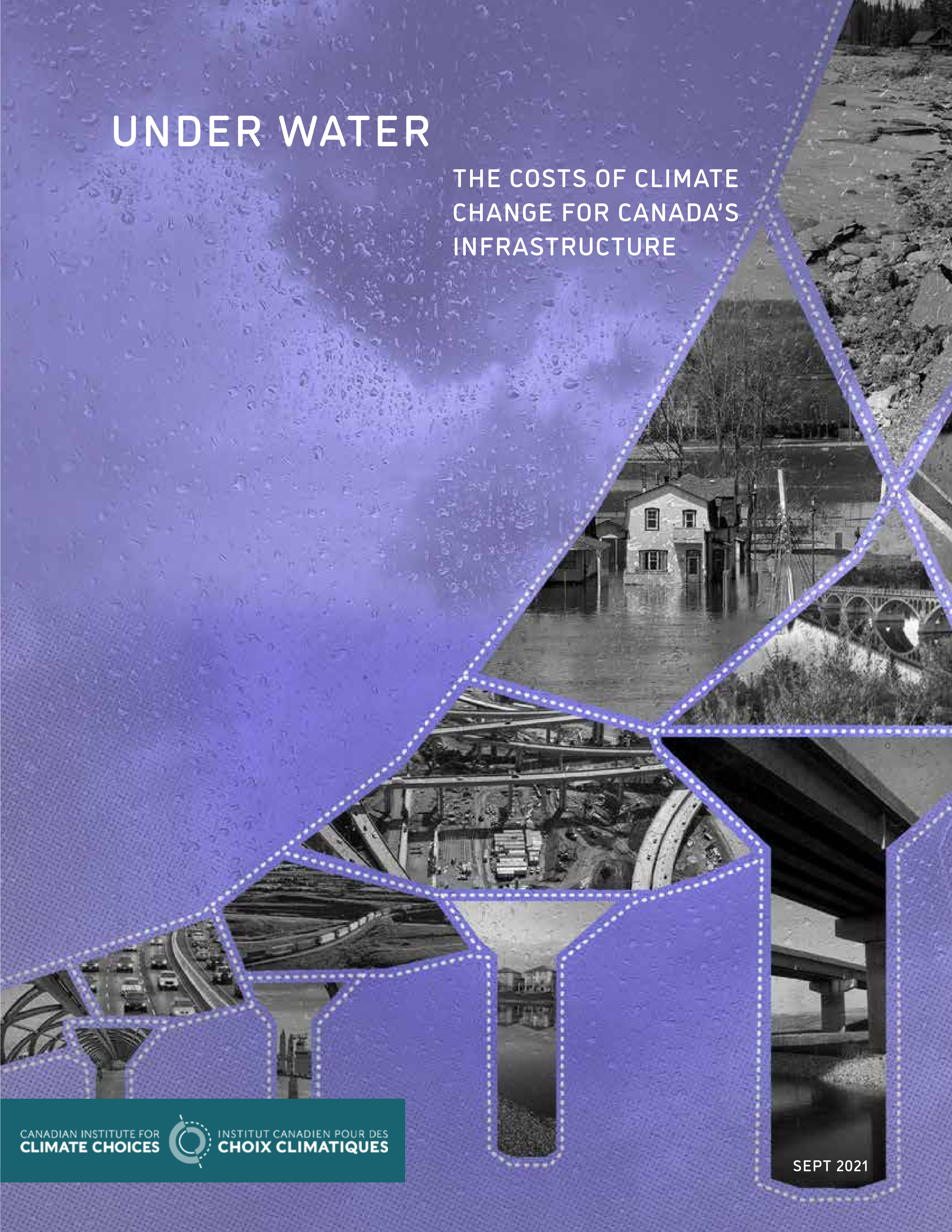


UNDER WATER

THE COSTS OF CLIMATE CHANGE FOR CANADA'S INFRASTRUCTURE

CANADIAN INSTITUTE FOR CLIMATE CHOICES
INSTITUT CANADIEN POUR DES CHOIX CLIMATIQUES

SEPT 2021

CONTENTS

The **Canadian Institute for Climate Choices** is an unparalleled collaboration of experts from a diverse range of disciplines and organizations across the country.

As an independent, non-partisan and publicly funded organization, we undertake rigorous research, conduct in-depth analysis, and engage a diverse range of stakeholders and rights holders to bring clarity to the climate challenges and transformative policy choices ahead for Canada. Learn more at climatechoices.ca.

Our ongoing research into the costs of climate change includes the following reports:

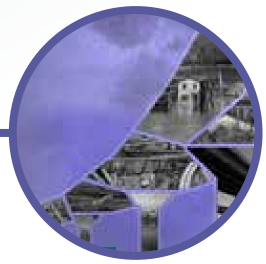
2020

TIP OF THE ICEBERG
FALL 2020

If we think of the costs of climate change as an iceberg ahead, this introductory paper zooms in on the tip of the iceberg—the known and measurable hazards—as well as the contours of what lies below the water.

THE HEALTH COSTS OF CLIMATE CHANGE
SPRING 2021

A closer look at health costs and adaptation opportunities, built around our analysis of the costs of heat-linked health burdens, Lyme disease, and air quality changes. The report includes a discussion of mental health impacts and other difficult-to-quantify health costs.



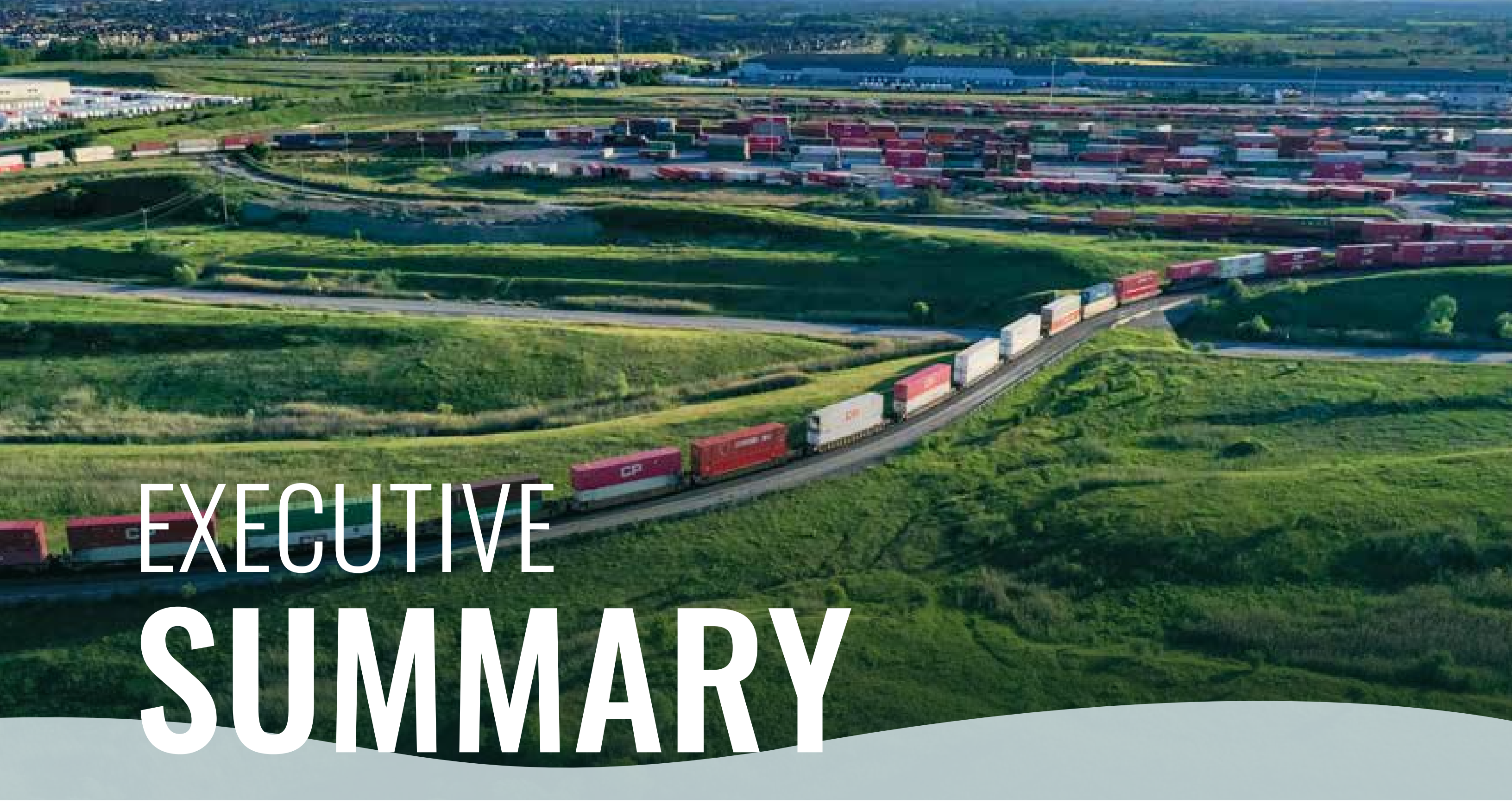
UNDER WATER
FALL 2021

A focused analysis on infrastructure costs and adaptation opportunities, built around our modelling of climate-induced impacts to flooding, transportation infrastructure, and electricity systems.

MACROECONOMIC
SPRING 2022

Using national macroeconomic modelling of potential climate change impacts to vulnerable sectors and assets, this report will outline the implications of a changing climate on economic productivity and well-being.

2022



EXECUTIVE SUMMARY

Infrastructure—our entire built environment—underpins life in Canada. When this infrastructure is damaged or doesn't function properly, people's health, safety, and livelihoods, and the strength of the economy are put at risk. Climate change is increasing the risk of damage and service disruption to infrastructure across Canada—infrastructure whose repair and maintenance costs are already a major national challenge.

Until now, the scale of risk to Canada's infrastructure has been poorly understood. This report looks at how a warming and increasingly volatile climate could damage infrastructure across Canada and what Canadian governments can do to prepare and to reduce damage, disruption, and costs.

We project impacts for some of the country's most important infrastructure—including homes and buildings, roads and railways, and electricity systems—and assess how various adaptation choices could influence future costs. Our findings suggest that to ensure new and existing infrastructure is "future proofed," investment must dramatically shift toward making infrastructure more resilient. Policy changes drive that shift: Canada must rapidly update the policies, codes, regulations, and funding decisions that determine what gets built and how it is maintained.

This is easier said than done. Even without considering the added stress of a warming climate, Canada already faces significant threats to the integrity of our roads, bridges, buildings, communications systems, water and sewer systems, electricity grids, and homes. Deteriorating roads and electrical grids and slow progress in modernizing transportation corridors and public transit systems are hampering business performance, trade and economic growth. And access to clean drinking water and safe housing remains a critical need for tens of thousands of people—and Indigenous communities in particular—eroding health, safety, and prosperity. Necessary repairs and upgrades are already overdue and underfunded—some estimates peg the money required to address this gap at over $250 billion. And in some places, like in many majority First Nation, Métis, and Inuit communities, essential infrastructure has never been built. The added pressure of climate change will make it even more difficult to rectify this inequality.

What's more, Canada's transition to net zero will require major infrastructure investments in low-carbon buildings, transportation, and electricity infrastructure. If these new investments are done right, they can help address infrastructure gaps and make infrastructure systems across the country more resilient to climate change. If they are done poorly, they will add to our stock of infrastructure at risk of damage and disruption from climate change and deepen gaps.

Canada has a clear opportunity to address existing infrastructure needs while also building climate resilience into infrastructure from the ground up. Failing to consider climate risks and the benefits of resilience will only increase costs and exacerbate Canada's existing infrastructure challenges.

FINDINGS

▶ The costs of damage and disruption from climate change to Canada's infrastructure, which is vulnerable from decades of underinvestment, could be massive.

Canada's warming climate will accelerate climate- and weather-related damage to some of the country's most important infrastructure. As sea levels rise and rainfall increases, flood damage to homes and buildings could increase fivefold in the next few decades and by a factor of ten by the end of the century, with costs as high as $13.6 billion annually. Temperature- and rainfall- related damage to roads and railways could increase by up to $5.4 billion annually by mid century and by as much as $12.8 billion annually by end of century. Heat and rainfall damage to electrical transmission and distribution infrastructure could more than double by mid-century and triple by end of century, costing utilities and ratepayers up to $4.1 billion annually.

Governments, utilities, businesses, and homeowners across Canada are already struggling to keep existing infrastructure in good condition and build the infrastructure needed for the future. Growing levels of damage and disruption as a result of climate change could make this even more difficult—and costly.

▶ Proactive investment in infrastructure adaptation is the most cost-effective way to protect the services that people, businesses, and the economy depend on.

Early investment in adaptation can substantially reduce the impacts and costs to infrastructure of a hotter and increasingly volatile climate. Building and moving homes out of high-risk areas can reduce the costs of coastal flooding by 2100 up to 90 per cent or up to $1 billion every year. When repaving roads, using asphalt mixes and base materials selected to withstand the climate two or three decades into the future can reduce costs by over 90 per cent, saving as much as

$4.1 billion annually by the 2050s. And during regular maintenance for electricity transmission and distribution infrastructure, replacing components with new ones designed to withstand increases in heat and rainfall for several decades to come can reduce damage costs by 80 percent by the end of the century, or up to $3.1 billion each year.

Despite the clear benefits of early, proactive investment in adapting Canada's infrastructure for climate change, progress has been limited. Public and private infrastructure owners have been more concerned with short-term budgets and balance sheets than long-term planning, leaving long-term risks like climate change unaddressed. The unprecedented investments in infrastructure over the next several decades to support the net zero transition are a key opportunity to build the climate resilience of virtually all infrastructure in Canada. However, if current short-term thinking around infrastructure continues, those investments will only increase the amount of infrastructure vulnerable to climate change impacts.

▶ Not all impacts and costs of climate change for infrastructure can be quantified—the loss of services and reliability will have far-reaching social and economic consequences.

Our analysis shows that the cost of climate change-induced damage to key infrastructure could be massive, yet our projections of costs are only a low-end estimate. Climate science cannot yet predict how climate change might affect many types of extreme weather events not included in our analysis—such as ice storms, tornadoes, hurricanes, and hail—that could cause much additional damage. Other types of critical infrastructure that we did not study, including telecommunications infrastructure, drinking water systems, healthcare facilities, and marine ports and seaways, are also at risk from climate change.

The costs of climate change impacts on infrastructure also go beyond the price of physical damage and repair. When infrastructure is put out of commission or made less reliable by more frequent damage, the services that it provides—transportation, power, healthcare, communications, and shelter, to name a few—are also interrupted. We show that the costs of delays from climate-induced damage to roads and railways borne by transportation operators alone could be in the billions annually. In reality, however, these effects will reverberate through supply chains and industries, multiplying costs and reducing economic productivity. Further, damage from climate change, or the threat thereof, could have far-reaching implications for the stability of the financial system and the availability of capital and insurance.

▶ A lack of climate risk information, transparency, and regulation is leading to bad infrastructure decisions.

In Canada, very little information is available regarding current or future climate risks to infrastructure. For example, we estimate that at least a half million buildings at risk of flooding in Canada are not identified by government-produced flood maps. The flood maps that are available are 20 years out of date on average and only show existing flood risk—virtually none of them show how climate change may affect the future risk of flooding. Even bigger information gaps exist for other major climate hazards, including wildfire. In the absence of this information, few infrastructure owners or investors are able to assess and manage existing climate risks, let alone future risks associated with climate change.

The codes and standards that dictate how infrastructure in Canada is built and managed largely do not account for climate change, and updates to reflect climate change risk are many years from being implemented. As a result, infrastructure is being built and operated based on the climate of the past, not the hotter and more extreme climate that is emerging. And regulations for financial decision making in Canada do not yet require owners and investors to assess and disclose climate change risks to physical assets and infrastructure. Markets are therefore not pricing this risk, allowing capital to continue to flow into risky investments.

BALANCE SHEETS ARE LITTERED WITH UNDISCLOSED CLIMATE INFRASTRUCTURE RISKS

The economic implications of climate change impacts on infrastructure in Canada extend well beyond the costs of repairing potholes or flooded homes. The accumulated costs of damage and disruption from flooding and extreme weather and from additional wear and tear from a warming climate, as well as from the impact of this damage on property and asset values, mortgages, and insurance rates, can also ricochet through the economy. Yet very few of these costs are being factored into financial systems and economic decisions today. Both public and private infrastructure owners risk big write-downs in the value of their assets, as well as challenges in obtaining credit and capital once it becomes clear that they face increased risk of flooding or other hazards in a changing climate. And stakeholders and investors in both government-owned and privately owned infrastructure are unknowingly buying into those risks.

Currently, the risks of climate change for infrastructure owned by individuals or businesses, such as homes and commercial buildings—and for the capital that finances them—are not being widely assessed or disclosed. For example, flood, wildfire, and permafrost risks are very difficult for asset owners in Canada to assess because there are no country-wide maps or data sources, and the local data that exists is frequently dated or obsolete. This means that the amount of climate risk threatening the value of a home or building is equally unknown to the owner, mortgage lender, and mortgage-backed security holder. Indeed, our estimates show that within 30 years, climate change will likely increase annual damages of coastal and inland floods to homes and buildings by $4.5 billion to $5.5 billion annually, three to four times today's costs. Yet the lack of information about flooding and other climate change risks means that not enough infrastructure owners or lenders are taking steps to protect themselves. For example, approximately 45 per cent of homeowners in Canada believe they have insurance that will pay for repairs and rebuilding after overland flooding, only about 10 to 15 per cent of households actually have this coverage. And mortgage lenders typically don't require purchasers of homes in flood zones to have overland flood insurance.

Risks to public and large-scale infrastructure like railways and electricity systems are also a concern. Governments and other major infrastructure owners continue to design and build for yesterday's environment without factoring in climate change risk. Stakeholders—users, taxpayers, ratepayers, lenders, and investors—are largely unaware of how the impacts of climate change to these major infrastructure systems will impact them. For example, our projections indicate that by around 2050, climate change-induced damage to roads could require governments across Canada to spend up to $3.1 billion more annually on road maintenance and repair—or almost 20 per cent more than what they currently spend. These costs will hurt the bottom line of municipal governments—which are responsible for most roads in Canada—and will ultimately impact residents through higher taxes, poor road conditions, and delays.

In addition to financial risks for individual owners, businesses, and governments, damage and disruption to infrastructure from climate change could have major systemic consequences. Cumulatively, the costs of infrastructure damage and loss of asset value could affect the stability of Canada's financial system. Lenders and investors will be less willing to provide capital—or will demand higher rates—to areas and industries where climate-related risks are clearly increasing. Similarly, insurance will become more expensive or even unavailable, meaning that more losses will be borne directly by owners or creditors. More frequent and severe damage means that infrastructure will more frequently be out of service or in poor condition, reducing the function that it performs in supporting people, communities, and businesses. For example, traffic congestion in the Greater Toronto and Hamilton area alone is already estimated to cost up to $11 billion per year in lost productivity—an amount that will only grow with roads in worse condition or more frequently closed for repair. Loss of vital infrastructure services will also affect productivity, mobility, trade, communications, and food and water security, among other things, with implications for economic growth and the health and well-being of people across Canada.

Quite simply, when it comes to forecasting the true scale of damage and disruption of infrastructure in a warming climate, we don't know what we don't know. The scale and extent of climate-related risks to Canada's infrastructure are only now coming into focus as climate models are updated, and the complex consequences of increasing infrastructure damage and loss of service for the financial system and the broader economy are beginning to come to light. It is therefore impossible to fully gauge the extent of the economic impact of future climate risk. However, without starting to act now to minimize future loss and damage based on the information today, Canada could find itself swamped by the pace of climate change and its impacts on our infrastructure.

CLIMATE CHANGE MUST FACTOR MORE PROMINENTLY INTO INFRASTRUCTURE DECISIONS

Decisions about where and how public and private infrastructure are driven by a complex web of government policies and market forces. In governments, infrastructure departments play an important role in deciding what gets built where, but other departments also influence infrastructure planning, design, financing, and operations through other levers, including building codes and standards, macroprudential decisions, financial system oversight, regulation of utilities, and land-use planning. And alongside government decisions, the practices of financial system actors, including banks, insurers, stock exchanges, investment companies, institutional investors, accounting firms, credit rating agencies, and real estate professionals, have a powerful influence over how and when markets finance infrastructure with private capital.

To date, the combined actions of governments and markets have not been enough to prepare Canada's built environment for the warmer and more volatile climate that lies ahead. The climate information developed by governments does not provide individuals and businesses the information they need to understand and prepare for climate risks. Building codes and standards have not kept up with the increased stresses of a warming world. Governments are also enabling risky decisions and bad investments by funding at-risk infrastructure and repeatedly providing financial assistance in response to climate-related infrastructure failures and disaster losses. And markets are failing to account for the true value of climate change risk because owners, lenders, and investors are not able or not willing to disclose how climate change will affect their infrastructure assets.

Governments and the private sector need a new blueprint for how to decide, fund, and insure what gets built. To avoid the costs and social and economic disruption of climate change impacts, infrastructure planning must be forward-looking, strategic, and coordinated across government departments and orders of government, encompassing funding, codes and standards, land-use planning, infrastructure asset management, and more. Government policies should also encourage the transparent disclosure and valuation of risk and stop financially backstopping risky public and private investments. And private sector lenders, investors and firms need to play their part in making better long-term decisions that incorporate climate change risk.

Canada is at an infrastructure crossroads. Governments, businesses, and communities are beginning to rethink what the roads, railways, homes, buildings, and electricity grids of tomorrow should look like, and how best to prepare for the changes we anticipate. Ultimately, continuing to build infrastructure the way Canada has in the past will cost more than future-proofing the country's built environment.

RECOMMENDATIONS

All orders of government have an important role in building the resilience of Canada's infrastructure in preparation for climate change. The following recommendations, if acted on by federal, provincial, territorial, Indigenous, and municipal governments, will help ensure that Canada starts building today for the climate of tomorrow.

1 Governments should develop and publish accurate and practical information about climate-related infrastructure risks.

To understand and manage current and future climate change risk and make informed investments in adaptation, governments, corporations, investors, and individuals need actionable and up-to-date risk information. However, current information about future climate change impacts and existing climate risks in Canada is inconsistent and incomplete. To ensure that all owners and investors of infrastructure understand climate risk and can account for it in their decisions, governments must develop useful and consistent climate risk information that is universally accessible.

2 Governments and regulators should require owners of existing and proposed infrastructure to disclose climate change risks.

Transparency about climate change risk promotes resilient decisions and discourages risky ones. But if infrastructure owners and investors are not made aware of and accountable for climate risk, that risk will grow dramatically as the climate becomes hotter and more volatile. Governments and regulatory bodies should use their authority to ensure that owners, lenders, investors and other financial system actors are analyzing, disclosing, and managing climate risk.

3 Governments should explicitly evaluate resilience benefits and climate risks for all infrastructure spending and regulatory decisions.

The long lifespan of most infrastructure means governments and others need to start building adaptation and resilience into infrastructure decisions immediately to avoid locking in decades or centuries of additional climate vulnerability. To make this happen, all orders of government should take a long-term, coordinated approach to setting infrastructure standards, funding and planning public infrastructure, regulating infrastructure operation, regulating urban development, evaluating major industrial and resource development projects, and maintaining and operating infrastructure.

4 Governments should create safety nets for the most vulnerable to make climate risk pricing equitable.

More transparency and disclosure of climate change risk will create price signals that have overall, long-term benefits for reducing climate risk. However, uncontrolled climate change risk pricing could create unsustainable costs for the individuals and communities that are already the most economically vulnerable to climate-related damage—for example by raising mortgage rates or insurance premiums. To avoid negatively impacting those who can already least afford to pay, governments should ensure that economically vulnerable individuals, businesses, and communities are made a priority for adaptation investments and for programs to ensure access to insurance and credit.

Northern infrastructure

Canada's infrastructure gaps are perhaps most visible when comparing differences between Northern and Southern Canada. Inadequate housing, unreliable electricity, and deficient roads and airports, among other issues, are major challenges to the health, well-being, and prosperity of communities across the North, and of Indigenous peoples in particular. The climate is also warming more rapidly in Northern Canada than almost anywhere else in the world. The speed of change, as well as the North's unique geography and history, mean that the patterns and consequences of climate change impacts on infrastructure are distinct in Northern communities.

The Canadian Institute for Climate Choices is examining the unique challenges facing northern Canada when it comes to climate-related infrastructure impacts and adaptation. These include the impacts and costs of permafrost thaw on airports, roads, and homes across the North and the impacts of shorter ice road seasons. In collaboration with Firelight, an Indigenous-owned consulting and research firm that works with Indigenous and local communities across Canada, we are also exploring what these infrastructure impacts mean to Inuit and First Nations communities. This analysis will be published in 2022.

1 INTRODUCTION

Climate change is causing unprecedented strain and damage to Canada's infrastructure—the buildings, roads, energy systems, and other vital physical assets that underpin all aspects of life in Canada. When infrastructure is under threat, it cannot reliably provide the critical services and functions that support social, cultural, and economic well-being in Canada. When infrastructure is at risk, so are trade, business, community life, and people's health and safety.

