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The Impact of Climate Change Risk on Pension and Retirement Investing

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The Impact of Climate Change Risk on Pension and Retirement Investing

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Executive Summary

In this project, the financial impacts of climate change risk on retirement investing are studied, with a focus on managing such risk from the perspective of pension funds. Two main components of climate change risk studied are:

- Physical risk: direct impact of extreme climatic events and global warming on assets and pension liabilities.
- Transition risk: financial risk arising from the process of adapting to a lower-carbon economy, including litigation risk related to the compliance to new protocols.

The effects of these risks on both the asset side and the liability side of pension funds' balance sheets are elaborated in this report, of which the key insights are summarized below:

1. It is beneficial for pension funds to incorporate climate change risk in their investment decision-making process due to the impacts of climate change on long term asset return as well as pensioner mortality, which have been concluded by the existing literature and further explored in this study (Chapter 1).
2. Using a representative set of stocks, climate change risk is found not to have been fully recognized and priced by both European and North American financial markets. In such a situation, this elevates the potential of future price correction and creates uncertainties for pension funds that have a high level of exposure to carbon-intensive assets (Chapter 2).
3. Quantitative methodologies are proposed in this study to assess the impacts of climate change risk on the asset side of the balance sheet, including fixed-income assets, equities, and stranded assets (Chapter 3). The associated numerical results show that:
   a. In the long term, the adverse impacts of transition risk on bond values are projected to be higher for issuers with higher carbon intensity levels and higher debt-to-value ratios;
   b. For equities, stocks from carbon intensive sectors (energy, utilities, and materials) and the real estate sector are expected to be negatively affected by climate change. In contrast, sectors such as health care and information technology are expected to remain resilient or even benefit from climate change.
4. On the pension liability side, climate change risk can have significant impact on human mortality. As such, a regression analysis is adopted to quantify the net association between temperature change and mortality rates (Chapter 4). The empirical results based on U.S. population mortality data lead to the following findings:
   a. Mortality rates of individuals between 40 and 80 years old decrease as temperature increases;
   b. Mortality rates of individuals above 80 years old increase as temperature increases.
5. Aside from the quantitative analysis above, there are additional practical considerations of climate change risk for pension funds (Chapter 5):
   a. Green bonds have been shown to be a suitable candidate for pension investments, although fund managers should be mindful of the issue of potential greenwashing.
   b. Climate change has direct and indirect impacts on real estate property values through multiple channels, calling for a thorough analysis to assess the net impact.
   c. Climate change risk may lead to new perspectives in the suitability of many existing default options of defined contribution (DC) plans, such as balanced funds and target date funds.

6. Drawing from the aforementioned insights and an existing liability-driven portfolio construction framework, the authors propose a portfolio optimization framework reflecting the impact of climate change for a defined benefit pension fund to achieve the desired risk-return profile in terms of funding status. A numerical example is carried out in this study to illustrate how this methodology can be applied in practice. Extension of the framework for applications in DC fund and personal retirement investing is also discussed (Chapter 6).

Chapter 1: Literature Review

This chapter summarizes key results from a selected literature review with the objective of providing critical insights into the questions raised in this research project. While the list of literature reviewed is not exhaustive, the works reviewed in this section enrich the analysis of these questions and inspire the development of the proposed solutions, which are presented in later chapters of this report.

1.1 EFFECTS OF CLIMATE CHANGE ON INVESTMENT ASSETS

In the last few decades or so, climate change risk has been increasingly raising major concern worldwide. It has been studied on the impact of all aspects of human life, from an increasing frequency and intensity of natural catastrophes to a deterioration of living and working conditions. Furthermore, the profound nature of uncertainty of global warming and its implications appear to present a substantial challenge to prediction and mitigation of climate change.

The book entitled "Pension Funds and Sustainable Investment: Challenges and Opportunities," by Hammond et al. (2023) is a collection of qualitative works which provides a comprehensive review of multi-faceted impacts of the changing climate on pension funds, the role of the pension sector in the global mitigation effort, and the possible reactions of funds to climate change. The pension sector finds itself in a unique position. On one hand, pension funds' large capital bases as well as intergenerational investment horizons give them a unique role to drive innovation such as reflecting climate change risk in their investment practices (Nikulina, 2023, Chap. 7). On the other hand, the long-term liabilities of pension funds make them particularly vulnerable to risks associated with climate change (Sautner and Starks, 2023, Chap. 6). For instance, disasters and environmental changes can adversely affect the future values of funds' assets in real properties and infrastructures, while the issuance of new climate regulations may generate greater uncertainty in the financial market performance depending on the affected sectors.

The impacts of climate change on the performance and the volatility of financial markets have been discussed in a number of quantitative empirical studies in this field, which mostly employ either event-study techniques or GARCH-type models to analyze the reactions of stock returns to the rising temperature and climate-related events. Two of the studies that utilized event analysis are Pagnottoni et al. (2022) and Antoniuk and Leirvik (2024). Pagnottoni et al. (2022) examined the impact of natural disasters (including biological hazards) on major stock indices and found that these indices had significant but geographically heterogeneous reactions to the events. Antoniuk and Leirvik (2024) investigated the effect of climate related policies on ETFs in climate sensitive sectors (energy, utilities, etc.) and showed that the renewable energy sector benefited from the introduction of climate control protocols, while the fossil fuel sector benefited from events that weakened such protocols. For utilities, transportation, and other energy-intensive sectors, climate change mitigation efforts introduced transition risk (i.e., the risk arising from the future adoption of new climate mitigation policies) that needs to be recognized. In Chapter 2 of this research, an event analysis will be adopted in a similar manner as Tan et al. (2018) to assess the effect of the ratification of major climate control protocols on the financial market and, hence, draw several perspectives on the pricing of carbon risk (which is the transition risk-related carbon intensive activities in the context of climate change). Event analysis, as a statistical tool used to examine the effect of an event, has been frequently upgraded in the last decades since it gained attention in the 1960s with the studies by Ball and Brown (1968) and Fama et al. (1969). Corrado (2011) is the most recent work that provides a detailed explanation of the technique and a summary of its history. So far event analysis has found wide applications in various disciplines and not limited just to accounting, finance, and economics.

GARCH-type models have also served as a useful tool to quantify the impact of climate change on asset returns. They were originally designed to capture stylized empirical characteristics of stock returns and are flexible enough to accommodate factors such as temperature changes or catastrophe occurrences. Notably, Wang and Kutan (2013) integrated natural disasters in a modified EGARCH model in their effort to compare the behavior of American and Japanese composite and insurance stock markets. The study showed that catastrophes affected the returns of both insurance stock sectors in opposite directions while increasing their volatilities substantially. For the commodity market, Tumala et al. (2023) included temperature in a model of fossil fuel price returns. They concluded that the returns reacted positively to a disaster accompanied by an increase in volatility.

Another important aspect of climate change contributing to the perceived increase in market volatility is the uncertainty related to stranded assets. A stranded asset is defined as "an asset which loses economic value well ahead of its anticipated useful life, whether that is a result of changes in legislation, regulation, market forces, disruptive innovation, societal norms, or environmental shocks" (Generation Foundation, 2013). A qualitative analysis conducted by van der Ploeg and Rezai (2020) classified stranded assets into four types: unexploitable fossil fuel reserves in line with climate mitigation goals, untransferable infrastructure and capital (e.g., oil drill or trained operating staff with specific skills) that would be abandoned in the green transitioning process, the devaluation of certain assets in light of news on the adoption of climate regulations, and the devaluation taking place once the new policies are actually implemented. Since a considerable portion of fossil reserves could not be exploited should climate goals be attained, the authors emphasized the optimistic view some researchers had on the carbon-intensive sectors was unrealistic. Given the significant capital market representation by carbon-intensive corporations, sudden repricing of stranded assets from these entities could mean a systemic risk in the financial market, similar to the mortgage sector in the 2008 financial crisis. For pension funds, stranded assets pose a serious threat to intended stable assets (such as bonds from oil companies) in their book.

1.2 CONSIDERATION OF SUSTAINABILITY FACTORS IN ASSET MANAGEMENT

An "Annual Survey of Emerging Risks" series conducted by Rudolph (2024) summarizes risk manager perceptions of emerging risks in their practice. This 17th survey involved 133 risk managers worldwide, who collectively placed climate change as the leading emerging risk for the fourth time in a row, and financial volatility as one of five top current risks among 23 risks presented.

These perspectives can be viewed as ones which could provide motivation for pension fund managers to consider climate change in their portfolio construction. The key issue which may challenge the deployment of sustainability considerations is the concern about the performance of sustainable assets, due to the pensions' financial fiduciary duties to their beneficiaries as mentioned in Bauer and Smeets (2023). While multiple European governments have recently included the sustainability goal in these duties, this has not been the case in the U.S., where this is still an ongoing discussion at the U.S. Department of Labor.

Cepni et al. (2023) investigated the connectedness and the spillover effect between conventional equity indices and their ESG components, as well as the evolution of the beta of ESG-friendly stocks and green bonds. They found that sustainable assets and bonds are less sensitive to shocks during periods of climate uncertainty, making them a good tool to hedge against physical and transition risk (the physical risk refers to financial losses as a direct consequence of natural disasters and changing weather patterns).

Meyers et al. (2023) have made the most recent attempt at synthesizing three decades of research on the performance of Socially Responsible Investing (SRI) funds. Examining a large sample of 54 papers on SRI equity funds from 1992 to 2021, the authors observed that the majority of the studies showed statistically insignificant differences between the performance of SRI funds and the benchmarks (which include conventional funds or various types of indices). They also identified the evolution of the research interests and methodologies, from the use of pair matching in the investigation of fund attributes and performance measures, to the introduction of the event analysis. The authors concluded that the performance of the SRI funds does not pose a major concern, and called for a shift in the focus of the debate to other more important issues such as better definitions, disclosure, standards, etc. For pension fund managers, these findings can provide insights into the consideration of including sustainability factors in investment decisions and how it may impact portfolio returns.

Although not included in the final list of the studies reviewed by Meyers et al. (2023), Ibikunle and Steffen (2017) reached a similar conclusion. In this article, the authors compared green mutual funds to their conventional and black counterparts (funds concentrated on fossil fuel and non-renewable energy) in the U.S. and Europe. Over the full sample period, the green funds were shown to display worse performance than the conventional funds but were comparable to the black funds. However, in recent years, the risk-adjusted returns of green funds have quickly improved to catch up with those of the conventional funds and exceed those of the black funds, showing that they have good potential to be included in the portfolio of environmentally conscious pension funds.

Another sustainable financial product that has been recently studied is a green bond. This is a tool for governments and companies to fund their climate change mitigation and adaptation projects. Larcker and Watts (2020) and Flammer (2021) have made use of the pair-matching technique in examining municipal and corporate green bonds, respectively. Both studies showed minimal price premium of a green bond over an otherwise identical conventional bond. Such finding supports the inclusion of green bonds in the fixed income allocation for pension fund investments, though the desired parameters (in terms of issuer, coupon, duration, etc.) may not always be available in the green bond market.

With all the aforementioned assets being reasonable candidates for the asset selection pool, fund managers would like effective strategies to include them in their portfolios. At the market level, Hambel et al. (2024) discussed the use of divestment from problematic corporations versus investment in climate-friendly projects by assessing the equilibria in a two-sector (renewable energy and fossil fuel) market. The authors recognized the trade-off between divesting and diversifying goals in sustainable investing strategies and recommended an optimal course of action in different climate scenarios. At the individual market agent level, especially from the point of view of pension funds, Lee (2023) summarized a number of aspects of ESG which include: how to work with ESG data, what are the financial implications of ESG ratings, what are useful practices in ESG rating construction, what are the ways to integrate ESG considerations in a portfolio, and what to keep in mind regarding climate change. The main concern with this study is the proposed approaches to incorporate ESG in building the investing strategies, including:

- Selecting assets to exclude or include (negative or positive screening) depending on their ESG ratings as well as the sector they are in;
- Manually changing or optimizing the weight of each asset based on the portfolio manager's objectives;
- A combination of the two strategies.

It is important for investors to compare potential investment strategies with each other, as well as with market benchmarks. There have been multiple works that formalized this idea. For example, Cao and Wirjanto (2023) proposed the use of a multiple objective optimization (MOO) program under the Markowitz portfolio mean-variance optimization setting. The algorithm allows explicit consideration of ESG ratings as part of the portfolio optimization objective along with the usual return and risk metrics, while the downside is elevated numerical complexity.

1.3 EFFECTS OF CLIMATE CHANGE ON PENSION FUND LIABILITIES

A pension fund refers to a type of investment fund set up by an employer, union, or government agency in order to provide retirement benefits for their employees. The main objective of a pension fund is to accumulate assets over time by means of contributions from both the employer and the employees, and by means of the investment performance of the fund's investments. The goal of the pension fund is to generate returns that will pay future retirement benefits. Portfolio performance is not the only concern of the pension sector in addressing climate change. Global warming also has implications for the liability side of pension funds which are manifested through longevity risk (which is defined as the risk that true mortality rates are lower than expected).

The discussion paper entitled "Climate Change and Mortality," published by the International Actuarial Association (IAA) (2017) delivered a holistic view of how changing climate affects human mortality. Rising temperatures lead to more frequent and intense catastrophes, more extreme weather, increasing political conflicts, and higher chances for dangerous diseases to breed. This view was shared by Gutterman (2023) which emphasized retirees' physical and financial vulnerability to adverse conditions. All of these factors tend to increase mortality. At the same time, the IAA's discussion paper acknowledged that warmer winter months, CO_2 fertilization effects, as well as climate mitigation and adaptation efforts, may lead to gradually favorable results in mortality over time. This trend was also acknowledged in Weiner et al. (2023), which highlighted the overall improvement in life expectancy and the increase in the proportion of elders in the population. Therefore, the net effect on mortality from these two contrasting forces from climate change is not unambiguous, calling for further quantitative study on the net effect of climate change on pension payouts.

There exist two main quantitative approaches to analyze this issue: extrapolative and explanatory, as per Seklecka et al. (2016). While the explanatory approach focuses on exploring the correlations between climate, human health and mortality, the extrapolative models describe mortality as mathematical processes that are relatively easy to estimate with statistical techniques. The latter is commonly used in the actuarial world such as policy pricing or hedging. Some of the earliest mathematical models of mortality were known as the De Moivre law and the Gompertz-Makeham law where the force of mortality depends solely on age. Starting in the early 1990s, researchers introduced time-series modeling of mortality and have since proposed various stochastic mortality models. In the seminal work of Lee and Carter (1992), the central mortality rate was modeled by a one-factor stochastic process. Subsequently, there have been many developments to this stochastic model including Renshaw and Haberman (2006), Cairns et al.(2006), Plat (2009), and O'Hare and Li (2012). A study of more interest was performed by Seklecka et al. (2017) who further enhanced the Lee and Carter (1992) model by adding a temperature component to the equation of mortality rates. The authors also showed empirical evidence of a negative correlation between temperature and mortality in the UK, confirming the potential of elevated longevity risk in the presence of climate change.

The explanatory approach has the advantage of being flexible and highly interpretable. Gasparrini et al. (2015) examined how the mortality rate reacts to temperature by using a combination of time series, quasi-Poisson regression, and a distributed lag non-linear model on a large sample consisting of 384 locations. The results showed that the majority of deaths were from winter months and that moderately cold days played a bigger role in death than extremely cold days. These findings may be intuitively interpreted as that warmer winters in regions with a cold climate would decrease mortality rates in the future. The model was later enhanced by Rai et al. (2022) which explore the impact of physiological adaptation (i.e., the change in human sensitivity to heat and cold) and socioeconomic adaptation (such as the use of better insulation or heating/cooling devices) on future mortality in Bavaria, Germany. Mortality rates were shown to decrease across climate scenarios, with the relative changes mostly attributed to a socioeconomic adaptation.

Some researchers in economics have also attempted to describe the effect of global warming on mortality by using damage functions. For instance, Bressler (2021) proposed an improvement to the Dynamic Integrated Climate-Economy (DICE) model by incorporating a metric called a mortality cost of carbon (MCC). This metric estimates the number of excess deaths caused by one additional metric ton of CO_2. In order to estimate MCC, the author forecasted excess mortality (which is defined as above the rates previously established by using conventional models) as a time-invariant function of predicted temperature. Although this approach is straightforward to implement, it does not take into account the age effect and questions on its robustness persist, thus it is not ideal for use in this study.

In summary, there exists a variety of approaches that can potentially be used to quantify the impact of climate change on pensioner mortality. Each of these has its own advantages and shortcomings for practical application. For the best interpretability in results, the exploration into the impact of climate change on mortality will be conducted via the explanatory approach and presented in Chapter 4 of this study.

Chapter 2: Market Pricing of Carbon Risk in Stock Portfolios

A critical aspect of building a sustainable investment portfolio under climate change is the historical pricing of carbon risk in the global equity market. If the risk has already been fully priced by the market, strategies targeting portfolio decarbonization will likely not add a substantial amount of return to the investment portfolio due to the forward-looking nature of the equity market.[1] Unfortunately, there are few studies for a precise quantification of the market pricing of this risk, likely due to its long-term nature and the absence of an easily quantifiable risk factor. This chapter presents a study extending the approach adopted in Tan et al. (2018) to address this topic. Both the North American and European Union (EU) markets are covered.

2.1 METHODOLOGY

To study the market pricing of carbon risk, an event analysis is a useful tool, as shown in Antoniuk and Leirvik (2024) and Tan et al. (2018). To make the scope of this study manageable, the authors focus on stocks from the three commonly recognized carbon intensive sectors as defined by the Global Industry Classification Standard (GICs), which are the energy, material, and utility sectors. The market's recognition of carbon risk should be reflected in structural changes of stock price returns (if any) around the launch of major emission control schemes (which represents the "event"). This effect is mostly pronounced for carbon intensive sectors due to their large emission and carbon footprint in daily operations. An event study allows for teasing out this effect and evaluating its significance. Readers interested in this methodology in its general form may find expositions in Antoniuk and Leirvik (2024) and Corrado (2011), while the specific steps of this methodology as applied in this study are presented below:

1. Determine the event period (which is the testing period). This period spans (for instance) one year before and one year after the formal launching date of the major climate control policy of interest to accommodate any leakage and diffusion of information.
2. Specify the stock return model to filter out a systematic price return driven by non-climate factors. Extending the approach used previously in Tan et al. (2018), the authors filter out the systematic portion of the stock market return by using a three-factor model adapted from the seminal work of Fama and French (1993) specified by:

$$r_{i,t} = \beta_{i,0} + \beta_{i,1} r_{m,t} + \beta_{i,2} SMB_t + \beta_{i,3} HML_t + \varepsilon_{it}$$

where:

- $r_{i,t}$ is the return of stock *i* in period t;
- $r_{m,t}$ is the market (index) return in period t;
- SMB_t is the market capitalization factor (Small-Minus-Big) return in period t;
- HML_t is the book-to-market ratio factor (High-Minus-Low) return in period t;
- $\varepsilon_{it} \equiv r_{excess,i,t}$ is the excess return for stock *i* in period *t* which is assumed to be attributable to carbon risk, the subject of interest in this study.

3. Select sample stocks from the carbon intensive sectors. Historical data of the stock prices, factor returns, and market index returns are collected for a sufficiently long horizon covering the testing period. The collected data is then partitioned to form a testing (determined in Step 1) set and a calibration set.
4. Calibrate the model specified in Step 2 by using data from the calibration set. Assess model fitness and statistical significance of the drivers of the return.
5. Calculate the excess returns for each stock in the testing period by using the calibrated model.

[1] Here, portfolio decarbonization refers to a reduction in portfolio carbon metric, which is generally the carbon intensity. The detailed route for portfolio decarbonization, such as the reduction in methane emissions, fossil fuels exploitation, etc. is beyond the scope of this study.

6. For a qualitative analysis, the cumulative excess returns over the testing period are plotted. If carbon risk is recognized and priced, a significant and sudden drop in cumulative excess return should occur around the event point, forming a "cliff" shape. Such drop points are further verified to ensure that they do not correspond to other market events such as dividends and stock splits.
7. For a quantitative analysis, a t-test is performed to test whether the average excess returns after the event are statistically lower than those prior to the event. This is taken as evidence of the market's recognition and pricing of carbon risk.

2.2 HISTORICAL PRICING OF CARBON RISK IN EUROPEAN MARKETS

Two events of interest are studied for the EU market:

1. The official launch of the European Union Emission Trading Scheme (EU ETS) in January 2005, and
2. The ratification of the European Climate Law in July 2021.

For this analysis, 15 stocks from the carbon intensive sectors are selected and listed in Table 2.1. Daily price data were collected spanning the period from January 1, 2002 to January 1, 2024 inclusive, subject to data availability. Factor return data were extracted from the Fama-French European three-factor dataset. For a robust analysis, the calibration set also excluded data from the years before and after the testing period. All factors were found to be statistically significant at the 5% level of significance for the sample stocks selected, except the market return for CNA.L and the Book-to-Market ratio for two other stocks. Details of the factor coefficients are in table A.1 in Appendix A.

Table 2.1
SELECTED STOCKS FROM THE EU MARKET'S CARBON INTENSIVE SECTORS

Name	Sector	Country	Market Index	Symbol
Centrica PLC	Energy and Utilities	UK	FTSE 100	CNA.L
BP PLC	Oil & Gas Production	UK	FTSE 100	BP.L
Shell PLC	Oil & Gas Production	UK	FTSE 100	SHEL.L
Anglo American PLC	Mining	UK	FTSE 100	AAL.L
Rio Tinto Group	Mining	UK	FTSE 100	RIO.L
TotalEnergies SE	Energy & Utilities	France	CAC 40	TTE.RA
Engie SA	Energy & Utilities	France	CAC 40	ENGI.PA
Airbus SE	Manufacturing	France	CAC 40	AIR.PA
BASF SE	Chemical & Materials	Germany	DAX	BAS.DE
E.ON SE	Energy &Utilities	Germany	DAX	EOAN.DE
RWE AG	Energy & Utilities	Germany	DAX	RWE.DE
Enel SPA	Energy & Utilities	Italy	FTSE MIB	ENEL.MI
Eni SPA	Oil & Gas Production	Italy	FTSE MIB	ENI.MI
Equinor ASA	Oil & Gas Production	Norway	OBX	EQNR.OL
Subsea 7 SA	Construction	Norway	OBX	SUBC.OL

Launched in January 2005, the European Union Emissions Trading Scheme (EU ETS) was the first formal ETS in the world. This initiative was seen as a demonstration of the potential active role that the financial sector can play in climate mitigation efforts by providing an effective mechanism to observe and price carbon risk via tradable contracts. The establishment of the EU ETS also sent a clear signal about the downside of carbon risk exposures, which should be priced by the market and reflected as return strains in emission-heavy stocks. The testing period spans from January 1, 2004 to December 31, 2005 inclusive. Results of the qualitative analysis are provided in Figures A.1 and A.2 in Appendix A. Only eight of the 15 stocks exhibit visible cliff-like shapes in their cumulative excess returns around the launch of the EU ETS. For the quantitative analysis, only two of the 15 stocks (RIO.L and EQNR.OL) showed a statistically significant inferior average excess return after the event. These results from this representative set of stocks may be interpreted as an imperfect recognition of carbon risk arising from this event by financial agents at the time in spite of the impact of the event in hindsight.

