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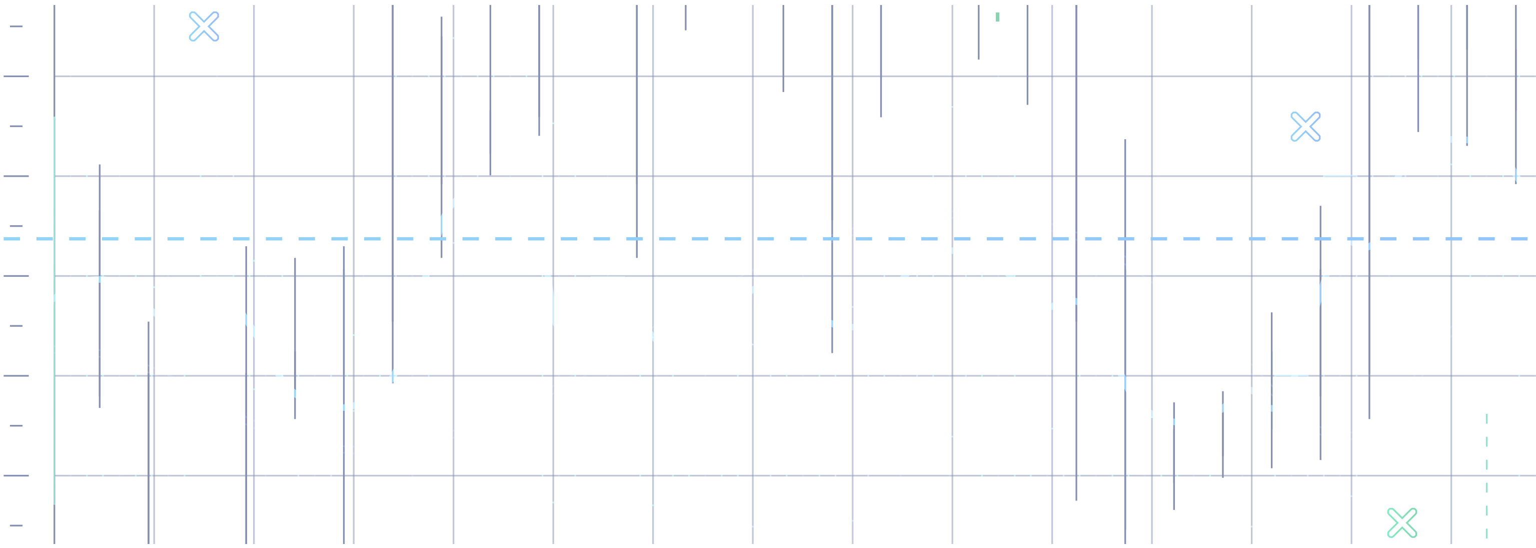

The Physical Costs of Climate Change: A Canadian Perspective

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EXECUTIVE SUMMARY

Canada has been warming twice as fast as the global average and is highly susceptible to the impacts of climate change. The Office of Superintendent of Financial Institutions (OSFI), the Bank of Canada (BoC), and several key financial institutions recently completed a pilot project that *examined transitional risks* to the Canadian economy under various climate change scenarios. That is, they considered the risks to businesses and investors created by the changes in the economy produced by efforts to transition to a low-carbon economy. However, the results of the BoC-OSFI analysis leave an important void with respect to the *impact of physical risks*, or the cost of physical damage caused by climate change such as loss of biodiversity, sea-level rise, and infrastructure damage due to fires and floods, etc. We fill this void by updating and extending to Canada, the ground-breaking Dynamic Integrated Climate and Economy (DICE) model developed by 2018 Nobel Laureate William Nordhaus.

Our results illustrate stark differences in physical costs under various warming scenarios, which highlights the importance of taking action to mitigate climate change. We find the total value of capital output lost due to climate change over the period 2015 to 2100 for each climate scenario ranges from $2.773-trillion under the 2°C scenario to almost double that amount at $5.520-trillion under a 5°C warming scenario. The costs of climate change damage grow gradually until 2050, around which time there is a sharp increase under all scenarios, and by 2070 there is an exponential increase in damages.

We then find the present value (PV) of the cost of climate change in each warming scenario which enables us to compare the cost of the damage to the capital required to cut Canada's greenhouse gas (GHG emissions) as demonstrated in ISF's 2020 "Capital mobilization plan" report. Specifically, we compare the PV of climate damage under our Business as Usual (5°C) warming scenario to that under a 2°C scenario and relate the difference in these figures to the PV of undertaking required annual investments to achieve Canada's emissions reduction targets. These results suggest that the PV of the difference in damages is $10.1b to $45.4b larger than the PV of the required investments.