Canadian governments can make choices now to protect Canadian infrastructure. Policy changes can create incentives for investing in resilient infrastructure that can withstand climate impacts—saving many private and public dollars over the long life of infrastructure projects and protecting the infrastructure services that people and the economy depend on. This is especially true now, as governments consider major new infrastructure investments to support a net zero transition. Failing to consider the costs of climate impacts, and opportunities to build resilience through these investments, will only increase the cost of the transition.

Damage to homes, businesses, and public infrastructure from storms, floods, and wildfires is increasing—and so is the cost of repairing the damage. Over the past several decades, the annual cost of weather-related disasters in Canada has jumped by a factor of 10, as have the average costs of disasters (Sawyer et al., 2020). Recent weather-related disasters have had unprecedented human and economic costs, such as the 2020 Alberta hailstorm that caused almost $1.2 billion in damages (IBC, 2020), the Toronto and Calgary floods of 2013 that resulted in over $7 billion in combined damages, and the Fort McMurray wildfire of 2016 that had an economic cost of nearly $11 billion (Alam et al., 2017).

But weather-related disasters are only one part of the picture—less dramatic and slower-moving climatic changes are also a major threat to infrastructure. Rising sea levels lead to more frequent shoreline erosion and flooding in coastal communities, higher summer temperatures cause roads and railways to buckle, permafrost thaw damages buildings and roads across the North, and ice storms shut down electrical grids and telecommunications systems. Although all these consequences of climate change are already happening in Canada, little is yet known about their total effect on infrastructure. Governments and other infrastructure owners and operators largely do not understand how rates of power outages, road closures, rail repairs, or flooding of homes and communities—and their economic and societal costs—are changing because of climate and weather. What is certain is that, as the climate continues to change, without adaptation these impacts to infrastructure in Canada will continue to worsen.

Escalating infrastructure damages caused by climate change could dramatically increase the cost of simply maintaining the services that people across Canada depend on. Federal government estimates peg the potential costs of climate-induced infrastructure damage at over $300 billion in the coming decade alone (Bush & Lemmen, 2019). These climate costs could consume funds needed to address existing infrastructure deficits, including housing shortages, water insecurity, and transportation gaps. Climate change impacts could also hinder Canada's transition to net zero and delay investments in new infrastructure that will be critical in a low-carbon world, such as updated power grids, public transit, and building energy retrofits. If action is not taken to adapt new and existing infrastructure to the effects of a changing climate, it cannot reliability support a Canadian net zero economy.

Fortunately, it's possible to avoid much of the potential cost of infrastructure damage and loss of infrastructure services from climate change. But avoiding tomorrow's costs hinges on governments, businesses, and communities investing today in adapting to climate change infrastructure risk. This includes ensuring that new infrastructure is designed to withstand climate change,

that existing infrastructure is made more resilient, and that all infrastructure is managed and maintained to protect its level of service in a changing climate. Changes in government policy can create the incentives and awareness necessary to drive these investments.

When it comes to building resilient infrastructure and adapting existing infrastructure, Canada has a lot of work to do. Despite knowing about climate change risks to infrastructure for decades, governments, businesses, and individuals have rarely accounted for these risks in their decision making. For example, provincial, territorial, Indigenous, and municipal governments have not regularly updated land use planning policies to reflect increasing flood risk in a changing climate. Government environmental assessment and regulatory approval processes for major industrial and resource development projects have limited and inconsistent requirements for proponents to plan for a climate that will be hotter and more volatile. National and regional building codes and infrastructure design standards are only very slowly starting to account for future climate change. Banks continue to lend to individuals and businesses to finance homes, buildings, and physical assets that are exposed to—and in many cases not insured for— current and future climate-related disasters. And insurers have not fully priced in the future risks of climate change to insured properties and assets, undermining incentives for policyholders to manage and avoid risk.

If Canada continues down the current path, not only will costs to governments, businesses, communities, and individuals continue to grow, but a decline in the services that infrastructure provides will have far-reaching social and economic consequences. More frequent damage to roads, railways, electricity systems, and telecommunications will disrupt businesses and supply chains. Healthcare facilities may be unreachable or inoperable during climate-related disasters like floods and wildfires. Failures of dams and bridges will cost lives. And rural and remote communities will be cut off from outside sources of food, healthcare, and other critical supplies.

Other effects will be less apparent but still profound. Growing weather-related damage and an increased awareness of climate risk will impact the value of many public and private infrastructure assets, with potentially catastrophic effects for owners and investors. Private insurance against weather-related disasters could become unavailable or prohibitively expensive, increasing the portion of costs of climate-related disasters that will need to be borne directly by individuals, businesses, utilities, and governments (Dolynny, 2019). And banks and mortgage lenders may refuse to finance or renew loans for buildings, properties, and physical assets that are at risk of severe damage or destruction.

This report describes the physical and economic risks of climate change for infrastructure in Canada. It illustrates both the consequences of not being prepared, and the opportunity that investing in adaptation presents to avoid costs and the loss of vital infrastructure services. We examine the costs of three major impacts of climate change on some of Canada's most important infrastructure:

HOMES AND BUILDINGS experiencing more frequent coastal and inland flooding;

ROADS AND RAILWAYS facing increased temperature- and rainfall-induced damage;

ELECTRICITY SYSTEMS seeing escalating climate-driven demands and stresses.

Our analysis examines the impacts and costs Canada can expect over the remainder of the century as climate change intensifies, both with and without more proactive planning. For scenarios in which Canada invests proactively in adaptation, we model the economic outcomes of protecting infrastructure or increasing its resilience in anticipation of a more extreme and volatile climate. In scenarios without investments in adaptation, we assume that infrastructure continues to be maintained, updated, and replaced without accounting for future climate change. Comparing the net costs with and without adaption measures shows how adaptation could substantially reduce the cost of maintaining infrastructure in the face of a changing climate.

We also examine two climate change scenarios: one in which greenhouse gas emissions continue unabated through the end of the century, leading to global temperature increases approaching five degrees Celsius by 2100, and one in which global emissions are reduced in line with global commitments as of 2020, limiting global warming to about 2.5 degrees by 2100 (see Section 3 for details). The first scenario illustrates the consequences that inadequate international action to curb greenhouse gas emissions may pose for Canada, including the additional costs and limitations of adaptation to a much warmer and more extreme climate. In contrast, the second scenario illustrates the benefits of a more committed and rapid emissions reduction pathway, including reduced impacts and better opportunities to control costs through adaptation.

Our findings illustrate the scale of the potential economic consequences of climate change impacts on Canada's infrastructure. While this report describes only a subset of the costs of climate change for infrastructure in Canada, the results clearly show that climate impacts represent a major risk that governments, banks, insurers, and financial regulators have so far failed to account for. Without proactive and appropriate actions to adapt and build resilience, the costs of repairing, replacing, and maintaining infrastructure in a warming climate will become overwhelming. The funds that will be needed in the future just to maintain current levels of infrastructure service will consume financial resources that could otherwise be spent addressing the national infrastructure deficit and investing in new infrastructure to support Canada's net zero transition. Immediate investment in managing the infrastructure risks of climate change is therefore critical to achieving a prosperous, resilient, low-carbon future.

We also draw attention to key actions that governments can take to drive infrastructure choices that build resilience and avoid future climate change impacts and costs. We consider how governments can provide essential information about climate risk that is available to everyone who makes infrastructure planning and investment decisions, not just to those who can afford to buy it. We consider how governments can drive private capital toward more resilient infrastructure by requiring disclosure of climate risks. We consider how governments can improve resilience of publicly funded infrastructure by explicitly considering resilience benefits and climate risks in ways they currently do not. And we consider how governments can protect economically vulnerable individuals, businesses, and communities to avoid exacerbating inequality.

Notably, this report does not address every important gap in research and policy advice related to climate change risks to infrastructure. The report is not a review of existing infrastructure-related adaptation policies and actions across Canada, nor of the efforts that communities, businesses, and individuals are already making to adapt. Nor does it examine in depth the ways that continued climate change impacts could disproportionately impact people and communities currently denied important infrastructure services or already bearing a greater burden from climate change, including people living on low incomes, Northern and remote communities, and Indigenous Peoples. Our own future work will help to fill some of these gaps, including our forthcoming report exploring climate impacts on infrastructure in the North.

The role of this report is to complement and support work in those other areas by highlighting the larger context: climate change threatens the infrastructure services upon which the prosperity and well-being of people across Canada depend, and governments need to do more to create conditions for better, smarter decision making about infrastructure and climate risk.

The remainder of this report is structured as follows:

- **SECTION 2** sets the context for Canada's infrastructure challenges, including the importance of infrastructure to prosperity and well-being in Canada, as well as the existing national infrastructure gap that climate change will only exacerbate.
- **SECTION 3** describes our methodology for estimating infrastructure impacts and costs from a changing climate and the benefits of adaptation.
- **SECTION 4** applies this approach to estimate the impacts of climate-related flooding on homes and buildings.
- **SECTION 5** considers impacts of a changing climate on roads and railways.
- **SECTION 6** assesses climate impacts on electricity systems.
- **SECTION 7** provides our overall conclusions and recommendations.

2 INFRASTRUCTURE AND CLIMATE CHANGE IN CANADA

Functioning infrastructure is essential to the Canadian economy and the well-being of people from coast to coast to coast. Climate change will increase the cost of maintaining that infrastructure and make it more difficult to sustain the level of service people across Canada expect. Immediate and sustained investment is needed to prepare Canada's infrastructure for a climate that is warming at twice the global rate (Bush & Lemmen, 2019); without it, communities can expect rapidly escalating costs and significant service disruptions.

The challenge of preparing Canada's infrastructure for a warmer and more volatile climate is compounded by the fact that Canada already has a significant infrastructure deficit, and is already struggling to fund, build, and operate infrastructure that provides the services people and the economy require. Failure to address this deficit will limit Canada's ability to successfully address the additional risks to infrastructure caused by a warming and increasingly volatile climate.

To set the context for our analysis of the threats and challenges ahead, this section describes the state of infrastructure in Canada and its degree of readiness for climate change.

A foundation for well-being and prosperity

Across Canada, people depend on the reliable services provided by infrastructure. Efficient and dependable roads and transportation, electricity, water, telecommunications, and healthcare lower business costs by decreasing production times and costs and increasing labour productivity and the reliability of operations. This increases private-sector returns and competitiveness while making the economy more productive, which in turn leads to increasing returns on investments, a higher standard of living, and long-term economic growth. In 2009, Statistics Canada estimated that up to half of all productivity growth in the previous 45 years could be attributed to investment in public infrastructure (Gu & Macdonald, 2009).

Dependable infrastructure and infrastructure services are also essential to the health and well-being of people across Canada. People's health and comfort depend on safe and affordable places to live, clean drinking water systems, and electricity and gas for heating. Wastewater treatment plants, recycling facilities, and landfills protect people from the environmental impacts of pollution and waste. Hospitals and clinics that are open and available are essential to quality healthcare. Roads, railways, and airports help families connect, and community centres and sports facilities help people maintain and improve their physical and mental well-being.

Infrastructure and infrastructure services are particularly important for Northern and remote communities, where safe housing and long-distance shipments of food and medicine can be a matter of life and death. For example, over 100 communities across Canada are not accessible by year-round roads and rely heavily on small ports, winter roads, and airports for supplies and access to the rest of Canada (NRCan, 2018).

Canada's infrastructure already wasn't keeping up

Despite its importance to every aspect of life in Canada, infrastructure across the country is deteriorating—and so is the level of service it provides to businesses, communities, and individuals. This is particularly true for public infrastructure. Over the past 50 years, investments in roads, bridges, airports, electricity grids, and water systems have not kept up with wear and tear and the demands of a growing population and economy.

Although public infrastructure spending in Canada has increased somewhat in the past two decades, recent estimates peg the funding needed to maintain existing infrastructure and fill gaps so the national economy can run at maximum efficiency at between $110 and $270 billion (Berz et al., 2020).

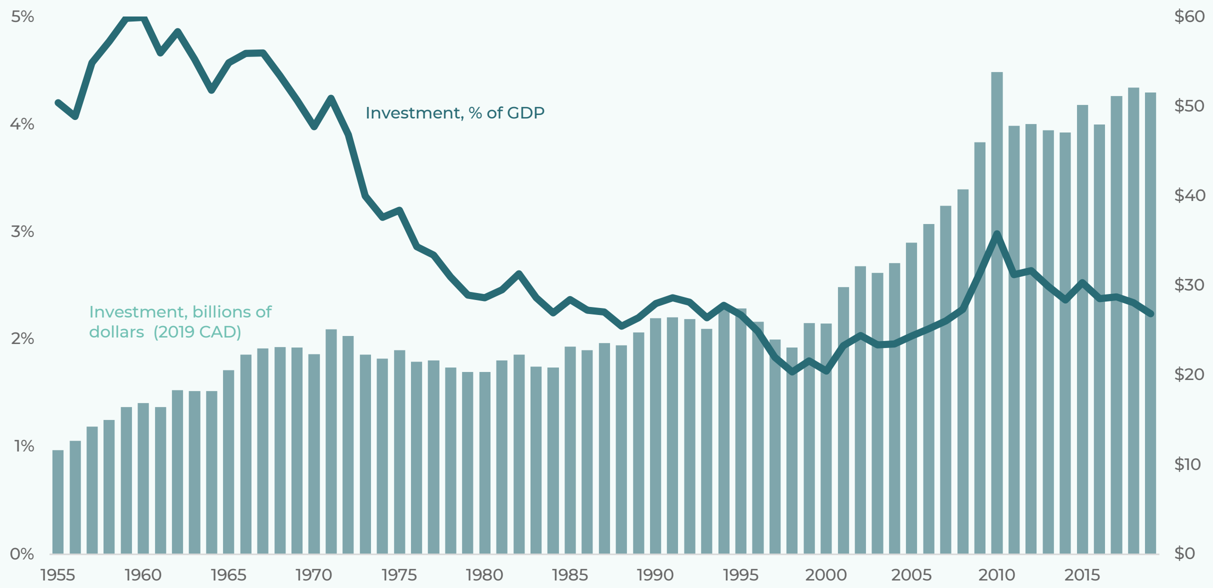
Although Canada's infrastructure deficit constrains productivity, prosperity, and well-being across the country, not all people are affected equally. The national infrastructure gap is not just the story of an inadequate stock of infrastructure overall but of slapdash investment in infrastructure and unequal access to infrastructure services. There are important disparities in Canada regarding who has access to quality roads, reliable electricity, clean water, and safe and affordable housing. For example, 32 Indigenous communities across the country are currently under long-term drinking water advisories, and 185 off-grid communities rely on diesel generators for electricity (Indigenous Services Canada, 2021; NRCan, 2018). An estimated one-third of households in Canada live in a dwelling that is inadequate, unaffordable, or unsuitable (Claveau, 2020). And homes and dwellings in Indigenous communities are three times more likely to need repairs than other communities nationwide (Thistlethwaite et al., 2020).

The story of Canada's infrastructure deficit is complex and started decades ago. Government investment in infrastructure peaked in the late 1950s and then declined continuously until the mid-2000s (Figure 2.1). In the late 1990s, infrastructure spending decreased to the point where the total value of Canadian public infrastructure was actually declining, taking into account depreciation (Mackenzie, 2013). In the late 2000s there was an uptick in public infrastructure spending associated with economic stimulus programs after the financial crisis, but this has subsequently tailed off.

Figure 2.1

Infrastructure spending in Canada is not keeping pace with the economy

Infrastructure investment as a percentage of GDP and in billions of dollars



Source: Data was obtained from Statistics Canada, 2020d; 2021a.

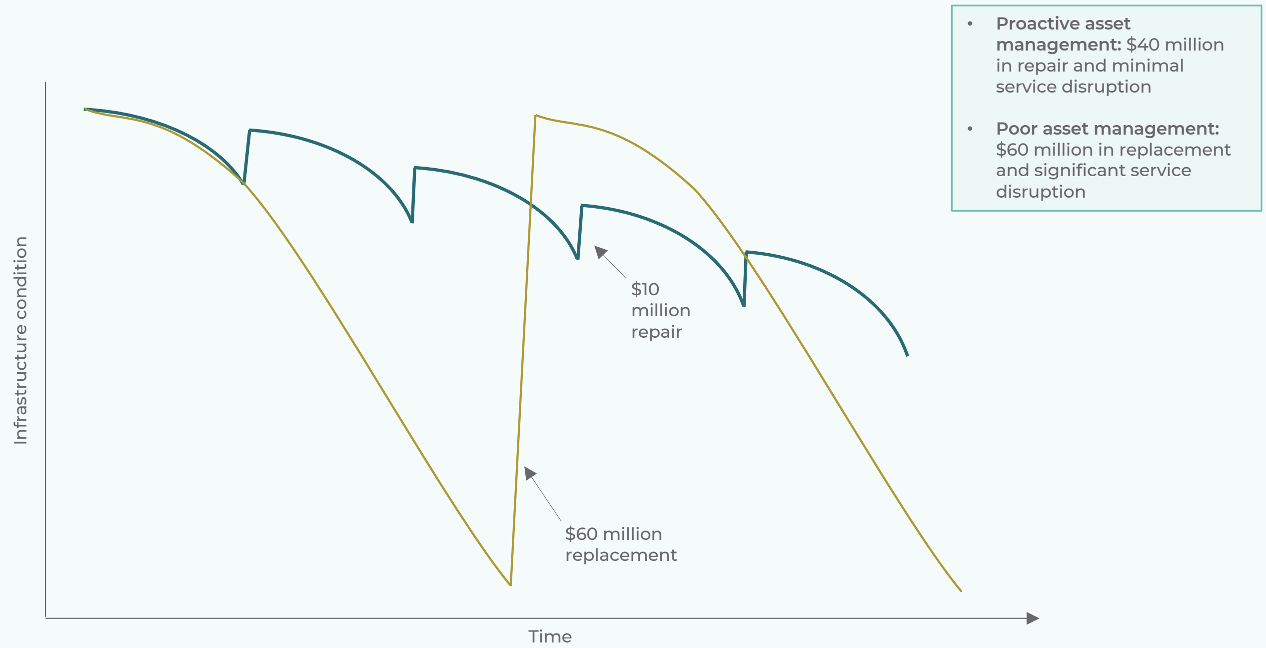
From the mid-20th century until today, responsibility for public infrastructure has also steadily shifted. In the early 1960s, the federal government owned about 25 per cent of public infrastructure, provincial governments owned 45 per cent, and municipal governments owned only about 30 per cent (Harchaoui et al., 2003). Presently, municipal governments own and are responsible for almost 60 per cent of infrastructure—including roads, bridges, water and wastewater treatment systems, recreational facilities, and public buildings—as compared to the federal government's two per cent (Infrastructure Canada, 2018). Since municipalities have few revenue-generating tools at their disposal and collect less than 10 per cent of all taxes paid in Canada, they have been unable to invest adequately in the construction of new infrastructure and the maintenance of existing assets, leading to an overall decline in the condition of infrastructure nationwide (Johal, 2019). Small municipalities and Indigenous governments with limited budgets have been particularly hard hit.

While recent federal government announcements regarding new infrastructure investment are good news, addressing the national infrastructure deficit will still be an uphill battle. Decades of underinvestment have left much of Canada's infrastructure in poor condition, so rehabilitating or rebuilding it will be expensive. Major investments will continue to be required to improve the condition of infrastructure until it can be maintained by moderate, regular spending on maintenance and repair (Figure 2.2).

Figure 2.2

It pays to keep infrastructure in good condition

Costs of timely infrastructure maintenance vs. deterioration and replacement



Climate change action can help close the infrastructure gap

Climate change poses a major challenge to addressing Canada's infrastructure gap, for three main reasons.

First, climate change could accelerate the deterioration of existing infrastructure, substantially reducing its lifespan. Warmer temperatures will strain electrical distribution systems and cause roads and highways to crack and rut (EPA, 2015). Floods will wash out culverts and bridge footings, and permafrost thaw will damage runways and building foundations in the North. This will push more infrastructure into poor condition, further decreasing levels of service and increasing costs for repair or replacement.

Second, climate change is increasing the need for new investment specifically focused on protecting existing infrastructure and the people it serves from harsher conditions (IBC & FCM, 2020). Examples include building seawalls, restoring wetlands to protect urban areas from flooding, and retrofitting public transit vehicles with more powerful air conditioning. These demands will further increase the investment needed beyond what is already required to address the national infrastructure deficit.

Third, meeting Canada's emissions reduction commitments to reach net zero will require investment in new, low-carbon infrastructure like modernized electricity grids, electric vehicle charging networks, zero-emissions public transit, and building renovations. These will create even more demand and competition for infrastructure funding. And if this new infrastructure is not constructed to be climate-resilient and is not maintained to reflect the stresses of a changing climate, it risks becoming part of Canada's pool of poor-condition infrastructure—further deepening the infrastructure gap and increasing the costs of Canada's efforts to achieve net zero.

However, forthcoming investments in infrastructure to support the net zero transition and to protect Canada from climate change are also an opportunity to leapfrog the infrastructure gap. The scale of these investments will be unprecedented, and if coordinated and integrated intelligently they can make the best use of committed resources to simultaneously reduce emissions and build resilience with maximum speed and at minimum cost (ACT, 2021). These investments can also help to restore the overall condition of Canada's infrastructure to a level that can be sustainably funded and maintained—even in the face of increased stresses from climate change. And focussed planning can ensure that new infrastructure provides services for people and communities that have been historically underserved.

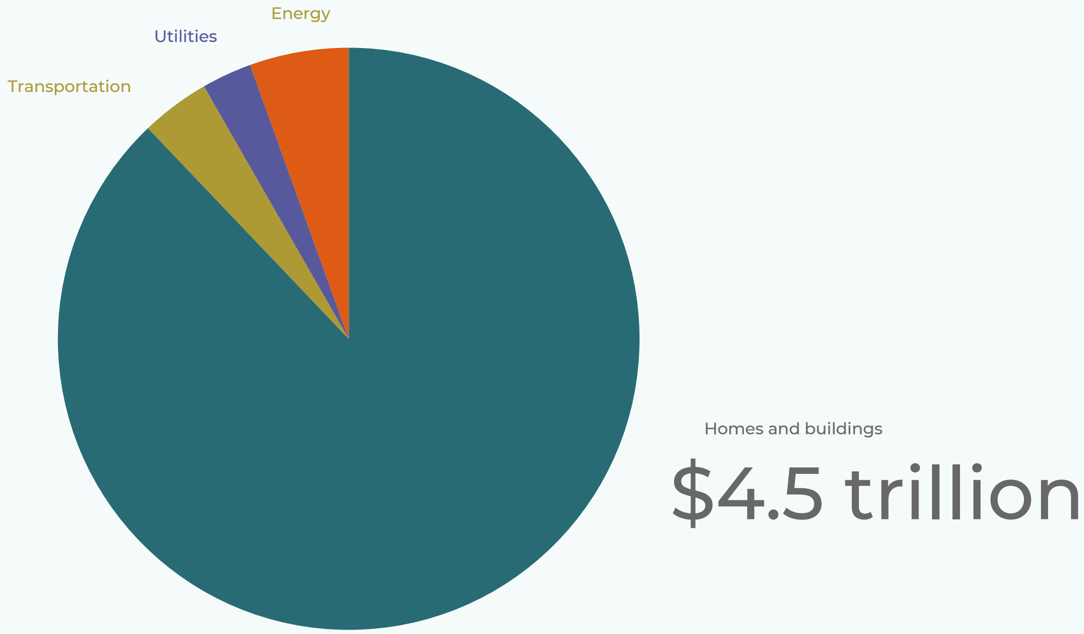
Real estate is a precarious pillar of national wealth

Most of Canada's infrastructure equity is privately owned. In 2019, Canada's private infrastructure was worth $6.1 trillion, amounting to about 13 per cent of national wealth (Figure 2.3) (Statistics Canada, 2021a, 2021b). Privately owned homes and buildings represent almost 85 per cent of this total infrastructure asset value (Statistics Canada, 2021b). In 2016, 63 per cent of people in Canada owned their home. And for most, their home is their largest asset—representing 41 per cent of the wealth of the average household (Statistics Canada, 2020b).

Figure 2.3

Homes and buildings are Canada's most valuable infrastructure

Canada's infrastructure asset stock



Source: Data was obtained from Statistics Canada 2021a; 2020b; 2021b.

Homes and buildings, like public infrastructure, play a crucial role in supporting the health, safety, well-being, and economic productivity of people in Canada. And like public infrastructure, private real estate is highly exposed to damage from climate change. The costs of damage to real estate from weather-related disasters such as floods, ice storms, and wildfires have been growing rapidly over the last few decades (Sawyer et al., 2020). While private insurance and government disaster assistance have historically covered much of this cost, there are growing signs that these backstops are reaching their limit. Insurance premiums are rising and are in danger of becoming unaffordable or unavailable to many home and business owners facing risks of flooding (Shaw & Baumann, 2020). The federal government has reduced its support for financial disaster assistance through major increases in the thresholds of financial damage before provinces and territories can access funding (Davies, 2020). And the 2021 federal budget allocated less than half the amount for disaster assistance the Parliamentary Budget Officer had said was required (PBO, 2016).