Another milestone in the EU emission control effort was the approval of the European Green Deal in January 2020 which embraced the goals to make Europe a net-zero emission continent by 2050, as well as the adoption of the European Climate Law in July 2021 which made these goals legally binding. These initiatives are expected to bring major changes to European countries' green economies over the next few decades potentially at the expense of the emission heavy sectors. The testing period spans from July 1, 2020 to July 31, 2022 inclusive. Stocks from the U.K. were excluded due to its exit from the European Union in January 2020, leading to a reduced sample set of 10 stocks. Though the event period partially overlaps with the COVID-19 pandemic, undue impacts from the pandemic on the stock return are expected to be largely captured by the corresponding market and factor returns, with possible residual impacts based on sector level exposures. As shown in Figures A.3 and A.4 in Appendix A, only five of the 10 stocks exhibit cliff-like patterns around the adoption of the European Climate Law. In the quantitative analysis, only one of the 10 stocks (EQNR.OL) showed a statistically significant structural reduction in average excess return after the event. The implications of the results from this representative sample of stocks are consistent with those from the analysis of the EU ETS launch: carbon risk has not yet been fully priced in the European stock markets in response to the major regulatory initiatives carried out in the EU region.

2.3 HISTORICAL PRICING OF CARBON RISK IN NORTH AMERICAN MARKETS

A similar analysis is conducted for the North American market. The events of interest are:

1. Signing of the Paris Agreement by both the U.S. and Canada in November 2016, and
2. Re-signing of the Paris Agreement by the U.S. in November 2021 after its withdrawal in June 2017.

The Paris Agreement represents a global commitment to act on climate change issues including emissions control and climate resilience. As it is the agreement with the most signatories on the same day, it has been considered to be one of the most important climate control protocols to date. In January 2025, the U.S. President announced that the U.S. would once again withdraw from the Paris Agreement. This exit will become official in January 2026 and not covered in this study due to its effect on the market still unfolding as of the day of completion of this report.

For this analysis, 10 American stocks and five Canadian stocks are selected as listed in Table 2.2. Daily price data and corresponding factor return data were collected spanning the period from January 1, 2002 to January 1, 2024 inclusive subject to data availability. The calibration period is defined in a similar manner to that used in the study for the EU. From the calibration, the market return remains a significant driver for all stock returns, yet the market capitalization and Book-to-Market factors are shown to lack statistical significance for four and seven of the stocks, respectively. Details of the factor coefficients are in table B.1 in Appendix B.

Table 2.2
SELECTED STOCKS FROM THE NORTH AMERICAN MARKET'S CARBON INTENSIVE SECTORS

Name	Sector	Country	Market Index	Symbol
ExxonMobil	Energy	U.S.	S&P 500	XOM
Chevron	Energy	U.S.	S&P 500	CVX
ConocoPhillips	Energy	U.S.	S&P 500	COP
Occidental Petroleum	Energy	U.S.	S&P 500	OXY
Air Products & Chemicals	Materials	U.S.	S&P 500	APD
DuPont	Materials	U.S.	S&P 500	DD
Duke Energy	Utilities	U.S.	S&P 500	DUK
American Electric Power	Utilities	U.S.	S&P 500	AEP
Southern Company	Utilities	U.S.	S&P 500	SO
Exelon Corporation	Utilities	U.S.	S&P 500	EXC
Suncor Energy	Energy	Canada	S&P TSX	SU.TO
TC Energy	Energy	Canada	S&P TSX	TC.TO
Canadian Natural Resources	Energy	Canada	S&P TSX	CNQ.TO
Cenovus Energy	Energy	Canada	S&P TSX	CVE.TO
Imperial Oil	Energy	Canada	S&P TSX	IMO.TO

The first event of interest to this study is the signing of the Paris Agreement by both the U.S. and Canada in November 2016. The testing period spans from November 1, 2015 to October 31, 2017 inclusive. Results of the qualitative analysis are shown in Figures B.1 and B.2 in Appendix B. Only seven of the 10 U.S. stocks and two of the five Canadian stocks exhibit cliff-like patterns around their governments' signing of the Paris Agreement. In the quantitative analysis, only one Canadian stock (SU.TO) showed a statistically significant structural reduction in average excess return after the event. These observations based on the selected representative stocks appear to indicate a lack of full pricing of carbon risk in the North American market as well, a finding similar to that for EU stocks.

The second event studied is the re-signing of the Paris Agreement by the U.S. in November 2021 after its withdrawal from the Agreement in 2017. The testing period spans from November 1, 2020 to October 31, 2022 inclusive. The observations are similar to those from the previous event. From the qualitative analysis shown in Figures B.3 and B.4 in Appendix B, only three of the 10 U.S. stocks exhibit cliff-like patterns around the government's re-signing of the Paris Agreement. In the quantitative analysis, none of the 10 stocks show any statistical difference in average returns for the periods prior to and after the event.

In summary, the intertemporal event analysis conducted using representative samples of stocks in this section appears to show that carbon risk has not been fully priced in the Europe and North American stock markets. This would call for a reduction of climate change risk exposures in long-term retirement portfolios with the expectation that the risk will be priced in the future.

It is worth noting that the events chosen for the present analysis represent carbon risk. The event analysis framework could potentially be applied to severe weather events in order to assess the pricing of physical risk, especially on stock issuers with a high exposure to losses from natural catastrophes such as in the insurance or the real estate sectors.

Chapter 3: Impact of Climate Change Risk on Asset Investment

When examining the effect of climate change on pension funds, both the asset side and the liability side of the book should be considered, as they are both vulnerable to climate risks. In this section, the impacts of climate change on the risk-return profiles of assets commonly deployed in pension fund investment portfolios are explored. To make the scope of the research manageable, the focus is on public capital market investments, but the authors acknowledge that private placements and alternative assets are also often used in certain pension fund models such as the "Canada model."

A pension fund's public market investments largely consist of two asset classes: fixed-income securities and equities. While fixed-income products such as bonds provide a reliable source of funding for pension liabilities, equities have the advantage of being relatively more rewarding from the long-term growth perspective. As such, the quantitative work in this section is divided into two parts by exploring the impacts of climate risk on fixed-income assets and on equities, respectively. Some comments will also be made on the effect of climate change on stranded assets and alternative investments.

3.1 THE EFFECT OF CLIMATE CHANGE ON FIXED INCOME ASSETS

To quantify the impact of climate change risk on a financial product, one may resort to the asset's issuer's ESG characteristics including its carbon footprint in operations, its climate adaptation strategy, and its exposures to climate-sensitive sectors. While a company-level ESG rating is a useful resource for such purposes, there have been concerns raised on the inconsistency of ESG ratings from different vendors as in Berg et al.(2022), as well as the black-box nature of the rating schemes. In Paquet et al. (2023) and Janosik and Verbraken (2021), Climate Value-at-Risk (Climate VaR) was used as an alternative index of climate risk exposure at a corporate level.

Introduced in 2017 by Carbon Delta (later owned by MSCI), Climate VaR measures companies' exposures to risks and opportunities from climate change in the long term. The underlying model identifies and quantifies climate-driven vulnerabilities of the business. Details can be found in a report published by the United Nations Environment Program Finance Initiative (UNEP FI, 2019). Below is a summary of the model.

1. Under a particular allocation approach, future climate costs or profits of the firm are projected for different global climate scenarios reflecting physical risk, transition risk, and technological advancements.
2. Such costs or profits are discounted to calculate the total present value at time zero using i) the firm's weighted average cost of capital (WACC) of the enterprise in the first few years, and ii) Sector average WACC in later years (for stability). This result is referred to as the Present Value of Carbon Cost (PVCC).
3. As the PVCC depends on the underlying scenario and the associated probability of realization, calculating this metric for all the scenarios in the sample probability space considered would create a distribution of carbon costs, from which tail metrics such as VaR are easily derived.

Although the exact procedure to project future costs remains proprietary, a similar logic is adapted into this study with a focus on transition risk. A customized model is built, where two additional parameters are introduced to better reflect actual practice in the industry:

- An adaptation rate $\theta \in [0,1]$: the rate at which a company decreases their emissions without fundamentally reducing operational efficiency, achieved through technological investments.
- Mitigation cap M: a maximum annual emission reduction that a firm may achieve due to willingness or capacity. Often this equals the firm's annual emission, though under certain scenarios additional reductions must be achieved to meet regulatory standards by obtaining excess carbon credits/allowances.

Given a projection horizon $[t_0, T]$ partitioned into annual intervals, the model further assumes that:

- Each firm maintains a fixed pro-rata share of the annual global emission reduction each year, calculated based on its starting emission level.
- As a going concern, annual emission reduction and carbon costs beyond the projection horizon remain the same as their last projected values in the projection horizon.

Let the sets $\{Emission_{s,t}\}_{t\geq t_0}$ and $\{Carbon\ price_{s,t}\}_{t\geq t_0}$ be respectively the projected pathways of global greenhouse gas (GHG) emissions and unit price of carbon (per ton) under a climate scenario s. The price of carbon represents the cost of emissions beyond those already captured under current policies. The required emission reduction for a firm in year t under the scenario, denoted by $ER_{s,t}$ is derived as follows:

$$ER_{s,t} = Firm\ emission_{t_0} \max\left\{\min\left(\frac{Emission_{s,t} - Emission_{s,t_0}}{Emission_{s,t_0}}, M\right) + (1-\theta)^{t-t_0} - 1, 0\right\},$$

where $Firm\ emission_{t_0}$ is sum of the Scope 1 and Scope 2 GHG emission of the firm at the projection starting point. Definitions of the scopes of GHG emissions are included in the Glossary of this report.

The carbon costs in the scenario for year t, $Cost_{s,t}$ is given by (where the prices can be adjusted for inflation):

$$Cost_{s,t} = \begin{cases} ER_{s,t}\ Carbon\ price_{s,t} & if\ t \leq T \\ Cost_{s,T} & if\ t > T \end{cases}$$

Finally, the PVCC of the firm at time t_0^* in scenario s is calculated using the following equation:

$$PVCC_s = \sum_{t=t_0}^{\infty} \frac{Cost_{s,t}}{(1+WACC)^{t-t_0}} = \sum_{t=t_0}^{T} \frac{Cost_{s,t}}{(1+WACC)^{t-t_0}} + \frac{Cost_{s,T}}{WACC(1+WACC)^{T-t_0}}$$

where $WACC$ is the weighted average cost of capital of the company calculated at the projection starting point.

For the application in this analysis, it is more convenient to convert this cost into a percentage of the firm value. The underlying logic is that once such climate change driven costs are recognized by the market, an adjustment to the firm value will occur and thus affect the fair value of its issued bond. A relative present value of carbon cost (RPVCC), calculated under a given scenario s, is introduced as:

$$RPVCC_s = \frac{PVCC_s}{Firm\ value_{t_0}},$$

where $Firm\ value_{t_0}$ is the starting fair value of a company.

Note that in practice, due to data limitations and limits of the scenario generator, the best estimate parameters need to be used. For example, in this research, the firm's 2020 emission data were used since those represent the most up-to-date data available, though the projection starting point is year 2024. The model also sets a framework only and can be adapted to include other risks such as physical risk as long as the associated cost data are available under the deployed scenarios.

In this study, the scenario projections are obtained from the Network for Greening the Financial System (NGFS). This is a collection of Integrated Assessment Models (IAMs) that forecast the future states of the Earth (temperature, precipitation, etc.) and related economic quantities (population, energy demand, carbon prices, etc.) until the end of the century for each climate goal and scenario as set out by the Intergovernmental Panel on Climate Change (IPCC). With a prudent assessment of the reasonability and the likelihood of each scenario given the current state of the world, three scenarios are considered in this study:

- Current Policies: there is no change to present climate control protocols. In this scenario, transition risk can be ignored as the carbon price (beyond those already incurred in existing schemes) remains zero until 2100. This scenario serves as a base scenario or benchmark in this sub-section.
- Below 2°C: climate policies are introduced immediately to limit global warming to 2°C above pre-industrial levels. In this scenario, transition risk is severe and global GHG emissions decrease instantly, but physical risk is limited.
- Delayed Transition: this scenario has the same objective as the Below 2°C scenario. However, the global GHG emissions are assumed not to decrease until 2030. As such, transition risk can be ignored in the near future, but it would be more pronounced around the time of the changes.

More information on the scenarios is available on the Scenarios Portal of NGFS. Corporate data such as the firm value and WACC were obtained from Bloomberg.

The above model provides an estimate of firm value lost as a result of climate change. To translate the results to an impact on fixed income (i.e., bond) values, additional quantitative tools are needed. Intuitively, from the traditional corporate finance perspective, given the face amount of the firm's total debt, the firm's equity represents a call option on the firm asset value with a strike equal to the debt face amount. The debt holders, aside from being entitled to the face value, are essentially in a short position of an otherwise identical put option, as can be derived from the put-call parity relationship. Hence, each dollar lost in firm asset value upon recognition of the PVCC does not entirely translate to the bond value but varies based on the option's delta dictated by the firm characteristics. Assumptions on the firm value dynamics must also be made.

For this purpose, a variation of the Merton model (Merton, 1974) is used. The Merton model is one of the most used credit risk models and provides a simple way to quantify the financial structure and credit risk of a company by using solely its enterprise values (which are the sum of its equities and debts). Under the Merton model, the time-t firm asset value (which is more commonly referred to as a firm value in practice) follows the dynamics given by the following stochastic-differential equation:

$$dV_t = \mu V_t dt + \sigma V_t dW_t \ ,$$

where W_t is a standard Brownian Motion under the real-world measure, μ is a drift parameter capturing the real-world growth rate of the firm value with the associated volatility parameter σ (both annualized by convention). Let E_t and D_t be a total equity value and a total debt of the company at time t. Then, two key results from the Merton models are obtained:

i) $V_t = E_t + D_t$ for all t (i.e. the firm value is the sum of the total equity and the total debt).

ii) Let D_τ be the total face value of the firm's debt maturing at time τ. Assuming that all the necessary conditions for risk-neutral valuation hold, the Black-Scholes formula gives:

$$E_t = V_t \ \Phi(d_1) - D_\tau \ e^{-r(\tau-t)} \ \Phi(d_2),$$

where Φ is the cumulative distribution function of the standard normal distribution, r is the risk-free interest rate,

$$d_1 = \frac{\ln{(V_t/D_\tau\,)} + (r + \sigma^2/2)(\tau - t)}{\sigma\sqrt{\tau - t}}, \qquad d_2 = d_1 - \sigma\sqrt{\tau - t}.$$

At time 0, we would trivially have $D_0 = V_0 - E_0$. Under consideration of climate change, for each scenario s, V_0 is replaced by $V_0(1 - RPVCC_s)$, and E_0 is re-calculated from the formula above.

From these formulas, one may assess the loss of the debt value D_0 due to transition risk under each climate scenario versus the base scenario. The relative loss in debt value, when estimated using bond-specific maturities, would capture the relative impact of climate change on the bond.

As illustrative examples, the model and methodology presented above are applied to six market-traded bonds of similar time to maturity (26-27 years) from six different sectors: materials, energy, utilities, consumer staples, telecommunications, and information technology. These issuers vary in their carbon intensity (as measured by a carbon-emission-to-enterprise-value ratio (Tan et al., 2018)) as well as their capital structure, which are critical factors that dictate the impact from climate change risk.

For data collection, quarterly enterprise values of each issuer from January 1, 2002 to December 31 inclusive, 2023 were obtained from Bloomberg. Return volatility is estimated and annualized. The risk-free rate is obtained and specified externally by using the U.S. treasury bill quote. Note that alternatively, one may perform a calibration exercise of the option valuation model to the actual market capitalization of each issuer. Table 3.1 summarizes the impact of climate change risk on bond values as of January 1, 2024, compared to the base scenario under the proposed methodology. Note that the carbon intensity calculation uses 2020 emission data.

Table 3.2

IMPACT OF CLIMATE CHANGE RISK ON BONDS FROM SELECTED ISSUERS

Issuer	Sector	Carbon Intensity (Ton/M Firm Value)	Debt to Value Ratio	Bond Value Loss (Below 2°C)	Bond Value Loss (Delayed Transition)
Air Products & Chemicals	Materials	364	0.18	18.08%	24.76%
ExxonMobil	Energy	245	0.11	10.88%	15.47%
Pacific Gas & Electric	Utilities	43	0.60	5.15%	6.19%
Coca-Cola	Consumer Staples	17	0.15	0.09%	0.10%
Walt Disney	Telecommunications	6	0.23	0.18%	0.20%
Microsoft	Information Technology	<1	0.04	<1 bps	<1 bps

From Table 3.1, several observations can be readily made. The bond values decrease more under the Delayed Transition scenario. This is due to a smoother transition to green energy under the Below 2°C scenario than under the Delayed Transition scenario, albeit having identical goals at the end. This indicates that the paths of the policy transition have a material impact on the financial market. All three firms from the carbon intensive sectors exhibit material vulnerability in their bond values to climate change risk. Specifically, Air Products & Chemicals is estimated to experience a 24.76% bond devaluation under the Delayed Transition scenario, which is equivalent to a 1% credit spread widening for a 25-year duration bond.

In addition, holding all else constant, the impact of climate change risk on the bond value is higher for issuers with:

1. Higher carbon intensity, which is usually observed for the carbon intensive sectors.
2. Higher debt-to-value ratio, which is often observed among utility companies

Complication in comparison arises when these two characteristics give opposite signals. For example, Walt Disney Company has a much lower carbon intensity than Coca-Cola, yet the projected bond value loss is higher due to a higher debt level. This highlights the importance of a healthy balance sheet, where a lower leverage is able to heavily offset the impact of climate change on the credit-sensitive instruments such as bonds. It also highlights the importance of the granular firm-level analysis when assessing the performance of fixed income instruments under climate change.

In terms of a practical implication, the impacts may be interpreted as bond devaluations (i.e., higher credit spread) in the presence of climate change risk with possible rating migrations. For pension funds which lack the management expertise for such climate driven exposures, a safe play is to place preference on lower leveraged issuers with low carbon intensities, such as Microsoft in the illustrative example.

Furthermore, readers are reminded that the present analysis has not considered physical risk. If this factor is included, the bond value losses may worsen across scenarios (i.e., an increased likelihood of operational disruptions due to damaged facilities) and hit more industries (e.g., real estate). For pension funds, these impacts may represent greater uncertainty on the asset side of the book, especially since fixed-income securities are expected to provide a reliable source of income to meet liabilities.

It is recognized that the proposed methodology suffers several limitations. For example, the Merton model does not take into account rare and extreme market events. The analysis carried out above also does not account for default on coupon payments. As a result, practitioners are encouraged to be mindful of these issues as well as to consider applying more refined credit risk models.

3.2 THE EFFECT OF CLIMATE CHANGE ON EQUITIES

This section explores the impact of climate change on the returns of an equity. The concept used here is climate risk exposure (CRE), originally introduced in Tan et al. (2018). The same methodology in Tan et al. (2018) and Fang et al. (2019) is used to quantify CRE and translate the associated risks to potential effects on equity returns.

In the previous analysis for fixed-income instruments, the risk of interest is a climate-driven loss in the issuer firm value and default probability, which calls for the deployment of granular structural models with reference to the firm's balance sheet. In contrast, for equity returns, a more modular approach is preferred as it allows a systematic and comprehensive assessment of risks and opportunities posed by climate change. Four factors of climate risk are assumed to affect the stock returns, which follow Tan et al. (2018):

- Technology (T): the effort in transitioning towards a greener energy economy. It takes into account the future investments in research, development, and implementation of new technologies. It also includes the adverse effects of green innovations on traditional energy sectors.
- Resource availability (R): the fluctuations in available natural resources due to the chronic changes of weather conditions. The general rise in temperature brings new weather patterns both on land and in the ocean, which may worsen or improve the profit, thus the investments, in industries relying on natural resources such as materials or agriculture.
- Physical impact (I): the damages caused by increasingly extreme weather events. This is the most identifiable factor with events causing public concern such as floods, wildfires, or hurricanes. This risk affects every industry with business in physical assets, such as real estate and insurance.
- Policy (P): the introduction and enforcement of future climate control protocols. New climate policies to reduce GHG emissions and improve use of resources are continuously adopted worldwide. Corporations with outdated practices either need to invest in technologies or may face compliance issues.

Since each of these four factors consists of numerous sub-drivers with intertwined financial consequences, it is common to quantify these factors by using proxies. Table 3.2 gives some examples of such proxies, where proxies in bold were used in this study.

Table 3.2

EXAMPLES OF PROXIES FOR CLIMATE RISK FACTORS

Factor	Proxies
Technology (T)	**Investment in CO2 transport and storage (USD/year)**, Investment in biomass energy (USD/year), etc.
Climate change (C) (including R and I)	**Global temperature above pre-industrial level (°C)**, Radioactive forcing (W/m2), Insurance claims (USD/year), etc.
Policy (P)	**Carbon price (USD/ton CO2)**, Emission reduction target (ton CO2/year), etc.

The same climate scenarios were considered: Current Policies, Below 2°C, and Delayed Transition. Projected proxy values in each scenario were collected from NGFS and are normalized by using the following formula (Tan et al., 2018):

$$f_{i,s,t} = \frac{pr_{i,s,t} - pr_{i,s,min}}{pr_{i,s,max} - pr_{i,s,min}}$$

where $f_{i,s,t}$ is the normalized indicator of factor $i \in \{T, C, P\}$ at time t in scenario s, $pr_{i,s,t}$ is the value of the proxy of factor i at time t in scenario s, $pr_{i,s,min}$ and $pr_{i,s,max}$ are the minimum and maximum value respectively of the proxy of factor i over the entire pathway in scenario s. This normalization is necessary to make the indicators of the three factors comparable, as they are combined in the following expression to measure the climate risk exposure (CRE) of a company or an industry sector (Tan et al., 2018):

$$CRE_{s,t} = \lambda_T f_{T,s,t} + \lambda_C f_{C,s,t} + \lambda_P f_{P,s,t}$$

where $CRE_{s,t}$ is the climate risk exposure at time t in scenario s. The coefficients λ_T, λ_C, λ_P are between -1.0 and 1.0, which represent the sensitivities of a company or sector to each factor (assumed to be constant over time). These sensitivity parameters are in practice subjectively assigned to each entity by considering its operations, geographic location, market served, and commitment to climate mitigation efforts, etc., and by consulting external references such as the Actuaries' Climate Index (ACI).

In this analysis, the effect of CRE movements is examined on mean equity returns at the sector level. Table 3.3 tabulates the sensitivity parameters assigned to each sector in this study, which is performed in increments of a quarter. Note that the sensitivities take negative and positive values depending on whether the factor presents additional risk or opportunity to the sector.

Table 3.3

FACTOR SENSITIVITES BY SECTORS

Sector	λ_T	λ_C	λ_P
Consumer Discretionary	0	0	-0.25
Consumer Staples	0	-0.25	0
Energy	-0.5	-0.5	-1
Financials	0	-0.25	0
Health Care	0.25	-0.25	0
Industrial	0	-0.75	-0.5
Information Technology	0.25	0	0
Materials	0	-0.5	-0.75
Real Estate	0	-1	0
Telecommunications	0	-0.5	0
Utilities	-0.25	-0.5	-0.75

Once the projected CRE results for each climate scenario are obtained, these time series are then translated into pathways of stock return changes by using a recalibrated transformation function suggested in Fang et al. (2019):

$$\Delta r_{s,t} = \frac{\pi}{10} * \arctan\left(0.08\left(CRE_{s,t+1} - CRE_{s,0}\right)\right)$$

where $\Delta r_{s,t}$ represents the change in equity return over the period $[0, t]$ in scenario s compared to the current mean return. In practice, pension fund managers could formulate a view matrix of stock return changes by using an appropriate $\Delta r_{s,t}$ projection where t aligns with the investment horizon of the portfolio. These changes in the mean equity returns also provide an overview of the reactions of the stock market sectors to climate change over the length of the investment strategy.