In other words, undertaking the required investments to reduce greenhouse gas (GHG) emissions more than pays for itself in terms of avoided physical damage alone, and this is without taking into account the potential economic benefits of transitioning to a low-carbon economy. Overall, our results provide important guidance for policymakers and other actors in the Canadian economy.

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1. INTRODUCTION

Despite the increasing amount of attention devoted to addressing climate change in recent years, progress has been too slow. For example, the 2018 Intergovernmental Panel on Climate Change (IPCC) report[1] notes that we are not on pace to limit global temperature increase to 1.5°C above pre-industrial levels by 2100, suggesting we are more on pace for a 3°C warming scenario based on current progress and commitments at the time. A more recent 2021 IPCC report[2] confirms a 3°C warming scenario as their best estimate, which is also consistent with the findings of the United Nations Environment Programme 2020 Emissions Gap Report[3] that is based on an examination of countries' existing Nationally Determined Contributions (NDCs). This is particularly bad news for Canada, which has been warming twice as fast as the global average and is highly susceptible to the impacts of climate change.[4]

Given the potential costs associated with climate change, it is informative to examine the relationship between delaying the required investments in transition versus the economic loss due to global warming incurred by such delays. We posit that economic value is sacrificed every day that action is not taken to mitigate the economic and ecological risks posed by climate change. Current economic models agree that losses are unavoidable without change and investment; however, questions remain regarding *how much* value will be lost and *how quickly*. The Economic Intelligence Unit (EIU) of the Economist released a 2015 report[5] which estimated the present value (PV) of losses of $18.4-trillion US to global investable assets (from a public-sector perspective) under a 5°C warming scenario. At a 6°C warming scenario this figure jumps to $43-trillion US — 30 percent of the entire stock of the world's manageable assets.

On the flip side, investing in transition has the potential to generate positive economic benefits. Such benefits have been estimated at $12-trillion US (by 2030) in terms of market opportunity, the generation of 470 million new jobs, and a 10 percent increase in the size of the global economy by 2050.[6] A New Climate Economy (NCE) (2018) report[7] estimates an even greater economic benefit, citing a $26-trillion US direct global economic benefit over the same timeframe.

Our study focuses on estimating the *physical costs* of climate change under various warming scenarios to Canada. The emphasis on physical risks fills an important gap in information regarding the impact of climate change to Canada's economy. In particular, in early 2022, the Office of the Superintendent of Financial Institutions (OSFI), the Bank of Canada, and several key financial institutions released the results of a pilot study that examined *transitional risks* to the Canadian economy under various climate change scenarios. Physical risks were notably absent, as noted in an accompanying press release:[8]

> "The scenarios also deliberately focus on transition risks rather than physical risks. The manifestation of physical risks, and efforts to avoid or mitigate their impact, could also have significant implications for the global and Canadian economies and the financial system. This is an area for future work." (para. 5).

In this paper, we examine physical risks by updating and extending to Canada, the ground-breaking Dynamic Integrated Climate and Economy (DICE) model, developed by 2018 Nobel Laureate William Nordhaus. The DICE model is an integrated assessment model (IAM) that uses a variety of macroeconomic inputs to project gross domestic product (GDP) and climate damages over time, based on CO2 emission concentrations. The model projects economic output using a Cobb-Douglas function that incorporates capital, productivity, and population to estimate GDP. Following this, climate damage is estimated as a fraction of this output, using atmospheric temperature and an exponential damage relationship that is related to climate change.

We develop a customized, Canadian-based DICE model that estimates projected economic outcomes for Canada under 2°C, 3°C, 4°C, and 5°C warming scenarios by using Canadian-specific inputs in the Cobb-Douglas function (i.e., incorporating Canadian economic growth, productivity and population growth inputs). Using these inputs, we project GDP for the Canadian economy up to the year 2100. Subsequently, we use the DICE model damage function to calculate the fraction of GDP lost as a result of physical climate change damages. This process generates a unique dataset of Canadian-specific outcomes from present day to 2100. The negative relationship between warming and GDP intensifies as temperature increases. This ultimately leads to specific inflection points (2030, 2050 and 2070), where action must have already been taken to avoid exponential growth in economic damage.

2. RESEARCH DESIGN

Through the years several models have been developed to quantify the physical damages of climate change to global economies (Nordhaus, 1993[9]; 2013[10]; 2016[11]). Other models have been designed to anticipate risk to investor holdings (Bansal et al., 2017[12]; Bolton and Kacperczyk, 2021[13]; Li et al., 2019[14]). Two recent models have been designed to describe collective beliefs and actions regarding global warming (Choi et al., 2020[15]) and valuation under global warming uncertainty (Barnett et al., 2020[16]).