The economic implications of escalating climate-related damage to buildings extend well beyond the costs of repair or replacement, whether borne by insurers, governments, or owners. Historically, property values have declined in the short term in areas impacted by weather-related disasters but have typically bounced back after a few years (Bin & Landry, 2013; Kousky et al., 2020; Pfeffer, 2017). However, there is growing evidence from the United States that property values in very high-risk areas are becoming permanently depressed as the frequency of disasters increases and the awareness of climate change risk grows (Beck & Lin, 2020; McAlpine & Porter, 2018). Further, climate change may devalue real estate completely in some areas as sea level rise permanently inundates some coastal homes or as more intense wildfires make it impossible to rebuild communities (Atkin, 2017).

In addition to a loss in real estate asset value, climate change risks and impacts could restrict property use, cause loss of rental income, and increase costs for insurance and mortgages (Chopik, 2019). Insurers facing increasing and unsustainable payouts are already increasing premiums to reflect risk (RATESDOTCA, 2021). Declining property values due to more frequent weather-related damage or perceived climate change risk could also make it more challenging for owners to renew or refinance their mortgages. And although 45 per cent of Canadian homeowners believe they have insurance that will pay for repairs and rebuilding after overland flooding, only about 10 to 15 per cent of households actually have this coverage (Joseph & Alini, 2017; Posadzki, 2017). Many of the homes that are most at risk of flooding cannot be insured, leaving owners financially vulnerable in the event of disaster. Mortgage lenders and banks, as well as investors and guarantors of mortgage-backed securities, could also be financially exposed. In the U.S., the implications of climate risks to real estate have been equated to the subprime mortgages that precipitated the 2008 financial crisis, but with even greater potential for economic loss and social disruption (Becketti & Lacy, 2016). In addition to direct economic losses and impacts on the stability of the financial system, increasing damage to homes and buildings will disrupt families and businesses, interrupt commerce and supply chains, decrease investment in local economies, and decrease regional or even national economic productivity (Boustan et al., 2017).

Damage to Canada's housing stock will also affect individuals who do not own their homes. Thirty-seven per cent of people in Canada live in rental units or band housing (Uppal, 2019). When the homes or buildings these people live in are damaged by flooding or other weather-related disasters, they often have little choice in how or when landlords make repairs, forcing them to live in inadequate and sometimes dangerous conditions (Wesseler, 2021). And evidence from the U.S. suggests that wealthier homeowners move away from neighbourhoods affected by climate impacts like floods, wildfires, and permafrost thaw, and that homes in these areas are often converted to rental units (Ajibade & McBean, 2014). This can worsen existing racial and economic inequities, as renters—who tend to have lower incomes and fewer financial resources and are more likely to belong to racialized communities than homeowners—will disproportionately bear the brunt of climate impacts where they live.

Canada is not accounting for climate risks to infrastructure

Despite evidence that climate risks are growing and will continue to grow, decisions about new infrastructure are failing to take physical climate risks into account. Governments and developers are continuing to build roads, buildings, and critical infrastructure in high-risk areas with materials that are not suited to a warmer and more volatile climate. And banks, investors, and pension funds are continuing to operate portfolios without adequately considering future risk, amplifying exposure to climate hazards and threats. For example, despite development restrictions in some flood zones, analysis we conducted previously found that in the last three years, 10 per cent of building permits in Vancouver were for projects situated on land that, not accounting for climate change, is deemed likely to flood once a century (Clark & Coffman, 2020).

Governments and regulators have made some efforts to protect and strengthen existing infrastructure and to ensure that new infrastructure is built to withstand a changing climate. These measures include providing funding for resilient infrastructure, requiring that climate risks be incorporated into some new infrastructure projects, and encouraging the finance sector to start accounting for and disclosing climate-related financial risks. However, thus far, these efforts have failed to move the needle on climate risk to infrastructure.

The federal government's Disaster Mitigation and Adaptation Fund (DMAF) is currently the largest dedicated pool of infrastructure adaptation and resilience funding in the country. DMAF provides approximately $500 million annually to provinces, territories, Indigenous governments, and municipalities to reinforce and improve existing infrastructure or to build new infrastructure that protects people, critical infrastructure, and essential services (Infrastructure Canada, 2021). However, a recent estimate by the Federation of Canadian Municipalities indicated that $5.3 billion of infrastructure adaptation investment is required annually at the municipal level alone—more than 10 times more than what is available through DMAF (IBC & FCM, 2020).

Through Infrastructure Canada's Climate Lens, the federal government has also attempted to incorporate resilience into new infrastructure projects that receive federal funding. This lens requires applicants to assess climate risks and build adaptation into project design (Infrastructure Canada, 2020). However, Infrastructure Canada provides little guidance on how those Climate Lens assessments should be conducted, leading to sometimes cursory efforts and inconsistent levels of rigour (Li et al., 2019). Furthermore, only a fraction of infrastructure projects are subject to the Climate Lens, which is not applicable to projects that do not receive federal funding, nor is it applicable to private-sector projects or real estate development. Smaller communities and businesses, as well as individuals, often lack the expertise and capacity to assess the climate vulnerability of existing or proposed infrastructure, limiting their ability to conduct Climate Lens-type assessments or to incorporate climate risk in infrastructure planning and maintenance (Engineers Canada, 2016).

Many of the codes and standards that dictate how infrastructure is built in Canada do not provide guidance on designing for climate hazards, and those that do are only starting to be updated to reflect changing future risks like stronger winds, more intense rainfall, and changing snow loads. Canada's national building code will not be fully updated to reflect climate change until 2025, after which provincial and territorial building codes will need a separate process to be brought up to date to mirror the national code, should provincial and territorial governments decide to do so (Arsenault, 2019). Owners, builders, and designers of infrastructure also lack access to information about existing and future climate risks—which keeps them from understanding and addressing risk even if they wanted to. For instance, Canada does not have comprehensive public floodplain maps that show homeowners or infrastructure owners whether their assets are at risk of flooding (Henstra et al., 2019). The limited maps that do exist are frequently outdated, contain insufficient detail, or are inconsistent from one area to the next. And only six per cent of people in Canada who live in flood risk areas are aware that this is the case (Ziolecki et al., 2020).

The physical risks of climate change to infrastructure and assets are also not being evaluated or disclosed in private and public sector finance. Both the Task Force on Financial Disclosures (TCFD) and Canada's Expert Panel on Sustainable Finance have recommended that physical climate risks should be disclosed so that they can be priced by markets and factored into financial transactions, yet this has not become mainstream practice in Canada (Government of Canada, 2019; TCFD, 2017). Physical climate risks to residential real estate are not disclosed by home insurers, banks, or other mortgage lenders, nor are they disclosed for mortgage-backed securities. Real estate investment trusts also do not typically look at climate risks to their portfolios or are not disclosing those risks to shareholders. This means that investors have no idea how likely it is that infrastructure, companies, and sectors in which they are invested could lose value because of growing damages from climate change. In some cases, the federal government is even helping owners access capital to buy or build in hazardous locations through mortgage insurance and economic development programs. Governments of all orders are also sending counterproductive price signals that encourage urban development in high-risk areas, for example by continuing to build hospitals and other public services in flood zones (Clark et al., 2021).

Proactive investments can dramatically reduce future costs

Climate change presents a real and present danger to Canada's public and private infrastructure and the vital social and economic services it provides. However, the response to this challenge has thus far failed to match the threat. More must be done to ensure that governments, owners, operators, and investors have the funds, information, and incentives they need to build resilient infrastructure and adapt existing infrastructure to a changing climate.

By examining both the potential costs of climate change to some of Canada's most important infrastructure and the economic benefits of proactive adaptation, we highlight the need and opportunity to do more immediately. And our recommendations point out what policy makers can do right away to create the conditions for smarter decisions that can address the gaps in Canada's infrastructure resilience.

3 OUR APPROACH

Our analysis of the likely impacts and costs of climate change on Canadian infrastructure focuses specifically on the magnitude of key climate change impacts and the resulting costs for roads, railways, homes and buildings, and electricity systems. The modelling included four main steps:

1. We identified climate-sensitive infrastructure categories that will be substantially impacted by a warming climate.
2. We projected future climate conditions and hazards across Canada.
3. We estimated the rate of future infrastructure damage, disruption, and loss of service.
4. We calculated both the economic costs of climate-related damage and the economic benefits of adaptation.

Our analysis was supported by Industrial Economics, which has extensive expertise analyzing the impacts and costs of climate change, including for the World Bank and the U.S. Environmental Protection Agency (EPA). The Industrial Economics team also included Resilient Analytics, which has developed sophisticated models to estimate the impacts and costs of climate change on infrastructure and the benefits of adaptation for the EPA and numerous other governments around the world. Additional information about the analytical approach and detailed results can be found in the technical analysis report here.

Navius Research also provided analytical support for the estimation of changes to electricity demand due to shifts in building heating and cooling needs because of projected changes in climate, as discussed in Section 6. Details on their methodology and results can be found in their technical report here.

Key infrastructure risks: buildings, roads, railways, and electricity systems

Climate change will alter climate-related hazards, threatening infrastructure and compromising infrastructure services. Table 3.1 lists some of the ways that climate change is projected to physically affect infrastructure in Canada, as well as key outcomes of those impacts. However, not all impacts can be quantified and assigned a cost. In some cases, it is not yet possible to project how climate change will affect a particular type of climate hazard that could damage important infrastructure, such as the impacts of ice storms and tornadoes on electricity grids. In other cases, the science and data do not yet exist to model exactly how a climate hazard could affect certain types of infrastructure and services, such as the effects of rising sea levels on ports and waterways. Even when it is possible to model impacts on infrastructure, it is not always possible to calculate the costs of repairing damage or of the loss of infrastructure service, such as the business interruption costs of weather-related power outages.

Table 3.1

Climate change threatens built infrastructure with implications for critical services

Infrastructure	Climate hazard	Physical impacts	Service losses
Electricity systems	▸ Shifts in precipitation ▸ Increase in temperatures ▸ More severe weather (e.g., hail, ice storms, extreme wind, tornadoes) ▸ Larger and more frequent wildfires	▸ Impacts to hydroelectricity generation ▸ Shifts in energy demand ▸ Reduced efficiency of power lines ▸ Downed and damaged power lines ▸ More frequent power outages	▸ Disruption of critical services like healthcare, water delivery, and public transit ▸ Heating or cooling outages ▸ Communication outages
Telecommunications	▸ More severe weather ▸ Increasing permafrost thaw	▸ Damaged equipment and conduits ▸ Power loss and disruption	▸ Temporary loss of internet and cell services ▸ Disruptions to emergency response
Roads and railways	▸ Shifts in avalanche risk ▸ More erosion and landslides ▸ More floods and higher storm surges ▸ Increase in temperatures ▸ Increasing permafrost thaw ▸ More severe weather	▸ Road or rail blockages from snow ▸ Destruction of roads and railways ▸ Road and rail washouts ▸ Damage to road surface and rails ▸ Dangerous driving and travel conditions	▸ Travel disruptions ▸ Delays in movement of essential goods like food and fuel ▸ Increased risk of travel-related accidents ▸ Higher taxes and shipping costs

Infrastructure	Climate hazard	Physical impacts	Service losses
Airports and air travel	▸ More severe weather ▸ Increase in temperatures ▸ Increasing permafrost thaw ▸ More floods and higher storm surges	▸ Dangerous flying conditions ▸ Damage to equipment and facilities ▸ Need for longer runways ▸ Increase in turbulence ▸ Runway damage and impacts to facilities	▸ Travel disruptions ▸ Delays in movement of essential goods (including food) and mail ▸ Reduced air service for some communities ▸ Higher fees and ticket costs
Water and wastewater infrastructure	▸ More floods and higher storm surges ▸ Increasing permafrost thaw ▸ More severe weather	▸ Overwhelmed storm and sewer systems ▸ Potable water contamination ▸ Damage to water treatment facilities ▸ Icing and overflow of storm drains	▸ Interrupted access to drinking water ▸ Local flooding and sewer backups into homes ▸ Higher taxes to cover repairs
Homes and buildings	▸ More floods and higher storm surges ▸ More severe weather ▸ Increasing permafrost thaw ▸ Larger and more frequent wildfires	▸ Flood damage to homes and buildings ▸ Hail, tornado, and wind damage to structures ▸ Damage to foundations and building stability ▸ Fire or smoke damage	▸ Loss or damage to homes and valuable possessions ▸ Increasing insurance premiums ▸ Displacement of neighbourhoods or communities ▸ Dangerous living conditions
Dams and mines	▸ More erosion and landslides ▸ Increasing permafrost thaw ▸ More floods and higher storm surges	▸ Tailing pond and dam failure ▸ Damage to mining equipment ▸ Damage to downstream infrastructure	▸ Higher taxes to cover costs of repairs and cleanup ▸ Damage to local ecosystems ▸ Displacement of neighbourhoods or communities
Marine infrastructure	▸ More floods and higher storm surges ▸ Sea level rise ▸ More severe weather ▸ Fluctuating inland water levels	▸ Disruption to port activities ▸ Damage to pilings and docks ▸ Debris in waterways ▸ Hazardous travel conditions	▸ Increased cost of goods ▸ Delay in delivery of food and other essential goods ▸ Impacts to ferry services

Infrastructure seldom fails in isolation. In many cases, when one infrastructure system is damaged, the impacts domino, knocking out other affected systems (U.K. Committee on Climate Change, 2016). Cities and towns across Canada consist of highly interconnected infrastructure. Stoplights require electricity, emergency services depend on cell towers, airports need a regular supply of fuel brought by truck and rail. Because of these and many other interdependencies, the costs and impacts from an initial event have the potential to cascade. Since we do not model these cascading impacts directly in this report, our results could significantly underestimate the costs and damages of actual climate change impacts.

Because it is not possible or realistic to quantify every climate change impact to infrastructure in Canada, we focussed on key infrastructure impacts for which we could analyze the potential for major costs at a national scale. We undertook a stepwise prioritization process to select the infrastructure and the climate impacts that would be the focus of the analysis. Table 3.2 illustrates the priority infrastructure types, climate hazards, and potential impacts that emerged from the following process:

1. We reviewed how climate hazards in Canada such as floods, heatwaves, overall climate warming, droughts, and blizzards are expected to shift over the century based on existing studies and science.

2. We examined the different ways these changing hazards could impact infrastructure in Canada and the services they provide by drawing on current research about climate-related infrastructure impacts worldwide.

3. We assessed which of the climate hazard-related impacts on infrastructure and infrastructure services would be likely to have the most substantial economic effects for Canada.

4. Finally, we assessed which of these most substantial impacts we could model and value at a national scale for Canada, given the current state of science, data availability, and modelling tools.

Table 3.2

Priority infrastructure impacts for analysis

Infrastructure type	Climate change hazard	Potential impact
Homes and buildings	▸ Increased flooding	▸ More frequent and severe damage
Roads and railways	▸ Rising temperatures and extreme heat ▸ Increased rainfall ▸ Freeze-thaw cycle changes	▸ More frequent and severe damage ▸ Reduced service life, ▸ Transportation system delays
Electricity systems	▸ Rising temperatures and extreme heat ▸ Increased rainfall ▸ Seasonal temperature changes	▸ More frequent and severe damage to transmission ▸ Distribution infrastructure, reduced service life ▸ Changes to electricity demand and demand timing for space heating and cooling

We validated our selection of infrastructure systems by looking at other national climate risk studies, such as the U.S. EPA Climate Impact and Risk Analysis project and the European Union's PESETA economics impact project (Ciscar et al., 2019; EPA, 2020). We found that these studies had largely prioritized the same infrastructure impacts and costs that we independently identified.

The full scope of climate-related infrastructure impacts and costs for Canada will of course be much larger than what we were able to analyze. There will be impacts to other types of infrastructure beyond those we focus on in this report, and there will be other types of impacts for the infrastructure we focus on that we could not quantify—particularly how the loss of infrastructure services affects economic output and the lives and lifestyles of people in Canada (Figure 3.1). However, just the costs and associated impacts we have focussed on are substantial—in the tens of billions of dollars annually—and illustrate both the overall scale of Canada's infrastructure climate risk and the benefits of early and thoughtful investments in adaptation.

Figure 3.1

Known and unknown infrastructure impacts in Canada: the climate costs iceberg

Climate change is increasing the risks of damage and service disruption to infrastructure across Canada. Some of these risks are relatively well understood, and their impacts and costs can be projected. However, many other risks are looming below the waterline—the science and data do not yet exist to fully understand how they will occur, and how severe they might be. And new risks will undoubtedly emerge that have not yet been anticipated. While Canada should strive for better knowledge, the impacts and costs of climate change will never be completely understood. In light of this uncertainty, infrastructure adaptation choices need to build resilience to a wide range of potential futures, and be flexible and adaptive to changing conditions.

RISKS IN CANADA'S PATH

for which we can start to calculate the scale of impact and cost

- Permafrost thaw undermining Northern roads, buildings and airports
- More frequent damage to homes and buildings from floods
- Strain on roads, railways, and electricity grids from more intense heat
- Damage to coastal communities and ports from rising sea levels

CLIMATE IMPACTS WE SUSPECT WILL AFFECT CANADA

but whose scope and scale we don't yet have the tools to understand

- More ice storms and extreme winds that will cause major electricity power outages
- More frequent loss of critical services, such as water supply and telecommunications, that depend on electrical power
- Unpredictable changes in hydropower generation capacity due to shifting precipitation patterns
- Increased wildfire damage to homes, buildings, and critical infrastructure

RISKS THAT MAY HAVE MAJOR IMPACTS

through complex interactions and processes and that are very challenging to predict

- Accelerated decay of building materials from a combination of warmer temperatures, increased rainfall, and higher CO_2 concentrations
- Major losses in real estate and physical asset values, leading to financial system instability
- Public health impacts from disruption to healthcare and food systems
- Cascading failures across interdependent infrastructure systems, causing widespread social and economic disruption

Projecting Canada's future climate

To model the impacts of climate change on infrastructure, we first need to understand what Canada's future climate might look like. Studies of climate change impacts typically draw on global climate models that project future shifts in the climate caused by global greenhouse gas emissions. Climate change models do not give a single picture of the future climate under changing emissions levels but rather a range of possible futures. This is because there are many ways to represent the complexity of the global climate system, as well as the uncertainty about societal choices that determine greenhouse gas emissions yet to come. We used the data from seven different climate models, under two different emissions scenarios, to capture a range of potential future climates in Canada.

We obtained outputs for the seven different climate models from the Canadian Centre for Climate Services.[1] Climate Services provided datasets developed by the Pacific Climate Impacts Consortium, which provides daily projections of temperature and precipitation from 2041 to 2100 on a ten-kilometre-by-ten-kilometre grid for all of Canada (PCIC, 2019). These seven climate models were used for all the impact analyses except the coastal flooding analysis. Because climate models do not directly produce projections of sea level rise, we obtained the most recent low, medium, and high projections of sea level change for Canadian coastlines from Natural Resources Canada to capture coastal flooding uncertainty (James et al., 2021).

For each climate model, we considered two possible emissions scenarios. Our *low-emissions* scenario corresponds with the Representative Concentration Pathway (RCP) 4.5 scenario of the Intergovernmental Panel on Climate Change's (IPCC) fifth assessment report (IPCC, 2014), reflecting global warming that corresponds with

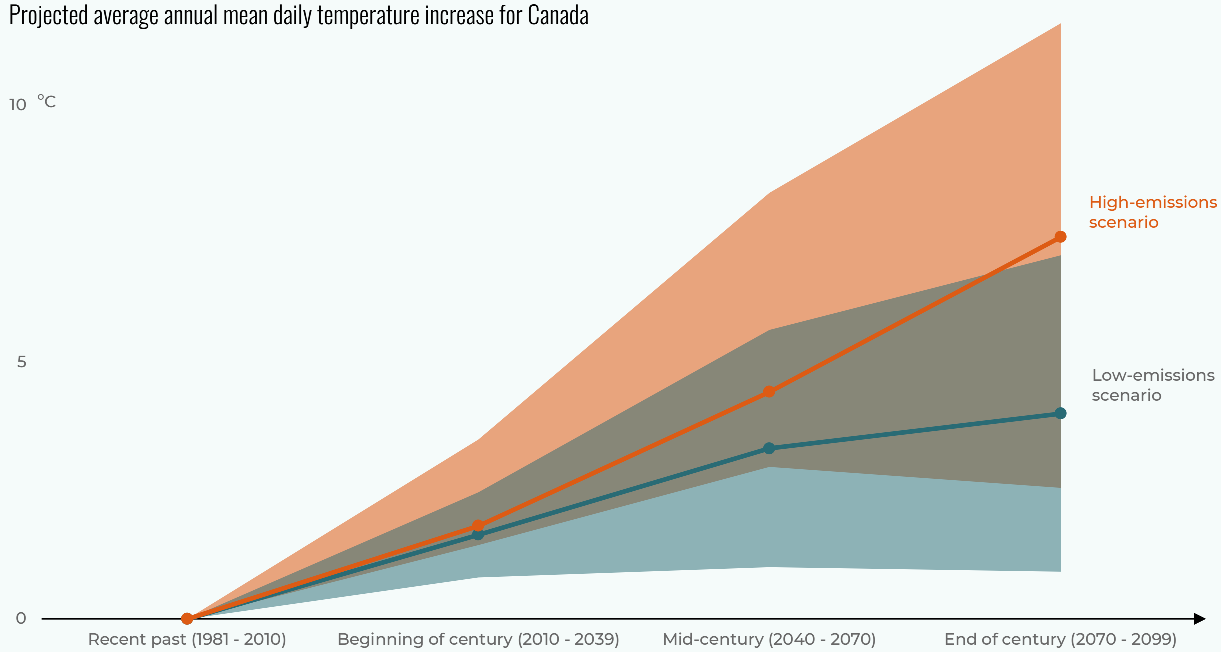
1. The seven General Circulation Models (GCM) used were: CCSM4, GFDL-CM3, GFDL-ESM2M, HadGEM2-AO, HadGEM2-ES, MIROC-ESM-CHEM, and MRI-CGCM3.

greenhouse gas emissions reductions policies announced globally in 2020 (see text box, p. 23). For the climate models we used in our analysis, this emissions scenario is projected to result in an average temperature increase in Canada of 3.3 degrees Celsius by mid-century and 4.0 degrees by end of century compared to the 1981 to 2010 average (Figure 3.2). Our *high-emissions* scenario corresponds with the IPCC RCP 8.5 scenario and reflects a trajectory where current emissions trends continue, and countries take little additional action on emissions reductions and other forms of mitigation. This scenario results in an average temperature change across Canada of about 4.4 degrees Celsius by mid-century and 7.4 degrees by end of century.

Figure 3.2

Temperatures in Canada will rise at twice the global rate

Projected average annual mean daily temperature increase for Canada



Source: Data was obtained from Pacific Climate Impacts Consortium, University of Victoria.

Anticipating climate change impacts in an uncertain future

In 2016, the Paris Agreement committed countries around the world to limiting the global average temperature rise in this century to "well below 2 degrees Celsius, while pursuing efforts to limit the temperature rise to 1.5 degrees." However, at the time our analysis was run in late 2020, the policies and pledges that had been set by governments were only likely to limit warming to around 2.5 degrees (Climate Action Tracker, 2020).

In our analysis, the "low-emissions scenario" is based on the IPCC RCP 4.5 scenario, which also leads to about 2.5 degrees of global warming. (As shown in Figure 3.2, Canadian temperatures are projected to rise at about twice the global average. Therefore, a 2.5 degree average global increase is equivalent to a 4.5 degree average Canadian increase.) In 2020, this scenario represented a realistic lower estimate of future emissions and global warming for us to use.

This does not mean that we are pessimistic about the potential to limit warming to 1.5 or 2 degrees. Since the end of 2020, the world has seen a raft of new commitments from countries pledging to reduce emissions dramatically by 2030 and to achieve net zero by the middle of the century. While these commitments, at the time of writing, are not yet sufficient to meet a 1.5- or 2-degree target, they are an important step in the right direction (UN, 2021).

We continue to believe that our low-emissions scenario is the right one for our analysis, despite these recent developments. At the time our analysis was run there was no climate modelling available simulating a world in which these kinds of net zero commitments are implemented. The modelling done for the IPCC fifth assessment report about 10 years ago had scenarios with more aggressive emissions reductions than RCP 4.5, but actual emissions between then and now have far exceeded what those scenarios forecasted (Carbon Brief, 2019). Our low-emissions scenario based on RCP 4.5 therefore likely provides a more accurate picture of what Canada's climate will look like by the middle of the century. It does a better job of accounting for the impacts of the world's past emissions—that are now baked into Canada's future climate—than more optimistic fifth assessment report scenarios. Our low-emissions scenario results therefore highlight how the benefits to Canada from the world moving aggressively to limit warming to 1.5 or 2 degrees will, at this point, likely not show until after 2050.

Our low-emissions modelling results are still helpful for visualizing the benefits of rapid global transition to net zero. It is likely that our mid-century results for the low emissions scenario approximate an upper limit under which impacts could be contained should a 1.5- to 2-degree world be achieved. And as our results also show, Canada's prospects for minimizing infrastructure impacts through adaptation improve significantly if global warming is kept in check.

For each climate model and concentration pathway combination, we analyzed the impacts of changing climate hazards on infrastructure and the associated costs for two future time horizons: 2041 to 2070, which we refer to as *mid-century,* and 2071 to 2100, which we refer to as *end of the century*. The mid-century analyses provide a sense of medium-term impacts, while the end-of-century analyses show how impacts may accelerate, plateau, or decline towards 2100. For road, rail and electricity transmission and distribution infrastructure we also analyzed a 2010–2029 *beginning-of-century* period to show how costs are already growing. The analysis of 30-year time periods is common in climate change impact assessments, as they average out short-term variability in the climate so that overall changes can be more clearly analyzed (Gillingham et al., 2018).

