV terms, at $10.69 trillion to $34.97 trillion. The revenue gap between 2.4°C and 3°C decreases in PV terms because the revenue generated from a carbon price under the 2.4°C scenario ends at 2050, while the revenue produced under the 3°C scenario continues until 2080. This generates more revenue over time, but these revenues also undergo significantly more discounting. Additionally, the PV of carbon price revenues under the 4°C scenario are significantly lower than the 2.4°C and 3°C scenarios due to the impact of both discounting and lower carbon prices.

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[vi] This is because the revenues from the 2.4°C stop at 2050, due to the ceasing of industrial emissions, while under the 3°C scenario, the emissions continue to 2085 and under the 4°C scenario, the emissions and carbon tax revenues continue to 2100.

# 3. CONCLUSION

The results of previous studies examining the carbon price required to achieve the Paris Climate Agreement goals have produced widely varying results. We address this issue by extending the ground-breaking DICE model, developed by 2018 Nobel Laureate William Nordhaus, to analyze various climate scenarios under alternative carbon prices.

Our analysis suggests that while carbon pricing can play a critical role in reducing greenhouse gas emissions and limiting global warming, it must be supported by other policy measures and innovations in order to reach the Paris Agreement targets. In particular, we found there was no feasible carbon pricing scenario that was high enough to limit emissions sufficiently to achieve anything below 2.4°C warming on its own. Our findings indicate that a significant increase in the global average carbon price, which we estimate at $2.79 per CO2 tonne of emissions as of 2022, is necessary to achieve the target of 2.4°C by 2100.

We project significant differences in global physical costs due to climate change across various warming scenarios, which highlights the urgency of taking action to mitigate global warming. Our projected cumulative physical damages under a 2.4°C scenario are $331.18 trillion by 2100, versus $480 trillion under a 3°C scenario, and more than double the 2.4°C scenario figure at $765 trillion under a 4.2°C scenario (which is the "zero carbon price" scenario). It is interesting to note that total damages even under the 2.4°C scenario at $331.18 trillion are 25% higher than under the 2°C scenario ($264.7 trillion) and are more than double (i.e., 118% higher) than under a 1.5°C scenario ($151.8 trillion), which confirms the importance of hitting these targets.

Our results highlight substantial differences in carbon prices and physical costs under various warming scenarios, emphasizing the need for a more stringent carbon pricing policy approach across the globe. For example, to reach a warming scenario of 2.4°C by 2100, we determine that the global average carbon price needs to reach $238.22/tCO2 by 2025, almost 100 times our 2022 global weighted-average carbon price estimate of $2.79. We also confirm 2050 and 2070 as important inflection points, where physical costs accelerate markedly under higher warming scenarios.

It is important to note that our model only projects a carbon price on CO2 emissions and global climate change, and using a holistic approach that incorporates multiple policies could produce more favorable results, such as lower required global carbon prices than we estimate. For instance, the ability to reach 1.5°C or 2°C warming scenarios requires more than just carbon pricing policies, and incentives and advancements in carbon reduction technology could lower the required global carbon price sooner than projected.

Additionally, our projections assume focused global action to achieve carbon price targets. However, if some countries exceed their carbon pricing goals while others set prices well below desired targets, the average global price could still be reached, but the CO2 reductions may not be realized due to carbon leakage[32].

Despite these limitations, our results support the benefits of carbon pricing as an effective tool in reducing global climate change, and demonstrate that there are significant economic costs associated with higher warming scenarios, without even considering the significant social and quality of life costs.

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# APPENDIX

## CARBON PRICE AND TEMPERATURE SCENARIOS

In the model, carbon prices are assumed to be set in 2023 and year-over-year price increases are determined by the original DICE model. We calibrate the carbon price set in 2023 to generate our warming scenarios. The DICE model calculates the global temperature using Equation 1.

$$AT_n = AT_{n-1} + AS * \left(RF_n - \frac{DF}{ET}\right) * AT_{n-1} - CHL * (AT_{n-1} - LOT_{n-1}) \qquad (1)$$

In this equation, $AT_n$ is the atmospheric temperature for a given year, $AT_{n-1}$ is the atmospheric temperature for the previous year. $AS$ is the "speed of adjustment parameter for atmospheric temperature." $RF_n$ is the "total increase in radiative forcing since preindustrial" for the given year, measured in Watts/m2. DF is the Forcings level at which CO2 doubles, and ET is the equilibrium temperature increase for CO2 doubling. CHL indicates the "coefficient of heat loss" from the atmosphere to the oceans, where heat loss is the amount of solar radiation that manages to escape the atmosphere into space.[i] $LOT_{n-1}$ is the Lower Ocean Temperature for the previous year.