As an illustrative example, Table 3.4 exhibits the projected return impacts under the three scenarios, where the investment horizon is set to 40 years. As one may expect, the impacts differ substantially across the sectors. As the Current Policies criterion is characterized by low technology and policy risk but a high physical risk, industries vulnerable to severe weather conditions such as real estate suffer heavily in this scenario. In contrast, Below 2°C and Delayed Transition are characterized by strong commitments to climate mitigation, and are, thus, associated with generally high technology and policy risks but a relatively low physical risk. As a result, information technology benefits from these scenarios even more than under the Current Policies scenario. Across the three scenarios, the carbon intensive sectors are most adversely impacted in expected return, while the information technology and health care sectors exhibit a strong defensive force against climate change.

Table 3.4
PROJECTED SHIFTS IN EQUITY SECTOR RETURNS OVER 2024 TO 2064

Sector	Current Policies	Below 2°C	Delayed Transition
Consumer Discretionary	0.00%	-0.35%	-0.50%
Consumer Staples	-0.35%	-0.62%	-0.62%
Energy	-1.31%	-3.57%	-3.57%
Financials	-0.35%	-0.62%	-0.62%
Health Care	-0.04%	-0.15%	-0.17%
Industrial	-1.05%	-2.55%	-2.86%
Information Technology	0.31%	0.47%	0.45%
Materials	-0.70%	-2.29%	-2.74%
Real Estate	-1.40%	-2.47%	-2.47%
Telecommunications	-0.70%	-1.23%	-1.24%
Utilities	-1.00%	-2.76%	-3.18%

3.3 STRANDED ASSETS

The final component of climate change risk affecting investment returns is stranded assets. These are assets whose economic values cannot be fully realized due to climate-related regulations and technological developments. The best example is the oil reserves owned by large energy producers. Although the reserves can still be exploited at a maximum capacity for many years, an exploitation may be banned under a strict enforcement of climate control regulations. Such a risk has been conceptually validated by climate scientists with the Below 2°C objective, where a large portion of the global oil reserves must remain unexploited for it to be achieved. Similar stranded assets may exist in the materials industry.

Stranded Asset Risk (SAR) has a long-term and highly uncertain nature, since it depends not only on which climate protocols are enforced, but also when they take effect. In this section, a summary of the single-period methodology introduced in Tan et al. (2018) to quantify SAR is produced.

SAR of an asset can be divided into three components: a probability of being stranded (PS), a current market value of the asset (M), and a percentage loss in market value if the asset becomes stranded (LGS).

$$SAR = M * LGS * PS$$

Firstly, PS can be estimated by using views of future policies and data on the expected capacity of the asset. In the example of an oil reserve, the information needed is estimates of its full capacity E and the exploitation threshold C beyond which exploitation is no longer economically viable due to relevant regulatory factors (i.e., the reserve is stranded if $E > C$). Note that C comes from climate control efforts and can be determined externally (such as when C is determined by the authority at a fixed level) or internally due to budgetary constraints (such as when the firm needs to pay carbon tax or purchase carbon allowances). Therefore, the following result is reached:

$$PS = P(E > C) = \mathbb{E}[1_{E>C}].$$

Secondly, the loss given the asset being stranded expressed as a percentage of the asset's current market value reflects the difference between the full capacity and threshold, as well as any recoverable R such as the sale of excess equipment or the transformation of excess resources. Note that LGS can be derived using the following formula:

$$LGS = \frac{E - C - R}{M}.$$

Clearly, the stranded asset risk represents a potential future loss in firm value upon recognition of the risk by the market. As a result, it affects both the fair values of bonds and equities issued by the firm, and in nature fits into the model and framework in Section 3.1 in arriving at an estimated devaluation percentage of each type of the asset. A stranded asset assessment and valuation requires highly granular and specialized insights into the asset of interest, which are generally viewed as being idiosyncratic. Note that this framework can be extended to a multi-period analysis, which is especially relevant for long-term investments such as pension funds' portfolios. Nonetheless, the single-period case is useful to demonstrate the key idea of it and its elements.

3.4 CONSIDERATIONS FOR ALTERNATIVE INVESTMENTS

In addition to the traditional fixed income and equity domain, specific considerations should also be made for alternative investments in the presence of climate change. Institutions have been increasingly turning to alternative investments to supplement their traditional fixed-income/equity asset mix. This is best exemplified by the Yale Endowment model and the Canada Pension Plan model (the Canada model) which have up to 50% of assets allocated to alternatives. This is particularly relevant for pension plans that often have the capacity to absorb the illiquidity embedded in major alternative investment vehicles (hence earning the liquidity premium). Notably, Ivashina and Lerner (2018) stated that on average, pension funds in developed markets increased their weights in alternative investments from 7.2% to 11.8% during the period of 2008 to 2017, representing a 64% increase.

Hedge funds and private equity (PE) are two of the top candidates among the alternative investment classes due to their proven abilities to enhance the risk-adjusted returns (hedge funds) or absolute returns (mostly PE funds) when added to the traditional bond-equity portfolio mix. However, these investments are extremely heterogeneous and require skilled managers to leverage a wide range of strategies and investment vehicles. This prevents drawing clear conclusions on the impact of climate change on such asset classes, where an analysis needs to be done on a granular case-by-case basis. In addition, many hedge fund strategies are relatively unaffected by systematic risks such as climate change in their return profile. Examples include event-driven strategies such as merger-arbitrage, relative value strategies including convertible arbitrage, equity strategies earning short term alphas such as equity market neutral, and most opportunistic strategies. In addition, unlike stocks and bond price data, reliable fund level performance data are rare and often subject to survivorship and self-reporting biases or based on smoothed valuations in the case of early stage private equity funds. This further erodes the feasibility of conducting a credible quantitative analysis.

As a result, the assessment of the impact of climate change should start with prudently examining the mandates and philosophies adopted by the hedge fund or private equity fund managers. This assessment focuses on whether climate-change impacts have been factored into the investment process or strategy. Following such a path, a preferred candidate may be a thematically driven global macro hedge fund with a focus on climate risk resilient securities, or private equity fund investing in projects that are expected to benefit from climate change. Relevant rules could be added to the selection process of the funds. Nevertheless, it remains challenging to estimate quantitatively the impact of climate change on the returns of these asset classes due to the active management involved.

Real estate investment, on the other hand, is an alternative investment class more affected by climate change in its exposure to direct physical risk from natural catastrophes associated with global warming. Thus, these assets should have uneven exposures to the physical risk component of climate change based on their geographic location. For real estate investments targeted at price appreciations, the proposed factor-based climate change impact quantification framework for equities in Section 3.2 can be adapted to obtain an estimated impact on price returns at a geographic level. Table 3.3 provides an illustrative risk factor sensitivity for the real estate sector in general, which could be modified to reflect the risk profile of the specific property's location and conditions. For example, the coastal region buildings will have a higher exposure to physical risk compared to in-land properties. Other analysis and valuation methodologies relying on property-specific features can also be incorporated but it is beyond the scope of this study. Transition risk also plays a role in real estate investment. As climate risk heightens, stricter building codes as well as higher insurance premiums in climate-sensitive regions could make an investment property "stranded" in a sense that the operating expenses exceed the revenues from the property. This will also be discussed in Chapter 5 of this report.

Finally, private credit is an alternative investment class offering additional exposure to the credit market by generating higher potential yields from loans to individual and smaller businesses that generally lack access to the traditional lending channels. From a risk-return perspective, under full information transparency, private loans should mimic their counterparts in the public market with a similar credit spread, where the climate risk impact quantification framework for fixed-income in Section 3.1 could potentially be adapted to serve this asset class. In practice, there exists significant heterogeneity among private borrowers with less-than-ideal information transparency, which calls for an elevated skill set on the part of the fund managers.

In summary, due to the vast heterogeneity among alternative investment classes, strategies, and level of active management involved, a universal quantitative framework for the impact of climate change on alternative assets appears to be highly intractable at the present time. While the possibility remains for adapting the frameworks in Sections 3.1 and 3.2 to certain asset class/strategy mixes, an analysis will be best performed at the granular investment level and on a case-by-case basis. On the other hand, future study of the implications of climate change for hedge funds and private equity managers is highly desirable, but outside the scope of this study.

Chapter 4: Impact of Climate Change Risk on Pension Liabilities

In the previous chapters, the effect of climate change on financial markets has been considered, covering only the asset side of the balance sheet of pension funds. In this chapter, the focus is shifted to the liability side. Multiple aspects of the effect of climate change on population mortality are examined which have key implications on pension liabilities. In particular, it is of interest to study the additional longevity risk potentially introduced by climate change over the long term, where "long term" in this study is defined as a period that spans over 50 years. Such an analysis is especially relevant for pension plans due to their nature. First, pension investment strategies are generally liability driven, and hence, they call for a separate consideration for the liability side of the balance sheet. In addition, the long investment term presents a sufficiently extended horizon for the impacts of climate change to unfold.

Under the assumption of an asymmetric distribution of heat and cold induced mortalities amongst age cohorts of a given population, an increase in global temperature over time could mean a shift in future survival rates of the general pensioner group away from those commonly assumed today by actuaries. This can result in a severe misestimation of the present value of pension liabilities. For a defined benefit plan such as the CPP in Canada, this could mean shortfalls in funding the future pension liabilities. Hence, it must be prudently assessed and factored into the plan's investment strategy in order to generate sufficient and sustainable growth in its asset portfolio.

The analysis presented in this chapter focuses on the present and future association between the mortality rate, temperature, and age cohorts by utilizing a set of statistical approaches, where projections are made under the three climate change scenarios defined in the previous chapter. Note that while climate change leads to increasingly unpredictable natural catastrophes, extreme weather events, and vector-borne diseases, these potential mortality drivers are not explicitly modelled in this study but captured indirectly via their association with temperature rise. This section is divided into two parts: a qualitative analysis based on a careful review of selected literature, and a quantitative framework which focuses on capturing the effect of climate change on mortality and longevity.

4.1 EXISTING STUDIES ON THE EFFECTS OF CLIMATE CHANGE ON MORTALITY

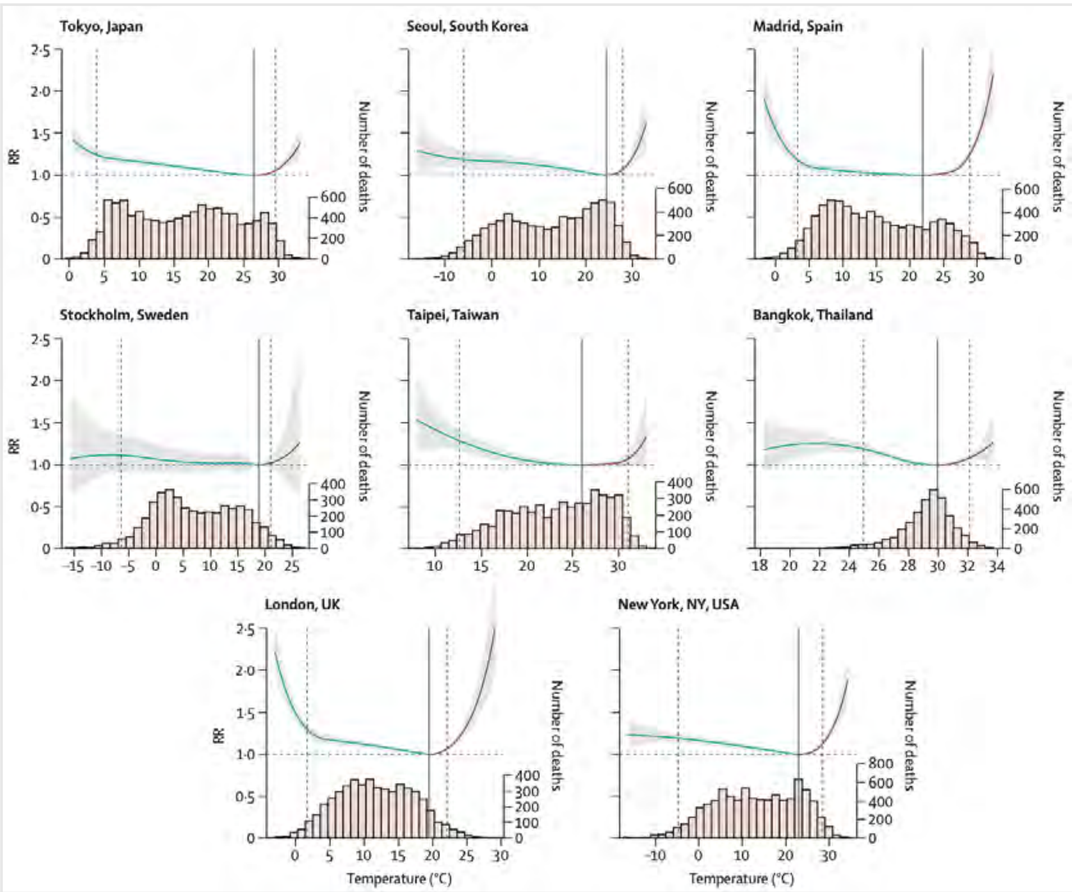
As mentioned in Chapter 1 of this report, there exist two main approaches to mortality modelling: extrapolative and explanatory. While it is a fairly common practice for actuaries to use extrapolative models to forecast future dynamics of a population, explanatory models are more frequently used in climate-risk research. Examples include Gasparrini et al. (2015), Heutel et al. (2021), Zhao et al. (2021); Carleton et al. (2022), Deschenes (2022), and Rai et al. (2022). Explanatory models allow us to assess the effects of climate change on elderly mortality on a granular level by considering several key factors such as:

- Physical sensitivity to temperature: the relationship between mortality rate and temperature (heat or cold) plays a major role in explaining historical trends and forecasting on how mortality would change in the future in the presence of climate change. It is worth noting that these correlation measures may be different from one geographic location to another and may change over time.
- Adaptation level: Socioeconomic adaptation to climate change (i.e., preventative measures such as air conditioning or shorter outdoor work hours) has proven to substantially lower human vulnerability to temperature. As a result, adaptation efforts are a critical component to any historical data analysis and future projections.

A number of studies have shown that an empirical relationship between mortality and temperature follows a J-shape (or a V-shape) curve, as illustrated in Figure 4.1 sourced from Gasparrini et al. (2015). The results in this figure were estimated for populations in selected cities globally using data ranging from 1986 to 2012. The observation implies that mortality rate is higher during extremely hot or cold days, and lower during days with a moderate temperature. Intuitively, this means that areas with hotter climate would bear a greater mortality risk emanating from anthropogenic global warming, while colder regions would benefit from climate change thanks to warmer winters. In fact, studies including Zhao et al. (2021) and Carleton et al. (2022) have found that most countries in North America and Europe have more deaths from cold than from heat, indicating that overall, global warming may lead to fewer deaths in these two continents, and hence, a higher pensioner longevity risk for large pension plans.

Figure 4.1

THE ASSOCIATION OF MORTALITY RATE AND TEMPERATURE IN SELECTED CITIES



Source: Gasparrini et al., 2015

However, many studies reaching this conclusion have not accounted for the heterogeneity of the mortality-temperature relationship arising from a physiological adaptation of the population to local climates. The findings in Heutel at al. (2021) shows that when compared to populations living in hot regions, those living in cold regions have lower mortality during extremely cold days but much higher mortality during extremely hot days. This means that they tend to be more resilient to cold but more vulnerable to heat. This suggests that the population residing in hot regions may be relatively less affected by global warming (especially for mild temperature increases), while people residing in cold regions may suffer from more frequent intensely hot days. As such, the net effect of climate change on local pension plan liabilities would be best assessed via quantitative studies tailored to the specific climate and demographics of the region. Moreover, this conclusion may encourage large pension plans to incorporate a spatial factor in the assessment of the climate change effect on their beneficiary mortality. For pension plans largely in the payout phase, such considerations become even more meaningful as changing climate has an exacerbating effect on most elderly pensioners who experience deteriorating health conditions and limited mobility, as mentioned in Gutterman (2023).

Adaptation efforts such as price regulations of air conditioning or building regulations are expected to lessen the effect of climate change on mortality since they make living conditions more comfortable and resilient to effects of climate change. As new adaptation policies are introduced, the J-shape of the mortality-temperature association as seen in Figure 4.1 is expected to flatten out over time. Those adaptation measures themselves require significant financial support. Thus, low-income countries are more vulnerable to the long-term negative mortality impacts from climate change, while developed countries remain resilient and more likely to reap the benefits of global warming on mortality. These considerations are discussed in detail in Carleton et al. (2022), who also present a projected impact of climate change on general mortality rates globally under the climate scenario “Shared Socio-economic Pathway (SS)) 3 – Representative Concentration Pathway (RCP) 8.5” (which corresponds closely to the NGFS scenario “Current Policies” mentioned previously). The estimates seem to imply that pension plans in the U.S. and in Europe on average would likely be subjected to a higher longevity risk in the presence of global warming.

Last but not least, it is critical in this study to consider the differential impacts of climate change on mortality rates by age. Even within a population in the same geographic region or socioeconomic status, the main causes of mortality could differ substantially among age groups, which may in turn display varied degrees of association with temperature shifts. Interestingly, this seems to be a comparatively understudied area in the non-medical literature, which inspired the deployment of the statistical regression model introduced in this study as presented in the next section.

4.2 QUANTIFICATION OF THE EFFECT OF CLIMATE CHANGE ON MORTALITY

A common approach deployed in the aforementioned studies is a statistical model used to regress mortality rates (which represents a response variable) against temperature (which represents a covariate). Inspired by the high level of interpretability of these regression models, in this analysis, a similar model is proposed which takes into consideration the different effects of climate change on mortality by age group. A generalized linear mixed regression is implemented (in particular, a “fixed-effect quasi-binomial logistic” regression model) incorporating key elements of insights drawn from the selected review of the literature conducted in the previous section:

- A general mortality improvement trend over time
- Long term temperature shifts under climate change
- Any age cohort effect

The regression model is specified as follows:

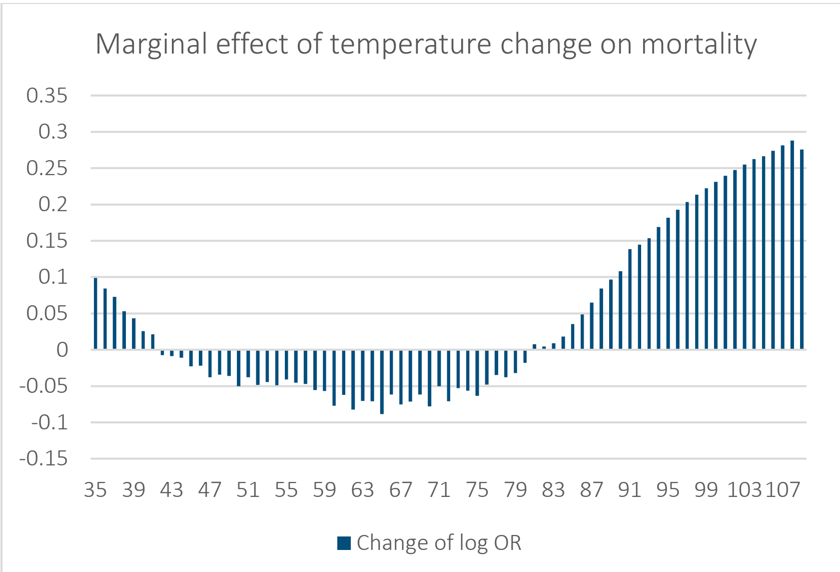
$$log\left(\frac{q_x(t)}{1-q_x(t)}\right) = \beta_0 + \beta_1 temp_t + \beta_2 t + \sum_{i=36}^{109} \beta_{3,i} 1_{\{x=i\}} + \sum_{i=36}^{109} \beta_{4,i} 1_{\{x=i\}} temp_t$$

where

- $q_x(t)$ is the probability a person aged x in year t dies within a year (as reported in life tables).
- t is a time index (where $t = 0$ for the year 1960).
- $temp_t$ is the mean temperature in year t in degrees Celsius.
- Indicator variable $1_{\{x=i\}} = 1$ if $x = i$ and 0 otherwise. The third term in the model captures the average age cohort effect on the future mortality path, while the last term captures the interaction between age cohort and temperature change.

In this equation, the response variable $log\left(\frac{q_x(t)}{1-q_x(t)}\right)$ is the log odds ratio (OR) of death occurring within a year for a person aged x at time t, where a higher log OR corresponds to a higher mortality rate. The effect of temperature on mortality is captured by the coefficients β_1 and $\beta_{4,i}$, where statistically significant coefficients $\beta_{4,i}$ highlight the differential effect by age. The time index variable is a proxy reflecting any general changes in mortality over time that are not explained by temperature changes, such as medical innovations or improved living conditions (i.e., $\beta_1 < 0$ represents a general mortality improvement over time). Finally, the coefficients $\beta_{3,i}$ capture the difference in long-term mean log OR of mortality by age. A more detailed explanation of each covariate in the regression model can be found in Appendix C.

Figure 4.2
COEFFICIENT ESTIMATES: MARGINAL EFFECT OF TEMPERATURE CHANGE ON MORTALITY BY AGE

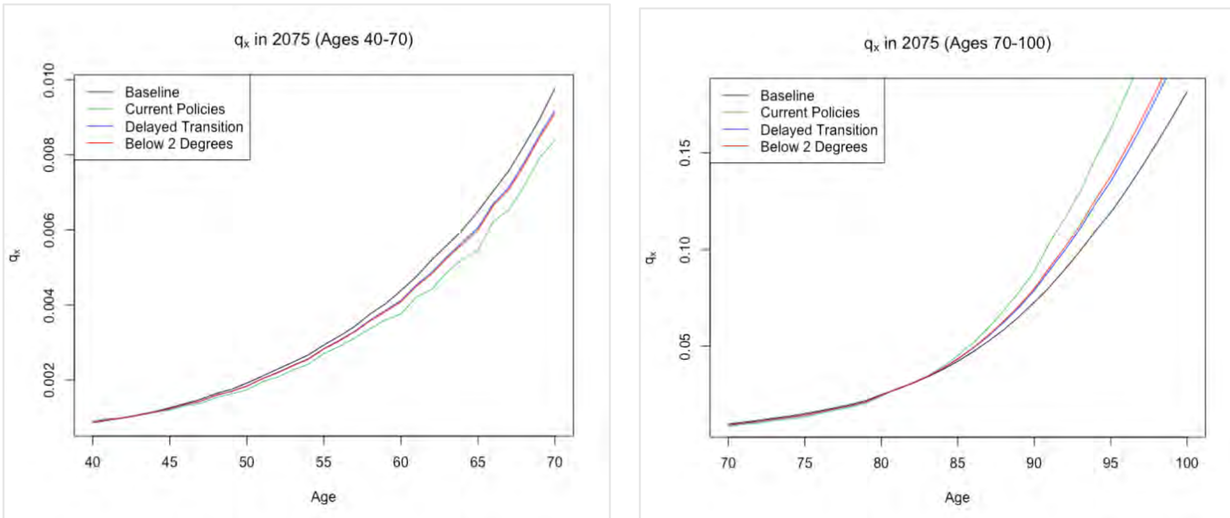


The model parameters are estimated using historical U.S. population mortality data for age cohorts 35 to 109 collected from the Human Mortality Database, as well as the U.S. annual mean temperature collected from Our World in Data (original data stored in the Copernicus Climate Change Service). Both estimation data sets cover the period from 1960 to 2019 inclusive. The estimation results are presented in Appendix C. The time index coefficient is estimated to be negative, consistent with the notion of mortality improvement over time as adopted in actuarial practice. On the other hand, the marginal effect of temperature change on mortality, which can be (loosely) viewed as the impact of 1°C temperature increase on the log OR of mortality (captured by $\beta_1 + \beta_{4,i}$) differs substantially by age group. See Figure 4.2. Overall, the impact of higher temperature on mortality rates is found to be a significant increase in mortality for the young (<40) and elderly (>80), but a significant decrease in mortality for the middle cohort (40 to 80). This interesting observation confirms our previous premise of the potentially differing impact of climate change on age groups, with important consequences for the projection of future pension liabilities.