As a result, for all impacts except coastal flooding, we modelled 28 scenarios of infrastructure impacts—permutations of seven climate models, two emissions scenarios, and two time periods. (For coastal flooding we used the three Natural Resources Canada projections of sea level rise instead of the seven climate models, for a total of 12 permutations.)

As we highlight in previous sections, infrastructure and related services in Canada are already experiencing disruptions and damages due to climate variability beyond the range of scenarios they were built for, and Canada is already experiencing climate changes that will accelerate those impacts. Furthermore, infrastructure decisions made today have major implications for the longer term, because the life-span of most infrastructure is measured in decades. For example, the infrastructure we focussed on in our analysis can last for 20 to 100 years, and gaps between major maintenance—where there may be opportunities to undertake substantial retrofits—can be as long as 20 years (Table 3.3). Therefore, the decisions that are made now about where and how infrastructure is built and maintained will determine how well it—and the services it provides to Canadian society and the national economy—will withstand the impacts of climate change, for decades if not longer.

Table 3.3

Infrastructure lifespan and maintenance cycles

Infrastructure	Major maintenance cycles (years)	Total useful life (years)
Homes and buildings	15–20	50–100
Roads	5–10	20–50
Railways	10–20	50–100
Electricity transmission and distribution	5–10	30–50

Source: (Gibson, 2017)

Costing climate-related infrastructure damages

To estimate the potential damage to infrastructure from key climate hazards, we adapted existing models or developed new ones to estimate rates of infrastructure damage, wear, and required replacement under different climate hazards. Each damage model is explained in more detail in the following sections.

These models require two types of inputs: infrastructure information and climate hazards data. We characterized the amount and location of the infrastructure that was the focus of our analysis using highly detailed digital maps and databases to plot the location of buildings, transportation infrastructure, and electricity transmission and distribution infrastructure across Canada. And we generated projections of future hazards that could present a risk to infrastructure using our detailed national-scale climate models, as discussed above.

We estimated the value of infrastructure damage using data on the costs of repair and replacement from national infrastructure databases, economic studies of infrastructure capital and operating costs, and engineering standards. Wherever possible, we used Canadian data, but where data specific to Canada was not available, we adapted information from other countries—most often from the United States. We isolated for the costs of damage attributable to climate change by estimating costs of infrastructure repair and replacement under a future climate and subtracting the costs of routine repair and replacement corresponding to past climate conditions, represented by the 1971–2000 period.

As described above, the economic impacts of infrastructure damage and failure extend well beyond the costs of repair and replacement. The loss and disruption of services provided by infrastructure result in numerous secondary and indirect impacts. Most of these secondary impacts and costs, such as the costs of supply chain disruption and business interruption, are difficult to model because they are extraordinarily complex. However, we were able to adapt research from the United States to estimate some of the business interruption costs of transportation delays associated with future road and railway system damage and service outages.

The results provide a partial but useful illustration that the indirect costs of loss and disruption of infrastructure services are of at least the same scale as the direct costs of infrastructure damage and repair. As such, the opportunity to avoid costs through adaptation clearly extends well beyond reducing costs of repair and replacement.

In most cases, we present costs or savings in terms of average annual values for the period in question—the mid-century and end-of-century time periods described above. Where analyses required weighing present expenditures against future costs or benefits, we applied a discount rate of three per cent.

For most of our analyses, we assumed that the amount of infrastructure—homes, buildings, roads, railways, and powerlines—would not change over the rest of the century. While we know that more infrastructure will be built to serve communities over the next 80 years, it is difficult to predict what kind and where such infrastructure will be built. For example, the number of roads and rail lines in the future will depend not only on population but on energy, land-use policies, and technological shifts. Assuming current levels of infrastructure in our analysis allows an apples-to-apples comparison of current and potential future costs. However, actual future costs for the infrastructure we focus on in our analysis could be substantially larger than our estimates if the new infrastructure that is built in Canada is similarly vulnerable to climate impacts.

For our analysis of electricity demand, the model we used already accounted for changes in electricity demand due to projected population and economic growth, as well as all currently implemented and announced federal and provincial climate policies that would affect demand into the future. Because these projections were already built into the model, we used them to calculate a new baseline for each time period in our analysis, allowing us to compare the relative contributions of increased demand from population and economic growth and of changing demand from shifting heating and cooling needs due to climate change.

Projecting the benefits of adaptation

For our baseline analyses, we assumed that the owners and operators of assets and infrastructure would not proactively adapt. This means we assumed that, when infrastructure is repaired or replaced as a part of regular asset lifecycles, it is replaced with infrastructure of similar design. For example, if a home is damaged by flooding in our model, we assumed that it would be rebuilt to the same condition as before it was damaged and that it would not be protected against future flooding. We called these scenarios *no adaptation*.

For roads and for electrical transmission and distribution infrastructure, we also considered scenarios in which infrastructure would be repaired or replaced with materials that reflect changes to the climate which occurred since the original infrastructure was built, since design standards for infrastructure are sometimes updated to reflect ongoing shifts in climate (although typically not to anticipate future changes). We called these scenarios *reactive adaptation*.

Finally, we incorporated what we called *proactive adaptation* actions or policies into our impact models to demonstrate the benefits of selected adaptations that could reduce the negative impacts of climate change by anticipating the future climate. In most cases, this involved modelling the benefits of replacing infrastructure with designs and materials that are based on future climate projections, rather than measurements of climate in the recent past. Some cases also involved protecting at-risk infrastructure against future climate hazards or moving or abandoning infrastructure where future climate hazards would create unacceptable levels of risk (Table 3.4). The policies and practices we considered do not cover all adaptation options for the infrastructure impacts we analyze in the report, but they serve to illustrate the benefits of early and proactive investment.

We estimated the net economic benefits of adaptation by assessing the reduction in costs of damage or loss, and then subtracting the cost of implementing the adaptation action. More detail on our adaptation analyses is provided in the following sections.

Table 3.4

Adaptation actions that we analyzed

Infrastructure category	Modelled adaptation measures
Homes and buildings	▸ Coastal flood protection works ▸ Strategic retreat from areas of high inland flood risk
Road and rail infrastructure	▸ Use of more climate-resilient materials when maintaining and replacing roads and railways ▸ Advanced rail temperature sensors to monitor for dangerous, high-heat conditions
Electricity systems	▸ Installation of more resilient transmission and distribution infrastructure (transformers, transmission lines, and poles)

4 IMPACTS ON HOMES AND BUILDINGS

Homes and buildings are central to the well-being of families and the functioning of businesses, governments, and communities. Access to safe, affordable, and culturally appropriate housing is a foundation for health and has been an important tool for the middle class to save and build wealth. Institutional, commercial, and industrial buildings are vital locations for work, trade, public services, and recreation. And real estate is critical to Canada's economy and financial system, as described in the previous section.

In Canada, flooding is the single largest cause of damage and loss to homes and buildings (PBO, 2016). While governments and researchers have not yet conducted comprehensive national analyses of the impact of climate change on flood risk, various regional and local analyses indicate that risks are increasing and will continue to increase. For example, a recent study of flood risk in Halifax estimated that annual flood losses could triple by the end of the century under a scenario of high global greenhouse gas emissions (Thistlethwaite et al., 2018). Without adaptation, studies estimate that annual losses from flooding of coastal properties in Canada could consume half of annual GDP growth by mid-century (Withey et al., 2016). These projections align with recent observations of growing flood risk and cost: between 2005 and 2014, government, insurance, and private costs for flooding exceeded $12 billion (PBO, 2016).

While our analysis focussed on the impacts and costs of flooding, climate change poses other major risks for homes and buildings across Canada. The risks of wildfire, for instance, are increasing across the country—climate change is creating longer wildfire seasons and the potential for larger, more destructive fires, while a growing number of people live and work near fire-prone wildland areas. Prior to 2003, no single wildfire in Canada had cost more than $10 million in losses, but this is changing quickly. The 2016 Fort McMurray wildfire is the costliest weather-related disaster in Canada's history, destroying 2,600 homes and causing insured losses of $3.8 billion. Total insured losses from wildfire between 2003 and 2017 were almost $5 billion (Tamm & Klose, 2019).

And climate change is likely to increase the frequency and intensity of other kinds of extreme weather that already cause major damage to homes and buildings, including thunderstorms, high winds, hail, and hurricanes and tropical storms (Brown et al., 2021).

Our analysis focuses primarily on direct physical damages. However, floods and other weather-related disasters entail many other costs for affected communities and people. These include the costs of disaster response and cleanup, mental health impacts, lost work time, business losses, and economic disruption (Clark et al., 2021). While the tools and data don't yet exist to quantify those costs in our analysis, growing evidence suggests that the indirect economic and social costs of weather-related disasters and climate change impacts could be as high as, and longer lasting than, the direct costs of physical damage (Deloitte, 2016; Hetherington et al., 2018; Rao, 2020). For this reason, our results should be seen as a conservative, lower-bound estimate of potential flood costs.

Modelling approach for homes and buildings

To model potential impacts of climate change on the risk of flooding for homes and buildings, we developed two unique models—one for inland flooding and one for coastal flooding.

Our coastal flooding model uses U.S. flood damage data from the National Coastal Property Model to provide a relationship between sea level rise and damage, as there is no equivalent data available for Canada (Lorie et al., 2020). To estimate the magnitude of damage and the property values of damaged buildings, we used home and building maps from Microsoft's open building footprint data for Canada and property values from the 2016 Census (Boehlert et al., 2021; Microsoft, 2019).

We identified representative U.S. areas that have similarities in location and development patterns to the coastal study areas of Canada. Using Natural Resources Canada estimates of sea level rise, we then estimated future sea levels and storm surge heights for our study areas. Using relationships between flooding depth and damage from the U.S. and Canadian data on building locations and property values, we estimated the total costs of damage along Canada's most populated coasts—the southern coasts of British Columbia and Quebec, and all coasts in New Brunswick, Nova Scotia, and Prince Edward Island. While populated areas of Newfoundland and Labrador, the Northwest Territories, Nunavut, and the northern coasts of Quebec and B.C. are also at risk of current or future coastal flooding, we did not include them because they represent only a small fraction of total homes and buildings at risk, and their sparse distribution would have required a large modelling effort. We also did not analyze the potential for coastal flooding in the Great Lakes because there is still significant uncertainty about how climate change may impact water levels in these lakes (Delaney & Milner, 2019).

Our inland flooding analysis uses flood risk modelling from JBA Risk Management, a private risk analytics firm (JBA Risk Management, 2020). We chose to use the JBA data because many regions across Canada are not covered by government flood risk maps, and therefore we could not rely on those maps to conduct national-scale analysis. This follows practices of the insurance industry and flood risk researchers who also use data such as the JBA mapping—which is available for purchase—to evaluate flood risk in the absence of more detailed and accurate government flood maps. JBA models fluvial flooding (flooding from rivers and streams) and pluvial flooding (local flooding of streets and buildings from overwhelmed urban drainage systems) across all of Canada and estimates both how often different areas will flood as well as the expected average annual damage costs for affected buildings. While private risk mapping such as the JBA data is somewhat less accurate than detailed government flood risk maps, in the absence of that mapping for many areas it provides invaluable insights into Canada's large-scale flood risk.

To establish a baseline against which to compare future projected damages, our modelling first estimated current flood damages using the JBA mapping. We then used our detailed climate projections to estimate how frequently the extreme rainfall events that cause flooding would occur in future. Based on those findings, we estimated increases in flood damage costs by scaling up the JBA estimates of current annual damages according to these increases in flood frequency.

We also examined the benefits of adaptation in the face of both coastal and inland flooding. For coastal flooding, our model simulated the benefits of implementing coastal protection measures. These included sea wall installation, the raising of vulnerable structures, or beach nourishment (supplementing sand and stone on beaches to absorb the energy of storm surges), depending on which approach was most cost-effective for each portion of coast. We then estimated the reduction in damage costs over a 30-year timeframe in contrast to the cost of the adaptation measures in order to establish an estimate of the net direct benefits. We focussed on these adaptation measures because they are some of the most common approaches used in coastal areas and because we could model their benefits with data and tools. However, there are other types of adaptation measures that we did not examine, such as buying out and removing the homes and buildings at greatest risk of flooding in coastal areas, known as strategic retreat. (We did, however, model strategic retreat for inland flooding.)

For inland flooding, we examined adaptation opportunities for each modelled scenario by costing strategic retreat for a varying number of high-risk homes and buildings. We then estimated the difference between the costs of buying out those properties at market value and the elimination of projected annual damage costs to those homes and buildings to establish an estimate of net direct benefits. While there are several other adaptation actions that can be taken to protect homes and buildings from pluvial and fluvial flooding, including building flood control works like diversion channels and dams, or installing devices in homes to prevent basement sewer backups, the choice of adaptation approach is specific to each location and to the type of flooding. As a result, it was not possible in our analysis to reasonably estimate the type, scale, and cost of the adaptation measures that would be required for the hundreds of thousands of at-risk homes and buildings across the country.

Climate change will increase the costs of flooding

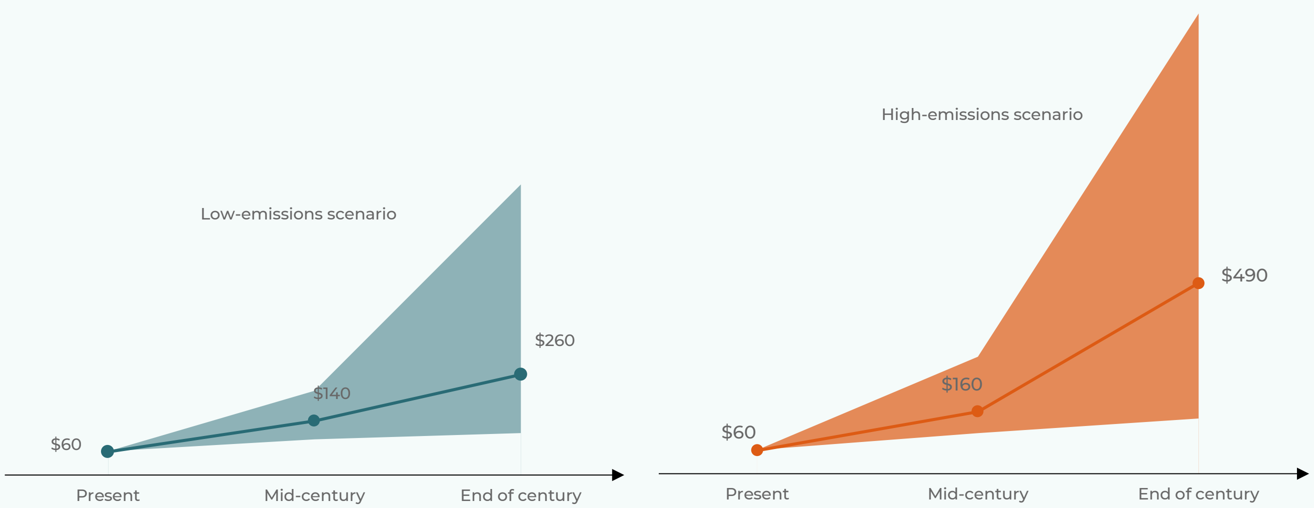
Our analysis finds that the costs of coastal and inland flooding could increase by a factor of almost 10 by the end of the century and that all parts of Canada are at risk.

The coastal flooding analysis shows that annual damages may increase from present levels ofre 4.1). This is a substantial increase, but estimates for the end of the century are even more concerning. While there is still a large amount of uncertainty about how much sea levels will rise, after mid-century the upper range of sea-level-rise projections result in many coastal neighborhoods being permanently flooded—with their value completely destroyed. Other neighbourhoods that have not historically been affected by storm surges could become regularly flooded during major storms. At the high end of the range of projections, annual damages could reach $750 million under a low-emissions scenario and exceed $1.2 billion under a high-emissions scenario for the end of the century—between 12 and 20 times more than current damage costs.

Figure 4.1

Coastal flooding costs will rise sharply through the end of the century

Projected annual costs of coastal flooding in millions of dollars (2019 CAD)



In our figures, each line reflects the median projected values of seven global climate models (GCMs). Shaded areas behind each line capture the range between the maximum GCM value and the minimum GCM value for each scenario. Teal lines and areas represent results under a low-emissions scenario. The orange lines and areas represents a high-emissions scenario.

Our analysis of inland flood risk using the JBA data finds that over 1.6 million of the 11.8 million mapped buildings in Canada—or 14 per cent of the total—are currently located in a 500-year flood risk zone for pluvial or fluvial flooding, meaning that, statistically, they have a 0.2 per cent chance of flooding in any given year. Over 950,000 buildings, or eight per cent, are in a 100-year flood risk zone (a one per cent risk of being flooded each year) and 550,000, or five per cent, are in a 20-year flood risk zone (a five per cent annual risk). At a national scale, our modelling estimates that this existing risk translates into an estimated $1.3 billion in inland flood damages each year, which aligns with other estimates of current annual flood damage in Canada (PBO, 2016).

In analyzing future flood risk, all seven of the climate models that we used projected increases in extreme rainfall. Figure 4.2 shows the changes in frequency that we project for a historic 100-year rainfall event for Canada's largest cities. A 100-year rainfall event typically results in significant flood damage—for context, the 2013 Calgary flood that caused billions of dollars in damage was caused by a 10- to 20-year rainfall event (Teufel et al., 2017). We estimate that what is historically a 100-year rainfall event in the Toronto, Edmonton, or Calgary areas could occur as frequently as every six years by the end of the century under a high-emissions scenario, a 17-fold increase in the annual risk of such an event.

When we applied increases in extreme rainfall driven by climate change to the JBA inland flood modelling, our median estimates showed an increase in damages to $5.7 billion and $6.8 billion by mid-centurey under the low- and high-emissions scenarios respectively, with some climate models producing estimates of up to $8.1 billion in damage annually under high emissions (Figure 4.3). Under the low-emissions scenario, average annual damages do not change much between the middle and end of the century, but under the high-emissions scenario damages could multiply once again, increasing to as much as $12.4 billion annually for the climate models that project the greatest increase in rainfall, a 10-fold increase from current conditions.

It is important to note that our approach only assesses the increase in damage under climate change for buildings the JBA data currently identifies as being at risk of flooding. Our analysis is only able to evaluate the potential increase in flood depth and resulting damage for homes in the zone of existing flood risk. Realistically, the size of the total land area at risk of flooding will increase substantially as extreme rainfall increases, putting even more homes at risk and increasing damages and costs beyond our estimates.

Figure 4.2

A warming climate means more frequent and severe floods in Canadian cities

Increasing likelihood of today's 1-in-100-year rainfall by end of century

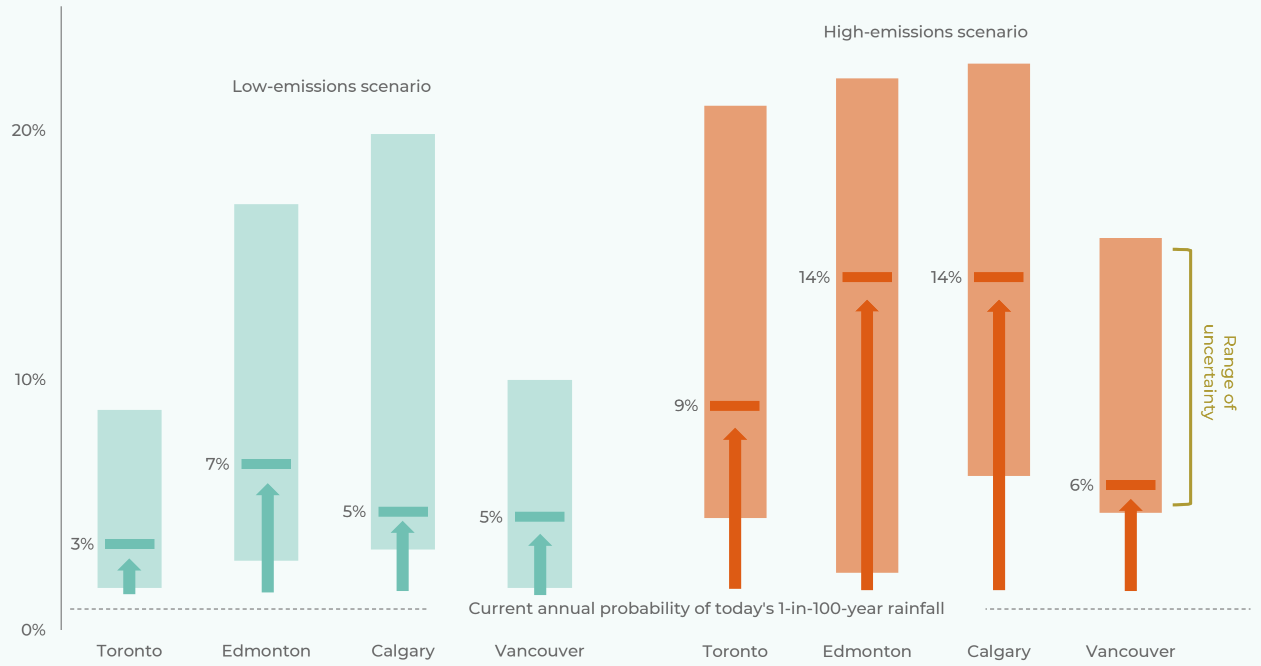
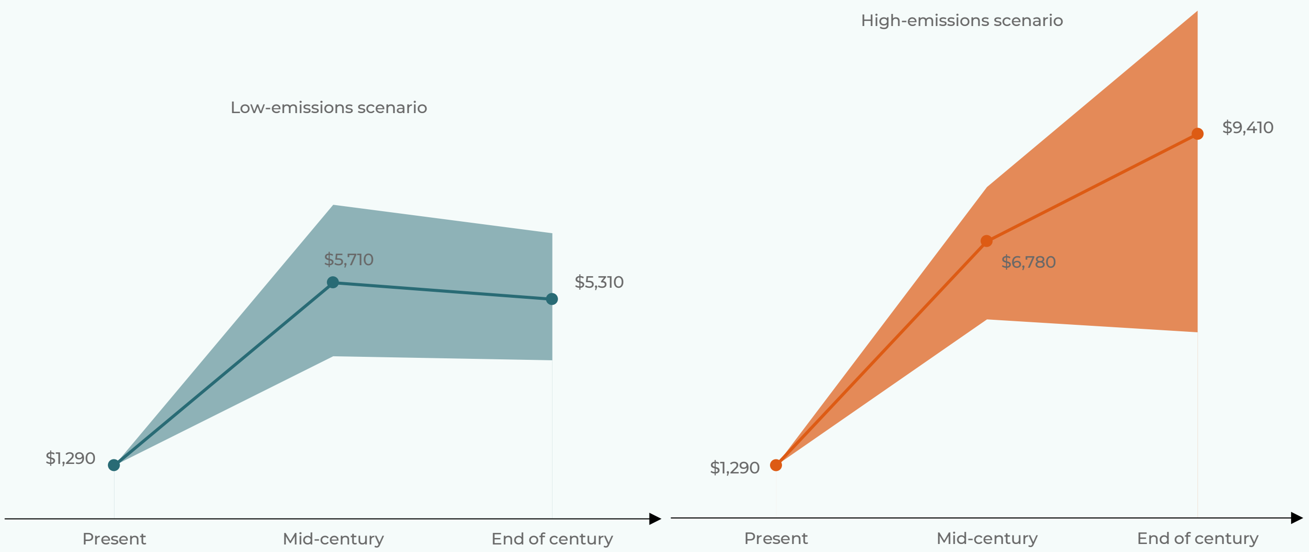


Figure 4.3

Inland flood damage could increase fivefold by mid-century

Projected annual costs of inland flooding in millions of dollars (2019 CAD)



Overlooking flood risk threatens real estate investments in major cities

While hundreds of thousands of homes and buildings across Canada are at risk of flooding, the greatest physical and economic risks are concentrated in some of the country's biggest urban centres. The Vancouver region of B.C. is a hotspot of concentrated risk for coastal flooding. In the Vancouver Metropolitan Area, $30 billion in home and building value sits within one metre of current sea level, and $77 billion within two metres. Our analysis estimates that coastal flood damage costs in the Vancouver area are currently about $30 million annually on average. By the end of the century, damages are projected to be up to $510 million annually under the low-emissions scenario and up to $820 million annually under the high-emissions scenario. Further, our analysis shows that, under the high-emissions scenario, the number of buildings in the area affected by coastal flooding could rise from 44,000 to 75,000 by the end of the century—while average annual damages for each affected property could rise substantially, from about $600 per year to almost $4,400 annually (Table 4.1).