In 2007, Sir Nicholas Stern published a comprehensive assessment of the global evidence dealing with the economics of climate change. This famous study, entitled *The Stern Review*,[17] employed an IAM to assess the macro-economic costs and effects of the transition to low-carbon energy systems for the global economy. Since 2007, many IAMs have been used to quantify the cost of climate change, with the most famous of these being the Nordhaus's DICE model. The DICE model quantifies economic costs due to climate change as lost productivity due to the impact of physical climate damages on capital. The DICE model has been widely used in academic literature (Popp, 2004[18]; Nordhaus, 1993, 2014[19]; etc.), and has also been used by the Environment Protection Agency to calculate the social cost of carbon.[20] The previously mentioned EIU (2015) report estimates the costs of global warming using the DICE model as their IAM.

The DICE model calculates physical climate damages as a fraction of overall productivity. An increase in CO2 concentrations leads to higher global temperatures. These increased global temperature estimates are used to calculate physical climate damages, which are identified as the loss of biodiversity, sea-level rise, and infrastructure damage. The model then uses a variety of equations that translate these ecological outcomes into economic costs. This is accomplished by projecting economic output using a Cobb-Douglas function that incorporates capital, productivity, and population to estimate GDP. Climate damage is then estimated as a fraction of the calculated output by estimating the capital cost of climate damages. This relationship is determined using atmospheric temperature and an exponential damage relationship related to climate change.

We use the DICE model to project economic outcomes for Canada under 2°C, 3°C, 4°C, and 5°C warming scenarios by using Canadian-specific inputs for the Cobb-Douglas function, which allows the model to calculate climate damage projections for Canada using global temperatures. We account for Canadian economic growth, productivity and population growth in our parameters. Using the DICE model, we generate unique data representing Canadian-specific outcomes from present day to 2100. We provide additional details of the model in Appendix A and Appendix B.

3. RESULTS

3.1 SCENARIO DEVELOPMENT AND PROJECTING DAMAGES

We implement the DICE model to generate the resulting global temperature in the year 2100 corresponding to each warming scenario. Under all warming scenarios except the 2°C scenario, we reach 1.5°C above pre-industrial levels by 2040 or earlier.

Figure 1 shows the climate damages that are projected by our model. As expected, it depicts significant increases in climate damage values under higher 2100 temperatures. The costs of climate change damage grow gradually until 2050, around which time there is a sharp increase under all scenarios, and by 2070 there is an exponential increase in damages. These dates correspond to two of the significant dates noted in the IPCC (2018) report.

FIGURE 1

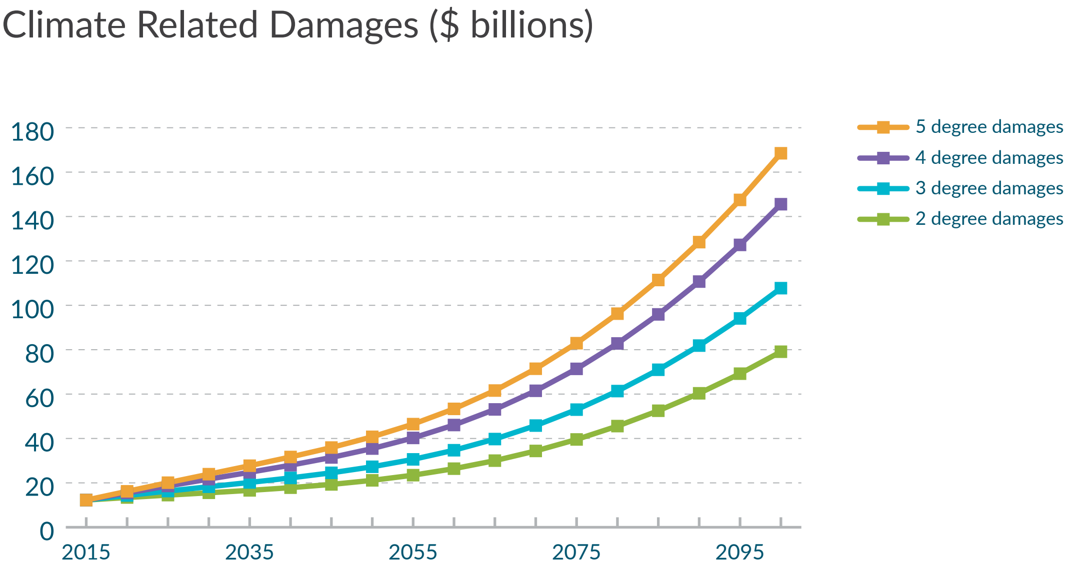

Table 1 reports the 2015-2100 climate damage estimates in terms of capital output lost in five-year increments. Columns 6-8 show the differences in climate damages for each global temperature increase (3°C, 4°C, or 5°C) relative to the 2°C base model.