The fitted model is used for projections of q_x until the end of the century under three climate scenarios: Current Policies, Delayed Transition, and Below 2°C, all of which were previously defined in Chapter 3. For comparison, projections are also made for a baseline scenario defined as a situation where future temperature remains at the 2019 level (i.e., in the absence of climate change). Figure 4.3 shows the projected one-year mortality rate by 2075. The graphs confirm the contrasting marginal effect of temperature increase on mortality rates. The projected mortalities of the middle-aged cohort (ages 40-80) are lower due to the rising temperature under the three climate change scenarios compared to the baseline. Since the Current Policies scenario entails a limited climate control effort and hence the largest temperature rise, it is associated with the highest level of mortality reduction among the three scenarios. This is followed by the Delayed Transition and Below 2°C scenarios, where climate control initiatives are in place to restrict the temperature rise. The exact opposite pattern is observed for the elderly (ages 80-100), who are predicted to be more vulnerable to temperature increase and would suffer more pronouncedly under the Current Policies scenario.

Figure 4.3

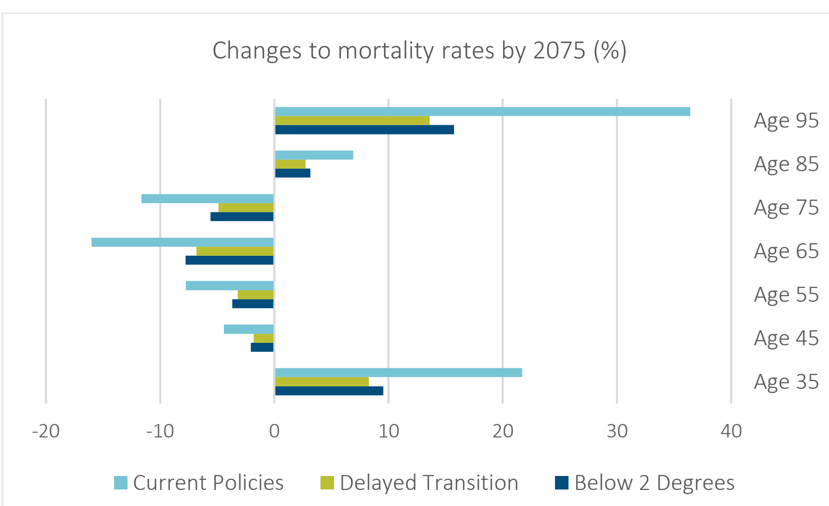
PROJECTED ONE-YEAR MORTALITY RATES BY 2075 UNDER DIFFERENT CLIMATE CHANGE SCENARIOS



Although climate change has an effect on mortality rates at every age (see Figure 4.3), the changes in mortality of younger ages are not as observable as those of older ages. For greater clarity, the mortality shifts due to the time component are removed (hence exclude general mortality improvement) in the next step. Figure 4.4 below gives a projected percentage change in mortality rates compared to 2019 attributable to only temperature change under the three scenarios. This percentage change is defined as $\frac{q_{x,s}(t)-q_{x,baseline}(t)}{q_{x,baseline}(t)}$ for age x at time t under the climate scenario s. The observations drawn from these results are largely consistent with those discussed previously. On a relative scale, the impact of climate change on mortality (positive or negative) is much greater under the Current Policy Scenario vs. the other two scenarios, which naturally follows from the uncontrolled physical risk from global warming it describes. However, the other two scenarios are associated with higher transition risks as discussed in the previous chapters. Such trade-offs in risks should be considered carefully by both pension plans and policymakers.

Figure 4.4

PROJECTED % CHANGE IN ONE-YEAR MORTALITY RATES BY 2075 ATTRIBUTABLE TO TEMPERATURE CHANGE



For illustration, a numerical example is shown below for a future pensioner aged 40 at the beginning of 2020 who expects a $1 beginning-of-year annual pension benefit starting at age 65. Using a 4% discount rate, the actuarial present value (APV) of future pension liability payments is shown for different scenarios in Table 4.1.

Table 4.3

EXAMPLE: PENSION LIABILITY FOR FUTURE PENSIONER AGED 40, 4% DISCOUNT RATE, UNIT ANNUAL BENEFIT

Climate Scenario	APV Pension Benefits	% Additional APV vs. Baseline
Baseline	5.0714	NA
Current Policy	5.0615	-0.195%
Delayed Transition	5.0904	0.374%
Below 2°C	5.0866	0.299%

The results show that compared to the baseline scenario, the pension liability for this representative pensioner is 0.2% lower under the Current Policy scenario of climate change, but 0.3% and 0.37% higher under the Below 2°C and Delayed Transition, respectively. From these results, it can be inferred that under the Current Policy scenario, the detrimental impact of global warming on mortality for the elderly-aged population is larger than the beneficial impact for the middle ages, and the opposite holds under the other two scenarios.

Although the projections from this numerical example are not comprehensive as the net effect of climate change on the liabilities of a pension policy depend on various factors within the model such as age, payout timeline, and interest rate, this example serves as an illustration of how the proposed model can be used to compute the effect of climate change on pension liabilities and how numerical results from this model can be interpreted. In practice, the model can be extended further to include additional covariates in the regression model to account for more relevant pensioner heterogeneity within the pension plan of interest (e.g. geographic location, socioeconomic status, and pre-existing health conditions, etc.), which renders a qualitative analysis of the effect of climate change on the pension plan's liabilities even more challenging.

Finally, the analysis in this chapter does not cover the impact of climate change on the economic actuarial assumptions used for pension liability valuations, notably the discount rate, which took a single constant value in the example. In fact, under both International Accounting Standards (IAS) 19 and Financial Accounting Standards Board (FASB) Accounting Standards Codification (ASC) 715, the discount curve used for pension liability valuation should be derived from yields of high-quality fixed income instruments, which can be affected by climate change in the long run following the arguments from Section 3.1. As pension liability valuation is known to be sensitive to discount rate assumption, practitioners may consider additional provisions to reflect future unfavorable discount rate shifts as the bond market reacts to climate change.

Chapter 5: Other Considerations of Climate Change for Pension Investments

In this chapter, several practical considerations for pension investments in relation to climate change risk are examined. These qualitative factors supplement our quantitative analysis, findings, and recommendations presented in the previous chapters, and should ideally be accounted for when building a sustainable portfolio of pension investments (both defined benefit and defined contribution).

5.1 THE USE OF GREEN BONDS FOR RETIREMENT INVESTMENT

Recent developments in sustainable finance have led to the creation of many sustainability-driven securities. Among them, green bonds, as a fixed-income asset, are a potential candidate for pension investments due to pension funds' asset allocations and cash-flow needs in funding pension payouts. Since green bonds are municipal or corporate bonds issued to fund green projects in climate adaptation or carbon sequestration, they could satisfy certain pension plan participants' sustainability preferences. However, as pension plans have fiduciary duties, the inclusion of an asset in these plans' portfolios would be based on the performance characteristics of the asset. Since green bonds are a relatively new product that has not been studied extensively, pension fund managers may be hesitant to consider them. Yet, some insights can still be drawn from the available studies.

Cortellini and Panetta (2021) provided the most recent comprehensive literature review that summarizes empirical studies on green bonds from 2007 to 2020. This review covers not only green bonds' yield premium (also known as the green premium or Greenium), but also their relationships to various markets, implications for green bond issuers, and characteristics of green bond markets. The term "green premium" refers to the yield difference between a green bond and an otherwise identical conventional bond. A negative green premium means investors are willing to pay a higher price to support the climate initiatives funded by the green bond. From the literature review, evidence on the existence and significance of a green premium is inconclusive, with 40% of studies on the primary market confirming the existence of a green premium, 40% having unclear results, and 20% showing no evidence of a green premium. Most of these studies use matching techniques where each green bond is compared to a conventional counterpart based on several criteria (credit rating, maturity, issuance amount, etc.). A practical implication here is that for a given bond, an investor may or may not be losing on yield by pursuing its green counterpart.

On the other hand, green bonds have been proven to be a good instrument to hedge the climate risk in a portfolio. Multiple studies mentioned in Cortellini and Panetta (2021) as well as a recent work of Dong et al. (2023) reach the same conclusion that compared to conventional bonds, green bonds have a lower return correlation with energy sector stocks. Therefore, green bonds are worthy of consideration for their hedging and diversification potential, especially for portfolios with heavy exposures to the energy market.

The framework proposed in this study recommends assessing green bonds at a granular security level, utilizing the techniques for quantifying the impact of climate change on fixed-income assets presented in Section 3.1. As a green bond represents the issuer's investments in climate adaptation and mitigation projects, the green aspect of the bond can be defined as a higher adaptation rate θ or a lower mitigation cap M in the required emission reduction of the bond issuer, thus lowering their present value of carbon costs. This would result in a lower future bond value loss across climate scenarios and reflects the feature of green bonds being (presumably) more resilient to transition risk than otherwise identical conventional bonds.

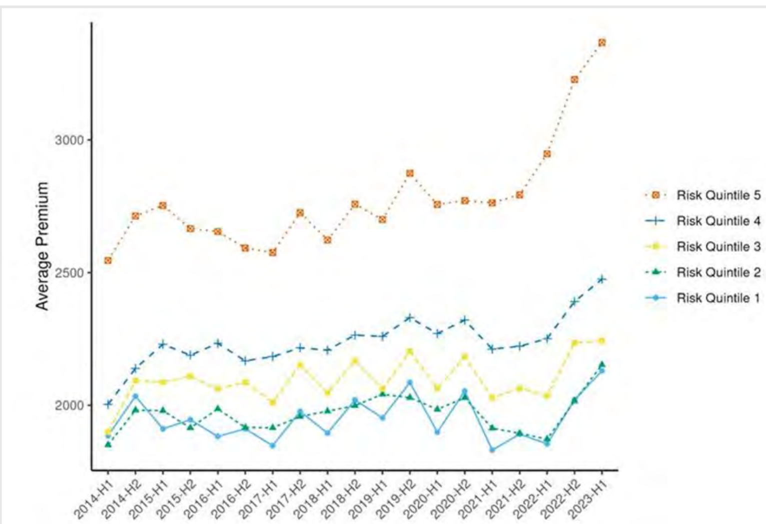
Note that in addition to the financial aspects, the analysis of green bonds requires extra prudence and investigation into the green initiatives being funded to avoid the risk of greenwashing. Greenwashing refers to companies making misleading claims about their environmental practices or products, whether deliberate or unintentional. This risk relates closely to the fiduciary duties of pension funds since greenwashing may trigger regulatory scrutiny and financial losses for the bond issuer and bondholders. Moreover, if the scope of fiduciary duties is extended to include non-financial sustainability considerations, holdings in greenwashed products may even present direct litigation risk for pension funds. To avoid the issue of greenwashing, pension funds' managers could make use of external opinions provided by the review and certification process of ESG rating agencies and green bond specialists.

5.2 IMPACT OF CLIMATE CHANGE ON REAL PROPERTY INVESTMENT

As climate change is accompanied by increasingly frequent and severe natural events, the real estate industry bears considerable climate risk. In this section, the effects of climate change on real estate as a physical asset are examined. While large pension funds would be more concerned with their investments in commercial real estate and infrastructure, for many individual retirees, their home is their most valuable asset, as pointed out by Abkemeier (2013) and Hill (2023). Therefore, for pension investing and more importantly personal retirement investing, it is essential to properly assess the effect of climate change on real properties and plan accordingly. Here the impact of climate risk on the value of a real estate property, related maintenance expenses, property insurance premiums, and potential stranding of the property are examined. Climate change drives real estate value via four forces: physical risk, transition risk, climate risk price correction, and climate migration, as introduced in Contat et al. (2024).

Figure 5.1

AVERAGE HOME INSURANCE PREMIUMS BY QUINTILES OF DISASTER RISK EXPOSURE



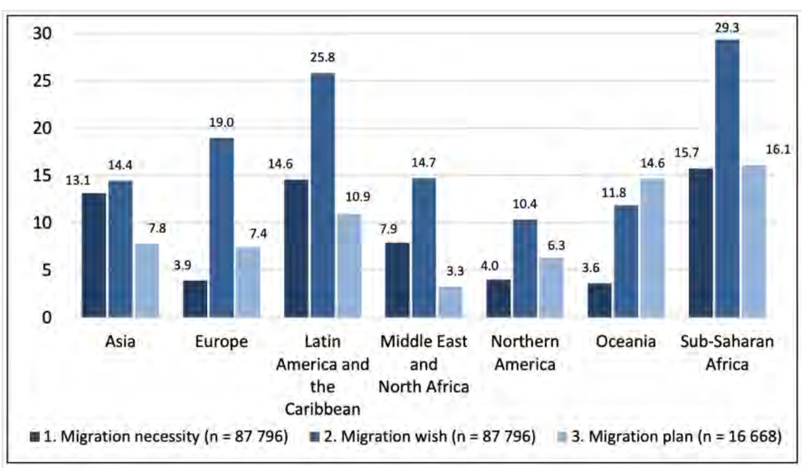
Source: Keys and Mulder, 2024

Physical risk refers to the physical impact of disasters and extreme weather conditions on the property. Increased frequency/severity of natural events such as hurricanes or wildfires leads to more property getting destroyed. Rapidly changing weather patterns may also accelerate wear and tear as mentioned by Burgess (2020). As such, the value of the real properties in affected areas would increase at a lower rate or even decrease due to higher maintenance expenses and higher insurance premiums, which is evident in highly vulnerable areas. Figure 5.1 shows the bi-annual U.S. home insurance premium in different zip codes grouped by quintiles of natural disaster risk exposure, reproduced from the study by Keys and Mulder (2024). The data on insurance premiums is from the U.S. National Association of Insurance Commissioners (NAIC), while the disaster risk exposure is measured by the National Risk Index (NRI) designed by the Federal Emergency Management Agency (FEMA). A large gap between high and low risk areas can be clearly observed and has started to widen in recent years. In areas vulnerable to climate-driven catastrophes, properties may even become too expensive to insure. On the other hand, in rare cases, the authority may deem a property unusable or uninhabitable before it actually gets ruined due to factors such as rising sea levels in coastal regions, according to the U.S. Environment Protection Agency (2022). For properties pending development, climate change leads to increasing costs of materials from resource scarcity and decreasing construction productivity from inclement or scorching weather, both adversely impacting their values.

Transition risk refers to the potential direct and indirect financial loss in real properties as new building codes and regulations are introduced in response to the threats of climate change. An example is the U.S. National Flood Insurance Program (NFIP)'s floodplain management requirements. These requirements involve continuously updated flood maps, where properties in areas prone to flooding must go through specific renovations to withstand extreme physical forces from flood events. On the other hand, building regulations targeting reductions in carbon emission and preservation of natural resources were introduced, which for example includes the energy efficient building codes in the UK. With the prevailing trend and initiatives in climate control and the green economy, further introduction and expansion of relevant regulatory schemes can be anticipated. Moreover, new rules may be enforced by property insurance schemes that warrant increased premiums or reduced coverage if the property does not meet the evolving requirement, especially for those in the "high risk" regions. All these prospects would induce larger upfront and recurrent expenses for property ownership and maintenance, thus lowering the value of the property.

The third factor is the market pricing of climate risk and potential future price corrections, which was discussed in Chapter 2 in the context of the stock market. A few references considered this factor in the context of private housing. Evans et al. (2022) and Gourevitch et al. (2023) quantified the unpriced flood risk in the U.S. housing market. They argued that residential properties in the U.S. today were overvalued by hundreds of billions of U.S. dollars as flood costs have not been accounted for. As a result, if the climate risk is fully priced in the future, the property value is expected to decrease substantially. These two studies also remarked that the effect of repricing is heterogeneous among homeowners with respect to geographic location and household income. Retirees need to be particularly mindful if they rely on their property values to fund some of their retirement expenses.

Figure 5.2
CLIMATE MIGRATION ASPIRATIONS BY GEOGRAPHIC LOCATION (%)



Source: Deuster, 2024

Finally, climate migration refers to population movements away from areas vulnerable to climate change. These displacements may be temporary due to the occurrence of natural disasters or permanent due to climate change threatening livelihoods and raising costs of living in such areas in the long run. As climate change unfolds, these displacements may happen more often and temporary displacements may become permanent as natural disasters become more frequent and the living conditions become more challenging (see Huang (2023)). As a result, people living in these regions are motivated to sell their properties and move away, while people from other regions are reluctant to move in. This results in a lower demand for private and commercial properties as well as infrastructure in these areas, creating a momentum of price decline in the associated real estate market which negatively affects local retirees whose main asset is their houses, as well as those pension funds with large investments in climate vulnerable areas. The opposite argument applies to real estate in regions benefiting from climate change (such as colder regions that are expected to experience warmer winters as global warming prevails). To show the significance of climate migration, Figure 5.2 is reproduced from Deuster (2024). It depicts (for different global regions) the share of respondents to the Gallup World Poll who considered themselves in need to move (migration necessity), who desired to move permanently to another country (migration wish), and who planned to move permanently to another country in the next 12 months (migration plan) due to climate change problems. It is interesting to observe that over 10% of North American respondents and about 20% of European respondents expressed their migration wish due to climate related issues. Figure 5.3 is reproduced from the 2021 report by the Internal Displacement Monitoring Center. It shows the number of people that relocated in North and Latin America in 2020 due to conflict and violence (230,000 people) and natural disasters (4,528,000 people) as well as their original location. These numbers sum up to 11.8% of total global displacements in the year. Among the natural disaster-driven displacements, the majority happened in the U.S. (1,700,000 people).

In addition to the devaluation of properties, climate change may also turn a property into a stranded asset. Through physical risk and transition risk, a property may become stranded if it is in a climate vulnerable area such as a coastal region with severe threat of rising sea level or hurricanes, even though the property itself is still structurally sound. The high cost of renovation (to meet stricter regulations) as well as higher insurance premiums could make the investment not economically viable. A commercial infrastructure may also be stranded due to transition risk if it is specifically built to serve carbon-intensive sectors such as oil production (as mentioned in Section 3.3). In both cases, the stranded asset risk quantification framework from Section 3.3 can be adapted to estimate the associated financial loss due to climate change.

Figure 5.3
NEW POPULATION DISPLACEMENTS IN NORTH AND LATIN AMERICA IN 2020 DUE TO CONFLICT & VIOLENCE AND DISASTERS

Source: Internal Displacement Monitoring Centre, 2021

In conclusion, there is a consensus among researchers in the field that climate change has impacts on the value of real estate investments, especially in climate-sensitive regions. However, one must note that the consideration of such risk in asset portfolios is not fundamentally different from other risks and must be quantified on a case-by-case basis. This should not come as a surprise, especially for residential real estate valuation, where the heterogeneity among properties and owners as well as stale market price reporting diminishes the reliability of a universal pricing model. Methodologies introduced in this study, such as the framework for stranded asset valuation in Section 3.3, can be adapted to serve the purpose of quantifying the physical and transition risk components of climate change on real property investments, while a scenario-based analysis similar to that introduced in Section 3.1 can be extended for estimating the market price correction associated with the recognition of climate risk. Detailed illustrations of these points are beyond the scope of this study.

5.3 CLIMATE RISK AND DEFINED CONTRIBUTION (DC) PLAN DEFAULT OPTIONS

In this subsection, the implications of climate change risk in the default options in defined contribution (DC) plans are discussed. In most DC plans, participants are presented with several investing strategies (options) to accommodate their variations in investment objectives and risk tolerance. A default option (also called a qualified default investment alternative (QDIA) in the U.S.) is one that participants are automatically enrolled in before making their choices. Due to inertia or procrastination, some participants may never actively choose their investment option, meaning that the plan should have a good default option in the first place.

According to the guidelines of the Canadian Office of the Superintendent of Financial Institutions (OSFI) in 2023, a good default option should consider the age and risk tolerance of the plan participants, and the costs associated with the investment, and offer long-term capital appreciation and preservation. Climate change may influence some of these criteria. For example, if the participants of the plan are heavily exposed to climate risk through their physical assets such as residential properties in climate-sensitive areas, or through their income from working in industries affected by changing weather, their investment risk tolerance may be dependent on the future state of climate change, and they could be more risk averse in their retirement investments. At the same time, as seen in previous chapters of this report, the investment returns in both fixed-income assets and equity bear a considerable amount of climate change risk, affecting the long-term capital appreciation and preservation of an investment portfolio. Modern theories of personal financial planning promote a diversification between investment assets and human assets (which mainly consist of future earnings). Hence, for plan sponsors in industries adversely affected by climate change, the ideal default investment options should contain either substantially mitigated climate change risk or even involve prudently designed exposures to sectors that are anticipated to benefit from climate change. Such an approach can be made more comprehensive by incorporating the liability side, mostly the expected mortality shifts under climate change based on the demographics of the participants. The approaches and methodologies introduced in Chapters 3 and 4 can be applied to serve this purpose.

In terms of implementation, Chapter 4 of the "OECD Pension Outlook 2020" proposes and illustrates a framework for pension plans to choose the most suitable default option. This process consists of the following steps:

- Select investment strategies to be assessed. Two popular candidates for DC funds' default options are balanced funds and target-date funds (TDFs) (also called life-cycle funds).
- Project future states of the world and corresponding performances of the candidates with stochastic processes. These processes should consider asset returns, economic scenarios, socioeconomic risks (such as labor market risk, financial risk, longevity risk, etc.) as well as their correlations.
- Examine the projected risk and potential of candidates. Multiple indices could be used to assess the risk of a portfolio, including dispersion, Value-at-Risk, or expected shortfall, while the potential could be measured by the 95%-quantile of returns or expected retirement income for example.
- Choose the best candidate as the default option. The best portfolio must have the maximum benefit while retaining its risk within a predetermined threshold.

Based on this framework, the default option can be made more resilient to climate change risk by incorporating climate considerations in the first and second steps. In the first step, the design and optimization of balanced funds and TDFs could include climate-related criteria and constraints (elaborated below). In the second step, future climate scenarios and subsequent impacts on socioeconomic risks (such as inflation, labor market risk, longevity risk, etc.) could be added to the projections. These adjustments would ensure that the projected risk and potential of candidate portfolios reflect climate risk and that the chosen default option is inherently climate risk resilient.