Many of Canada's other major cities are already hotspots of inland flood risk, with large numbers of homes and buildings at risk of both fluvial and pluvial flooding. Our analysis shows that Toronto, Winnipeg, Calgary, Mississauga, Edmonton, and Ottawa are the major urban centres with the greatest current and future flood risk. Our median estimate indicates that the annual cost of flood damage in those cities could increase by a factor

Table 4.1

Climate change will leave more homes at risk of coastal flooding

		Number of homes at risk of storm surge			
		Low-emissions		High-emissions	
Province	Baseline	Mid-century	End of century	Mid-century	End of century
British Columbia	45891	57780	65628	59151	69738
New Brunswick	25332	27698	29016	28048	30186
Nova Scotia	12406	14609	15583	14894	16387
Prince Edward Island	5068	6235	6903	6420	7482
Quebec	6489	46004	47510	46836	50255

of three to 10 by the end of the century, with most of the increase taking place by mid-century (Table 4.2). In Toronto, for example, average flood damage to the more than 145,000 homes at risk could increase from about $700 per year to almost $4,000 in any given year.

Because these cities are home to Canada's most expensive real estate markets, they may be driving asset overvaluation that risks leaving homeowners not just financially underwater but physically flooded out. Studies in the U.S. have shown that flood risk generally is not yet reflected in housing prices, meaning that homes at risk of damage from flooding are priced the same as homes that are not at risk—even when detailed government-produced flood maps clearly show which properties are in flood zones. This leads to overvaluation of homes and real estate that's at risk of flooding, incentives for sellers to avoid disclosing risks in real estate transactions, and an absence of price signals to stop investment in flood-prone areas (Hino & Burke, 2021). Since government-produced flood maps in Canada are substantially more incomplete and outdated than those in the U.S. (see *Murky understanding of flood risk is limiting adaptation*, p. 36), it is likely that flood-prone properties here are at least as overvalued. In hot real estate markets such as Vancouver and Toronto, this means that property buyers—from individual homeowners to commercial real estate investors—are likely paying too much for homes and buildings whose value will drop when their flood risk becomes apparent.

Flood risk in urban areas is not limited to existing homes and buildings—cities are continuing to approve new development in areas already known to be at risk of flooding. As noted earlier, 10 per cent of permits approved for new building in Vancouver between 2017 and 2020—representing $1 billion in value—were in a known 100-year floodplain (Clark & Coffman, 2020). Given that government-produced flood maps do not capture many areas of flood risk, particularly for pluvial flooding, it is likely that even more flood-prone development is being approved in urban areas across Canada than what is officially understood.

At some point, the extent of the flood risk of high-value urban real estate will become known, whether through the efforts of governments to update public flood mapping; of insurers, banks, and institutional investors to understand their exposure to flood risk; or through repeated flood events that cause

Table 4.2

Homes at risk of inland flooding will face more damage more often

Flood damages, millions of dollars (2019 CAD)

CMA Name	Province	Households in flood zone	Baseline	Mid-century, low-emissions	Mid-century, high-emissions	End of century, low-emissions	End of century, high-emissions
Toronto	Ontario	146,798	$99	$557	$592	$548	$566
Winnipeg	Manitoba	250,918	$54	$285	$239	$259	$325
Calgary	Alberta	105,441	$37	$193	$195	$193	$234
Mississauga	Ontario	38,341	$24	$162	$166	$157	$165
Edmonton	Alberta	108,171	$35	$131	$108	$129	$144
Ottawa	Ontario	75,514	$44	$114	$92	$109	$114

certain areas and neighbourhoods to be known as flood-prone. The exact outcome of this awareness cannot be predicted, but economists and regulators in the United States are already warning that regional climate-induced market corrections are a strong possibility in some states (Keys & Mulder, 2020). Insurance providers will likely continue to raise rates or stop providing coverage (Moorcraft, 2020), governments may stop providing disaster assistance funding after multiple occurrences (CBC, 2019), and homeowners left liable may not be able to afford the costs—now completely out-of-pocket—to rebuild. Property values in affected areas could decrease, causing individual home and business owners to lose a major proportion of their wealth, with banks and other lenders left holding the bag on defaulted loans and mortgages. At a large enough scale, this could have national impacts on consumer spending, lending and credit, and productivity and economic growth.

Murky understanding of flood risk is limiting adaptation

Canada has a flood risk information deficit. Unlike other countries, including the United States, Canada does not have a federally led program for mapping flood hazards and risks at a national scale. Provinces and territories set their own standards for flood mapping, which varies considerably in coverage, age, and quality both within and among jurisdictions. A 2014 federal government review of flood mapping in Canada estimated that there was no flood risk information for up to one-third of households in Canada (MMM Group Limited, 2014). The median age of floodplain maps for the areas that are covered was 18 years, meaning that most floodplain mapping does not reflect the current state of climate and land development in the areas that are mapped.

Further, almost all existing flood maps in Canada present only partial information about flood risk. The maps present flood exposure rather than flood vulnerability—meaning that, while they show which areas may be affected by flooding in general, they do not show how deep or how fast-flowing flood waters may be, nor how much damage they would cause or the danger they pose to life and safety.

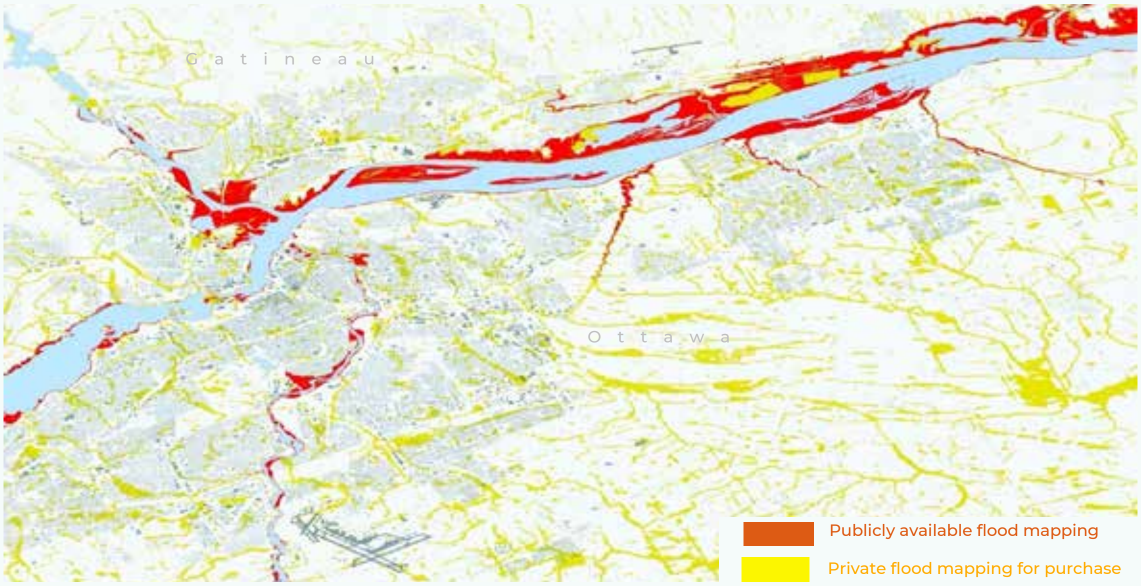
Government-produced flood maps, where they exist, are almost always limited to flooding along coasts (coastal flooding) and beside rivers (fluvial flooding). They rarely, if ever, capture pluvial flooding, the local flash flooding of streets and sewers in urban areas that can also cause major damage. Our analysis suggests pluvial flooding is currently responsible for about 20 per cent of total flood damages across the country. For context, almost all the nearly $1 billion in insured losses from the July 2013 floods in Toronto was the result of pluvial flooding (Mills, 2013).

Our analysis, using the JBA risk analytics data, shows that about 650,000 buildings in Canada are currently at risk of fluvial flooding and about 325,000 buildings are at risk of pluvial flooding for a one-in-100-year or smaller event. If about a third of buildings at fluvial flood risk are not mapped and pluvial flood risk is not mapped at all, as the 2014 federal review suggests, then owners of about 540,000 buildings in Canada have no way of knowing that their properties are at risk of flooding. Figure 4.4 illustrates this gap in Ottawa, Hull, and Gatineau, showing the buildings that are currently identified as being within the 100-year floodplain in government-produced flood mapping and highlighting the additional buildings JBA risk data shows have a 100-year or greater risk of fluvial and pluvial flooding.

Figure 4.4

Risk is seriously underestimated in publicly available flood mapping

1-in-100-year flood risk zones in the National Capital Region



Source: The private flood hazard information was provided by JBA Risk Management Limited. The public flood data was provided by the Mississippi Valley Conservation Authority and the Rideau Valley Conservation Authority. Copyright JBA Risk Management.

Even where flood maps do exist, property owners face significant barriers to identifying their own flood risk. A 2016 survey of 2,300 homeowners across Canada who lived in areas defined as high-risk in flood maps showed that only six per cent were aware that their home was in a flood risk area (Henstra & Thistlethwaite, 2018). Flood mapping prepared by governments is often difficult to obtain and is frequently not included in open data portals. In certain cases, the responsible agencies—such as some Conservation Authorities in Ontario—require payment to release detailed floodplain maps, despite the fact they were developed with public funds. Privately developed flood risk data such as the JBA mapping used for our study is too costly for most individuals, or even small municipalities, to obtain. And these private datasets generally do not provide sufficient detail for homeowners or other building owners to understand the extent or severity of the flood risk on their properties.

Perhaps the most important gap of all is that, apart from a handful of experimental efforts (NRCan, 2018a), flood maps do not incorporate climate change. They reflect flood risk that is based on the historic climate, not the future climate that will be determined by global warming. Therefore, even if Canada's flood maps were complete and up to date, they would not capture ongoing changes to flood risk associated with a shifting climate.

Canada's flood risk information gaps are limiting understanding of the need for action and the measures that could help minimize current and future flood risk. The absence or limited availability of flood maps constrains individuals and communities from reducing the risk to their properties. It also prevents current and future flood risk from being adequately considered in real estate transactions. Insurers and mortgage lenders may similarly be unaware of the risk to many of the properties they are underwriting—and passing on to reinsurers, governments, and taxpayers. Municipal governments may unknowingly permit new development in areas of risk. And governments themselves are in the dark about much of the growing flood risk to existing homes and buildings that could be prevented or reduced through adaptation.

Coastal flood adaptation substantially reduces risk

We used methods developed for the U.S. national coastal property model to assess the potential benefits of proactive coastal flooding adaptation (Lorie et al., 2020). Our analysis estimated which of three adaptation options—sea walls, elevation of buildings at risk, or beach nourishment—was most cost-effective for each segment of Canadian coastline in our analysis, given property values and potential flood exposure. We then re-ran our coastal flood impact and damage model to estimate the net benefit of proactive adaptation, accounting for both the initial costs of adaptation measures and discounted avoided flood damages over the next 30 years.

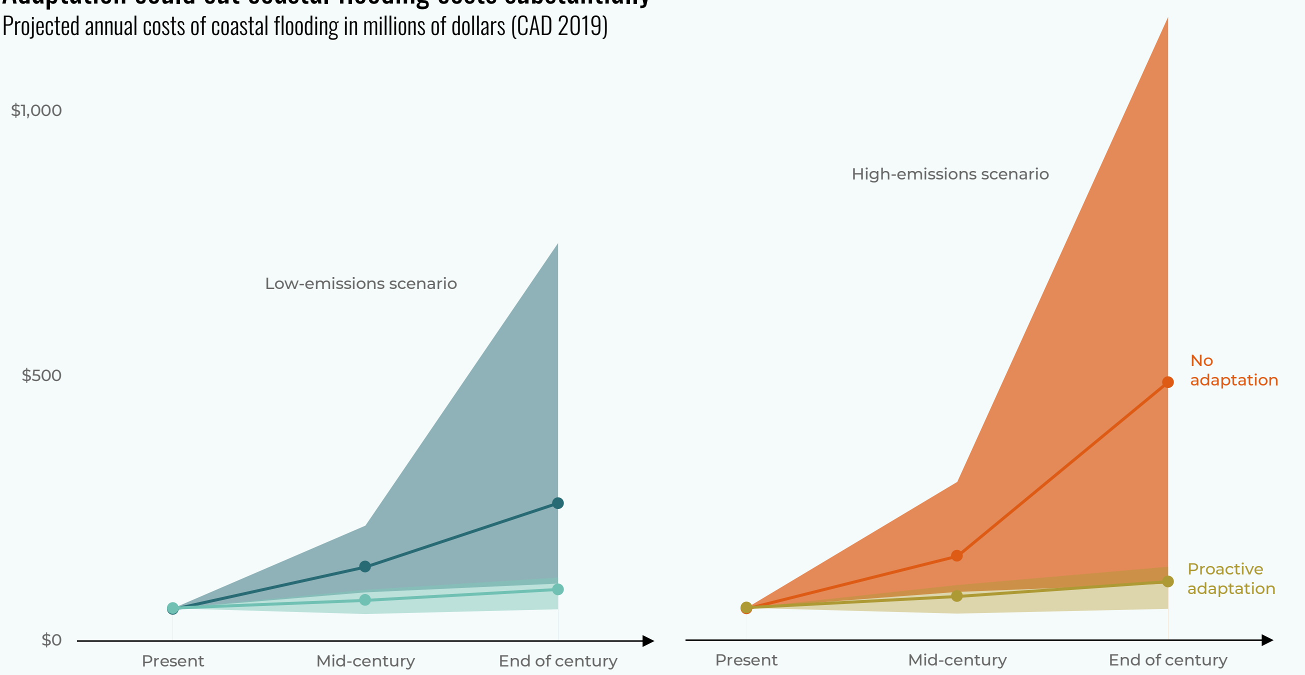
The results (Figure 4.5) show that coastal flood costs can be reduced by 45 to 60 per cent by mid-century, depending on the emissions scenario. By the end of the century, cost savings could amount to 45 to 75 per cent, even after accounting for the costs of constructing sea walls, raising up buildings, or adding rock and sand to protect coasts. More importantly, our analysis shows that proactive coastal flooding adaptation using combinations of these three measures drastically reduces the worst-case outcomes for damages under the highest sea-level scenarios.

For example, without adaptation, the end-of-century projection for the high-emissions scenario results in estimated costs in British Columbia of

Figure 4.5

Adaptation could cut coastal flooding costs substantially

Projected annual costs of coastal flooding in millions of dollars (CAD 2019)



up to $820 million annually, with nationwide costs of $1.2 billion. Adaptation can reduce the costs of the worst-case scenario to $60 million annually in British Columbia and $120 million nationally—decreases of approximately 90 per cent. While the construction and ongoing maintenance of protective coastal infrastructure will be a massive undertaking, our high-level analysis suggests that the net benefits are well worth the cost.

It is important to note that we considered only three of the most common coastal flood protection measures. There are a variety of other adaptation measures that could be used in some circumstances, such as restoration of coastal wetlands, which could have similar or greater benefits. And our analysis only considered the direct economic benefits of avoided damage and loss—some coastal adaptation actions may also generate additional benefits that are difficult to quantify economically, such as creating public amenities or restoring wildlife habitat (Chausson et al., 2020; ACT, 2020).

Strategic retreat for inland flooding has benefits and challenges

To examine inland flooding adaptation, we modelled the potential outcomes of strategic retreat—the intentional relocation of people and property out of flood-risk areas. Typically, strategic retreat requires publicly funded buyouts of at-risk buildings and properties, after which those buildings may be demolished, and the floodplain returned to a natural state or converted to lower-risk uses such as parks.

To be clear, strategic retreat is not the only adaptation option for reducing inland flood risk. At-risk buildings could also be protected through building large-scale structural defences such as dams, dikes, or natural infrastructure solutions. In some cases, there are measures that home and building owners can take to protect their properties directly, particularly for pluvial flood risk, which can be supported by governments. However, the appropriateness, effectiveness, and costs of these actions are highly dependent on the characteristics of the homes, neighbourhoods, and areas that are at risk. Therefore, it was not possible for us to develop estimates of the costs and benefits of these kinds of actions at a national scale.

Analyzing strategic retreat as a measure to address inland flood risk helps to illustrate how proactive adaptation decisions can reduce costs. It also provides insights on the effectiveness of the measure, given that it is being considered by the federal government as a key element of its long-term strategy for dealing with high-risk properties (PSC, 2020).

We looked at a series of hypothetical scenarios in which governments implement strategic retreat by buying out high-risk properties at market value and found that the projected benefits are substantial in some cases. For example, with strategic retreat involving buyouts of 10 per cent of properties in the neighbourhoods that our analysis determined are in the highest one per cent for flood risk across the country, annual inland flood damages decrease by an average of about 2.2 per cent nationally by end of century for both low- and high-emissions scenarios. This represents a savings of $120 million and $200 million annually under the low- and high-emissions scenarios, respectively (Table 4.3). At market value, the buyouts of these approximately 7,500 properties would cost almost $1.9 billion. The discounted net present value of the investment would be about $1.9 billion for the high-emissions scenario and $540 million for the low-emissions scenario—a significant net economic benefit in both cases.

However, these returns diminish quickly if buyouts are extended to lower-risk neighbourhoods. Strategic retreat for neighbourhoods in the highest two per cent risk category—instead of the highest one per cent as described above—delivers a net economic benefit under the high-emissions scenario, but a negative benefit under low emissions. And net benefits quickly disappear for both high- and low- emissions scenarios thereafter.

Table 4.3

Strategic retreat offers benefit but with diminishing returns

Values in millions of dollars (2019 CAD)

Neighbourhood risk percentile	Buyout cost	Annual avoided damages (end of century)		Net present value	
		Low-emissions scenario	High-emissions scenario	Low-emissions scenario	High-emissions scenario
Top 1%	1,900	120	200	500	1,900
Top 2%	4,200	180	290	-600	1,500
Top 5%	10,500	270	440	-5,400	-1,900
Top 10%	22,600	350	580	-15,800	-11,300

Our results suggest that strategic retreat is a solution best applied to the highest-risk properties. However, strategic retreat need not necessarily have a positive net present value in cost-benefit analysis to be a viable option. It may still deliver greater economic value compared to other forms of flood adaptation that have extremely high upfront costs, such as the construction of dams, dikes, and flood diversions. Strategic retreat has a significant advantage compared to structural defences in that it is a permanent solution and requires no ongoing operations or maintenance. Further, flood damage carries other costs such as those for emergency response and the long-term impacts to the physical and mental health of those affected, and strategic retreat has other benefits associated with converting flood-prone land to natural or public uses (French et al., 2019).

However, relocating families and neighbourhoods can have long-term impacts on individual and community well-being that are not captured in conventional cost-benefit analysis. In particular, strategic retreat proposals require significant consideration of equity implications as well as meaningful consultation, considering that Indigenous Peoples, other racialized communities, and people living in lower-income neighbourhoods at risk of flooding are often disproportionately disrupted by strategic retreat programs and experience long-term social impacts (Siders, 2018). Co-developing potential strategic retreat options alongside Indigenous rights holders is particularly important in the context of Canada's long history of colonization, forced removal, and relocation—which, in many cases, saw Indigenous Peoples forcibly removed from higher-value or less-risk-prone areas and relocated to areas that are more exposed to flooding and other climate-related risk—and to ensure recognition of Indigenous land, resource, and treaty rights. Strategic retreat plans will therefore need to evaluate less tangible societal considerations alongside more quantifiable considerations like economic costs and benefits and returns over time to determine the most appropriate adaptation solution.

Our analysis of strategic retreat also illustrates the much larger scale of the challenge of inland flood adaptation. While coastal flood adaptation can be managed effectively in a relatively small proportion of Canada's coastlines where risks are concentrated, inland flooding risk affects a much larger number of properties that are dispersed throughout the country. Solutions for inland flooding adaptation will require combinations of strategic retreat, major structural measures, measures implemented by owners, and financial supports such as new insurance tools, all designed specifically for and by affected neighbourhoods and communities across the country.

5 IMPACTS ON ROADS AND RAILWAYS

Roads and railways are essential to Canada's society and economy. People across Canada depend on road and railway networks to access healthcare, groceries, jobs, and schools; for essential travel as well as leisure and vacation time; and to meet family, friends, and colleagues. Businesses and the economy also rely on roads and rail to move goods and services across the country efficiently. Approximately 750 million tonnes of freight were transported on Canada's roads and 330 million tonnes of freight were transported on railways in 2018, with trains alone helping move about $175 billion in goods to export (Statistics Canada, 2021c). In 2017, the total value of goods moved on roads in Canada was over $2.2 trillion (Statistics Canada, 2017).

A warming and increasingly volatile climate over the coming decades will increase the stress on Canada's roads and railways and reduce their reliability and level of service. Our analysis of roads focusses on the impacts of rising heat, increasing rainfall, and changing freeze-thaw patterns on pavement, which can cause damage and premature deterioration. Our analysis of railways focusses on the impacts of increasing summer temperatures that can cause rails to kink and deform, forcing operators to slow or stop trains because of the potential for derailments.

There are other important climate-related risks to roads and railways, however, that we could not include in our analysis, such as the impacts of flooding, which can wash out roads, railways, bridges, and culverts. The 2013 flood in Alberta destroyed 1,000 kilometres of roads and washed out hundreds of culverts and bridges (CCA, 2019; Palko & Lemmen, 2017). Intense rainfall can also lead to landslides on roads or tracks, such as the 2019 event that caused delays and cancelled shipments on the Edmonton-Jasper segment of the Canadian National Railway, one of CN's busiest network areas (CN, 2021). High winds, heavy precipitation, and freezing rain can damage traffic signals and make travel more hazardous (Palko & Lemmen, 2017). Even higher relative humidity and increased carbon concentrations in the atmosphere can increase the risk of deterioration of bridges (Nasr et al., 2019). However, it is not currently possible to model and estimate the costs of any of these impacts with confidence. As with our analysis of impacts to homes and buildings and electrical infrastructure, the results of our analysis here reflect a lower bound of the range of potential impacts and costs.

Growing rates of damage to roads and railways could substantially increase the cost of maintenance. For example, Canada's 2.8 million kilometres of roads already cost federal, provincial, territorial, Indigenous, and municipal governments approximately $20 billion per year to maintain (Statistics Canada, 2021a), so even moderate increases in damage and degradation could result in major costs.

More frequent closures and delays from damage or repair will further reduce the reliability of road and rail networks, with consequences to the lives and livelihoods of those who depend on them, as well as knock-on effects for the economy. Poor road conditions already cost drivers in Canada $3 billion every year in higher vehicle operating costs (CAA, 2021), and traffic congestion in the Greater Toronto and Hamilton Area alone costs up to $11 billion per year in lost time and economic opportunities (Dachis, 2013). Studies from the U.S. show that climate-related road and rail transportation delays could cost between $25 billion and $60 billion over the 21st century (Chinowsky et al., 2019; Neumann, *under review*).

Modelling approach for roads and railways

To estimate climate impacts and costs on roads and railways, we used the Infrastructure Planning Support System, a tool used widely around the world for analysis of climate change impacts to infrastructure, including for the U.S. Environmental Protection Agency's National Climate Assessments (Resilient Analytics, 2021). Using detailed mapping of Canada's road and rail networks data from DMTI Spatial and Natural Resources Canada (DMTI-Lightbox, 2020; Boehlert, et al. 2021) and applying future climate projections from the seven climate models, we used the Infrastructure Planning Support System to analyze the physical impacts and associated costs of key change climate hazards on Canada's roads and railways (Table 5.1). As discussed in Section 3, for the purposes of our analysis we assumed that the total length and type of roads remained constant over the remainder of the century.

For paved roads, rising temperatures and warmer summers mean the maximum temperatures that binders in the asphalt are designed for will be exceeded more frequently, leading to rutting and premature aging that makes pavement more brittle and prone to cracking. This deterioration creates poor road conditions and increases the frequency with which resurfacing is required. Increased precipitation may also cause rutting, while changing freeze-thaw cycles can alter the amount of subsurface shifting and heaving, leading to bumps and potholes. On unpaved roads, increasing precipitation is a significant concern because it can lead to increased erosion and make road travel more difficult or impossible.

Table 5.1

Climate-related damages, costs, and adaptation scenarios for road and rail infrastructure

Infrastructure type	Stressor	Damage sources	Outcomes without adaptation	Adaptation scenario
Paved roads	Temperature	Surface degradation and increased roughness due to thermal cracking and rutting	Increased maintenance and repair costs to maintain level of service; delays	Alter asphalt mix to include binder with appropriate temperature performance
	Precipitation	Erosion of base and sub-base due to infiltration; increased cracking		Modify binder/sealant and increase base layer depth
	Freeze-thaw	Base layer degradation due to soil heaving; increased surface damage from settling and movement		Modify design to increase surface density and reduce infiltration
Unpaved roads	Precipitation	Surface erosion and rutting	Increased maintenance and repair costs to maintain level of service; delays	Increase base material depth to increase strength and drainage
Rail lines	Temperature	Track expansion and buckling during heat events	Increased repair costs; blanket speed orders and widespread delays	Install track temperature sensors to target speed orders

The total cost of damage to roads and railways is not limited to the costs of repair and replacement. It also includes the costs of reductions in service levels. Repair and reconstruction of roads create traffic jams and bottlenecks, slowing travel times and affecting the flow of people, resources, and goods. When temperatures increase substantially, the risks of track buckling and train derailment are so severe that railway operators typically reduce the speed of trains or even stop traffic completely when temperature-related buckling is a risk, dramatically reducing overall rail traffic and freight volumes. These delays already cost businesses and the economy hundreds of millions of dollars annually (Johnson, 2018), and could grow significantly under climate change.