Examining the differences at the key dates outlined by the IPCC (2018) report, namely 2030, 2050, and 2070, there are distinct differences across the various warming scenarios. In 2030, the differences between the 3°C, 4°C, and 5°C scenarios when compared to the 2°C base scenario are $2.72-billion, $6.16-billion, and $8.38-billion respectively.

By 2050, the differences relative to the base case are $6.12-billion, $14.32-billion, and $19.62-billion, and by 2070, the differences are $11.42-billion, $27.10-billion, and $37.03-billion. The bottom of Table 1 shows the total value of capital output lost due to climate change over the period 2015 to 2100 for each climate scenario, which ranges from $2.773-trillion under the 2°C scenario to almost double that amount at $5.520-trillion under a 5°C warming scenario.

TABLE 1

Climate Damages ($billions)

Year	2°C	3°C	4°C	5°C	3°C – 2°C	4°C – 2°C	5°C – 2°C
2015	12.25	12.25	12.25	12.25	0.00	0.00	0.00
2020	13.40	14.32	15.45	16.19	0.91	2.05	2.78
2025	14.48	16.31	18.60	20.09	1.83	4.12	5.60
2030	15.53	18.25	21.69	23.92	2.72	6.16	8.38
2035	16.62	20.19	24.77	27.73	3.57	8.15	11.11
2040	17.84	22.23	27.96	31.66	4.40	10.12	13.83
2045	19.30	24.53	31.44	35.91	5.23	12.14	16.62
2050	21.13	27.25	35.46	40.75	6.12	14.32	19.62
2055	23.46	30.58	40.25	46.47	7.12	16.79	23.00
2060	26.40	34.70	46.06	53.34	8.30	19.66	26.94
2065	30.02	39.74	53.09	61.60	9.72	23.07	31.58
2070	34.39	45.81	61.48	71.42	11.42	27.10	37.03
2075	39.56	52.99	71.36	82.93	13.43	31.81	43.37
2080	45.58	61.36	82.81	96.23	15.78	37.23	50.65
2085	52.50	70.96	95.90	111.39	18.46	43.41	58.90
2090	60.35	81.85	110.68	128.46	21.50	50.33	68.11
2095	69.20	94.08	127.21	147.48	24.89	58.02	78.28
2100	79.08	107.72	145.54	168.49	28.63	66.46	89.40
Total	**2,772.78**	**3,635.65**	**4,794.57**	**5,520.06**	**862.87**	**2,021.79**	**2,747.28**

It is interesting to note that a 2021 Royal Bank of Canada report[21], discusses the need to save $40-billion annually to cover the costs of physical damages due to climate change, if we continue to emit at our current rate. The $40-billion estimate is very close to our 2050 estimate of climate damage under a 5°C warming scenario ($40.7-billion), and sits between our 2030 estimate of $23.9-billion and our 2070 estimate of $71.4-billion.

Table 2 discounts the climate damage estimates provided in Table 1 back to today using a discount rate of 5.58 percent, which is the mean-weighted average cost of capital of Canadian companies as determined by the Institute for Sustainable Finance in its Capital Mobilization Plan (CMP) 2020 report[22]. There are stark differences across the warming scenarios, underlining the importance of immediate action to reduce our climate change to 2°C or below. For example, Table 2 shows that an increase from 2°C to 3°C warming leads to additional cumulative physical damages by 2100 with a PV of $80.9-billion in today's dollars. This figure escalates to $187.4-billion under a 4°C scenario, and to $255.6-billion under a 5°C scenario.

TABLE 2

Present Value of Climate Damages (in 2020 $b)

Year	2°C	3°C	4°C	5°C	3°C – 2°C	4°C – 2°C	5°C – 2°C
2015	16.07	16.07	16.07	16.07	0.00	0.00	0.00
2020	13.40	14.32	15.45	16.19	0.91	2.05	2.78
2025	11.04	12.43	14.18	15.31	1.39	3.14	4.27
2030	9.03	10.60	12.60	13.90	1.58	3.58	4.87
2035	7.36	8.94	10.97	12.28	1.58	3.61	4.92
2040	6.02	7.51	9.44	10.69	1.48	3.42	4.67
2045	4.97	6.31	8.09	9.24	1.35	3.12	4.28
2050	4.14	5.34	6.95	7.99	1.20	2.81	3.85
2055	3.51	4.57	6.02	6.95	1.06	2.51	3.44
2060	3.01	3.95	5.25	6.08	0.95	2.24	3.07
2065	2.61	3.45	4.61	5.35	0.84	2.00	2.74
2070	2.28	3.03	4.07	4.73	0.76	1.79	2.45
2075	2.00	2.67	3.60	4.19	0.68	1.61	2.19
2080	1.75	2.36	3.19	3.70	0.61	1.43	1.95
2085	1.54	2.08	2.81	3.27	0.54	1.27	1.73
2090	1.35	1.83	2.47	2.87	0.48	1.12	1.52
2095	1.18	1.60	2.17	2.51	0.42	0.99	1.33
2100	1.03	1.40	1.89	2.19	0.37	0.86	1.16
Total	**426.38**	**507.24**	**613.76**	**681.93**	**80.85**	**187.38**	**255.55**