Two common types of default options offered by DC plans are balanced funds and target date funds. According to this study's literature survey, little evidence is found on the incorporation of climate change risk into the design of these default fund options. A balanced fund is a portfolio with a strategic asset allocation fixed at the beginning and periodically rebalanced to maintain the allocation. A typical balanced fund used for the DC default options allocates 40% to 60% of its assets to risky securities and the remaining to fixed-income products, according to OSFI (2023). It is up to the plan participants to adjust their investment allocations reflecting their evolving investment objectives and risk tolerances through their life cycles. Within the scope of this study, building the optimal portfolio for a balanced fund under climate change involves considering and quantifying the effect of climate change on the various investment securities, as elaborated and demonstrated in Chapter 3 of this report. The results from such risk quantification lead to parameters to be input into a portfolio optimization framework. Tan et al. (2018) propose a framework to construct such an optimal portfolio, which will be adapted to pension funds in Chapter 6.

On the other hand, a target date fund (TDF) is a fund that gradually decreases its risk as the plan participant approaches retirement. This is done by reducing the fund's allocation to risky assets following a schedule (commonly called a glide path). The idea is derived from modern financial planning theory. When the plan participant is early in the life cycle, they are heavy in human capital that consists of future earning streams from the job, which (for most industries) resemble a fixed-income asset. As a result, they should invest more in risky securities such as stocks for portfolio growth, which creates a natural asset class diversification facilitated by a higher risk tolerance at early ages. As the participant gets closer to retirement, they have less human capital from future employment income and hence need to be more conservative with the assets they have accumulated in previous years. The shift in allocations takes place in the fund automatically, and the plan participants choose the TDF fund option with a target date matching their desired retirement schedule.

The work by Brière (2021) listed three factors affecting the appropriateness of a TDF to an individual: their income profile, their net debt exposure, and the availability of social security. Firstly, the assumption that a person's income stream can be approximated by a fixed-income asset could be challenged, which influences the basis of the glide path. If a person's income is highly correlated with the stock market, such as for certain financial sector jobs, their optimal pension asset allocation should tilt more towards fixed income instead of risky assets over time. Secondly, the net debt exposure as measured by home equity level impacts their optimal pension investment, as discussed in Chetty et al. (2017). The amount of home equity can be loosely defined as the difference between the value of the property and the respective outstanding mortgage balance. If the mortgage balance is high, they have a financial commitment to the lender and would be more conservative with their retirement investment. In contrast, if the share of home equity is high, they are more tolerant of growth-oriented investments. Lastly, if high-quality social security is available, a pension plan member would be willing to take greater risk with their pension investment to potentially earn a higher retirement income.

Among the three factors above, the first two can be vulnerable to climate change risk, since both the future income for certain industries and real property values in climate-sensitive regions can be heavily affected by climate change as described in Section 5.2. Therefore, including an analysis of the plan members' real property exposure and income stream exposure to climate change is necessary in designing and choosing the best investment mix. As an example, for participants in the mining and farming sectors, their income streams need to be projected under different climate change scenarios, where potential reductions in future incomes support a faster glide away from risky assets in favor of fixed-income assets. A similar reasoning can be applied to emission-heavy industries such as oil production where job security can be undermined by transition risk. While the climate change does not necessarily augur a reduction in future income, the higher uncertainty would require them to be more prudent with a higher allocation to low-risk assets.

In terms of practical implementation, it is intuitive that the ideal TDF should be personalized to accommodate the heterogeneity of plan participants' risk profiles. Indeed, as shown by Tang and Lin (2015) and Inkmann and Shi (2016), a TDF is mainly characterized by its glide path, and personalized glide paths would increase the adoption of the default option by pension plan members. In cases where such customization is cost-prohibitive, assessments may need to be done on a cohort level based on the demographics of the participants and industries of the sponsors.

OECD (2020) lists five possible glide paths, four of which consist of a decline of risky assets' share in the portfolio based on the plan participant's age, and one based on both age and account balance. However, these guiding strategies are static over time. To properly account for climate risk, a pension fund needs to optimize the glide path utilizing projections from different plausible climate scenarios and then aggregate the resulting glide paths using likelihood-based weightings. Another way to make the glide path more resilient to climate risk is to make it adjustable as the climate scenario unfolds. For example, pension funds can derive optimal glide paths for different climate scenarios and regularly review them to decide on which glide path to follow. The scenario-based methodologies and tools introduced in Chapter 3 of this report can be adapted to serve both purposes, though with the additional complications in income stream projections in deriving the optimal glide path.

Finally, note that although a sustainable and resilient default option may bring greater protection to pension plan members' investments against climate risk and lower the effort required in subsequent investment allocation adjustments that members need to make, building such a default option in the first place requires a considerable amount of time and effort, raising the cost passed on to plan participants. Whether the benefits outweigh the costs needs to be carefully and systematically examined.

Chapter 6: Investment Portfolio Construction under Climate Change Risk

This chapter presents a framework for building an optimal investment portfolio for a defined benefit pension plan fund utilizing all key results presented in the previous chapters. This framework can be extended to serve similar applications for defined contribution plans and personal retirement investments.

6.1 LIABILITY-DRIVEN PORTFOLIO OPTIMIZATION

For a defined benefit pension scheme, the top priority is to ensure that sufficient assets are available to fund the pension benefit payouts as they are due. Fund managers thus take into account the future pension liability when building the asset investment portfolio. This problem is formally called "liability-driven portfolio optimization" and has been explored by multiple studies such as Ang et al. (2013), Aro and Pennanen (2017), and Jang et al. (2024).

In this study, a focus is on deriving the optimal investment mix for the accumulation phase of a defined benefit pension scheme. Unlike the traditional mean-variance optimization approach, our formulation focuses on the fund's surplus variable. Denote the time-t value of the fund's assets and liabilities by A_t and L_t, respectively. At the end of the accumulation phase at time T, the terminal surplus is given by:

$$S_T = A_T - L_T$$

While the portfolio growth rate is a random variable driven by the individual asset returns and asset mix, the liability value is equal to the actuarial present value (APV) of future benefit payouts which is independent of the asset performance. Given a starting asset value A_0 at the beginning of the investment horizon and *n* available assets from the asset universe to choose from, the terminal surplus S_T is given by:

$$S_T = A_0 \prod_{t=1}^{T} (1 + w'R_t) - L_T,$$

where:

- w is the n by 1 vector of weights for the *n* assets;
- R_t is the n by 1 random vector of asset returns from time point $t-1$ to time t. The vectors R_t are further assumed to be independent and identically distributed across time periods with a common mean vector μ and covariance matrix Σ.

Further algebra leads to the following results for the terminal surplus variable:

$$E[S_T] = A_0(1 + w'\mu)^T - E[L_T]$$

$$Var(S_T) = A_0^2[(w'\Sigma w + (1 + w'\mu)^2)^T - (1 + w'\mu)^{2T}] + Var(L_T)$$

The optimal portfolio mix is obtained by solving the following optimization problem that aims for the minimum variance of terminal surplus:

$$\min_{w} Var(S_T)$$

$$subject\ to: E[S_T] \geq S,$$

$$w'1_n = 1,$$

where S is the minimum surplus level specified exogenously by the pension fund and 1_n is the n by 1 vector of ones.

For practical interpretation, this formulation calls for minimizing the uncertainty of the DB plan's final funding status subject to a minimum target surplus level. Further practical constraints such as strategic asset allocations can be easily added to reflect relevant regulations and risk management guidelines. In the case of a balanced fund default option mentioned in the previous chapter, the limit on allocation to risky assets may be incorporated as a constraint as well.

This formulation represents several major improvements over the traditional mean-variance optimization setup. First, it explicitly incorporates pension liabilities into the problem and hence liability funding into the solution. In addition, the objective function is more relevant for defined benefit pension practice, which focuses more on future funded status and shortfall risks instead of a static portfolio risk-return profile. Finally, the formulation provides the flexibility to incorporate climate change risk management into the solution, which is presented in detail below. The downside of this formulation is higher computational complexity as the objective function is a polynomial of order T. Nevertheless, further algebraic transformations reveal that the minimum surplus constraints can be converted into a linear form, which greatly improves computational efficiency.

6.2 PORTFOLIO OPTIMIZATION WITH CLIMATE RISK

There are three channels to reflect climate risk management in this optimization problem.

- Introduce additional constraints on sectors and/or asset weights to tilt the fund's exposure away from assets that are negatively impacted by climate change;
- Quantify and reflect the impacts of climate change on asset returns (as in Chapter 3) in the existing problem;
- Quantify and reflect the effects of climate change on future pension liability payments due to shifts in mortality rates (as in Chapter 4) in the existing problem.

When applied simultaneously, these channels ensure that climate risk is managed in the optimal portfolio concerning its impact on both pension assets and liabilities. Leveraging a few key results from Tan et al. (2018), the recommended framework calls for the following steps:

1. Liability estimation: Liability assumptions are specified and the expected time-T pension liability L_T is derived. This estimate is driven by both the defined benefit plan specifications and relevant actuarial assumptions.
2. Asset universe selection: A universe of investible assets is defined. This is a managerial decision that is subject to pension regulations, asset availability, internal risk management procedure, and (if required) policyholder's ESG preferences.
3. Risk-return characterization: The mean vector μ and covariance matrix Σ of asset returns within the chosen universe are estimated. These estimates should be adjusted for dividends and stock splits.
4. Strategic asset allocation: Asset class and sector allocation constraints may be incorporated for compliance with regulations and governance policies. This is common in top-down portfolio management. Examples include:
   - The sum of investment weights in information technology is greater than or equal to 20%;
   - A 60%/40% split for stocks and bonds.

   Other fundamental constraints such as short-selling restrictions are also set out during this step.
5. Climate risk exposure management: The fund manager may control the portfolio exposure to sectors and companies vulnerable to climate risk while in compliance with relevant regulations. This can be done by consulting climate risk measures such as Climate VaR described in Section 3.1.
   - Example: Refrain from investing in companies in the top 5% in Climate VaR.

6. Stranded asset management: Stranded asset risks are identified based on available information and managerial views on future climate policies. Their effects on asset returns are then quantified and reflected in the mean return vector μ in this step following the process in Section 3.3.
7. Climate change scenario and view formulation: A set of feasible future climate scenarios and their probabilities of realization are determined. Following the procedures described in Chapter 3, the effects of climate on asset returns under each scenario s are quantified and reflected in the mean return vector μ_s and return covariance matrix Σ. Similarly, under each scenario s, the liability $L_{T,s}$ and the associated survival probability are calculated for each scenario following the methodology in Chapter 4.
8. Estimation of surplus parameters under climate change: The mean and variance of the terminal surplus reflecting climate change risk are expressed as functions of the scenario-contingent results from Step 7. Details of these expressions are provided in Appendix D.

Combining results from the previous steps, the new portfolio optimization problem is formulated as follows:

$$\begin{gathered}\min_{w} Var(S_T)\\ subject\ to:\\ E[S_T] \geq s,\\ w'1_n = 1,\\ Aw = a,\\ Bw \leq b\end{gathered}$$

where:

- The expressions for $Var(S_T)$ and $E[S_T]$ are as derived in Step 8;
- A is a n by n matrix, a is a n by 1 vector, which collectively describe equality constraints from Steps 4 and 5;
- B is a n by n matrix, b is a n by 1 vector, which collectively describe inequality constraints from Steps 4 and 5.

Note that only Steps 5-8 correspond to the management of climate risk in a liability-driven optimal portfolio. Steps 1-4 are general steps for liability-driven portfolio optimization and are presented here for completeness.

6.3 ILLUSTRATIVE EXAMPLE

In this section, a numerical example is presented to illustrate the application of the framework. The example considers a defined benefit plan with a unit (i.e., $1) beginning-of-year annual pension payout after retirement contingent on survival of the pensioner. No death benefit or survivor benefit is paid under the plan. To keep the scope of this example manageable, the subject is a representative plan participant currently aged 40 who will retire at 65 (thus the time horizon in this example is $T = 25$). To facilitate comparative analysis, the example starts with a benchmark scenario where no climate change impact is applied to assets or liabilities. The plan is currently 80% funded.

Assumptions

- All pension liability payments are discounted at an annual effective rate of 6.5%.
- Mortality follows the life table in 2019 under the benchmark scenario.
- Bond values are only affected by transition risk and not physical risk.
- Bond yields remain at current levels under the benchmark scenario. They are deterministic and independent of stock returns.
- There is no significant identifiable stranded asset.

Liability Estimation

Based on the plan specifications and assumptions above, the expected value and variance of the terminal liability viewed from time zero is given by:

$$E[L_{T,s}] = \ddot{a}_{65,(s)\,25}p_{40,(s)}$$

$$Var(L_{T,s}) = \left(\ddot{a}_{65,(s)}\right)^2 {}_{25}p_{40,(s)}(1 - {}_{25}p_{40,(s)})$$

where:

- $\ddot{a}_{65,(s)}$ is the present value of the $1 whole-life annuity-due starting at age 65 under climate scenario s (as mentioned in the numerical example in Chapter 4);
- ${}_{25}p_{40,(s)}$ is the probability of a person of age 45 remaining alive at age 65 under climate scenario s.

Here, the terminal liability L_T is treated as a binary variable when viewed at time zero.

Asset Universe Selection

The asset universe consists of 100 stocks from the S&P100 index with minor changes due to data availability, as well as five representative bonds of similar time to maturity (25-26 years) from different sectors. Details of the asset universe are provided in Appendix E and Table 6.1.

Risk-Return Characterization

For bonds, the yields retrieved from Bloomberg are used as their return under the benchmark scenario. For the stocks, the return covariance matrix Σ^* is estimated using historical daily closing price data (adjusted for dividends and splits) from August 2014 to December 2023. The mean return vector μ^* is estimated under the equilibrium approach as in Black and Litterman (1990) with a risk aversion coefficient of 3.5. Details of the estimated mean return vector μ are in Table 6.1 and Appendix E. For brevity, the estimated covariance matrix is not presented.

Table 6.1
BONDS IN THE ASSET UNIVERSE AND THEIR RETURNS UNDER DIFFERENT SCENARIOS

Company	Sector	Benchmark/Current Policies	Below 2°C	Delayed Transition
Walt Disney (DIS)	Consumer Discretionary	5.66%	5.65%	5.65%
Coca-Cola (KO)	Consumer Staples	5.55%	5.55%	5.55%
ExxonMobil (XOM)	Energy	5.70%	5.21%	4.99%
Microsoft (MSFT)	Information Technology	5.30%	5.30%	5.30%
Air Products & Chemicals (APD)	Materials	5.66%	4.82%	4.46%

Strategic Asset Allocation

To avoid undue influence of subjectively introduced sector allocations, only a general 60%/40% split for stocks and bonds is imposed. A short-selling constraint is also applied, which is common for pension funds.

Climate Risk Exposure Management and Stranded Asset Management

In this example, no subjective constraints on climate risk exposure are introduced. It is also assumed that no significant stranded asset is identified within the chosen asset universe.

Climate Change Scenario and View Formulation

The same three climate scenarios from the previous chapters (Current Policies, Below 2°C, Delayed Transition) are used, and are assumed to be equally likely. Future mortality rates under the scenarios are estimated using the methodology from Chapter 4. The associated liability estimates are reported in Table 6.2.

Table 6.2
LIABILITY ESTIMATES UNDER DIFFERENT CLIMATE SCENARIOS

Scenario s	$L_{T,s}$	$E[L_{T,s}]$	$Var(L_{T,s})$
Benchmark	11.204	10.075	1.0154
Current Policies	11.918	10.766	1.0406
Below 2°C	11.948	10.789	1.0467
Delayed Transition	11.951	10.794	1.0448

Shifts in equity mean return under each climate change scenario are projected using the methodology from Section 3.2 at the sector level, which has been presented in Table 3.4 (not reproduced here). These shifts are applied to the benchmark mean return vector to arrive at the expected stock returns under each climate change scenario.

For bonds, the impacts of climate change are modelled using the methodology from Section 3.1. The projected bond value losses under climate change (graded over the investment horizon) are added to the benchmark scenario yields to arrive at the bond returns under each climate change scenario. Since only transition risk is assumed for bonds, the bond return under the Current Policies scenario (representing no transition risk) is the same as that under the benchmark scenario. The results are summarized in Table 6.1.

As mentioned previously, for simplicity, the asset return covariance matrix is assumed to remain the same across climate change scenarios.

Estimation of Surplus Parameters under Climate Change

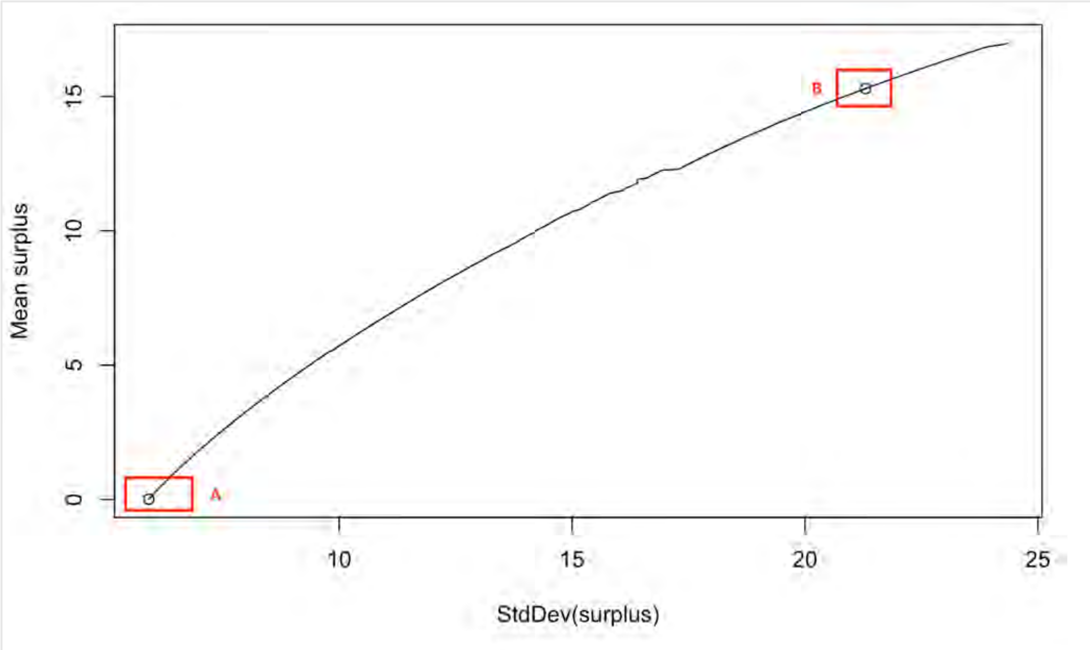
Expressions of the conditional mean and variance of the terminal surplus under each climate change scenario (i.e., conditioning on the scenario being realized) are fundamentally the same as those presented in Section 6.1. Expressions for the unconditional mean and variance of the terminal surplus are given in Appendix D, which become the key variables of interest in this problem.

Formulation of a New Optimization Problem Reflecting Climate Change Risk

The new optimization problem is formulated based on the results from the previous steps. Due to the lack of subjectively introduced climate risk exposure constraints and stranded assets, the new optimization problem differs only in the expressions for the variance and mean of the terminal surplus in the objective function and constraint.

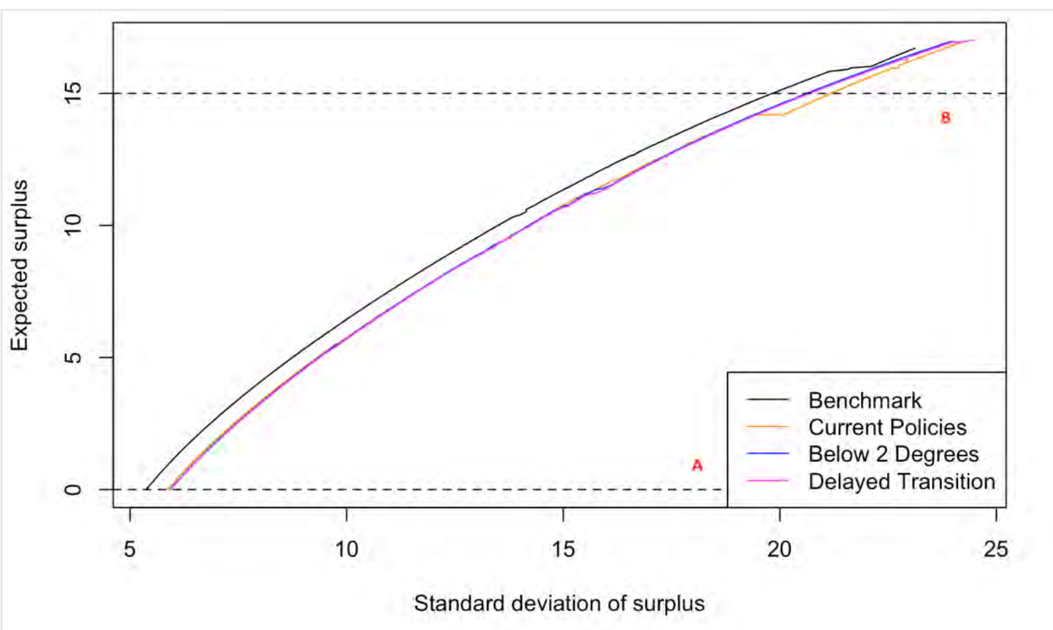
Figure 6.1 shows the positive-slope section of the efficient frontier from the final portfolio optimization incorporating climate change risk. The polynomial order of the objective function in this formulation makes the frontier much "steeper" than those typically observed under the traditional mean-variance optimization framework. Figure 6.2 shows the positive-slope section of the efficient frontiers obtained individually under the benchmark and each climate change scenario, with a zoomed-in left corner shown in Figure 6.3 for enhanced presentation. The frontiers under all three climate change scenarios fall below the benchmark, indicating heightened risk in terminal surplus once climate change has been taken into account. On the other hand, the efficient frontiers under the three climate change scenarios exhibit similar shapes, especially under the Below 2°C and Delayed Transition scenarios. This implies that similar terminal surplus risk-return profiles can be achieved across scenarios via the proposed optimization algorithm. These observations highlight the importance of incorporating climate change risk management in retirement investing.

Figure 6.1.
EFFICIENT FRONTIER INCORPORATING CLIMATE RISK



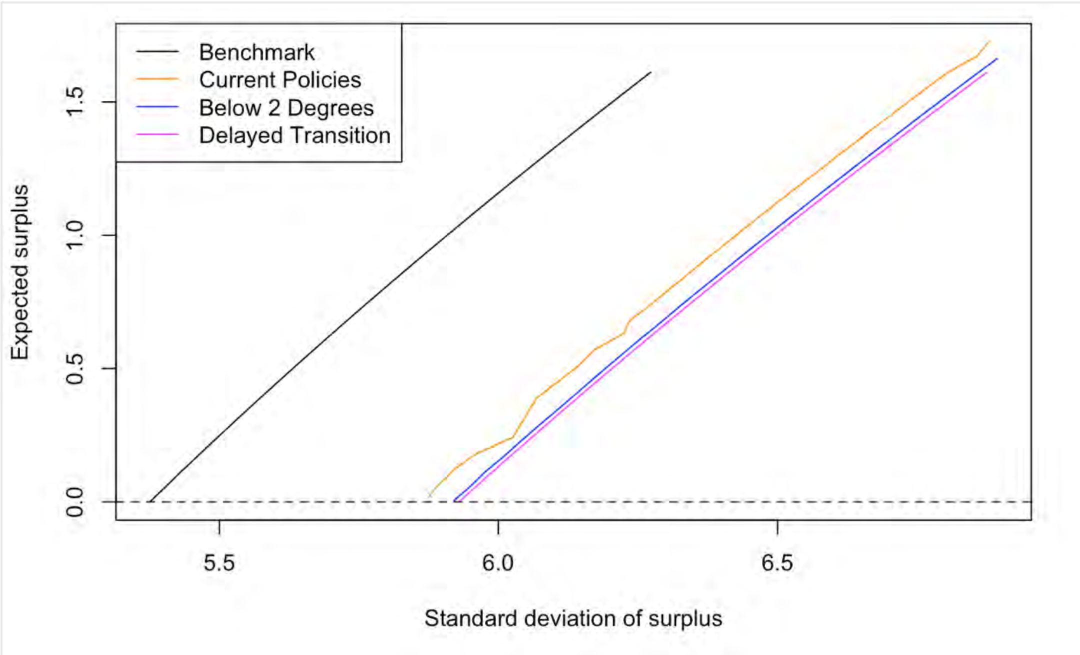
For illustration: Point A corresponds to the optimal portfolio with zero expected surplus. Point B corresponds to the optimal portfolio with an expected surplus of $15.