Using methods developed in the United States, we examined delay costs associated with poorer road conditions, increasing travel times, and freight transport delays caused by reduced travel speeds (Boehlert et al., 2021). We calculated delay costs to passengers based on the value of travel time savings, and we also calculated the costs of freight delay borne by shippers and truckers (Boehlert et al., 2021; National Academies of Sciences, Engineering, and Medicine, 2016). Delays will also impact businesses and economic productivity through supply chain interruptions, with costs that are likely to be much larger than the direct costs borne by shippers. However, the tools and data were not available to develop estimates of these additional costs.

To calculate delay costs associated with speed orders on railways, we used the Infrastructure Planning Support System to model the reduction in travel speed that more frequent heat-related speed orders would cause throughout Canada's rail networks. We then estimated the costs of delay to both freight and passenger travel based on current levels of railway network traffic. Costs to passengers include impacts to leisure and work-related travel, while freight costs include costs to rail owners and operators incurred from delays due to speed reduction orders (Boehlert et al., 2021; Chinowsky et al., 2019). Again, we were not able to model costs to other business and sectors whose supply chains rely on rail shipments. These costs would likely be substantially higher than the costs borne by rail passengers and operators alone.

Roads built to current standards are a future liability

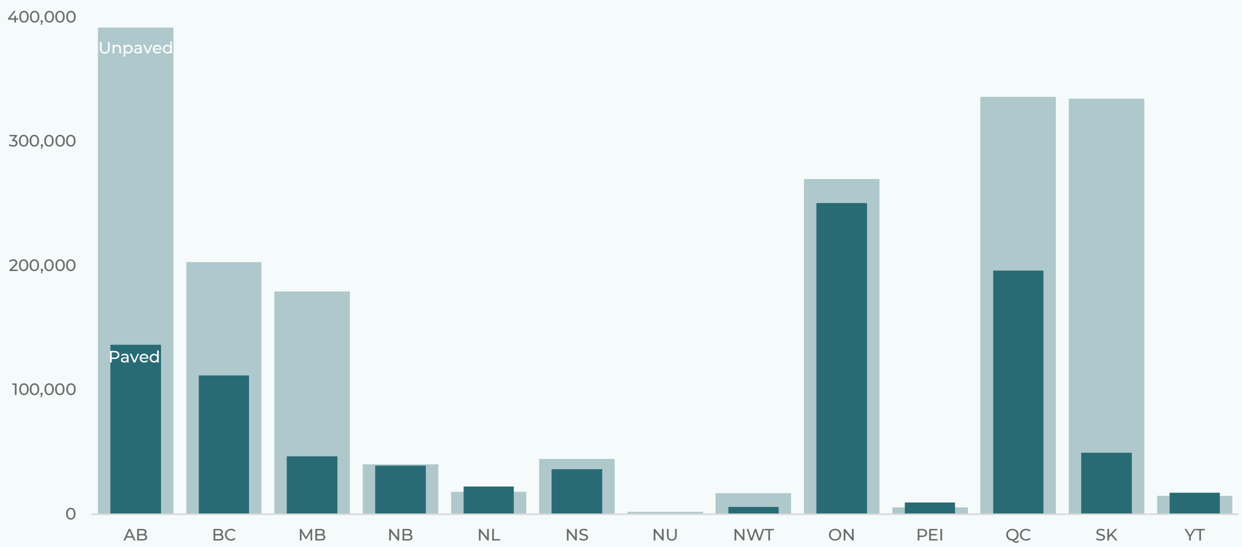
Road systems are the single most valuable publicly owned infrastructure assets in Canada—the nearly 2.8 million kilometres of roads and highways have a value of $142 billion (Statistics Canada, 2021a). With relatively short lifespans, roads require significant annual investments by all levels of governments for maintenance and replacement, as do bridges, culverts, and other related infrastructure. Between 2016 and 2020, federal, provincial, territorial, Indigenous, and municipal governments invested an average of $20.2 billion annually in capital and operating costs in the national road network (Statistics Canada, 2021a).

Our analysis indicates that increasing temperatures and precipitation in Canada will accelerate

Figure 5.1

Canada has millions of kilometres of paved and unpaved roads

Road lane kilometres across Canada



Source: Data was obtained from Statistics Canada, 2018.

the wear and tear on roads. Our median estimates of the annual costs of repair and replacement for the low-emissions scenario are $2.3 billion by mid-century and $3.1 billion by end of century. Our high-emissions median cost estimates are substantially higher, at $3.4 billion and $7.7 billion annually for mid-century and end of century (Figure 5.2). Notably, the range of potential costs rises under the high-emissions scenario by end of century as the estimates for the climate models showing the most dramatic warming for Canada indicate that costs could approach $12.6 billion annually.

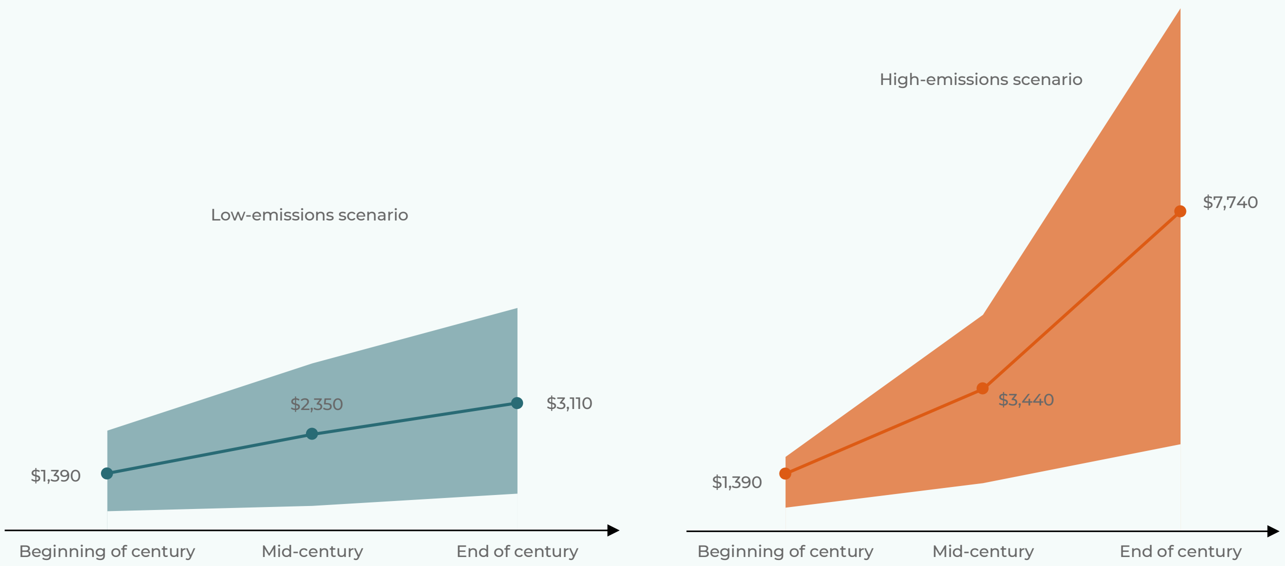
Road damage due to rising temperatures and extreme heat is by far the costliest of climate impacts modelled in our analysis. Across the scenarios we modelled, temperature-related damage represents 87 per cent of total climate-induced damage to roads across Canada, with the impacts of increasing precipitation making up most of the remainder. We found that warming conditions may result in less freeze-thaw damage in many areas as the climate changes, but any economic benefits are far outweighed by the costs of damage from higher temperatures and increased precipitation.

Alberta, Quebec, and Ontario will bear the largest overall costs as the regions with the most extensive road networks (Figure 5.3). As early as mid-century, damage induced by climate change will cost those provinces hundreds of millions more to maintain their road networks, under the lower-emissions scenario. Costs relative to the size of provincial and territorial road networks depend on the proportion of paved and unpaved roads, as paved roads are much more expensive to build and maintain. For example, the fact that P.E.I. has the highest proportion of paved roads to unpaved roads of any province or territory drives high costs

Figure 5.2

Climate change is increasing road repair and replacement costs

Projected annual costs of road damage in millions of dollars (2019 CAD)



relative to the size of that province's road network (Statistics Canada, 2018).

On average, climate-related impacts could increase typical capital and operating costs of road networks—for which provincial, territorial, and municipal governments are almost exclusively responsible—in many regions by more than 30 per cent by the end of the century in the high-emissions scenario (Figure 5.3). The relative increase will vary regionally, based on both the scale of historic investment in road infrastructure in each province and territory, as well as differential impacts from rising temperatures. In P.E.I., costs could almost double, illustrating how climate change impacts could quickly consume infrastructure funding that is needed for modernization and addressing infrastructure deficits.

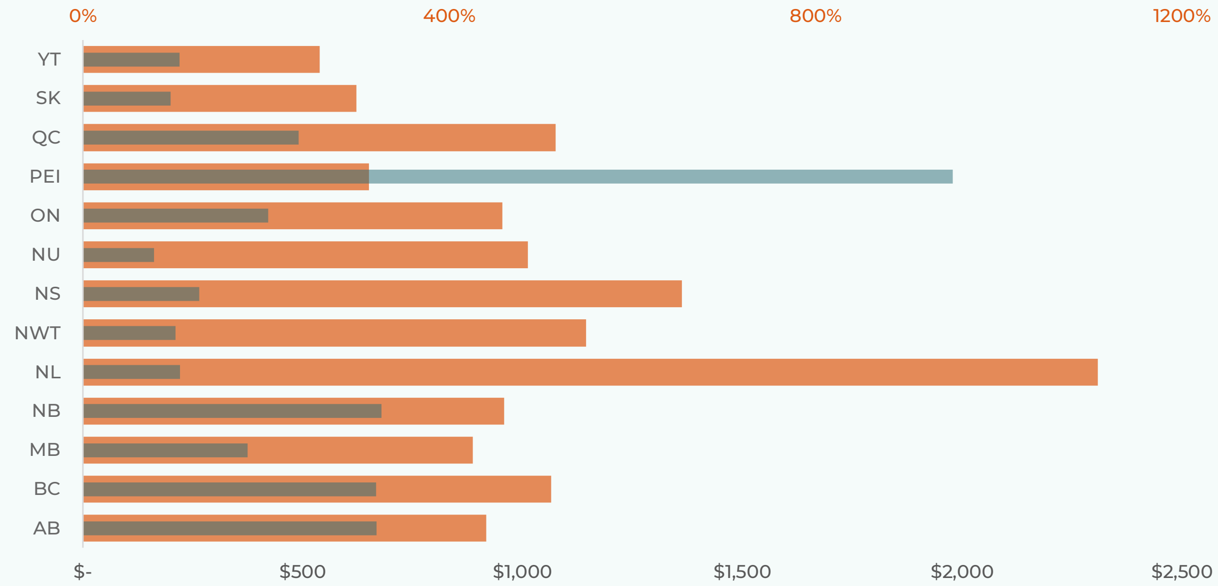
Damage to road and rail infrastructure leads to costly delays

Our analysis shows that the costs of delays and travel disruptions on road and rail systems could be nearly as high as the costs of direct physical damage to the infrastructure itself. For railways, our analysis suggests that damage costs are relatively low, between $1 and $180 million per year depending on the timeframe and emissions scenario (Figure 5.4). Even in the worst case, under high emissions by end of century, these costs are relatively minor, representing less than one per cent of the combined 2019 operating costs of Canadian Pacific and Canadian National (CN, 2021; CP, 2021). However, it is important to note that these are only the costs of repairing buckled rail segments—as

Figure 5.3

The cost of road damage will increase the most where there are more paved roads

Projected annual costs for road damage by millions of dollars (2019 CAD) per land KM and per cent change from present to end of century under a high-emissions scenario



we discuss above, climate change may cause other types of substantial damage to rail networks.

Our delay cost estimates show that even the first-order costs of delays from track buckling and slow or stop orders could outweigh the costs of physical damage by a factor of 10 or more. These costs increase dramatically over the century, reaching a median value of $1 billion annually in a high-emissions scenario by the end of the century (Figure 5.5).

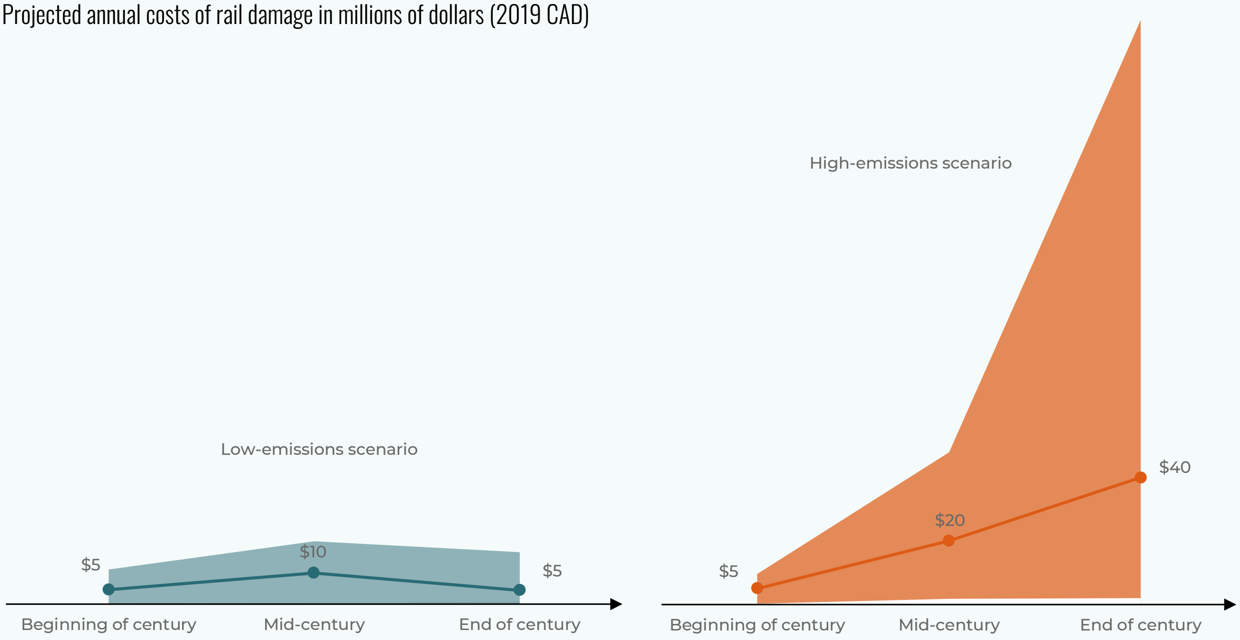
We estimate that the costs of delays for road travel will be of similar magnitude to those for railways, from the hundreds of millions of dollars to over $2 billion annually. As with railways, we project that these costs will increase over the course of the century, particularly under high emissions, although even under low emissions, road delay costs remain substantial. Our estimates of rail delay costs are generally lower than road delay costs, except for the high-emissions, end-of-century scenario—illustrating the potential sensitivity of the rail sector to temperature change above key thresholds.

Combined, delay costs across road and rail networks will be roughly distributed regionally across Canada according to population and economic activity. Large delay costs in Ontario reflect the size of the population, extent of the road network, and high volume of rail traffic. Quebec, B.C., and Alberta experience similar costs in proportion to their population. We estimate that Saskatchewan, despite its smaller population, will

Figure 5.4

Heat increases rail damage costs

Projected annual costs of rail damage in millions of dollars (2019 CAD)



experience delay costs approaching those in B.C. and Alberta because of the volume of rail freight traffic in the province.

Proactive road and railway adaptation can save billions

Of the three types of infrastructure analyzed in this report, road and rail systems have perhaps the most straightforward and cost-effective adaptation opportunities. For roads, we considered proactive measures to increase resilience to future changes in climate that can be incorporated into ongoing maintained or replacement cycles, including:

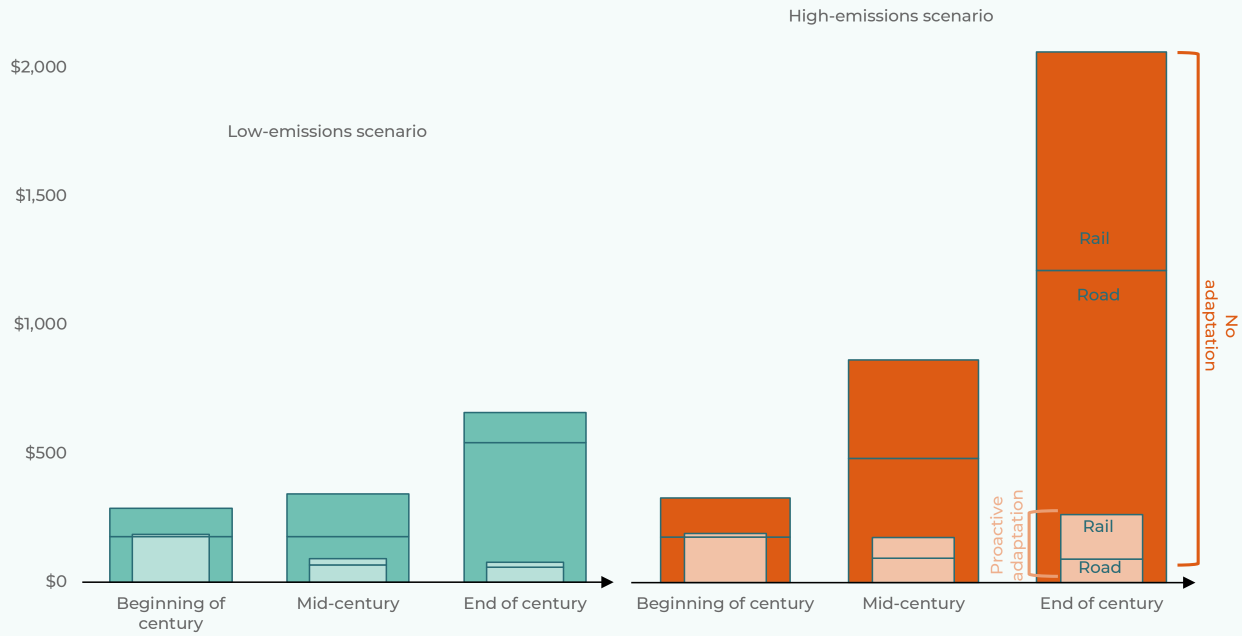
1. Altering asphalt mixes with materials suitable for future summer temperature increases;
2. Modifying asphalt materials and surface sealants to better withstand future increases in precipitation and increasing base layer depth in paved roads for better drainage;
3. Modifying road surface design to increase surface density and reduce infiltration when increases in freeze-thaw frequency are expected;
4. Increasing the base layer depth of unpaved roads to allow for better strength and drainage.

Our analysis shows that, even after accounting for the up-front costs, these proactive measures could reduce net climate-related costs for road repair and replacement by 77 to 84 per cent by mid-century and by 90 to 98 per cent by end of century, depending on the emissions scenario (Figure 5.6). These reductions are median estimates—under some climate scenarios the benefits may be even greater and could result in net cost savings. This

Figure 5.5

Delays add to the already high costs of damage but can be minimized with adaptation

Projected annual road and rail delay costs in millions of dollars (2019 CAD)



means that not only would proactive adaptation eliminate increased costs associated with climate change, but that the future cost of road maintenance and repair could be lower than current expenditures. This reflects the fact that freeze-thaw cycles will become less damaging with a changing climate across most of the country by the end of the century. Therefore, if the impacts of increased temperature and precipitation can be managed through proactive measures, reduced freeze-thaw damage could result in less overall climate-related damage to Canada's road networks and lower costs for operations and maintenance.

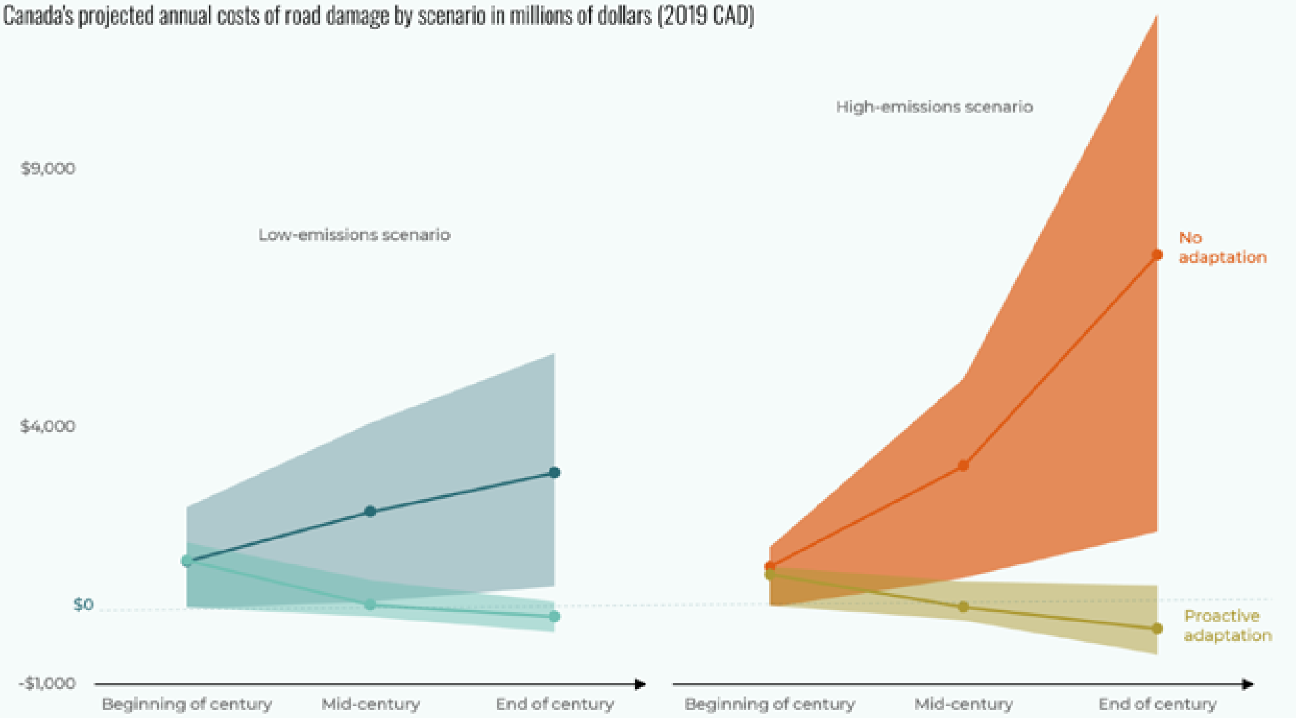
We also estimate that reduced road damage, repairs, and replacement will result in a significant reduction in road delay costs. Our analysis shows that the increase in serviceability of roads with proactive adaptation will reduce delay costs substantially, with the greatest benefit (a 92 per cent reduction in net annual costs) under high emissions and at the end of the century, but with substantial benefits (a 62 per cent reduction) even under low emissions in the mid-century (Figure 5.5).

For railway adaptation, our analysis used the Infrastructure Planning Support System tool to model the benefits of installing track temperature sensors that allow rail operators to implement a more targeted and risk-based approach to speed orders. This technology—an adaptation measure being considered in many parts of the world to address heat impacts (Chinowsky et al., 2019)—allows operators to target speed orders to specific locations based on track temperature instead of blanket speed orders that apply to all rail lines in a region and result in longer delays. We recalculate rail delay costs considering these more targeted orders. Our results show that this form of adaptation can dramatically reduce delay costs by a median of 80 per cent by end of century under the high-emissions scenario.

Figure 5.6

Proactive adaptation will reduce costs of road repair and replacement

Canada's projected annual costs of road damage by scenario in millions of dollars (2019 CAD)



6 IMPACTS ON ELECTRICITY SYSTEMS

Electricity systems are essential to daily life and economic activity across Canada. In addition to powering homes and buildings, virtually every critical service that individuals, communities, and businesses depend on—including hospitals, water treatment systems, grocery stores, airports, telecommunications systems, and many more—require functioning, reliable electricity systems. In Canada, the electricity sector also contributes $34 billion annually to the economy through exports to the United States (IEA, 2020; Statistics Canada, 2020d). When electricity systems go down, even for a short time, industrial production is halted, employees sit idle, data is lost, and power exports may be compromised. And damage to Canada's electrical infrastructure—worth over $235 billion—can mean big expenses for repair and replacement (Statistics Canada, 2021a).

Climate change will damage both the quantity and reliability of electricity distributed to households and businesses across the country. Our analysis focusses on two impacts. The first is accelerated deterioration and loss of function of electricity distribution systems from rising temperatures and increasing precipitation from and the costs of more frequent repair and replacement. The second is the change in patterns of demand for electricity as the climate in Canada gets warmer, reducing the demand for electricity to heat homes and buildings during the winter but increasing loads during summer months as more homes and businesses are driven by unprecedented heat to install air conditioning and use it more often (Navius Research, 2020).

Besides the impacts we focus on in this report, there are many other ways that climate change will impact electricity systems and electrical infrastructure, disrupting life and business in Canada and creating significant costs that we could not model. Electricity systems are vulnerable to extreme wind and ice storms—hazards that are likely to become more frequent in Canada under climate change (Dowling, 2013; Government of B.C., 2019). Canada's most catastrophic experience with such impacts was the Northeast Ice Storm of 1998, which brought down high-voltage transmission lines and damaged transformers, leaving close to half of Quebec's population and parts of Ontario and New Brunswick in the dark for weeks. Costs of damage and economic disruption exceeded $5 billion and reduced national GDP by 0.2 per cent (Lecomte et al., 1998). More recently, in 2018, tornadoes in Ottawa left more than 300,000 residents without power (Crawford, 2018). However, although scientists theorize that ice storms and extreme wind will become more frequent and severe under climate change, global climate models are not currently able to precisely project these shifts (Fant et al., 2020; Klima & Morgan, 2015).