3.2 THE COST OF DELAYING INVESTMENT

The CMP (2020) report estimates that achieving Canada's Paris Agreement target of a 30 percent reduction in 2030 GHG emissions from 2005 levels would require an investment of $128-billion over 10 years, or $12.8-billion annually. We incorporate these figures, based on the assumption that making such investments would limit warming to 2°C while committing no investments to transition would leave us on track for the business as usual (BAU) 5°C scenario. We recognize that Canadian-only investment will not by itself limit future global and Canadian warming scenarios; but it does provide anecdotal evidence of the benefits associated with such investment, at least in terms of reduced physical costs.

Table 3 compares our annual climate damage estimates to Canada's required annual investments according to the CMP (2020). Column 2 shows the PV of the required annual investments of $12.8-billion per year continued until 2100. Column 3 shows the PV of the $12.8-billion annual investments if they are only required until 2053.[i] Columns 4 and 5 show the PV of climate damages over the same timeframe under the 2°C and BAU 5°C warming scenarios respectively. Finally, Column 6 shows the difference in the PV of climate damages between these two scenarios.

TABLE 3

Comparison of the PV of Required Investment versus Climate Damages (in 2020 $b)

Year	CMP Investment	CMP Investment to 2053	2°C Climate Damages	5°C Climate Damages	Difference between 5°C – 2°C
2020	12.80	12.80	13.40	16.19	2.78
2025	9.76	9.76	11.04	15.31	4.27
2030	7.44	7.44	9.03	13.90	4.87
2035	5.67	5.67	7.36	12.28	4.92
2040	4.32	4.32	6.02	10.69	4.67
2045	3.29	3.29	4.97	9.24	4.28
2050	2.51	2.51	4.14	7.99	3.85
2055	1.91		3.51	6.95	3.44
2060	1.46		3.01	6.08	3.07
2065	1.11		2.61	5.35	2.74
2070	0.85		2.28	4.73	2.45
2075	0.65		2.00	4.19	2.19
2080	0.49		1.75	3.70	1.95
2085	0.38		1.54	3.27	1.73
2090	0.29		1.35	2.87	1.52
2095	0.22		1.18	2.51	1.33
2100	0.17		1.03	2.19	1.16
Total	**239.21**	**203.96**	**351.50**	**600.83**	**249.33**

If we assume that making the required investments according to the CMP allows Canada to avoid a 5°C climate scenario, and instead realize a 2°C scenario, then we can compare the PV of these investments to the PV of the difference in damages under the two scenarios. This provides us an estimate of the net benefits, in terms of avoided physical costs, of making such investments.

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[i] In other words, if $12.8-billion per year investment reduces GHG emissions 30 percent over 10 years, then it could require an additional 20.33 years to reduce the other 70 percent of emissions to get to net zero. In this case, no further investments would be required after 2053.

We note from Table 3 that the PV of total investments to 2100 is $239.21-billion, or $203.96-billion if we assume such required investments cease in 2053. The PV of climate damage under a 2°C scenario is $351.50-billion versus $600.83-billion under the 5°C scenario, so the difference in damage is $249.33-billion, in today's dollars. The PV of the difference in damage is $10.12-billion *larger* than the PV of the required investments if we assume they are made until 2100. This $10.12-billion can be thought of as the net benefit of investing to mitigate climate change.

We recognize that assuming that continuous annual investments of $12.8-billion until 2100 represents a scenario that may overstate the total investment requirement (i.e., if GHG emissions are reduced to zero by 2053). Therefore, we also consider another scenario in which the required additional investments cease in 2053. Under this scenario, the PV of investments is $45.37-billion less than the PV of the difference in climate damages under the 5°C versus 2°C warming scenarios.

In results not reported here, but available upon request, we repeat the analysis in Table 3 using the discount rates used in the EIU (2015) report — i.e., public sector (3.8 percent, declining to 2.0 percent) and private sector (5.5 percent, declining to 4.0 percent). The results are similar to those in Table 3, but are much more supportive of the net benefits to investing to mitigate climate change. In particular, the net benefits to investing are $78.8-billion to $134.6-billion using the private sector discount rates, and are significantly higher at $389-billion to $544.5-billion using the much lower public discount rates. These results suggest that our use of a 5.58 percent discount rate generates conservative estimates of the net benefits associated with investing to mitigate climate change.