Figure 6.2
EFFICIENT FRONTIERS UNDER DIFFERENT CLIMATE SCENARIOS



For illustration: The intersections between the efficient frontiers and line A/B correspond to the optimal portfolios with expected surplus of $0/$15, respectively.

Figure 6.3
EFFICIENT FRONTIERS UNDER DIFFERENT CLIMATE SCENARIOS (FIGURE 6.2)—ZOOMED IN AT LEFT CORNER

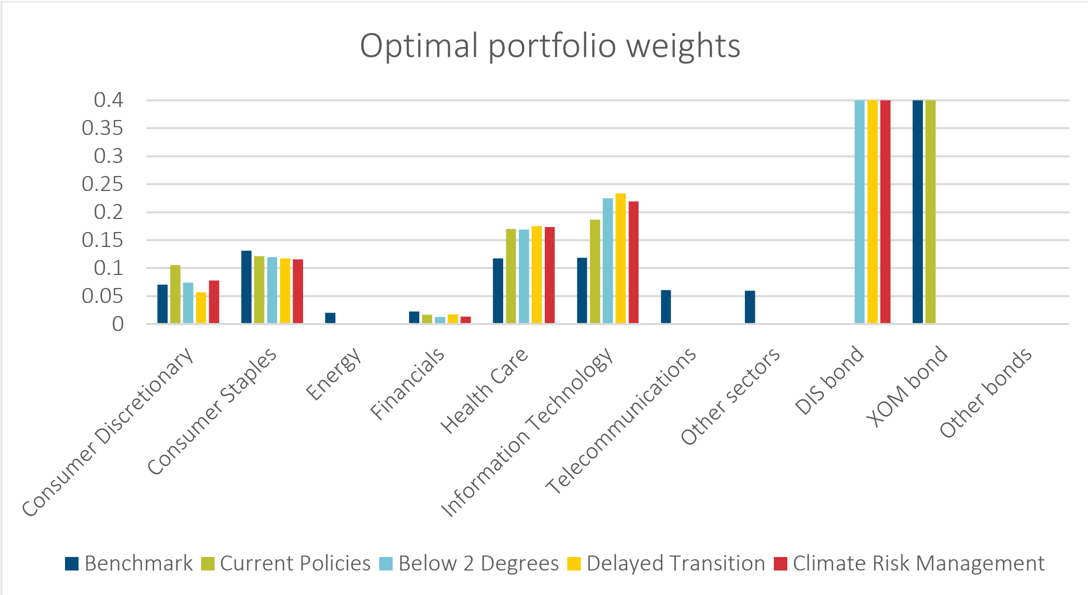


Figures 6.4 and 6.5 summarize the optimal portfolio weights by sectors under two surplus targets under the proposed algorithm: a minimum expected surplus of \$0 (Point/Line A in Figures 6.1 and 6.2) representing a conservative target where the fund aims to achieve just fully funded status, and a minimum expected surplus of \$15 (Point/Line B in Figures 6.1 and 6.2) representing an aggressive target where the fund aims to accumulate significant surplus by the start of the benefit payout phase.

Consistent with expectations, a significant decrease in allocation to the carbon-intensive sectors such as energy, industrial, utilities, and materials (the last three are grouped in the "other sector" category) is observed as the scenario switches from the benchmark to the climate change scenarios, accompanied by an increase in the IT sector which is deemed more resilient to climate change. Between the two surplus targets, the aggressive portfolio is heavily concentrated in the IT sector with much less weight in the consumer and healthcare sectors even in the benchmark case. Such an investment mix is needed to meet the high expected surplus requirement, yet the high concentration amplifies the risk in the terminal surplus. For bond allocation, the portfolio trivially concentrates on the bond with the highest return under each scenario due to the simplifying assumptions in this example, captured by a shift from an energy sector issuer to a consumer sector issuer once climate change is incorporated.

Figure 6.4

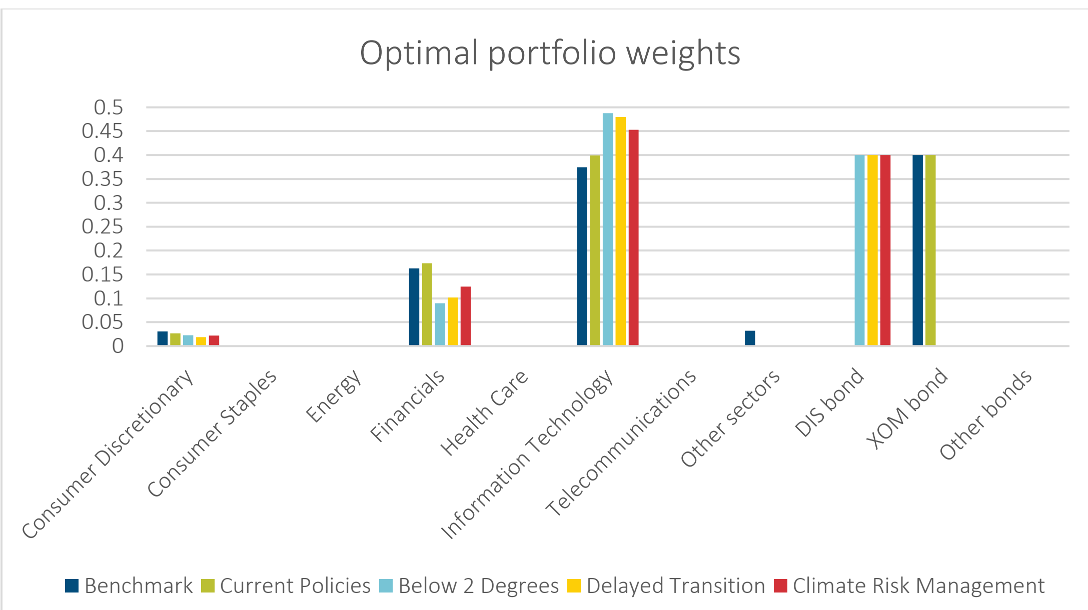
OPTIMAL PORTFOLIO ALLOCATION FOR ZERO EXPECTED SURPLUS



"Other sectors" include Industrials, Materials, Real Estate, and Utilities sectors. "Other bonds" refers to the total weights of the KO, MSFT, and APD bonds.

Figure 6.5

OPTIMAL PORTFOLIO ALLOCATION FOR AN EXPECTED SURPLUS OF $15



"Other sectors" include Industrials, Materials, Real Estate, and Utilities sectors. "Other bonds" refers to the total weights of the KO, MSFT, and APD bonds.

6.3 APPLICATION FOR DEFINED CONTRIBUTION PLANS AND PERSONAL RETIREMENT INVESTING

Defined contribution (DC) plan sponsors do not bear the risk of underfunding the retirement expenses of their pensioners. However, the sponsors are obligated to offer appropriate investment options suitable for pension participants in funding their post-retirement expenses. Hence, the portfolio optimization framework can be applied with a few adaptations by managers of the funds offered in a DC plan, especially for target date default options. The fund managers carry a fiduciary duty to the mandate of the funds they manage, making the proposed methodology especially relevant if funding a target-day retirement is part of the fund mandate. Major challenges may reside in projecting the terminal liability L_T for the participant pool, which (unlike under a defined benefit plan) is unspecified and requires a view into the post-retirement expenses. Once this is overcome, the steps from Section 6.2 can be followed to build the optimal investment mix under climate change risk.

More adaptations to the framework are needed to serve personal retirement investing, which typically follows a different formulation adopted by modern financial planning theories. At a high level, there exists tremendous heterogeneity among individuals in retirement plans, where the liability to be funded is often defined in terms of goals. The goals may include “needs” such as maintaining the current standard of living post retirement, or “wants” such as an extended trip abroad. The problem formulation often involves maximizing the probability of achieving the goals, making the objective function highly complex. A possible workaround is to obtain a mapping between the achievable terminal surplus parameters and these probabilities. For example, using Normal approximation, each point on the efficient frontier in Figure 6.1 maps to a probability of shortfall (the complement to the probability of achieving the goal). The rest of the steps in the framework can then be systematically followed. However, users of the framework must note that individuals have fundamentally different investor characteristics from institutions such as pension plans. For example, while they are not subject to many regulatory constraints placed on pension funds, they also lack access to certain asset classes in the asset universe available to institutions such as direct hedge funds and private equity placements. Due to the numerical sophistication of the framework, in practice, it is more likely to be used by financial advisors in providing asset allocation advice to their clients in the retirement planning process (instead of the individuals themselves).

Chapter 7: Conclusion

In this report, the effects of climate change on retirement with a focus on defined benefit pension plans from both the asset and liability sides were examined. Using a representative sample of stocks, it was concluded that to this date carbon risk has not been adequately priced by both the European and North American stock markets, highlighting the importance of considering climate change in long-term portfolio management. Frameworks to assess the impact of climate change on assets (fixed-income and equities) and pension liabilities were then presented. A method to quantify stranded asset risk was also presented. Some insights could be drawn from numerical examples of these methodologies:

- The impacts of climate change on bond returns are best assessed at the issuer level. An issuer with higher carbon intensity and/or higher debt-to-value ratio is prone to higher bond value loss from changes in climate policies (i.e., transition risk).
- The impacts of climate change on stock returns differ fundamentally across sectors, which can be quantified using the proposed factor-sensitivity approach. Overall, the impacts include reduced long-term returns for the carbon intensive sectors (energy, utilities, material) while certain others (IT, health care, etc.) remain resilient.
- On the liability side, the impacts of climate change on pensioner mortality rates differ across age cohorts based on the regression study, which projects a decrease in one-year mortality for middle-aged cohorts but an increase for the elderly holding all else constant.

These findings further emphasized the importance of assessing both sides of the balance sheet when managing climate change risks from the perspectives of pension plans. Other considerations such as the impact of climate change on real property investments, and on defined contribution (DC) plan default investment option design were also examined. Finally, a comprehensive framework was proposed for building the optimal investment portfolio under climate change for a defined benefit pension plan, accompanied by an illustrative example. This framework is well designed for practical application, as it directly targets the plan's terminal funding status considering both the asset and liability risk-return profiles under climate change. The framework utilizes methodologies from previous chapters and can be easily extended to serve DC pension schemes and personal retirement investing with proposed adaptations.

Nevertheless, one should note that the framework is built on a representative defined benefit plan specification, with several simplifying assumptions in the illustrative example. Future work on the areas below would be desirable in improving the robustness of the framework and conclusions reached:

- Introducing stochasticity to bond yields and hence reassessing the framework under a more comprehensive asset return correlation structure.
- Quantifying and introducing the impact of climate change on asset return correlations, which is currently assumed to remain the same across climate change scenarios in the framework.
- Revisiting the assumption of independence between the asset and liability growth rates, as the impact of climate change on market returns may also affect the discount rate used in liability valuation.
- Extending the final portfolio optimization framework to serve DC plan and individual retirement investing, with illustrative examples. A few directions of the adaptations required and potential challenges that need to be resolved in this exercise were already identified in this study.
- Further research which incorporates scenario analysis, risk assessment, and integration of climate considerations into investment strategies with practical applications for DC plan management.
- More extensive research on the fiduciary duty of pension plans in relation to climate risks, as well as on global legal practices and concerns to address this issue, with emphasis on transparency, disclosure, and responsible investment.

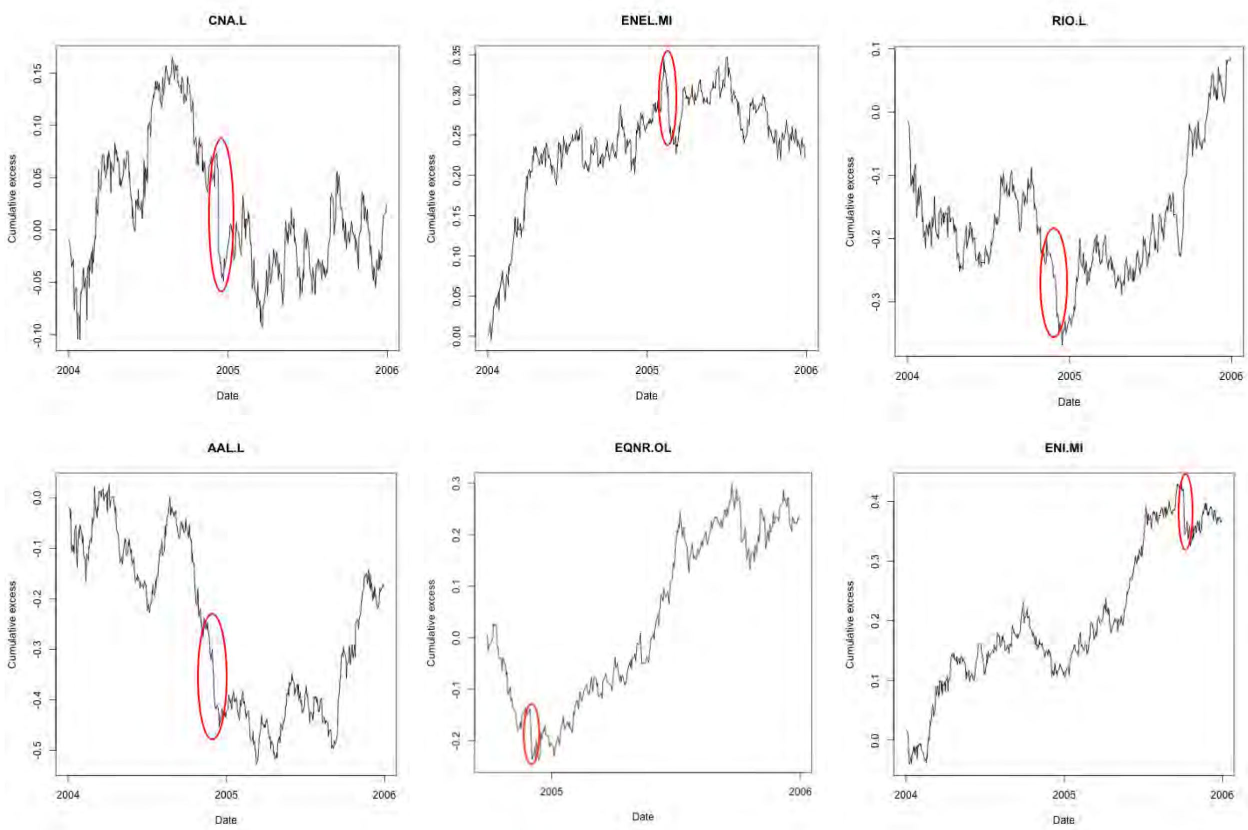
Appendix A: Pricing of Carbon Risk for European Stocks—Qualitative Assessment

This appendix presents the cumulative excess return plots obtained in the event study analysis in Chapter 2 for selected European stocks. As explained in the report, one looks for cliff-like patterns around the middle of the event period characterized by three features:

- A sudden and significant drop in the cumulative excess return;
- Followed by a period of tranquility of small price adjustments;
- *Ideally*, such a stable period after the drop results in cumulative excess returns being comparable to or lower than those before the drop.

Figure A.1

CUMULATIVE EXCESS RETURN PLOTS FOR EUROPEAN STOCKS SHOWING THE PRICING OF CARBON RISK FOR THE LAUNCH OF THE EU ETS (JAN 2005)



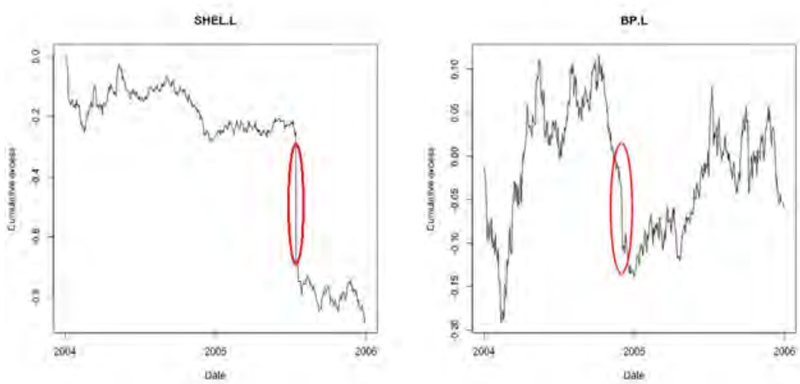
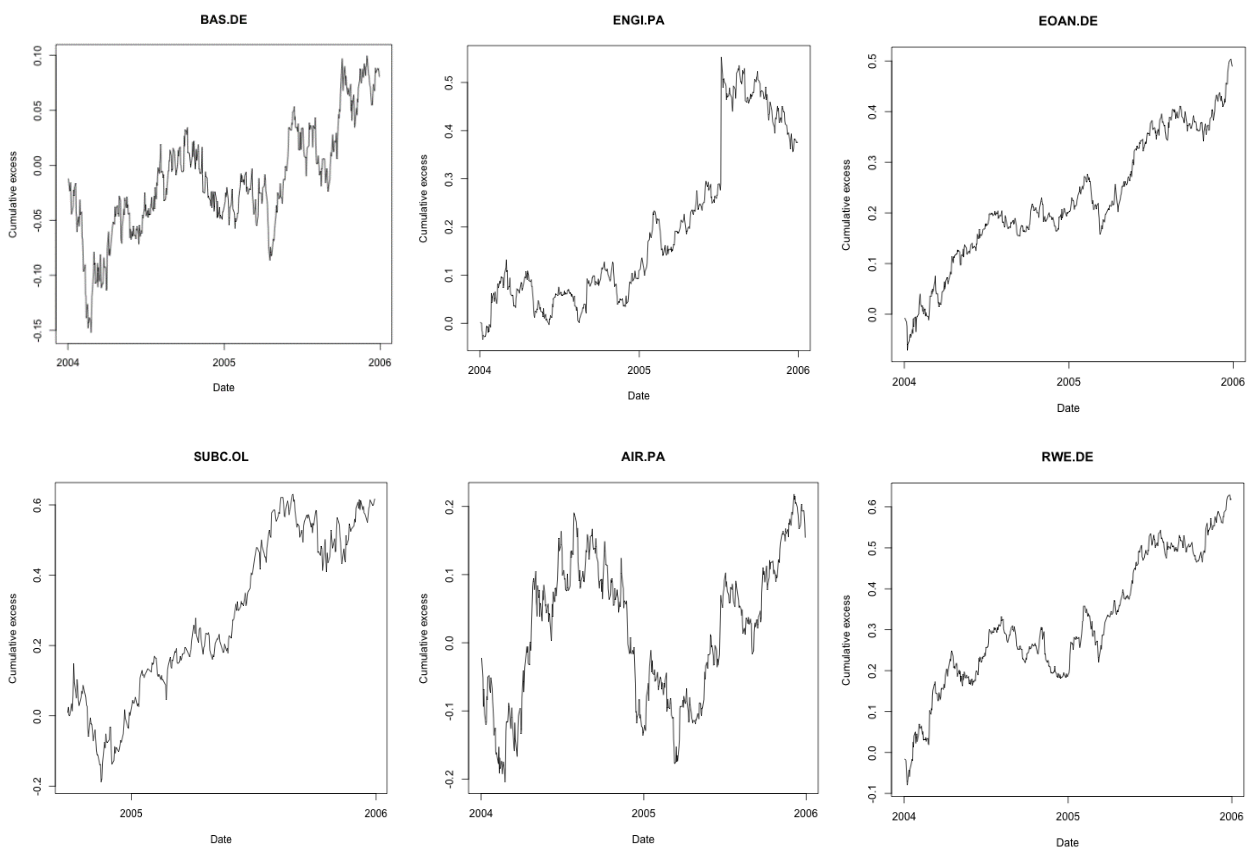


Figure A.2

CUMULATIVE EXCESS RETURN PLOTS FOR EUROPEAN STOCKS NOT SHOWING THE PRICING OF CARBON RISK FOR THE LAUNCH OF THE EU ETS (JAN 2005)



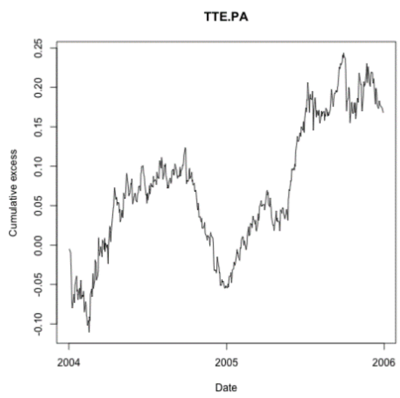


Figure A.3

CUMULATIVE EXCESS RETURN PLOTS FOR EUROPEAN STOCKS SHOWING THE PRICING OF CARBON RISK FOR THE RATIFICATION OF THE EUROPEAN CLIMATE LAW (JULY 2021)