Climate-induced shifts in precipitation patterns will alter the flows of rivers, creating uncertainty in the supply of hydroelectricity, which makes up over 60 per cent of Canada's electrical generation (NRCan, 2021). However, simulating the effects of these changes on hydroelectricity generation in Canada requires complex models of river basins and generating stations that do not yet exist in the public domain. And more frequent and severe floods resulting from changes in rainfall and snowmelt under climate change can also impact electricity systems. Canada has already seen these impacts; in Toronto's 2013 flash floods, for example, flooding of one of the two main electrical substations that feed the city resulted in long-term power outages for over 70,000 residents (Küfeoğlu et al., 2014).

Our analysis focusses on the costs of repairing and replacing damaged infrastructure, which will be substantial given the sheer scale and extent of electrical infrastructure in Canada. Such damage and resulting outages will also have major economic impacts on businesses and economic productivity that we were unable to cost. Estimates put the current cost of electrical outages in Canada—most of which is weather-related—at approximately $12 billion annually, with over $8 billion of this cost incurred during short outages (McMullen, 2018). If climate change increases the number and length of power outages, additional costs could be substantial. Unfortunately, the science and data are not yet in place to model how power outages may shift with climate change.

Modelling approach for electricity infrastructure

To examine the impacts of rising temperatures and increasing precipitation on transmission and distribution infrastructure, we developed an inventory of power lines, transformers, transformer stations, and transmission poles across Canada (Table 6.1). Data on transmission infrastructure (electrical substations and transmission lines) is available from DMTI Spatial, but comprehensive information on distribution infrastructure (distribution transformers, poles, and lines) is not available for Canada. To overcome this gap, we used data from the United States to relate quantity of distribution infrastructure to population density and estimated the location and amount of this distribution infrastructure across regions.

Table 6.1

Canada’s electrical transmission and distribution infrastructure network is massive

*estimated

Province / Territory	Substation transformers	Transmission lines	Distribution transformers*	Distribution lines*	Power poles*
Alberta	542	11,300	676,000	253,000	6,418,000
British Columbia	210	13,100	586,000	135,000	5,486,000
Manitoba	356	9,900	309,000	68,000	2,604,000
New Brunswick	138	5,500	224,000	48,000	1,721,000
Newfoundlnd and Labrador	80	5,900	187,000	39,000	1,338,000
Nova Scotia	246	5,100	209,000	44,000	1,562,000
Ontario	3,238	23,000	1,102,000	260,000	10,850,000
PEI	10	300	146,000	29,000	909,000
Quebec	404	27,600	1,377,000	327,000	13,708,000
Saskatchewan	280	9,200	276,000	60,000	2,260,000
Territories	18	1,400	141,000	28,000	858,000
TOTAL	5,522	112,000	5,230,000	1,289,000	47,713,000

To estimate the impacts and costs of future damage from climate change, we adapted a model used by the U.S. Environmental Protection Agency’s Climate Change Impacts and Risk Analysis program to predict climate change-induced damages and costs to electrical system infrastructure (Fant et al., 2020; EPA, 2020). This model allowed us to analyze and cost the impacts of climate change on key infrastructure components, and to examine the effects of reactive and proactive adaptation choices on damages and costs (Table 6.2).

Table 6.2

Climate damages and adaptations for transmission and distribution infrastructure

Component damage	Description	No adaptation: No consideration of climate change	Reactive adaptation: Replace based on current climate	Proactive adaptation: Design using climate projections
Reduced transformer lifespan (both substation and distribution)	Increases in air temperature shorten the lifespan of large power transformers	Build replacement transformers with the existing design (historical climate)	Build replacement transformers specified to recent climate	Build replacement transformers specified to projected climate (30-year horizon)
Reduced transmission and distribution line capacity	High temperatures on lines cause a reduction in transmission capacity	Build additional transmission lines using existing design	Upgrade ampacity of existing lines based on recent climate	Upgrade ampacity of existing lines using climate projections
Wood pole decay	Increases in precipitation and temperature accelerate the rate of decay at the base of wood poles	Replace decayed poles with new wood poles as needed	Use steel reinforcement as needed based on recent climate	Use steel reinforcement as needed based on climate projections
Change in vegetation management	Changes in climate result in altered vegetation growth, which requires changes in vegetation management	Increase operations and maintenance (no adaptation options)	Increase operations and maintenance (no adaptation options)	Increase operations and maintenance (no adaptation options)

We also examined how rising temperatures will affect future electricity demand in Canada. Summers will get substantially warmer across the country, and since air conditioning already accounts for about a third of electricity use on hot days in warm provinces like Ontario (IESO, 2015), additional demand could increase competition for electricity supply across the country. We modelled shifts in electricity consumption with the Navius Research Inc. Integrated Electricity System Dispatc model, using our climate model projections. Our results include estimates of changes to overall and peak electricity demand across Canada, and estimates of costs of installing the generating capacity to meet this increased demand.

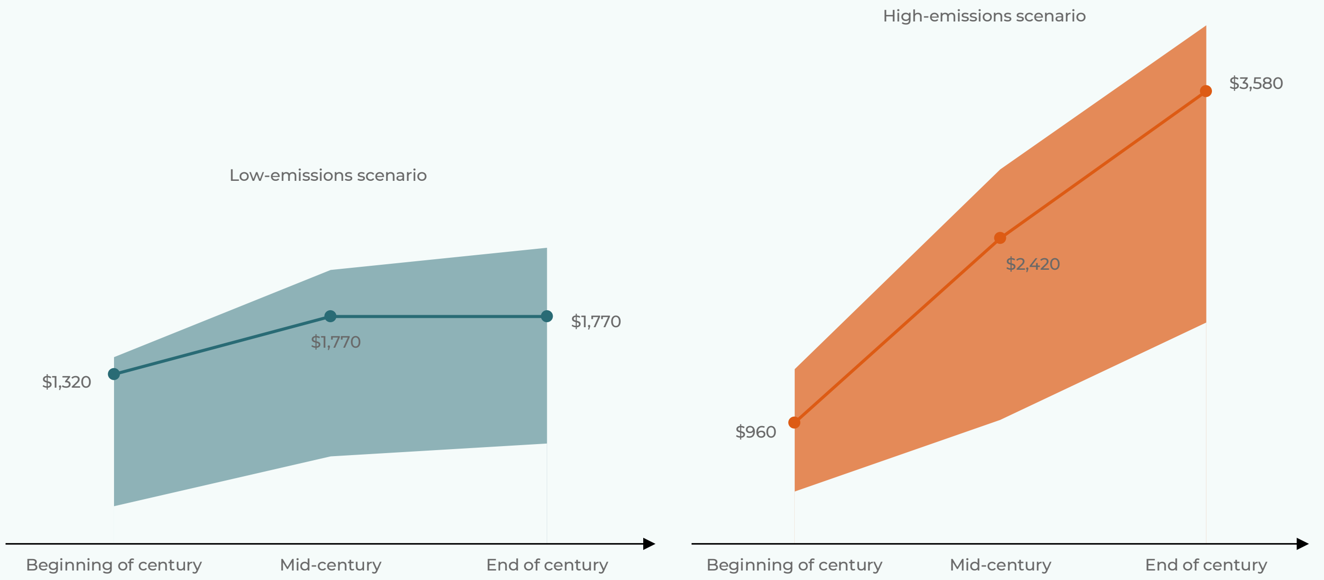
Climate-related damage to electrical infrastructure could cost billions each year

Our results show that if electrical transmission and distribution infrastructure is not adapted to future climate conditions, the median estimate of increased damage for providers is $2.4 billion annually by mid-century and about $3.6 billion annually by the end of the century under a high-emissions scenario (Figure 6.1). Under a low-emissions scenario, costs could still be substantial, with a median estimate of $1.8 billion annually for both mid-century and end of century. Of the five types of electrical

Figure 6.1

More heat and rain will raise costs for maintaining electricity infrastructure

Projected annual costs for transmission and distribution infrastructure in millions of dollars (2019 CAD)



transmission and distribution infrastructure that we modeled, we project that the the costliest impacts—about 75 per cent of the total—will be from premature failure of electrical substation transformers and from the accelerated decay of the tens of millions of wooden utility poles across Canada.

Climate-related impacts also vary geographically, with costs in Ontario and Quebec comprising over half of the national total costs (Table 6.3), reflecting both the size of the population in both provinces and the infrastructure associated with Quebec's vast hydroelectric generation and transmission system. No region will be unaffected, however; per capita costs could be highest in some of Canada's less populous provinces, territories, and regions where more electrical infrastructure is needed to service a widely dispersed population. Rural, remote, and Northern areas require more lines, poles, and transformers to serve each customer and c ould experience higher increases in electricity rates to cover the cost of damage..

Again, some major climate change risks to electrical infrastructure are not reflected in our analysis, including the impacts of potential increases in ice storms and high winds. When data and tools become available to model these impacts, the total costs of climate change impacts could increase substantially. The distribution of costs across different types of infrastructure and different regions could shift as well.

Table 6.3

Costs are highest where the most electrical infrastructure is found—in Ontario, Quebec, and Alberta

Median values in millions of dollars (2019 CAD)

	Low-emissions scenario		High-emissions scenario	
	Mid-century	End of century	Mid-century	End of century
Alberta	$149	$189	$211	$361
British Columbia	$107	$131	$152	$244
Manitoba	$86	$90	$125	$179
New Brunswick	$77	$73	$102	$130
Newfoundland and Labrador	$42	$37	$53	$68
Northwest Territories	$12	$8	$20	$27
Nova Scotia	$56	$51	$72	$90
Nunavut	$12	$8	$20	$27
Ontario	$468	$488	$595	$872
Prince Edward Island	$32	$27	$39	$50
Quebec	$473	$482	$656	$942
Saskatchewan	$61	$71	$94	$142
Yukon	$12	$8	$20	$27

Impacts on reliability, availability, and cost of electricity could threaten net zero transition

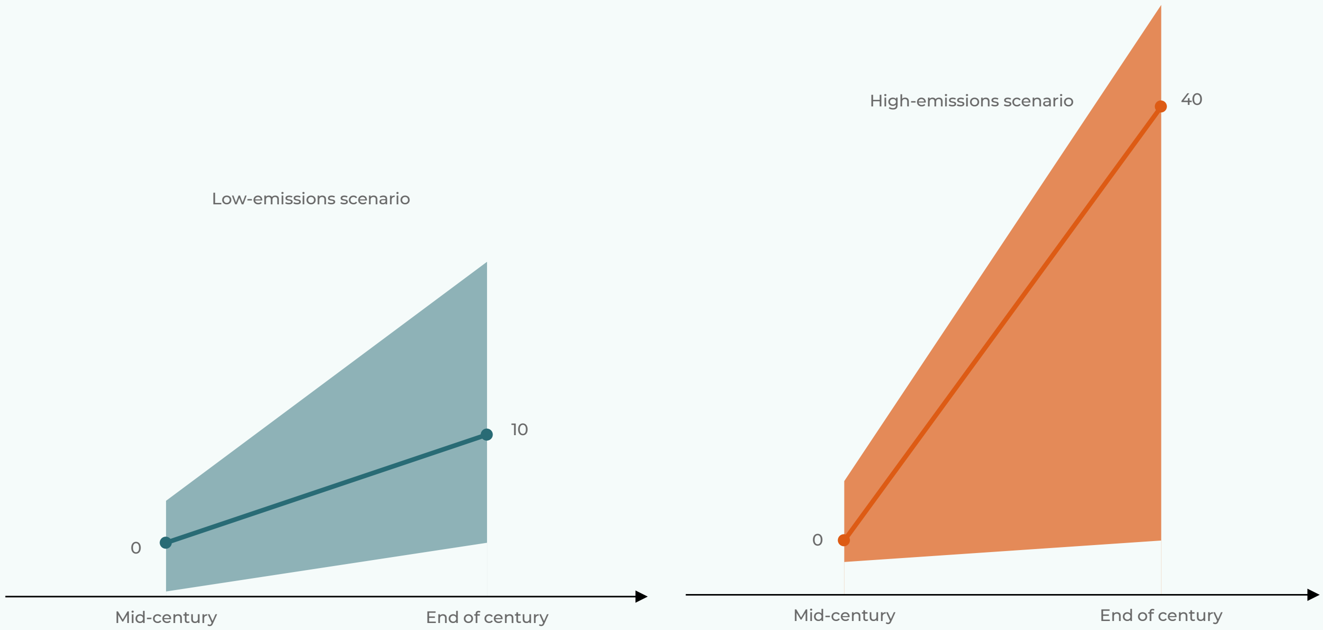
The damages to electrical transmission and distribution infrastructure described above will decrease the reliability of the electricity system as more of those components will fail more often, leading to more frequent outages. We could not estimate the number of these outages in our analysis, or the costs of the business interruption and delay they would create. However, it is certain that those costs will increase dramatically as electricity becomes increasingly essential for power, heating, and mobility needs in Canada's transition to net zero.

A warming climate will itself increase demand for electricity as time goes on. Rising temperatures and increased need for space cooling will lead to a rise in overall and peak electrical demand in the coming decades. We estimate that electricity demand from home heating will decrease due to lower space heating requirements, but that the increase in demand for air conditioning in summer

Figure 6.2

A hotter climate will drive up electricity demand for heating and cooling

Projected annual electricity demand (TWh) relative to a scenario with no climate change



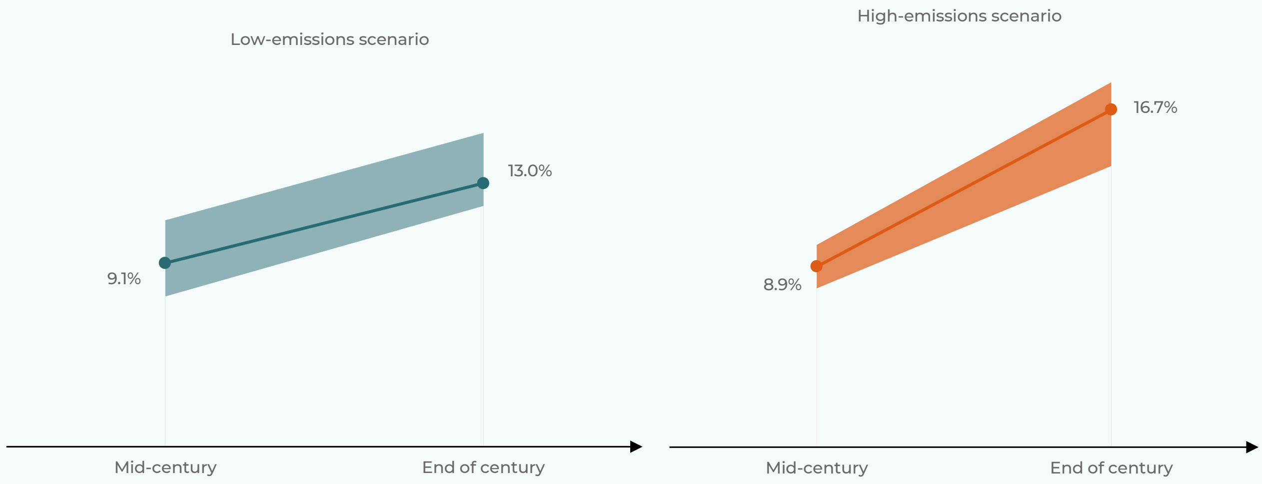
will outweigh winter reductions by mid-century and beyond (Figure 6.2). The difference between a low- and high-emissions scenario is especially apparent at the end of the century: under a high-emissions scenario, total national electricity demand for heating and cooling is projected to increase by a median of 43 per cent by the end of century compared to present levels due to increased air conditioning needs alone.

Our estimates of peak electricity demand show even more dramatic increases. We estimate that peak demand will rise in every province relative to what would have been driven by economic and population growth alone in the absence of climate change (Figure 6.3). In all provinces except Ontario and Saskatchewan, peak electricity demand currently occurs in the winter, primarily because of electricity use for baseboard heaters and other forms of space heating. Our analysis finds that in a high-emissions scenario, the warming climate will shift peak demand from winter to summer for most provinces by mid-century and for most regions by end of century in a high-emissions scenario. This will have the aggregate effect of increasing peak electricity demand nationally by nine per cent by mid-century and 13 to 17 per cent by the end of the century. Regionally, the largest increases are projected to occur in Ontario—where demand already peaks on the hottest summer days—with an increase of up to 30 per cent anticipated by mid-century, even in our low-emissions scenario.

Figure 6.3

A hotter climate will drive up peak electricity demand

Projected change in peak electricity demand compared to a no-climate-change scenario



To avoid triggering rolling outages or blackouts on dangerously hot days, substantial new electrical generation capacity across Canada will be needed to meet these dramatic increases in peak demand—requiring additional investment well beyond what would be otherwise necessary to supply a growing population and economy. Not only is this a challenge in itself, it will also complicate the task and increase the expense of electrifying the economy as Canada transitions to net zero and new, competing demands for electricity at peak times come online. Heat-related infrastructure damage, along with performance declines in transmission and distribution infrastructure in hotter temperatures, will further exacerbate the challenge of providing reliable electricity during the summer when it will be most needed (CEA, 2016).

Building resilience into Canada's electricity systems will reduce costs

Because so much other infrastructure and so many critical services depend on electricity—a dependency that will only grow as electricity becomes Canada's most critical energy system in a net zero world—a resilient grid is a critical element of a resilient and prosperous country.

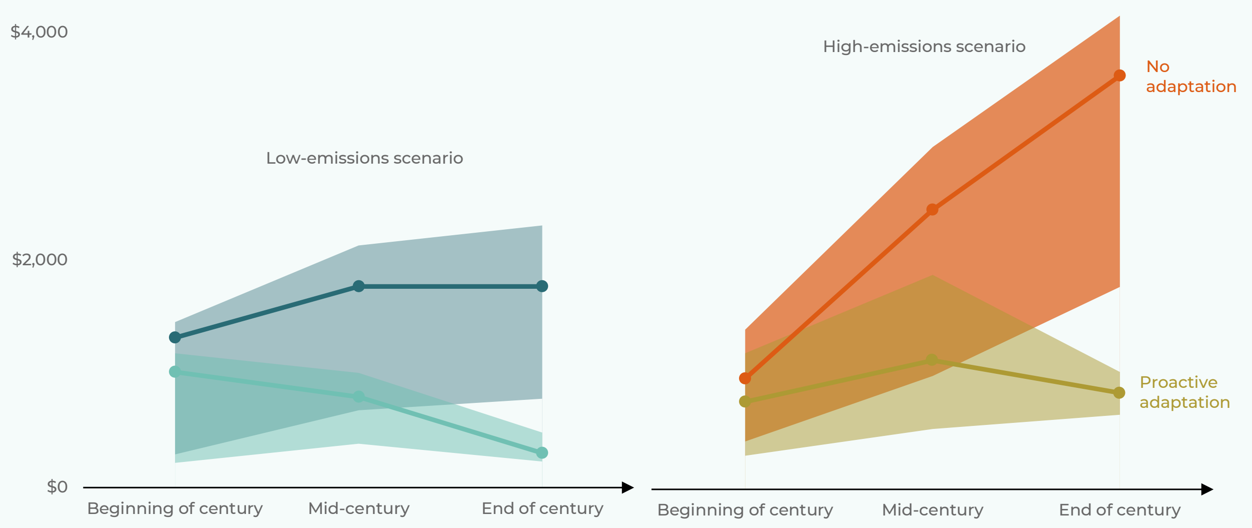
Our analysis shows that improving the resilience of electrical transmission and distribution infrastructure in anticipation of future temperature and precipitation changes could significantly reduce the frequency and cost of damage to transmission while increasing the reliability of the grid. And these investments are relatively simple and low-cost. Replacing transmission and distribution infrastructure components at the end of their life with more resilient materials and components—in many cases a marginal expense—can eliminate 83 to 77 per cent of damage costs that would have occurred without adaptation by the end of the century for the low- and high-emissions scenarios, respectively (Figure 6.4). Even a "reactive" adaptation scenario, where replacement components and materials are updated to the climate of the day, can save between 52 and 66 per cent compared to an approach where climate change is not factored in at all.

Remember that our analysis only captures the damages associated with certain climate hazards to electrical transmission and distribution infrastructure and that our cost/benefit analysis is limited to costs of direct physical damage and the benefits of adaptation in reducing this damage. In practice, the adaptation measures we consider would also increase the reliability of the grid, which will reduce interruptions in critical services like water supply, medical care, and telecommunications caused by power outages—and the associated costs of cascading economic and social disruption. There will also be opportunities beyond what we have modelled to adapt and improve the resilience of electricity systems to other climate change hazards, thereby increasing grid reliability and reducing both direct and indirect costs.

Figure 6.4

Adaptation can dramatically reduce costs of climate-related electricity infrastructure impacts

Projected annual costs of electricity damage in millions of dollars (2019 CAD)



7 CONCLUSIONS AND RECOMMENDATIONS

Our analysis confirms that climate change poses major risks to Canada's public and private infrastructure—risks that could prove extremely costly and threaten infrastructure services that are critical to social and economic health. Proactive and judicious adaptation measures have the potential to dramatically reduce or even reverse these costs and service losses, but the incentives and policy supports to drive adaptation at the scale that is required do not yet exist. Meeting the challenge that climate change represents to Canada's infrastructure will require major improvements in the current understanding of risk, technical guidance, funding and investment, price signals, and regulatory drivers.

CONCLUSIONS

The following specific conclusions expand on our findings:

Climate-related infrastructure damage and losses in Canada will cost tens of billions of dollars each year at a minimum—total costs will likely be much higher.

Without adaptation, the costs of climate change damage to homes and buildings, roads, railways, and electricity systems are on track to increase to tens of billions of dollars annually. Climate change threats to infrastructure are already costing Canada billions of dollars annually, and without action, impacts and costs will continue to grow—even if global greenhouse gas emissions are reduced. Many regions will face the largest costs towards the end of the century, particularly if global action in the next few decades to reduce emissions falls short of the ambition science indicates is necessary.

Moreover, our estimates are only a lower bound for the potential costs Canada could face. Our estimate is conservative because we were not able the quantify some of the direct consequences to the three types of infrastructure that were the focus of our analysis. For example, we were not able to examine the impacts of more frequent wildfires on homes and buildings, of ice and storms that could knock out electrical transmission and distribution systems more often, or of larger and more frequent floods on roads and railways. And we were not able to examine direct and indirect costs of climate change to other types of important infrastructure, such as telecommunications infrastructure, drinking water systems, healthcare facilities, or marine ports and seaways. Recent experience with weather-related disasters that we were not able to include in our analysis—such as the 2016 Fort McMurray wildfire, the 1998 ice storm, and the 2020 Calgary hailstorm—clearly indicate that the future costs of these types of climate-driven events could be of equivalent or greater magnitude to those we quantify in this report.

We were also not able to quantify most of the indirect costs of the loss of infrastructure services for individuals, businesses, or the economy. Our analysis of just the first-order delay costs associated with interrupted road and rail service suggests that the sum of indirect costs of delay and economic disruption could match or exceed the direct costs of infrastructure damage, repair, and replacement. Therefore, while our estimates provide an important insight into the scale of potential impacts and costs to Canada's infrastructure that could result from climate change, the total costs will undoubtedly be much higher.

Flooding and other climate-related hazards will reduce the value of buildings and infrastructure and threaten investments, markets, and the economy.

We found that up to 15 per cent of homes and non-residential buildings in Canada are exposed to some level of coastal or inland flood hazard, while about eight per cent are located within a 100-year floodplain. And because risk is concentrated in expensive property markets such as Toronto and Vancouver, we estimate that almost one quarter of Canada's home and building value is exposed to flooding. As climate change further drives sea level rise and causes what are currently considered 100-year rains to occur on average every 25 years, 10 years, or less, the risk to these properties will increase dramatically.

We estimate current annual damages from coastal and inland flooding at about $1.3 billion. By the middle of the century, we estimate that these costs will increase by a factor of five—even in our lower-emissions scenario. If emissions are not reduced, by the end of the century, these costs could increase by a factor of 10 or more. As damages accumulate, property values will decrease in flood-prone areas across the country. Owners will have less collateral to negotiate or renew mortgages, loans, and other debt obligations. Banks and other lenders could see an increase in defaults as owners walk away from homes and buildings that are no longer insurable, or for which repairs become unaffordable—and lenders could incur larger losses because the collateral value they can collect from those buildings will be reduced. And investors in real estate, such as through real estate investment trusts or mortgage-backed securities, could see substantial losses.

Impacts to asset values and the associated financial risks are not limited to real estate. Utilities, municipalities, and private industry with infrastructure exposed to flooding and other growing climate hazards will experience unexpected devaluation of physical assets. Their credit ratings could decline, they may experience greater challenges in borrowing or raising capital, and insurance for climate-related hazards will become more expensive or may be withdrawn completely. These costs will be passed on to taxpayers, ratepayers, and investors. And lenders and bond holders who provide long-term capital could experience credit losses and lower returns.