Finally, we note that the NCE (2018) report estimates a global benefit of $26-trillion US over 10 years (2020-2030) by transitioning to a sustainable, low-carbon economy. This direct economic benefit is produced through the generation of millions of low-carbon jobs, higher GDP growth, and carbon price revenue coupled with reductions in fossil fuel subsidies, in addition to other benefits. If we estimate Canada's share of this benefit using Canada's 1.34 percent share of global GDP, this would create a direct economic benefit of $348.4-billion US, or $465.95-billion Cdn.,[ii] over the next 10 years.

[ii] Using an exchange rate of $1.3374 CAD/USD.

4. CONCLUSIONS

The results of the pilot study on transitional risks due to climate change by OSFI, the Bank of Canada, and several key financial institutions leave an important void with respect to the impact of physical risks and the associated costs of climate change for Canada. We fill this void by updating and extending to Canada, the ground-breaking DICE model developed by 2018 Nobel Laureate William Nordhaus.

Our results illustrate stark differences in the physical costs under various warming scenarios, which highlights the importance of taking action to mitigate climate change. For example, we find that an increase from 2°C to 3°C warming leads to additional physical damage by 2100 with a PV of $80.9-billion, which escalates to $187.4-billion under a 4°C scenario. We also find that 2050 and 2070 are inflection points, at which physical costs accelerate markedly.

We compare the PV of climate damage under a BAU (5°C) warming scenario to those under a 2°C scenario and relate the difference in these figures to the PV of undertaking required annual investments to achieve Canada's emissions reduction targets. These results suggest that the PV of the difference in damages is $10.1-billion to $45.4-billion *larger* than the PV of the required investments. In other words, undertaking the required investments to reduce GHG emissions more than pays for itself in terms of avoided physical damage alone, and without taking into account the potential economic benefits of transitioning to a low-carbon economy. Overall, our results provide important guidance for policymakers and other actors in the Canadian economy.

We note the following caveats regarding our study. First, our Canadian adaptation of the DICE model assumes that global temperature increases affect Canada equally, whereas we know that Canada is warming faster than the rest of the world. This implies our model estimates of climate damages are likely conservative. Secondly, like the original DICE model, we estimate physical costs only, but do not account for associated transition costs. Finally, we do not formally account for the long-term benefits associated with climate mitigation, which have been estimated to be very significant.

As a result of these limitations, our results paint an incomplete picture of the total economic outcomes under each warming scenario. For example, under a 2°C warming scenario Canada may experience significant economic benefits that we do not account for. Additionally, we assume the benefits of climate change mitigation are from global action. If Canada were to take action alone, these projected benefits may not be realized. On the other hand, if the world were to act and Canada did not engage in mitigation efforts, Canada would realize some of the projected benefits in the absence of making the required investments.

Despite these limitations, our results provide strong support for the benefits of investing in the transition to a sustainable, low-carbon economy.

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APPENDIX A

Temperature Adjustments

Our first step in implementing the DICE model is to calibrate it so that, by 2100, global temperatures reach levels of 2°C, 3°C, 4°C, and 5°C above pre-industrial temperatures. For our purposes, the temperature used for our projections is the increase in global temperatures, with our base model being 2°C above preindustrial levels by 2100. We use global projections of temperature increases and carbon output, which we then apply to Canada. We do so because the DICE model cannot elegantly differentiate between global temperature increases and those for a particular nation or region.

The global atmospheric temperature in a given year is determined using equation A.1:

A.1

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

Where 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 per square meter (W/m^2). 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 oceans.

LOT_{n-1} is the "lower ocean temperature" in °C above preindustrial temperatures for the previous year, where LOT_n is updated every year using Equation B.1 of Appendix B. The initial 2016 lower ocean temperature value is set to 0.007°C above pre-industrial temperatures as in the original DICE model, which determines this figure using 2015 environmental data. Ocean temperatures are important because they feed into heat loss, by acting as a heat sink.

The baseline DICE model projects the world temperature at 0.85°C above pre-industrial in 2015, while the coefficient on heat loss (CHL) is set at 0.088. We maintain the original DICE model's temperature sensitivity (referred to as the "equilibrium temperature increase for CO2 doubling" or ET), which means that our model assumes that Canada is equally affected by global warming as the rest of the world.

We adjust the atmospheric temperature by adjusting the radiative forcings in W/m^2. Forcings are the difference between solar irradiance absorbed by the Earth and energy that is radiated back to space. Upward changes to these forcings increases atmospheric temperatures.