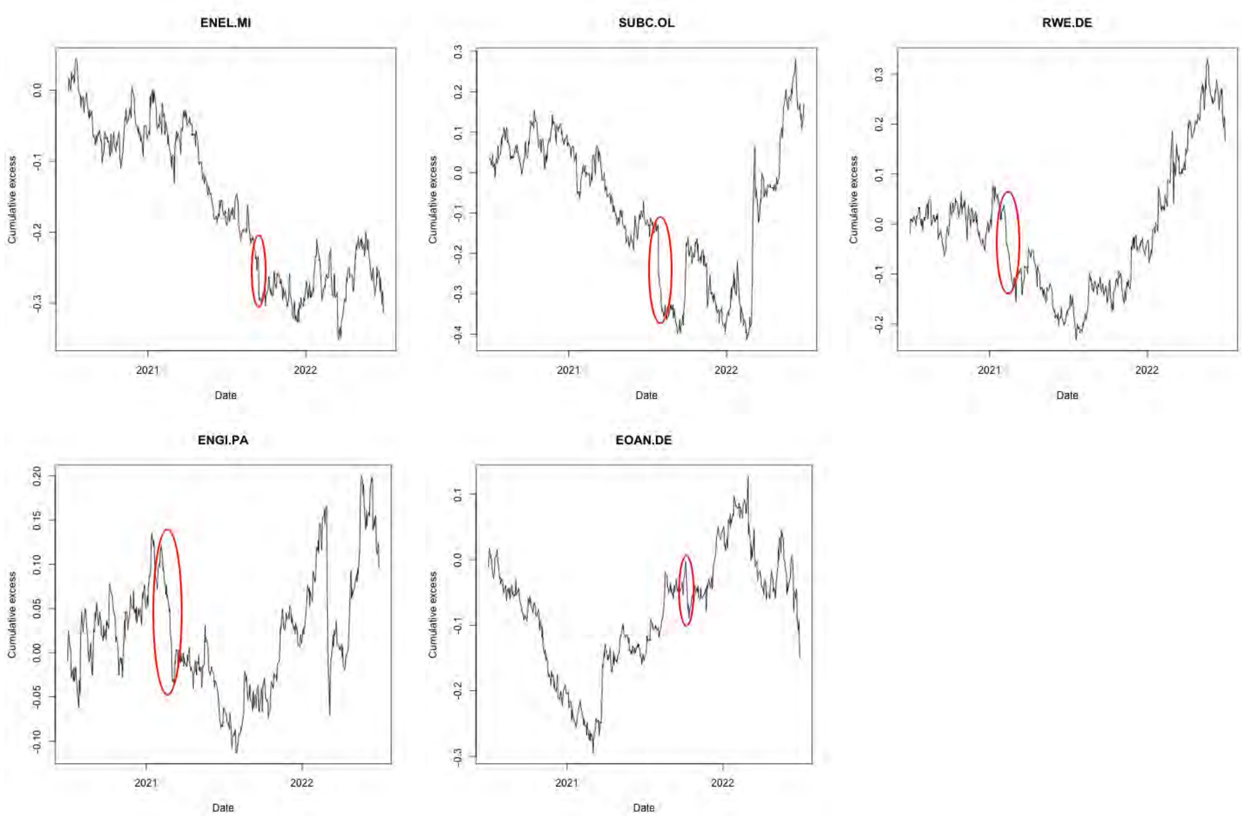


Figure A.4

CUMULATIVE EXCESS RETURN PLOTS FOR EUROPEAN STOCKS NOT SHOWING THE PRICING OF CARBON RISK FOR THE RATIFICATION OF THE EUROPEAN CLIMATE LAW (JULY 2021)

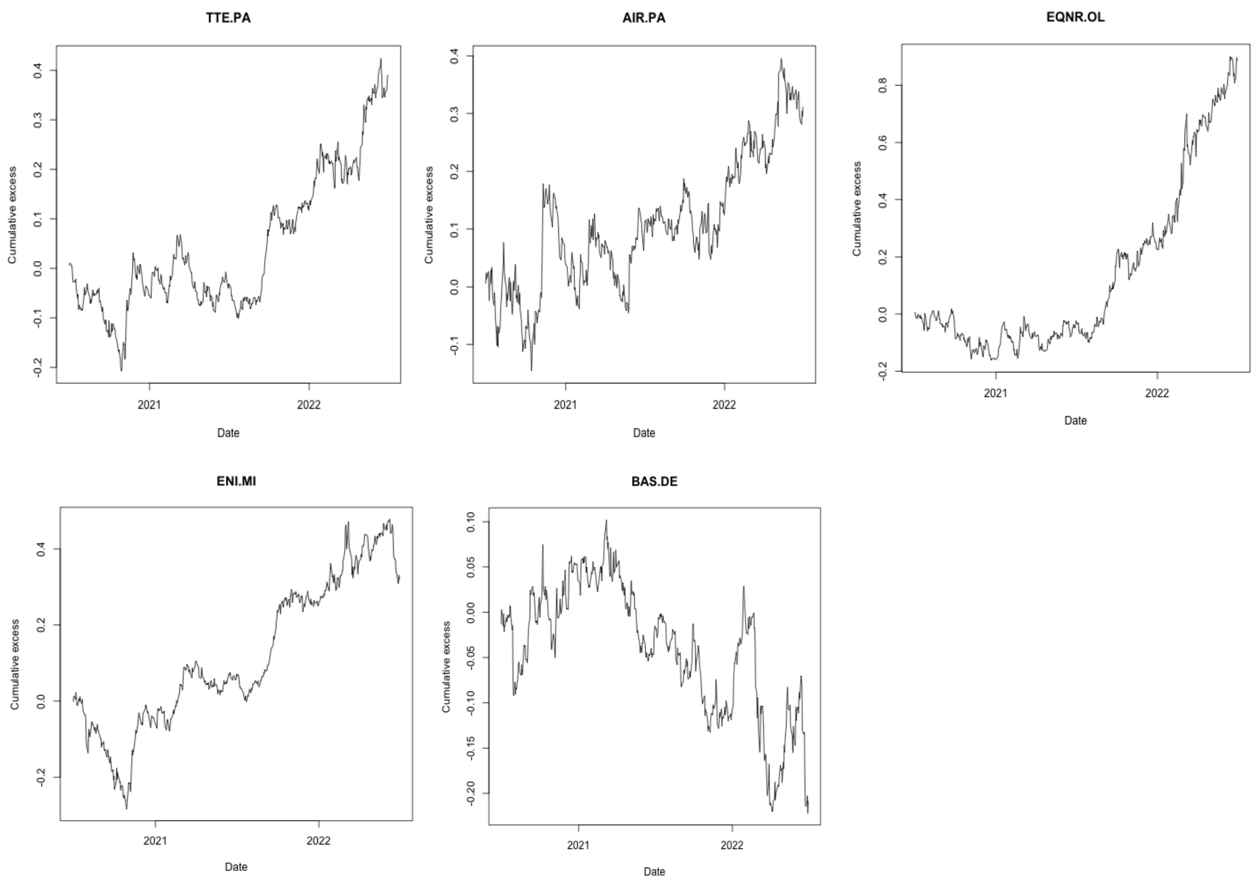


Table A.1

FACTOR MODEL REGRESSION COEFFICIENTS FOR STOCKS IN THE EUROPEAN MARKET

Stock	Intercept	Market Return	SMB	HML
CNA.L	-0.0000903	**0.76931418**	0.00775783	**0.18071233**
BP.L	0.00002941	**1.13852592**	**0.20805306**	**0.60022805**
SHEL.L	0.00013562	**1.11454289**	**0.40061517**	**0.58998894**
AAL.L	0.00025358	**1.8376779**	**0.74937579**	**0.74794834**
RIO.L	0.00046035	**1.53726169**	**0.34720639**	**0.37472109**
TTE.PA	0.00028106	**0.83469144**	**-0.2151195**	**0.51526735**
ENGI.PA	-0.0000071	**0.78783559**	**-0.6445289**	-0.0465877
AIR.PA	**0.00054172**	**1.27074591**	**0.68567445**	0.09601964
BAS.DE	0.00018466	**1.05557765**	**0.12112948**	**0.2928564**
EOAN.DE	-0.0000562	**0.70404818**	**-0.4567902**	**-0.1176556**
RWE.DE	-0.0000520	**0.72827207**	**-0.2687604**	**-0.091604**
ENEL.MI	**0.00033156**	**0.84171807**	**-0.1872725**	**-0.2447607**
ENI.MI	0.00030072	**0.74135655**	**-0.4868741**	**0.27032317**
EQNR.OL	0.00011503	**1.04381732**	**0.15472554**	**0.29514164**
SUBC.OL	-0.00000223	**1.32413756**	**0.36579304**	**0.65151737**

The coefficients in bold are statistically significant at level 5%.

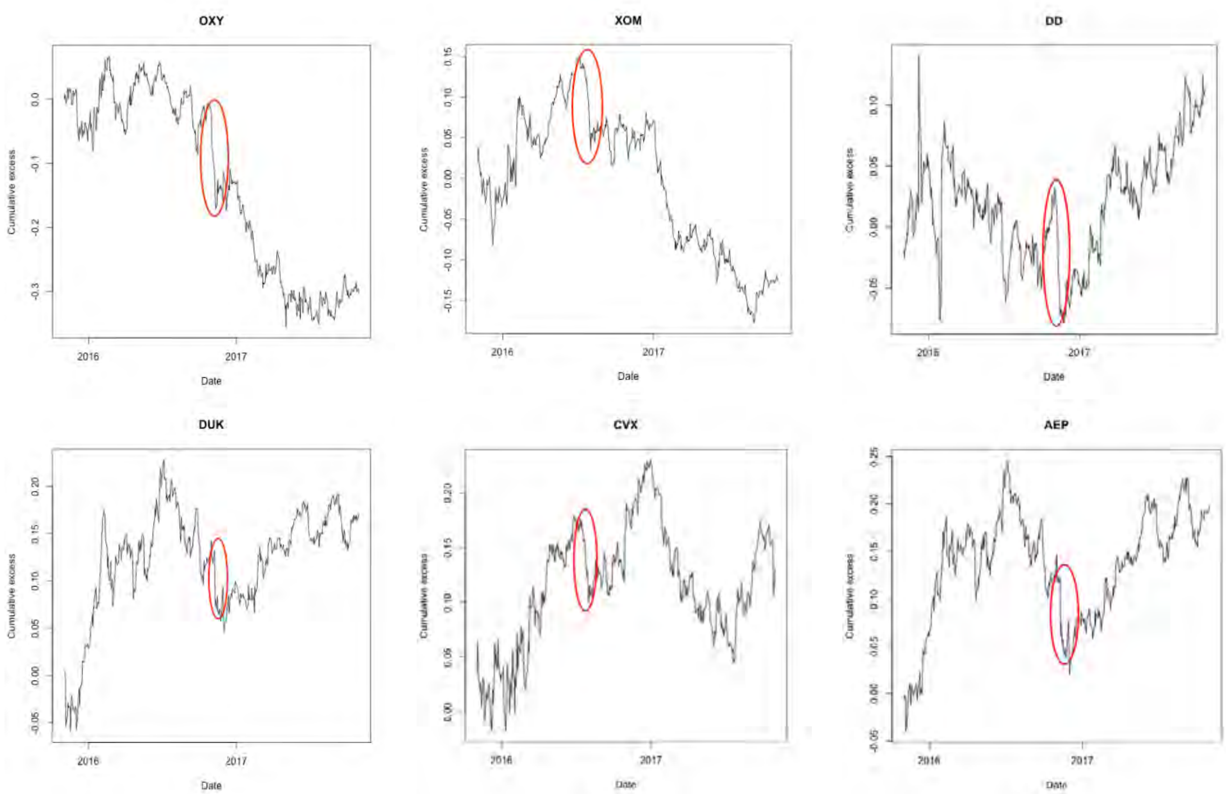
Appendix B: Pricing of Carbon Risk for North American Stocks—Qualitative Assessment

This appendix presents the cumulative excess return plots obtained in the event study analysis in Chapter 2 for selected North American stocks. As explained in the report, one looks for cliff-like patterns around the middle of the event period characterized by three features:

- A sudden and significant drop in the cumulative excess return;
- Followed by a period of tranquility of small price adjustments;
- *Ideally*, such a stable period after the drop results in cumulative excess returns being comparable to or lower than those before the drop.

Figure B.1

CUMULATIVE EXCESS RETURN PLOTS FOR NORTH AMERICAN STOCKS SHOWING THE PRICING OF CARBON RISK FOR THE SIGNING OF THE PARIS AGREEMENT (NOVEMBER 2016)



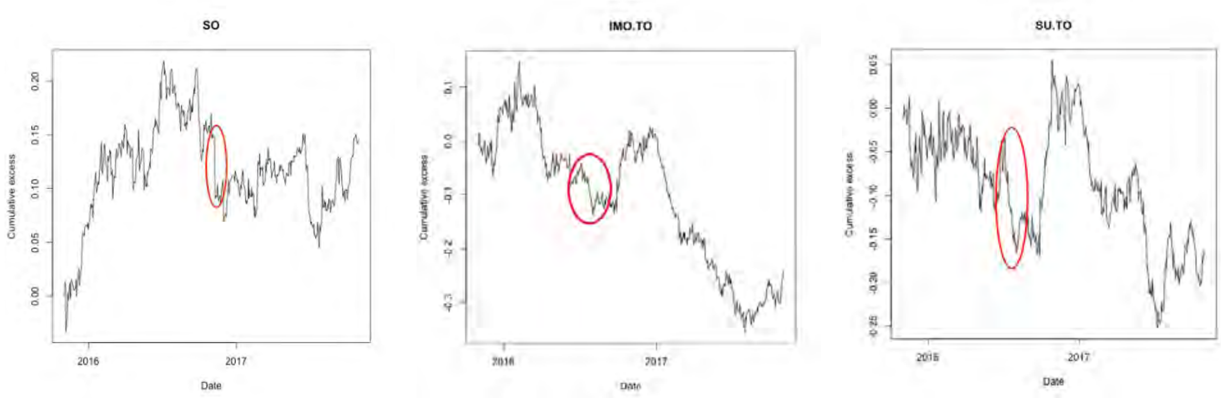


Figure B.2

CUMULATIVE EXCESS RETURN PLOTS FOR NORTH AMERICAN STOCKS NOT SHOWING THE PRICING OF CARBON RISK FOR THE SIGNING OF THE PARIS AGREEMENT (NOVEMBER 2016)

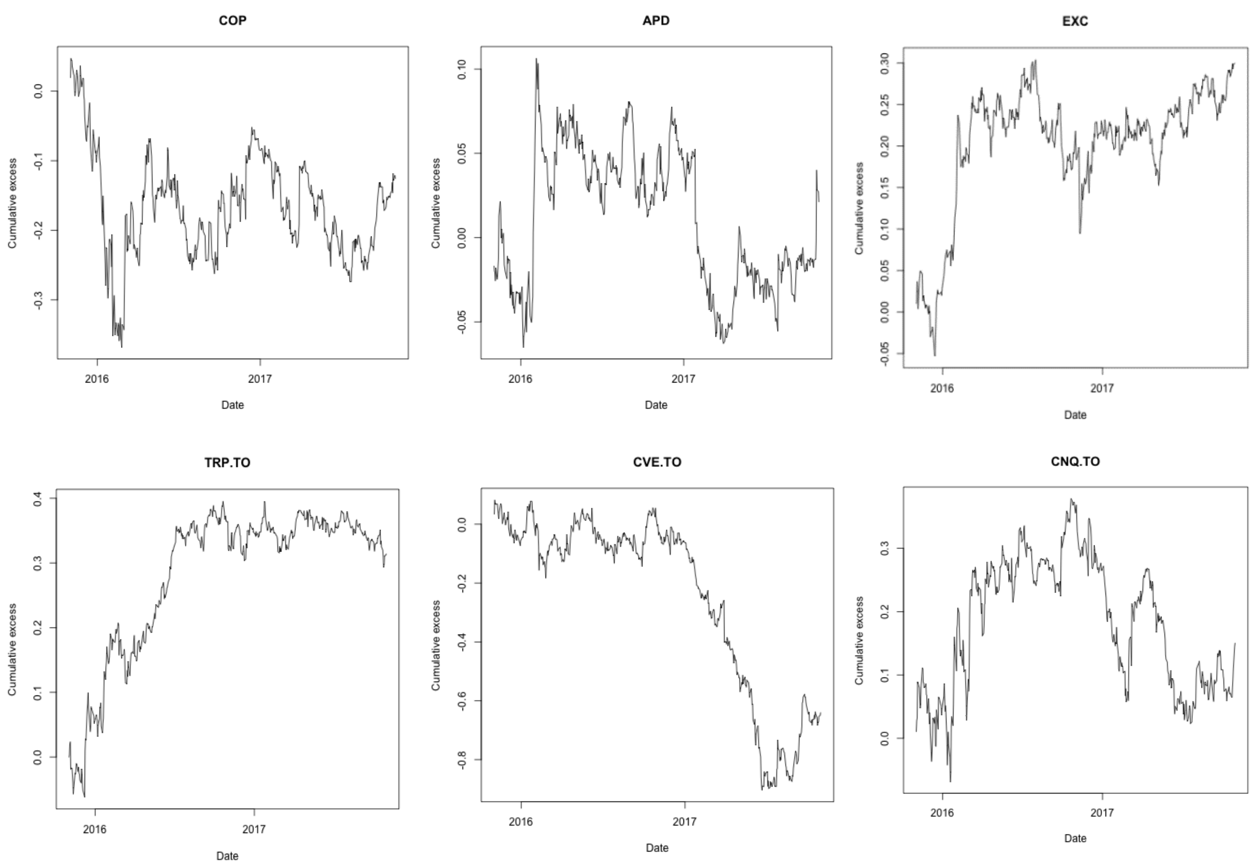


Figure B.3

CUMULATIVE EXCESS RETURN PLOTS FOR NORTH AMERICAN STOCKS SHOWING THE PRICING OF CARBON RISK FOR THE RE-SIGNING OF THE PARIS AGREEMENT (NOVEMBER 2021)

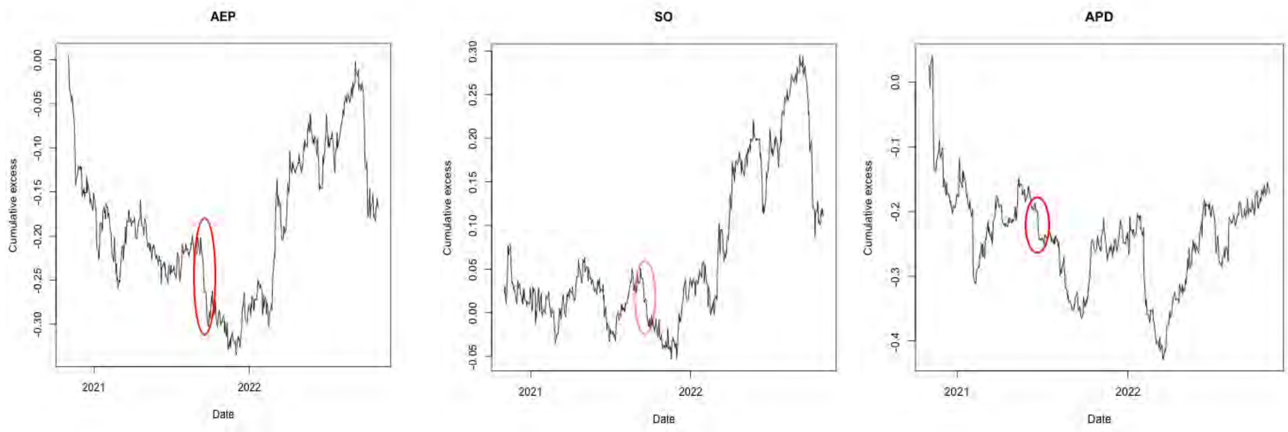
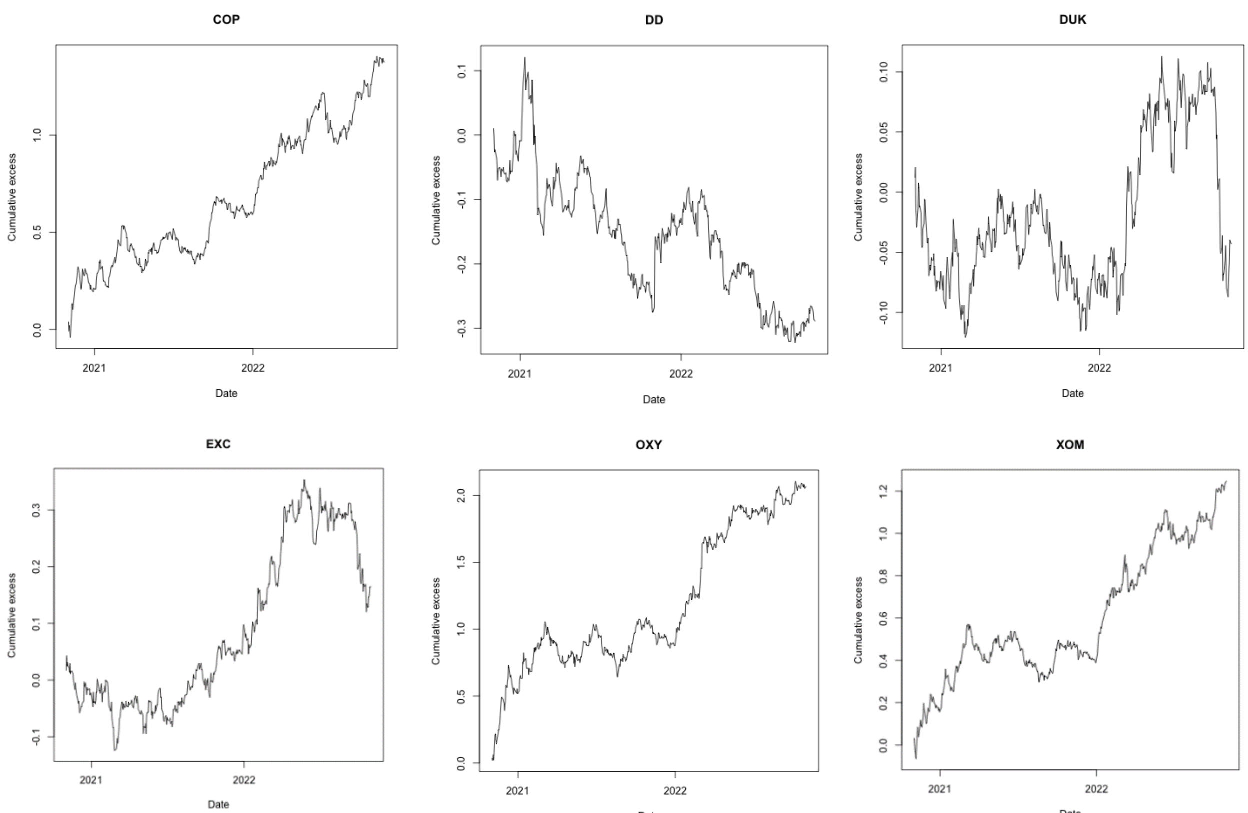


Figure B.4

CUMULATIVE EXCESS RETURN PLOTS FOR NORTH AMERICAN STOCKS NOT SHOWING THE PRICING OF CARBON RISK FOR THE RE-SIGNING OF THE PARIS AGREEMENT (NOVEMBER 2021)



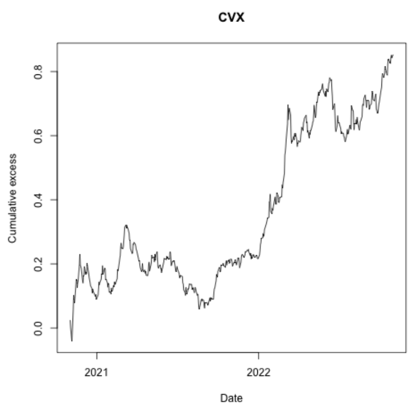


Table B.1

FACTOR MODEL REGRESSION COEFFICIENTS FOR STOCKS IN THE NORTH AMERICAN MARKET

Stock	Intercept	Market Return	SMB	HML
XOM	0.00014818	**0.94693845**	**-0.3393614**	-0.02261400
CVX	0.00026431	**0.96285938**	**-0.2108867**	**0.16666147**
COP	0.00022901	**1.00415069**	**-0.0948258**	**0.29455759**
OXY	0.00033906	**1.15596722**	0.06854563	**0.31854653**
APD	0.00030051	**1.0256686**	**0.12164394**	-0.04620250
DD	0.00005665	**1.21452212**	**0.43433267**	**0.42180934**
DUK	0.00024844	**0.61505676**	**-0.3052330**	0.03995465
AEP	0.00027131	**0.70010729**	**-0.3403934**	**0.17627358**
SO	**0.00039031**	**0.47044964**	**-0.2825339**	0.043387870
EXC	0.00016015	**0.72789564**	**-0.3069192**	**0.17308413**
SU.TO	0.00013154	**1.59623335**	-0.0343700	0.02871610
CNQ.TO	0.00041036	**1.62667055**	0.00380175	**0.11824370**
TRP.TO	**0.00041035**	**0.53568328**	**-0.1348200**	-0.01057160
CVE.TO	-0.0003547	**1.48237006**	0.01845455	**0.24638078**
IMO.TO	0.00016637	**1.11368143**	**-0.0928463**	0.00398390

The coefficients in bold are statistically significant at level 5%.