Cumulatively, these impacts could pose a risk to the stability of markets and to the financial system. Increasing damages and losses from more frequent extreme weather and other climate change effects in Canada and around the world could cause banks and other lenders to reappraise the creditworthiness of a wide range of individuals, businesses, and even entire industries, making credit more difficult to access. Investors could begin to divest from businesses and sectors that have infrastructure and assets at risk, further reducing the value of buildings and physical assets and making credit even more expensive. Insurers could withdraw coverage from at-risk households and businesses if climate-related payouts continue to increase, putting not only owners but lenders at risk. At a sufficient scale, these effects could lead to reinforcing cycles of credit contraction and reduced activity and growth that would affect Canada's entire economy (FSB, 2020). Moreover, as the world shifts to a low-carbon economy, physical climate risks will interact with transition risks—losses and costs to owners, lenders, and investors in high-carbon industries—that could further reinforce financial and economic instability.

Poor understanding and disclosure of climate risk are leading to risky decisions and mounting liabilities.

In Canada, remarkably little information is available on the risks to physical infrastructure from climate change. Current publicly available climate change information—such as that provided by the federal government's Canadian Centre for Climate Services and other regional data portals—is largely limited to climate and weather variables (CCCS, 2021). These data show the climate conditions Canada may experience in the future but do not describe the risks that accompany those conditions—the potential physical damage, the direct and indirect economic costs, or the social and cultural consequences.

Other government products that aim to characterize climate-related risks are also inadequate for supporting adaptation. For example, even though flooding has consistently been the costliest type of weather-related disaster in Canada, government-produced flood maps that describe *existing* flood hazards are incomplete, largely out of date, and difficult to obtain. And despite decades of research showing climate change will likely exacerbate flooding in much of Canada, virtually no progress has been made on estimating future flood risk in any part of the country. As a result, homes and other buildings continue to be built in high-risk locations, while current property owners and prospective buyers have little understanding of their existing or potential future risk of flooding. Similar information gaps exist across Canada regarding current and future wildfire risks (Lewis, 2019).

The lack of risk information and guidance in codes and standards means that new infrastructure continues to be designed, and existing infrastructure continues to be managed, for the climate of the past, creating billions of dollars in potential liabilities—as we demonstrate in our analysis. Although decision makers have known for decades that many of Canada's building and infrastructure codes and standards were no longer relevant in a changing climate, updates to reflect the risks of the potential future climate have only just begun (Arsenault, 2019).

In the absence of publicly available climate risk information, the private sector has developed some risk information products that serve the needs of certain business sectors such as the insurance industry. However, these products are costly, and intellectual property restrictions prevent them from being made widely available.

In addition to a lack of information on the physical risks of climate change, there is an even larger gap in knowledge about how to calculate the costs associated with those risks. While bodies such as the Task Force on Climate-related Financial Disclosures and Canada's Expert Panel on Sustainable Finance have highlighted the importance of making physical climate risks transparent in financial systems, most homeowners, small businesses, and even large corporations and governments lack the expertise to determine the effect that climate change impacts will have on their bottom line—even if the data on impacts were available (Government of Canada, 2019; TCFD, 2017). As a result, most individuals, organizations, and sectors are not able to build climate risk into their financial planning and decision making. And specialized insurers, providers of adaptation solutions, and holders of private capital are largely unable to develop business cases for products, services, and investments that could help individuals and firms address some of their climate risk.

Governments and taxpayers are financially exposed on many fronts.

Governments—and by extension, taxpayers—will directly pay for climate-related infrastructure damage. Federal, provincial, and territorial governments will pay a large part of the growing costs of damage through disaster response programs. However, financial resources are not meeting the demand. Even with commitments in recent budgets, funding for disaster response and recovery is far short of what the Parliamentary Budget Officer has said is needed (Government of Canada, 2021; PBO, 2016), potentially leaving more costs to be passed on to provincial, territorial and Indigenous governments, local governments, and individuals.

Provincial, territorial, and municipal governments—the nation's largest owners of public infrastructure —will also be liable for the increased costs of maintaining and replacing infrastructure damaged by changing climate conditions. Indigenous governments could also be exposed as they continue to gain greater ownership over infrastructure in their territories and communities. Paying for this damage could require cuts to other programs, more borrowing, or increases in taxes. As our analysis shows, exposed assets include public buildings, roads, and electrical infrastructure. Many other types of public infrastructure are also at risk, including drinking water and sewer systems, bridges, airports, ports, and public transit systems.

Private-sector insurers have always played an important role in helping people and business rebuild after weather-related disasters, but their business model is threatened by rapidly growing payouts.

If insurers choose—or are mandated by governments—to continue to provide insurance to owners of buildings and assets at growing risk from climate change, they will need to pass the costs on to all property insurance customers in the form of substantially higher premiums. Alternatively, they may no longer offer coverage for certain customers—for example, flood insurance is already either unaffordable or unavailable for the homes and buildings at greatest risk of flooding in Canada (Dolynny, 2019) and will no doubt be even more difficult to obtain for more and more property owners as flood risk increases with climate change.

Beyond direct liabilities, governments and individuals are also exposed indirectly through the impacts of infrastructure damage and loss on the broader economy. Business interruption and supply chain impacts caused by increasingly unreliable infrastructure will ultimately impact government coffers through declines in productivity, economic growth, and tax revenues—shortfalls that would lead to tax hikes or cuts to programs and services that people in Canada rely on.

The net zero transition requires—and can help create—climate-resilient infrastructure.

Canada is faced with two infrastructure transition challenges over the coming decades. The first is the need to make massive infrastructure investments while supporting a fundamental transition in our economy to meet Canada's 2050 net zero target—investments of a scale that may not occur again for generations. The second is the need to invest in making existing and future infrastructure in Canada resilient to a warming and increasingly volatile climate. Currently, investments to meet these two infrastructure challenges occur separately. But Canada has limited resources, little time, and no margin of error to achieve both—so efforts to support the net zero transition and make infrastructure more resilient must be aligned to make greater progress while avoiding investments in either priority that compromise the other.

For example, the electrification of Canada's economy is a critical pathway for reaching net zero emissions, with electricity demand projected to increase by at least 45 to 65 per cent by mid-century from 2015 levels (Dion et al., 2021). However, our analysis shows that, in the absence of adaptation, electrical transmission and distribution infrastructure will be at greater risk of deterioration and failure in a warming climate, while hotter summer temperatures will cause demand spikes and breakdowns at the most critical times. Therefore, if investments in renewable energy and grid modernization are to successfully advance Canada's net zero goals, they must include actions to improve the resilience of the grid itself.

All new infrastructure can be designed to provide reliable service in a future climate while at the same time reducing emissions. Examples include building energy retrofit programs that also incorporate resilience upgrades for wildfires, floods, and heat waves, or urban redevelopment plans that reduce storm runoff while increasing density and walkability.

The federal government has taken initial steps to build resilience into infrastructure investment through Infrastructure Canada's Climate Lens, a requirement that applications for some federal government infrastructure funding programs assess climate risks to proposed infrastructure and describe how these risks will be addressed. However, the Climate Lens does not apply to many federally funded projects, to infrastructure wholly funded by provinces and municipalities, or to infrastructure investments by utilities and the private sector. It also does not direct proponents to consider how projects might enhance the resilience of the communities or areas where they are located, either alone or in concert with other infrastructure projects. A broader suite of tools is required to leverage the resources and authority of all orders of government to ensure that every infrastructure investment contributes to building resilience.

Climate-related infrastructure costs will be unevenly distributed in Canada.

Our analysis shows that some individuals, communities, and regions will be disproportionately affected by climate change infrastructure impacts and costs. For example, the physical and financial risks of flooding are mostly concentrated in less than ten per cent of homes and buildings. Not only are the owners of these properties far more likely to experience direct damages from flooding, but they will also be most affected by declining property values and loss of access to insurance as flood risk grows under climate change. Communities with a large proportion of flood-prone homes and buildings—especially small towns and settlements with limited resources—could be devastated, not only by the costs of rebuilding after flood disasters, but also from loss of property tax revenues if assessed values decline and residents abandon hazardous properties to move elsewhere.

Communities facing existing infrastructure gaps are particularly exposed. For many Indigenous Peoples, especially those living in chronically risk-prone areas because of colonization and forced relocation, climate impacts could exacerbate deficits in critical infrastructure—for example, clean water and roads—while undermining rights, cultural practices, and health and well-being (Waldron, 2021). Moreover, Northern, rural, and remote communities that rely on single road and rail connections or small airports will be at risk of disruption from infrastructure failures. These communities may also be most affected by costs of repairing infrastructure passed on by electrical utilities, because they require more extensive transmission and distribution systems on a per-customer basis than in the south and in urban areas.

Infrastructure impacts and costs induced by climate change will also have greater impacts on people and communities that are already at an economic disadvantage. People living on low incomes and less wealthy communities already have fewer resources to respond to extreme weather and weather-related disasters and will continue to be hardest hit as these events become more frequent and severe. But as banks and insurers seek to cover their growing portion of this risk, increased costs of insurance, loans, and capital will create new expenses for people and communities with fewer financial resources and will further reduce their ability to invest in adaptation that could reduce these risks.

Proactive adaptation can eliminate much of the risk but faces hurdles.

Our results show that proactive adaptation can substantially reduce the damages and losses induced by climate change. The analyses of adaptation benefits for roads, railways, and electrical transmission and distribution show that relatively straightforward actions—such as making sure repairs and replacement infrastructure are designed for long-term climate change—can reduce net costs by 50 to 90 per cent. Furthermore, we project that adapting these systems and adaptation to address coastal flooding, are highly effective in reducing the risks associated with the most drastic projections of climate change and sea level rise for Canada—a critical hedge against worst-case outcomes.

Despite the clear benefits of acting on adaptation, many barriers remain. As noted above, the lack of relevant, usable, and credible information about current and future climate-related risk means that homeowners, businesses, and communities are not aware of, or motivated to reduce, risks. Canadian building and infrastructure codes and standards, which are updated very slowly, are only just starting to incorporate climate change risks. Governments, businesses, and investors are more concerned with short-term benefits and profits from operating and developing infrastructure than in managing long-term risk. Both public and private entities have limited knowledge of the opportunities to adapt infrastructure and make it resilient, and they struggle to fund adaptation actions because it is difficult to develop business cases based on uncertain future impacts or avoided costs. And some potential adaptation solutions, such as coordinating strategic retreat from flood risk areas by expending public funds to buy homes and properties at risk, can be deeply emotional and contentious. While such options may have net economic benefits, they may not be a viable or culturally appropriate option—particularly if those negatively affected are from low-income, racialized, or otherwise-marginalized communities.

Projected climate-related costs and risks to infrastructure in Canada are just the tip of the iceberg.

While we have been able to identify some of the most important impacts of climate change on infrastructure and infrastructure services in Canada and their potential costs, we have quantified only a fraction of the overall risks. Our analysis was able to estimate major direct costs of climate-related damage to key infrastructure; however, a lack of information about some types of future climate hazards and how infrastructure will respond to those hazards mean that many direct damages cannot be practically quantified. Indirect costs are even more challenging to evaluate. While analyses such as ours can analyze some first-order costs of delays and disruption, it is extremely difficult to predict how losses of infrastructure service—in the interactions of multiple types of infrastructure interruptions—propagate through supply chains and the economy. How those losses and interruptions will affect the health and well-being of individuals and communities also remains unclear.

Despite these information gaps, our analysis is sufficient to highlight both the scale of the climate change infrastructure challenge and the opportunity to dramatically reduce impacts and costs through adaptation.

Important decisions about the future of Canada's infrastructure are now being made, with the forthcoming National Infrastructure Assessment mapping out future investments, including the transition to net zero (Government of Canada, 2021). There is no time to lose, and these initiatives must incorporate what is already known about climate change risks to build modernized, low-carbon infrastructure that better serves communities and businesses in a rapidly changing world.

In the longer term, the absence of publicly available climate risk information will continue to limit adaptation action by infrastructure owners and operators—from governments to private corporations to individual homeowners. As Canada's Expert Panel on Sustainable Finance has highlighted, tools to translate climate data into tangible impacts are virtually non-existent in Canada (Government of Canada, 2019). This is a gap that must be addressed to develop robust practices of assessing, measuring, pricing, and managing climate risk and opportunity in the development and operation of infrastructure in Canada.

RECOMMENDATIONS

The following recommendations aim to help all orders of governments across Canada address impending infrastructure impacts and costs, close gaps in policies and incentives, and drive better climate change risk management and adaptation:

1 Governments should develop and publish accurate and practical information about climate-related infrastructure risks.

To understand and manage current and future climate change risk and make informed investments in adaptation, governments, corporations, investors, and individuals need actionable and up-to-date risk information.

Currently, information about future climate change impacts and existing climate risks in Canada is inconsistent and incomplete. Governments are mostly publishing historic climate data and the basic output of future climate models, which provide little, if any, direct insight into climate change risks to infrastructure and infrastructure services. Other government products that are intended to communicate climate-related risks, such as flood mapping, are out of date and incomplete and do not reflect the future risk of climate change. Commercially developed climate risk information is useful to those who can afford to pay but creates an unfair playing field when it comes to factoring risk into decisions and transactions.

Governments have an important role to play in ensuring that consistent and useful climate risk information is universally accessible. The federal government should lead the basic research and modelling required to understand the threats to infrastructure presented by a warming and increasingly volatile climate, including monitoring of ongoing weather and climate in Canada, as well as ongoing development of nationally relevant future climate modelling. It should also develop standards for the use of this information in climate change risk products such as flood mapping and in climate risk assessments. Provincial and territorial governments should apply these data and standards to develop and publish information on climate risks that are priorities for their residents and their economies. And all orders of government should work together to develop arrangements—including the private sector where appropriate—to ensure that these applications are adequately and equitably funded.

The current lack of climate risk information, however, does not justify continued inaction on adaptation. Climate change is already damaging infrastructure and costing billions annually across the country and requires an immediate acceleration of adaptation investment in response. Existing risk information and a growing catalogue of recent climate-related impacts and disasters have shed enough light on the magnitude of climate change risks to infrastructure in Canada to initiate more adaptation actions for the biggest risks and for the most vulnerable areas. Governments should continue to press forward with adaptation strategies and actions that can be updated and evolved when the next generation of climate risk information is available.

2 Governments and regulators should require owners of existing and proposed infrastructure to disclose climate change risks.

As we highlighted in our introductory adaptation report, *Tip of the Iceberg: Navigating the Known and Unknown Costs of Climate Change for Canada*, transparency about climate change risk promotes resilient decisions and discourages risky ones. The Task Force on Climate-Related Financial Disclosures and Canada's Expert Panel on Sustainable Finance have also highlighted that disclosure of physical climate risks—and of strategies to manage those risks—are critical for directing investment away from risky infrastructure and physical assets and towards more resilient options (Government of Canada, 2019; TCFD, 2017).

Our analysis sheds light on the current and projected consequences of insufficient assessment, disclosure, and management of climate change risks. It shows that if public and private infrastructure owners are not made aware of and accountable for climate risk, they will continue to accumulate risk that will grow dramatically with climate change. Similarly, if lenders, insurers, and investors do not analyze the climate risk in their portfolios, they will continue to enable poor infrastructure decisions through credit, insurance, and capital.

Governments, along with regulatory bodies overseen and legislated by governments, should ensure that infrastructure owners, lenders, and insurers are analyzing and managing climate risk. They should also ensure that these actors are disclosing their risks and their risk management strategies so that stakeholders and markets can incorporate this information into their decisions. For example, federal bodies such as the Office of the Superintendent of Financial Institutions, the Bank of Canada, and the Department of Finance should integrate climate risk disclosure into the supervision of federally regulated financial institutions, as suggested by the Expert Panel on Sustainable Finance. And provincial bodies that regulate securities, real estate, utilities, and municipal infrastructure should require disclosure of physical climate risk and risk management strategies in planning, decision making, and transactions.

As discussed in Recommendation #1, not all the data, tools, and expertise required to assess climate infrastructure risks are in place. Many aspects of disclosure can begin now with the information that exists, but governments and regulators must support the development of resources for implicated sectors and organizations and help guide them through a swift but staged transition to full and consistent disclosure.

3 Governments should explicitly evaluate resilience benefits and climate risks for all infrastructure spending and regulatory decisions.

The long-lived nature of infrastructure means that decisions made today—and yesterday—will dictate the resilience of Canada's infrastructure to climate change over the remainder of the century. This means that governments and others cannot act too soon to start building adaptation and resilience into all infrastructure decisions. This is especially true for the coming surge of public and private infrastructure investment required for Canada's net zero transition. If not carefully planned with resilience in mind, these investments could lock decades or centuries of additional vulnerability into new infrastructure across the country while neglecting opportunities to increase the resilience of communities and the economy.

In combination, federal, provincial, territorial, Indigenous, and municipal governments can influence nearly all infrastructure decisions made in Canada. Their roles in setting infrastructure standards, funding and planning public infrastructure, regulating infrastructure operation, regulating urban development, evaluating major industrial and resource development projects, and maintaining and operating infrastructure can all be leveraged to reduce current and future risks in infrastructure decisions.

For example, the federal government should make climate resilience a key goal of long-term national infrastructure strategies and infrastructure funding programs. It should dramatically accelerate the incorporation of climate change risks and adaptation principles into national building and infrastructure codes and standards. And it should extend the Climate Lens concept so that it applies to all federally funded infrastructure projects and requires funded infrastructure to not only be resilient but also contribute to broader societal resilience.

Provincial and territorial governments should adopt similar criteria for funded public infrastructure projects and provincial/territorial standards. Provincial governments should also establish standards and regulations to ensure that climate change risks are reflected in provincial and municipal public infrastructure asset management. And provincial, territorial, Indigenous, and municipal governments should use their land-use planning authority to ensure that new development and infrastructure is built to avoid climate risk and to improve the resilience of existing communities.

4

Governments should create safety nets for the most vulnerable to make climate risk pricing equitable.

More transparency, disclosure, and accounting for climate risk in markets, financial systems, and other venues of infrastructure decision making will create price signals that reduce investment in high-risk infrastructure and assets. This will have a beneficial effect in the long term and in the aggregate. But, if uncontrolled, the transition to an economy where climate change risk is priced into all transactions could create barriers to adaptation for communities and individuals who are already the most economically vulnerable to climate-related damage. For example, homeowners who are already struggling to find the funds to invest in home flood protection will have even less money to spend if banks raise mortgage rates and insurers raise property insurance premiums in flood-prone areas.

To avoid outcomes in which those who can least afford to pay are the most impacted, governments should ensure that economically vulnerable individuals, businesses, and communities that would be disproportionately and inequitably impacted by climate risk pricing are identified in adaptation planning. Prioritizing these groups for public investment in protective infrastructure or resources to support risk reduction actions they can undertake themselves will help prevent climate risk pricing from making existing inequities worse. All orders of government must work together to this end: the federal government should encourage these choices through conditions on adaptation funding, and provincial, territorial, Indigenous, and municipal governments should focus adaptation resources and investments on individuals, businesses, and communities at greatest risk without delay.

Adaptation will not always be able to eliminate the climate risks to homes, properties, and physical assets before risk pricing comes into broad effect. In these cases, governments should develop programs that allow economically vulnerable homeowners, businesses, and communities to access insurance and credit while long-term adaptation solutions are developed. For example, government-supported high-risk flood insurance pools—which exist in many countries, including the United States and United Kingdom, and are currently being contemplated in Canada by the federal Task Force on Flood Insurance and Relocation—can ensure that affected homeowners can continue to afford home insurance (PSC, 2020). The federal government should work with provincial, territorial, and Indigenous governments to identify areas and economically vulnerable groups that will require such supports. And all orders of government should collaborate, engaging the private sector as appropriate, in the creation of financially sustainable instruments to pool and share these risks at national or regional scales.

GLOSSARY

Adaptation Actions that reduce damage and loss from actual or expected climate change, while taking advantage of potential new opportunities.

Adaptive capacity The strengths, attributes, and resources available to an individual, community, society, or organization that can be used to adapt to climate change.

Asphalt binder An essential component of asphaltl that holds the aggregate together.

Baseline The state against which change is measured. A current baseline represents observable, present-day conditions. A future baseline is a projected future set of conditions excluding the driving factor of interest. Alternative interpretations of the reference conditions can give rise to multiple baselines.

Buckling The formation of large lateral misalignments in continuous welded rail track, often resulting in catastrophic derailments. One of the most frequent causes of buckling is hot weather, which can weaken and distort the steel rails by essentially softening the tracks.

Climate The average weather in a place over a long period of time, typically 30 years or longer.

Climate change Changes in the climate of the Earth, predominantly caused by the burning of fossil fuels, which add heat-trapping gases to Earth's atmosphere. It manifests as overall global warming but also in sea level rise, melting of previously permanent snow and ice fields, and more extreme weather.

Climate model A climate simulation based on well-documented physical processes. Climate models, also known as general circulation models (GCMs), use mathematical equations to characterize how energy and matter interact in different parts of the ocean, atmosphere, and land.

Climate projections A simulated response of the climate system to a scenario of future emission or concentration of greenhouse gases and aerosols, generally derived using climate models. Climate projections are distinguished from climate predictions by their dependence on the emission, concentration, or radiative forcing scenario used, which is in turn based on assumptions concerning, for example, future socioeconomic and technological developments that may or may not be realized.

Climate-related hazards The potential occurrence of a climate-related physical event that may cause loss of life, injury, or damage and loss to property, infrastructure, service provision, and environmental resources. Due to climate change, frequencies of some hazards are expected to continue to increase.

Coastal flooding Flooding of normally dry, low-lying land from an adjacent body of water. Typically the result of high water levels from tides and storm surges or from a combination of high water levels and stormy conditions in which waves and wind drive water onshore. Sea level rise caused by climate change will increase coastal flooding in the future.

Disaster Severe disruption of the normal functioning of a community or society due to hazardous physical events interacting with conditions of social vulnerability, leading to widespread negative human, material, economic, or environmental effects that require an immediate emergency response and may require external support for recovery.

Electrical distribution infrastructure The final stage of the electrical grid, which distributes electricity to homes, industry, and other end users. Distribution infrastructure reduces power to safe customer-usable levels through substation transformers.

Electrical transmission infrastructure Infrastructure responsible for delivering generated electricity—usually over long distances through transmission power lines—to the distribution grid located in populated areas.

Exposure The presence of people; livelihoods; environmental services and resources; infrastructure; or economic, social, or cultural assets in places that could be adversely affected by climate change.

Extreme weather The occurrence of a weather variable (such as temperature) that exceeds the upper or lower limit of observed values for that variable. These events are often short-lived and include heat waves, ice storms, heavy downpours, tornadoes, tropical cyclones, and floods.

Flood maps Maps that identify areas that are expected to experience periodic coastal or inland flooding. Flood maps or floodplain maps typically show ground elevation contours, the location of buildings and roads, and the horizonal extent of the high-water mark for one or more flood events, such as a 100-year flood. In Canada, flood maps are typically developed by provincial or municipal governments.

Floodplain An area of land adjacent to a river that stretches from the banks of its channel to the base of the enclosing valley, and which experiences flooding during periods of high rainfall. Five-hundred, 100, 50, and 25-year flooding events serve as a classification of statistical occurrence referring to a 0.2, one, two and four per cent chance of occurrence respectively in any given year.

Fluvial flooding Occurs when the water level in a river or stream rises and overflows onto the surrounding banks, shores, and adjacent land. The severity of a flood is influenced by the amount of rainfall in the catchment area of the river as well as in-stream flow conditions such as ice jams or the operation of human-made dams.

Impacts Effects on natural and human systems. In this report, the term impacts is used to refer to the effects on natural and human systems of physical events, disasters, and/or climate change.

Infrastructure gap The difference between infrastructure investment needs and past or current expenditures, resulting in inadequate stock of infrastructure overall, sparse and unequal investments in infrastructure, and unequal access to infrastructure services.

Inland flooding Occurs when precipitation over land accumulates locally or runs off and elevates the water level in rivers, streams, and other inland water bodies. It can manifest as either fluvial flooding or pluvial flooding.

Pluvial flooding Caused when heavy rainfall creates a flood event independent of an overflowing water body. It occurs when intense rain overwhelms urban drainage systems, causing water to flow out into streets and nearby structures, or when inense rain falls on surfaces that are unable to drain or absorb it, causing runoff to pool in low-lying areas.

Public infrastructure Infrastructure facilities, systems, and structures that are owned and operated by government.

Resilience The ability of a physical, social, or ecological system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a disaster in a timely and efficient manner.

Risk The potential for consequences where something of value is at stake and where the outcome is uncertain. Risk is often represented as probability of the occurrence of hazardous events or trends, multiplied by the potential impacts if these events or trends occur. Risk results from the interaction of vulnerability, exposure, and hazard. In this report, the term risk is used primarily to refer to the risks of impacts related to climate change.

Sensitivity or susceptibility The degree to which an individual, asset, household, community, business, or ecosystem is affected, either adversely or beneficially, by climate change.

Speed orders Temporary speed limit reductions on trains because of dangerous conditions. High heat is one of the main causes of speed orders, because it creates the risk of track buckling and train derailment.

Strategic retreat The purposeful, coordinated relocation of people and assets away from a perceived or real risk. It can include buying out and removing the homes and buildings at greatest risk of coastal or inland flooding.

Vulnerability The degree to which a system is susceptible to, or unable to cope with, negative effects of climate change, including climate variability and extremes.

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