Climate Damage Modelling

Equation A.2 determines the GDP for a given year by combining the population, productivity, and available capital. In particular, "Output (Gross of abatement cost and climate damage)" is calculated from the model's Cobb-Douglas function which projects output as a function of capital, labor, and productivity, where K_n is the capital investment in a given year. TFP_n is the total factor productivity for the year being examined. TFP is a measure of productive efficiency, which is how much output can be created from a given amount of inputs (Sickles & Zelenyuk, 2019)[1]. The starting value for TFP_n used in our calculations is set to the 2015 value of 0.9857 (Feenstra et al., 2015)[2], which is then adjusted every year using Equation B.2 of Appendix B. The capital investment (K_n) is determined using Equation B-4 of Appendix B. The original DICE model projects 0.300 as the capital share (CS), which we use in our model. POP_n is the population in a given year, determined using Canadian-specific population metrics from Equation B.12 of Appendix B, which uses population projections from the Century Initiative.[3]

A.2

$$Output\ (Gross\ of\ abatement\ cost\ and\ climate\ damage)\ = TFP_n * K_n^{CS} * \frac{POP_n^{1-CS}}{1000}$$

Equation A.3 estimates total damage as a fraction of gross output, where AT_n is the atmospheric temperature for a given year as determined in Equation A.1. ED is noted in the DICE model as the "exponent on damages" and represents the exponential relationship of AT's effect on climate damages. DT is the damage coefficient on temperature, which is set to the original DICE value of 0.0023600. The exponent on damages is set to 2.0 as in the original DICE model, which has been pre-determined by impact analysis in the original DICE model documentation. Like Burke et al (2015)[4], the DICE model calculates an exponential relationship between temperature increase and climate damage. As temperature increases by the same amount over time, the damages grow exponentially for a given period. Adding exponential relationships to ED and AT_n in the equation below allows the DICE model to capture this exponential relationship and translate it into economic terms.

A.3

$$Total\ damage\ (fraction\ of\ gross\ output) = AT_n * DT + (DT^2 * AT_n^{ED})$$

Equation A.4 is our main equation as it provides annual estimates of climate damage (i.e., damage due to climate change). Equation A.4 multiplies the outputs from Equation A.2 (i.e., "output (gross of abatement cost and climate damage)") and from Equation A.3 (i.e., "Total damage"). The resulting products are estimates of the amount of GDP lost, in a given year, due to climate damage.

A.4

$$Climate\ Damage = Output\ * Total\ damage$$

The inputs for these equations are acquired through a variety of other macroeconomic inputs and calculations. We have provided greater details and explanations for these inputs and calculations in Appendix B.

APPENDIX B

Canadian Macroeconomic Variables

Equations A.1 through A.4 of Appendix A require several Canadian macroeconomic inputs, and estimates, which are discussed below.

Equation A.1 requires the calculation of “lower ocean temperature” $\left(LOT_{n-1}\right)$ for the start of each year. The initial temperature for this variable is set by the original DICE model at 0.007 °C above preindustrial for 2015. Each subsequent year uses the following equation:

B.1

$$LOT_n = CHG * (AT_n + LOT_{n-1})$$

In this equation CHG is the Coefficient of “heat gain by deep oceans,” AT_n is the atmospheric temperature for the given year (as calculated in Equation A.1), and LOT_{n-1} is the Lower Ocean Temperature for the previous year. CHG is set to 0.025 as it is in the original DICE model.

TFP_n from Equation A.2 estimates total factor productivity for the year being examined. The initial value for total factor productivity is set to the 2015 value of 0.9857, as in Feenstra et al. (2015). After 2015, TFP_n is determined using Equation B.2 below for each subsequent year. In Equation B.2, ga_n refers to the growth rate of productivity, which is estimated using Equation B.3 based on the growth and decline rates of technology per half decade. The required inputs for Equation B.3 are the growth rates (GRT) and decline rates (DRT) for technology per half decade, which are set by the original DICE at 0.0760 and 0.0050 respectively.

B.2

$$TFP_n = \frac{TFP_{n-1}}{1 - ga_n}$$

B.3

$$ga_n = e^{(-DRT*5*(n-1)*GRT)}$$

Equation A.2 also requires an estimate of K_n, or Canadian capital investment, which we estimate using Equation B.4 below. We follow the approach of the EIU (2015) report, and use the ratio estimates for manageable assets provided by the 2015 Financial Stability Board report.[5] This report indicates that 66 percent of total financial assets in Canada are considered manageable. Statistics Canada (StatsCan) reports the total value of Canadian financial assets to be $31.5 trillion at the end of 2018, and so we use 66 percent of this figure ($20.8 trillion) as our initial capital estimate. The capital in a given year is a function of the prior year’s capital figure less depreciation, plus gross investment (GI) during the year. A given year’s depreciation figure is determined based on the depreciation rate (Dp), which is set at 0.10, as in the original DICE model.