Appendix C: Estimation Results of the Mortality-Temperature Regression Model

In Chapter 4, the following regression model is considered:

$$log\left(\frac{q_x(t)}{1-q_x(t)}\right) = \beta_0 + \beta_1 temp_t + \beta_2 t + \sum_{i=36}^{109} \beta_{3,i} 1_{\{x=i\}} + \sum_{i=36}^{109} \beta_{4,i} 1_{\{x=i\}} temp_t$$

It is important to point out that the proposed regression model used in this section is specifically designed to capture unaccounted heterogeneity in the data through the employment of both fixed effects and time effects. Fixed effects capture unaccounted cross-sectional variations of factors that move slowly over time, while time effects capture unaccounted time-series factors that move slowly across cross sections. Thus, the employment of this study's model is intended to make the results robust to a variety of unaccounted factors in the regression model.

This equation can be rewritten to highlight the marginal effect of each covariate on mortality for different ages:

$$log\left(\frac{q_i(t)}{1-q_i(t)}\right) = (\beta_0 + \beta_{3,i}) + (\beta_1 + \beta_{4,i}) temp_t + \beta_2 t \ \ for\ i \in \{35, \ldots, 109\}$$

where:

- $\beta_{3,35} = \beta_{4,35} = 0$.
- $\frac{q_i(t)}{1-q_i(t)}$ is the odds ratio (OR) that a person of age i at time t dies within one year.
- $\beta_0 + \beta_{3,i}$ is the average log OR that a person of age i at time t dies within one year.
- $\beta_1 + \beta_{4,i}$ is the amount by which log OR that a person of age i at time t dies within one year increases when the annual mean temperature rises by 1°C (i.e., the marginal effect of temperature on mortality).
- β_2 is the average annual change of log OR that a person of age i at time t dies within one year. This coefficient is estimated to be -0.0115935 (which is statistically significant at the 0.1% level).

Figure C.1

MODEL COEFFICIENT ESTIMATES AND THEIR SIGNFICIANCES VIA THE METHOD OF MAXIMUM LIKELIHOOD

Age	Intercept $\beta_0 + \beta_{3,i}$	Significance	Marginal effect of temperature $\beta_1 + \beta_{4,i}$	Significance
35	-6.9809779	***	0.09896239	**
36	-6.7850388		0.08415832	
37	-6.6144512		0.07272216	
38	-6.3468821		0.05293485	
39	-6.2128704		0.0433398	
40	-5.9702925	*	0.02550761	
41	-5.8532307	**	0.02131496	
42	-5.4978845	***	-0.0074781	*
43	-5.4106994	***	-0.0086644	**
44	-5.3159379	***	-0.0108997	**
45	-5.1148121	***	-0.0227318	**
46	-5.0364323	***	-0.0217821	**
47	-4.8024873	***	-0.0377401	***
48	-4.73847	***	-0.034176	***
49	-4.6531034	***	-0.0361306	***
50	-4.4255142	***	-0.0500717	***
51	-4.4552075	***	-0.0378031	***
52	-4.2634631	***	-0.0485171	***
53	-4.2270754	***	-0.0442714	***
54	-4.1063938	***	-0.048961	***
55	-4.0933499	***	-0.0407336	***
56	-3.9700816	***	-0.0454278	***
57	-3.8729207	***	-0.0472964	***
58	-3.7000194	***	-0.0554619	***
59	-3.6185328	***	-0.0566097	***
60	-3.3333524	***	-0.0771276	***
61	-3.3986679	***	-0.0620103	***
62	-3.1069768	***	-0.0825718	***
63	-3.1513626	***	-0.0705428	***
64	-3.0790656	***	-0.0707404	***
65	-2.8264157	***	-0.0883841	***
66	-3.0069276	***	-0.061836	***
67	-2.7996913	***	-0.0753805	***
68	-2.7531516	***	-0.0714169	***
69	-2.7669191	***	-0.0616519	***
70	-2.5168956	***	-0.077992	***
71	-2.702424	***	-0.0503488	***
72	-2.4078606	***	-0.0707144	***
73	-2.4907136	***	-0.0530387	***
74	-2.3763454	***	-0.0565292	***
75	-2.2196293	***	-0.0632371	***
76	-2.2757938	***	-0.0481565	***
77	-2.3133812	***	-0.0347075	***
78	-2.1946615	***	-0.0378073	***
79	-2.1505609	***	-0.0321325	***
80	-2.1523907	***	-0.0181175	***
81	-2.3056128	***	0.00777439	**
82	-2.16578	***	0.00457279	**
83	-2.1012088	***	0.00891494	**
84	-2.080285	***	0.01809766	*
85	-2.1351212	***	0.03514071	
86	-2.1523381	***	0.04862223	
87	-2.196176	***	0.06474338	
88	-2.2775458	***	0.08443105	

Age	Intercept $\boldsymbol{\beta_0 + \beta_{3,i}}$	Significance	Marginal effect of temperature $\boldsymbol{\beta_1 + \beta_{4,i}}$	Significance
89	-2.2828495	***	0.09673096	
90	-2.2791062	***	0.10830909	
91	-2.4664837	***	0.13869578	
92	-2.4075632	***	0.1445196	
93	-2.3848991	***	0.15356282	
94	-2.423238	***	0.16877481	*
95	-2.4587405	***	0.18178986	*
96	-2.4641576	***	0.19286356	**
97	-2.4648364	***	0.20325138	**
98	-2.4644001	***	0.21330585	**
99	-2.4562546	***	0.22232815	**
100	-2.4484643	***	0.23112555	**
101	-2.4396263	***	0.23954454	**
102	-2.4287531	***	0.24745755	**
103	-2.4174342	***	0.25495904	**
104	-2.4114811	***	0.26254159	*
105	-2.3725441	***	0.26647761	*
106	-2.370356	***	0.27401759	
107	-2.3767374	***	0.2815559	
108	-2.3681587	**	0.28782338	
109	-2.1999861	*	0.27573611	

(Significance: ***: the coefficient is significantly different from zero or from their counterpart of age 35 at level 0.001, **: at level 0.01, *: at level 0.05)

Table C.1 confirms that while in general mortality rates decrease (as $\beta_2 < 0$), the extent to which mortality improves depends on the age and the mean annual temperature. For ages 42 to 80, $\beta_1 + \beta_{4,i} < 0$, meaning that their mortality decreases as the mean temperature rises. On the other hand, for ages below 41 and above 81, $\beta_1 + \beta_{4,i} > 0$, meaning that a higher temperature reduces the mortality improvement.

Appendix D: Expressions for Surplus Mean and Variance Incorporating Climate Risk

Under a climate change scenario *S*, the conditional mean and variance of terminal surplus are given by:

$$E[S_{T,s}] = A_0(1 + w'\mu_s)^T - E[L_{T,s}]$$

$$Var(S_{T,s}) = A_0^2[(w'\Sigma w + (1 + w'\mu_s)^2)^T - (1 + w'\mu_s)^{2T}] + Var(L_{T,s})$$

In Step 8 of the framework, the unconditional mean and variance of the terminal surplus are needed for the formulation of the optimization problem. These can be expressed in terms of $E[S_{T,s}]$ and $Var(S_{T,s})$ as follows

$$E[S_T] = \sum_s \gamma_s E[S_{T,s}]$$

$$Var(S_T) = \sum_s \gamma_s Var(S_{T,s}) + \sum_s \gamma_s E[S_{T,s}]^2 - \left(\sum_s \gamma_s E[S_{T,s}]\right)^2$$

where γ_s is the probability of climate scenario s occurring (with $\sum_s \gamma_s = 1$).

Appendix E: Information about the Stock Universe

Table E.1

STOCK UNIVERSE FOR THE REPRESENTATIVE DEFINED BENEFIT PENSION FUND

Company/Equity name	Symbol	Sector	Equilibrium return
Booking Holdings Inc	BKNG	Consumer Discretionary	12.37%
Comcast Corp	CMCSA	Consumer Discretionary	9.39%
Walt Disney	DIS	Consumer Discretionary	10.65%
General Motors	GM	Consumer Discretionary	12.73%
Home Depot Inc	HD	Consumer Discretionary	10.54%
Lowes Companies Inc	LOW	Consumer Discretionary	11.24%
McDonald’s Corp	MCD	Consumer Discretionary	7.38%
Netflix Inc	NFLX	Consumer Discretionary	13.81%
Nike Inc	NKE	Consumer Discretionary	11.05%
Starbucks Corp	SBUX	Consumer Discretionary	10.81%
Tesla Inc	TSLA	Consumer Discretionary	17.43%
Colgate-Palmolive	CL	Consumer Staples	5.72%
Costco Wholesale Corp	COST	Consumer Staples	7.89%
Coca-Cola	KO	Consumer Staples	6.19%
Mondelez International Inc	MDLZ	Consumer Staples	7.63%
Altria Group Inc	MO	Consumer Staples	6.00%
PepsiCo Inc	PEP	Consumer Staples	6.75%
Procter & Gamble	PG	Consumer Staples	5.94%
Philip Morris International Inc	PM	Consumer Staples	6.89%
Target Corp	TGT	Consumer Staples	8.58%
Walmart Inc	WMT	Consumer Staples	5.64%
ConocoPhillips	COP	Energy	11.88%
Chevron Corp	CVX	Energy	10.47%
Exxon Mobil Corp	XOM	Energy	9.04%
American International Group Inc	AIG	Financials	12.21%
American Express	AXP	Financials	12.92%
Bank Of America Corp	BAC	Financials	13.20%
Bank Of New York Mellon Corp	BK	Financials	10.90%
Blackrock Inc	BLK	Financials	13.15%
Berkshire Hathaway Inc Class B	BRK.B	Financials	9.24%
Citigroup Inc	C	Financials	14.07%
Chubb Ltd	CB	Financials	8.36%
Capital One Financial Corp	COF	Financials	14.53%
Goldman Sachs Group Inc	GS	Financials	12.70%
JPMorgan Chase & Co	JPM	Financials	11.86%
Mastercard Inc	MA	Financials	13.01%
MetLife Inc	MET	Financials	12.59%
Morgan Stanley	MS	Financials	14.16%
Charles Schwab Corp	SCHW	Financials	12.62%
US Bancorp	USB	Financials	11.53%
Visa Inc	V	Financials	11.73%
Wells Fargo	WFC	Financials	12.21%
AbbVie Inc	ABBV	Health Care	7.69%
Abbott Laboratories	ABT	Health Care	9.23%
Amgen Inc	AMGN	Health Care	8.51%
Bristol Myers Squibb	BMY	Health Care	6.32%
CVS Health Corp	CVS	Health Care	7.70%
Danaher Corp	DHR	Health Care	9.25%
Gilead Sciences Inc	GILD	Health Care	6.97%
Intuitive Surgical Inc	ISRG	Health Care	12.77%
Johnson & Johnson	JNJ	Health Care	6.02%

Company/Equity name	Symbol	Sector	Equilibrium return
Eli Lilly	LLY	Health Care	7.48%
Medtronic Plc	MDT	Health Care	8.76%
Merck & Co Inc	MRK	Health Care	6.27%
Pfizer Inc	PFE	Health Care	6.74%
Thermo Fisher Scientific Inc	TMO	Health Care	9.63%
UnitedHealth Group Inc	UNH	Health Care	9.17%
Boeing	BA	Industrials	14.36%
Caterpillar Inc	CAT	Industrials	11.13%
Deere	DE	Industrials	10.30%
Emerson Electric	EMR	Industrials	11.45%
FedEx Corp	FDX	Industrials	11.52%
General Dynamics Corp	GD	Industrials	8.50%
GE Aerospace	GE	Industrials	11.56%
Honeywell International Inc	HON	Industrials	10.21%
Lockheed Martin Corp	LMT	Industrials	6.67%
3M	MMM	Industrials	9.00%
RTX Corp	RTX	Industrials	9.94%
Union Pacific Corp	UNP	Industrials	10.07%
United Parcel Service Inc	UPS	Industrials	9.15%
Apple Inc	AAPL	Information Technology	13.63%
Accenture Plc	ACN	Information Technology	11.51%
Adobe Inc	ADBE	Information Technology	14.38%
Advanced Micro Devices Inc	AMD	Information Technology	18.14%
Amazon Com Inc	AMZN	Information Technology	13.77%
Broadcom Inc	AVGO	Information Technology	15.15%
Salesforce Inc	CRM	Information Technology	14.16%
Cisco Systems Inc	CSCO	Information Technology	10.80%
Alphabet Inc Class C	GOOG	Information Technology	13.30%
Alphabet Inc Class A	GOOGL	Information Technology	13.30%
International Business Machines Co	IBM	Information Technology	8.97%
Intel Corporation Corp	INTC	Information Technology	13.84%
Intuit Inc	INTU	Information Technology	14.37%
Meta Platforms Inc	META	Information Technology	14.82%
Microsoft Corp	MSFT	Information Technology	13.77%
ServiceNow Inc	NOW	Information Technology	15.31%
Nvidia Corp	NVDA	Information Technology	19.39%
Oracle Corp	ORCL	Information Technology	10.57%
Qualcomm Inc	QCOM	Information Technology	13.94%
Texas Instruments Inc	TXN	Information Technology	12.93%
Air Product & Chemicals Inc	APD	Materials	9.62%
American Tower REIT Corp	AMT	Real Estate	8.20%
Simon Property Group REIT Inc	SPG	Real Estate	11.23%
Charter Communications Inc	CHTR	Telecommunications	9.30%
AT&T Inc	T	Telecommunications	6.64%
T Mobile US Inc	TMUS	Telecommunications	8.69%
Verizon Communications Inc	VZ	Telecommunications	4.98%
Duke Energy Corp	DUK	Utilities	5.50%
NextEra Energy Inc	NEE	Utilities	6.98%
Southern Co	SO	Utilities	5.83%

Table E.2

AVERAGE EQUILIBRIUM RETURNS BY SECTOR

Sector	Average Expected Return
Consumer Discretionary	11.58%
Consumer Staples	6.72%
Energy	10.47%
Financials	12.28%
Health Care	8.17%
Industrials	10.30%
Information Technology	13.80%
Materials	9.62%
Real Estate	9.72%
Telecommunications	7.40%
Utilities	6.10%

Glossary

Adaptation rate: The rate at which the company decreases their emissions without fundamentally reducing operational efficiency, achieved through technological investments.
Anthropogenic global warming: Global warming caused by human activities such as burning fossil fuels, as opposed to the temperature rise due to natural factors such as solar activity.
Beta of an asset: A measure of the risk of the asset's systematic return, calculated as the expected move in the asset price relative to movements in the market.
Biological hazards: Biological substances that pose a threat to the health of living organisms, primarily humans, such as micro-organisms, viruses, and toxins.
Black fund: Mutual funds that mainly invest in stocks from carbon-intensive industries.
Book-to-market ratio: The ratio between the market value and the book value of an asset, highlighting its undervaluation or overvaluation.
CPP model: The Canada Pension Plan model. An investment strategy characterized by active portfolio management and the use of internally managed alternative investments.
Carbon allowance: A permit allowing countries and organizations to emit a certain amount of greenhouse gases (GHG), which is issued by governments under a trading scheme (such as the EU ETS).
Carbon credit: A permit allowing countries and organizations to offset a certain amount of their GHG emissions, which is sold by carbon capturing projects.
Carbon footprint: The amount of carbon dioxide equivalents emitted due to the consumption of fossil fuels or other activities by a particular entity. For a stock, this term refers to the carbon footprint of the underlying company.
Carbon intensity: A measure of carbon footprint normalized by the magnitude of the associated business activity.
Carbon risk: The portion of transition risk related to carbon intensive activities in the context of climate change.
Carbon tax: A tax on CO_2 emissions from goods and services production, which is intended to make visible the hidden costs of carbon emissions, thus incentivizing corporations to be more eco-friendly.
Carbon-intensive sectors: Industry sectors that emit a large amount of greenhouse gases (e.g., oil production, materials).
Climate (change) risks: Different types of environmental and socioeconomic risks caused by climate change as well as climate mitigation and adaptation efforts.
Climate adaptation: The process of adjusting to the current and future effects of climate change.
Climate migration: Population movements away from areas vulnerable to climate change. These displacements may be temporary, due to the occurrence of natural disasters, or permanent, due to climate change threatening livelihoods and raising costs of living in such areas in the long run.
Climate mitigation: The process of reducing the severity of climate change consequences.
Climate scenario: A plausible presentation of the future climate of the Earth, commonly associated with a socioeconomic pathway. Climate scenarios are estimated using integrated assessment models (IAMs).
Climate-sensitive sectors: Industry sectors that are sensitive to physical damage due to adverse weather conditions (such as real estate), or to financial losses caused by future climate mitigation schemes (such as oil production).
CO_2 fertilization effect: The increasing carbohydrate production in plants with improved growth and yield due to the rise in level of a crucial ingredient—CO_2.
Connectedness: The concern that the failure of one asset or market would provoke the failure of another asset or market.
Delta of an option: A measure of the option value's sensitivity to the changes in the underlying security's value, calculated as the change in the option's value corresponding to a change of $1 in the underlying security's value.
Diversifying goal: The goal of including in an investing strategy assets that are not highly correlated to one another. This allows the poor performance of an asset to be offset by the strong performance of another asset, thus keeping the portfolio's performance stable.
Divesting goal: The goal of lowering the allocation of an investing strategy to carbon-intensive assets.
Dynamic Integrated Climate-Economy (DICE) model: An Integrated Assessment Model (IAM).

Emission-heavy sectors: Synonym to "carbon-intensive sectors."
ESG rating: The rating of a company based on its performance in three pillars: Environment, Social, Governance. ESG ratings are provided by rating agencies using companies' public disclosures and media records.
EU ETS: Acronym for the European Emission Trading Scheme, the first and largest emission trading scheme in the world. It was launched in 2005 as a climate mitigation effort after the introduction of the Kyoto protocol. The scheme allows installations to trade carbon allowances in order to cover their excess emissions (above their allotted maximum emission amounts) during the year, or to make profit from unused carbon allowances. Allowances could also be saved (to be used in subsequent years) or borrowed (from the subsequent year) if the scheme is in an "open trading phase," while in a "closed trading phase," unused allowances expire at the end of the year with no value.
European Climate Law: The set of laws that make the goals set out in the European Green Deal legally binding. It was passed in July 2021. It also includes a target of 55% carbon reduction by 2030.
European Green Deal: A set of policy proposals approved in December 2019 with the overarching goal of making the European Union climate neutral in 2050. It includes a circular economy action plan, the review and revision of existing climate law and instruments (such as the EU ETS), as well as the introduction of new EU climate, energy, transport, agriculture, and finance policies.
Green bonds: Bonds issued by governments or corporations to fund projects that benefit the environment and mitigate climate change.
Green economy: A low carbon, resource efficient, and socially inclusive economy. In a green economy, growth in employment and income are driven by public and private investment into such economic activities, infrastructure, and assets that allow reduced carbon emissions and pollution, enhanced energy, and resource efficiency, and prevention of the loss of biodiversity and ecosystem services (UN Environment Program).
Green equity: Equity from companies whose primary business is beneficial to the environment. Such companies are concentrated in sectors such as alternative energy, pollution control, and recycling.
Green fund: Mutual funds that mainly invest in the green stocks and green bonds markets.
Green premium (Greenium): The difference in yield premium between a green bond and an otherwise identical conventional bond.
Green transition: The transition towards a green economy.
Greenhouse gas emission scopes: The greenhouse gas emissions of an entity are measured under three scopes: 1) Direct emissions that are owned or controlled by the entity; 2) Indirect emissions the entity emits by purchasing energy used in their economic activities; 3) All emissions not included in scopes 1 and 2 and created by the value chain of the entity.
Greenwashing: Misleading claims made by companies about their environmental practices or products, whether deliberate or unintentional.
Integrated Assessment Models (IAMs): Scientific models used in the environmental sciences and environmental modeling, integrating knowledge and methodologies across multiple disciplines. In climate change research, such numerical models are commonly used to predict future climate scenarios as well as to quantify their potential impact on the economy.
Longevity risk: The risk that policyholders live for longer than is currently expected.
Market capitalization: The total value of a company's outstanding shares of stock (including publicly traded shares and privately held shares).
Mitigation cap: The maximum annual emission reduction the firm may achieve due to willingness or capacity. Often this equals the firm’s annual emissions.
Mortality cost of carbon: The number of excess deaths caused by one additional metric ton of CO_2 emissions.
Negative/Positive screening: The act of excluding/including an asset in the asset universe based on its ESG characteristics when constructing the portfolio.
Physical risk: The risk associated with the direct impact of climate change (extreme weather events and chronic climate conditions).
Physiological adaptation: Changes in a human body’s response to heat or cold, which may lead to more or less severe reactions to the same temperature.

Policy risk: The portion of transition risk to the market value of assets arising from the unexpected introduction of future climate control protocols.
Portfolio decarbonization: The intent or effort to reduce the carbon risk exposure of an investment portfolio.
Pre-industrial temperature: The average Earth surface temperature commonly used as baseline in setting climate-related goals. The pre-industrial period is often defined as 1850-1900.
Risk pricing: A risk is (fully) priced (recognized) if the future effects of the risk are fully accounted for in the present values within the financial market.
Risk-adjusted return: A measure of investment performance where the asset's excess return (meaning average return minus the risk-free return) is normalized by the risk of the returns (such as volatility, beta, or drawdowns).
Scope 1 emission: greenhouse gases that a company emits directly. This can be through company vehicles, fugitive emissions (leaks from equipment or infrastructure), or any emissions from owned or controlled sources. These emissions are often the first area of focus in a company's efforts to reduce greenhouse gas emissions as they are the ones it has direct control over.
Scope 2 emission: emissions that a company generates indirectly through the purchase and use of electricity, steam, heating, and cooling. These emissions come from the energy a company consumes.
Sea level rise: The increase in the average height of the ocean's surface, which is caused by climate change, mostly due to a combination of melt water from glaciers and ice sheets and thermal expansion of seawater as it warms.
Socially Responsible Investing (SRI): The practice of investing while taking into account the social impacts of the investments. In the 1990s, SRI emphasized the consideration of ethical issues such as investments associated with addictive substances, gambling, terrorism, etc. SRI started to focus on environmental impacts in later years.
Socioeconomic adaptation: Changes in socioeconomic conditions such as purchasing power or health care that allow the population to have milder reactions to adverse weather conditions.
Spillover effect: The impact that an event happening to an asset/market has on another seemingly unrelated asset/market.
Stranded asset: An asset which loses economic value well ahead of its anticipated useful life, whether as a result of changes in legislation, regulation, market forces, disruptive innovation, societal norms, or environmental shocks (Generation Foundation).
Sustainable investing: a range of strategies in which investors include environmental, social, and corporate governance (ESG) criteria in investment decisions and investor advocacy.
Systematic risks: Risks affecting the entire market caused by economic, social, or environmental origins. They include climate change risks.
Systemic risk: The risk of downturn or collapse of the entire market triggered by the failure of a market agent.
Transition risk: The risk arising from the future adoption of new climate mitigation measures (new policies, technology advancements, etc.).

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