By applying a carbon price in our model, we indirectly influence $RF_n$ the variable, reducing the amount of industrial emissions by making them more costly to emitters. Equations 2 through 6 show how carbon prices are calibrated in our model and how they influence the atmospheric temperature through climate relationships in the DICE model. Equation 2 calculates the emissions control rate (ECR), the fraction of emissions that are reduced or controlled by a climate change policy.

$$ECR_n = Min\left(\frac{Carbon\ Price_n{}^{\frac{1}{ECC}-1}}{BSP_n}, 1\right) \qquad (2)$$

$Carbon\ Price_n$ represents the carbon price in a given year, while $BSP_n$ is the Backstop Price (in $1,000 per ton) for a given year, which is the price at which all industrial emitters transition to net-zero, green tech. $ECC$ is the Exponent of Cost Control function, which is set to 2.600 as in the original DICE model. ECR is a critical part of the annual industrial CO2 emissions, which are calculated in Equation 3 based on a combination of economic output, emissions control and efficiency:

$$Industrial_{CO2e_n} = Sigma_{Industrial_n} * OAD_n * (1 - ECR_n) \qquad (3)$$

$Sigma_{Industrial_n}$ is the yearly emissions output ratio, which is a measure of industrial efficiency. $OAD_n$ is the Output gross of abatement and climate damage in a given year, calculated using Equation in Appendix A.2 of Cleary and Willcott (2023[ii]). $ECR_n$ is the Emissions Control Rate for a given year, which is directly influenced by the carbon price from Equation 2.

As the carbon price increases, the ECR rises, causing the industrial CO2 emissions to drop, which lowers total emissions. Total yearly emissions are comprised of yearly land and industrial emissions, shown in Equation 4.

$$Emissions_{CO2total_n} = Industrial_{CO2e_n} + Land_{CO2e_n} \qquad (4)$$

Since industrial emissions are lower, the amount of CO2 in the atmosphere $(ATCO2_n)$ is reduced. This effect is seen in Equation 5.

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[i] DF, ET, and CHL are set by the DICE model to 3.681, 3.100, and 0.101 respectively.

[ii] Cleary, S., Willcott, N. (2023). Carbon Pricing, Necessary but Not Sufficient. Working Paper.

$$ATCO2_n = Trans_{a-a} * ATCO2_{N-1} + Trans_{b\&so-a} * CO2_{bios_n} + Emissions_{CO2total_n} * \frac{5}{3.666} \qquad (5)$$

$Trans_{a-a}$ and $Trans_{a-so}$ are components of the carbon cycle transfer rate which moves CO2 from the atmosphere into the deep oceans. $Trans_{a-a}$ and $Trans_{b\&so-a}$ correspond to "atmosphere to atmosphere" and "biosphere to shallow ocean" components respectively. $ATCO2_{N-1}$ is the atmospheric CO2 from the previous year in Gigatonnes of CO2. $Emissions_{CO2total_n}$ corresponds to the total CO2 emissions in a given year in Gigatonnes of CO2. $Trans_{a-a}$ and $Trans_{b\&so-a}$ are set to 0.8800 and 0.1960 respectively as in the original DICE model. $CO2_{bios_n}$ is the concentration of CO2 in the biosphere and the upper oceans in a given year.

A reduction in $ATCO2_n$ determined in Equation 5 reduces the $RF_n$ , calculated in Equation 6.

$$RF_n = DF * \left( \frac{LOG\left(\frac{ATCO2_n}{EqConcCO2}\right)}{LOG(2) + EXOF_N} \right) \qquad (6)$$

EqConcCO2 is the equilibrium concentration of CO2 in the atmosphere in Gigatonnes of CO2, which is set to 588.00 Gigatonnes as in the original DICE model. $EXOF_N$ is the Exogenous Forcings in watts per square meter in a given year. The reduction in radiative forcings (as reflected in the $RF_n$ variable in Equation 1) produces a lower global temperature.