B.4

$$K_n = K_{n-1} * (1 - Dp)^{Year-(Year-5)} + GI^{Year-(Year-5)}$$

The GI variable in Equation A.4 is determined using Equation B.5 which multiplies net output (NO) times the savings rate (SR). We obtain an estimate of 21.05% for the savings rate in 2015 using World Bank data for “Gross Domestic Savings (% GDP),” and we maintain this value for all years. Net output (NO) is output “net of abatement and damages,” which is estimated in Equation B.6 by taking output gross of abatement (OAD) costs (estimated in in Equation B.7) and subtracting abatement costs.

B.5

$$GI = SR * NO$$

B.6

$$NO = OAD - Abatement\ Cost$$

B.7

$$OAD = Output - Climate\ Damage$$

The abatement cost estimates used in Equation B.6 is estimated using Equation B.8 as a function of the abatement cost function coefficient (ACF), the emissions control rate (ECR), and the exponent of control cost function (ECC). We set ECC equal to 2.600, as it is in the original DICE model.

B.8

$$Abatement\ Cost = ACF * ECR^{ECC} * 1^{1-ECC}$$

The ACF variable in Equation B.8 is estimated in Equation B.9 as a function of the Backstop Carbon Price (BSP), ECC, and the sigma industrial (σ_n) value, which estimates energy cost at the industrial level. Sigma is calculated every 5 years using Equation B.10, which applies a growth rate (GRS) to the prior period's value. The DICE model sets this growth rate at -0.015. Intuitively, as technology and industry become more efficient, this value should decrease and the abatement cost should also decline.

B.9

$$ACF = BSP * \frac{\frac{\sigma_n}{ECC}}{1000}$$

B.10

$$\sigma_n = \sigma_{n-1}^{\left(GRS*\left(n-(n-5)\right)\right)}$$

The ECR variable from Equation B.8 is estimated using Equation B.11 as the minimum (MIN) of a function based on carbon price (CP) (per ton of CO2, plus hotelling rent[i]), the backstop price of CO2 (BSP) (in $1,000 per ton), and ECC. Both CP and BSP are set by the DICE model, with a decline rate of 0.025 applied per half decade to BSP.

B.11

$$ECR = MIN\left(\left(\frac{CP}{BSP}\right)^{\frac{1}{ECC}-1}, 1\right)$$

Finally, POP_n (the population each year from 2015 to 2100 in 5 year increments) from Equation A.2 is determined using Equation B.12.

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[i] "Hotelling Rent" defines a price path as a function of time, it is the maximum rent that can be obtained while exhausting a non-renewable resource. In the case of the DICE model, the "Hotelling" is designed to augment the carbon price to reduce consumption. The original DICE model value for this is set at 0, which we do not modify.

B.12

$$POP_n = POP_{n-1} * \left(\frac{Asymptotic}{POP_{n-1}}\right)^{parameter_{2050}}$$

The Canadian population projections obtained from Equation B.12 are used to calculate the output of Canada's economy, as well as its climate damage estimates. The world population estimates from the original DICE model are used to calculate the world's carbon production and intensity, as well as global temperature increases. This allows us to examine the effect that global warming has on Canada's economy. For our Canadian values, we use 35.7 million people for the 2015 population as reported by StatsCan, we then set the "Asymptotic" variable to 100 million, which is chosen as the population of Canada by 2100 that would allow Canadian social systems and labour to remain intact, according to the Century Initiative report. The "parameter_{2050}" variable is a projected growth rate per five-year period. We calibrate this variable such that the population achieves the Century Initiative projection of 100 million people by 2100.

Appendices Endnotes

1 Sickles, Robin C., and Valentin Zelenyuk. *Measurement of productivity and efficiency.* Cambridge University Press, 2019.

2 Feenstra, Robert C., Robert Inklaar and Marcel P. Timmer, "The Next Generation of the Penn World Table." *American Economic Review* 105 no.10 (2015): 3150-3182.

3 Century Initiative. *For a bigger, bolder Canada. Long-term Thinking. Starting Now.* 2019, https://uploads-ssl.webflow.com/5f931bff6aee7ca287dbada2/5f99ce137eaf1ee0243f1d98_CI-Report.pdf

4 Burke, Marshall, Solomon M. Hsiang, and Edward Miguel. "Global non-linear effect of temperature on economic production." *Nature* 527, no. 7577 (2015): 235-239.

5 Financial Stability Board. *Global Shadow Banking Monitoring Report.* November 12, 2015, https://www.fsb.org/wp-content/uploads/global-shadow-banking-monitoring-report-2015.pdf.