A Multi-model Analysis of Climate-related Financial Risk Disclosure and De-carbonization Investment Portfolios Piloting to the TCFD

Shuqin Gao[1,2]

[1] Harvard Economics Department, Harvard University, Cambridge, USA

[2] UNDP Sustainable Finance Hub, New York, USA

Correspondence: Shuqin Gao, Research fellow at Harvard Economics Department, Harvard University, USA; Senior Roster Climate Economist at UNDP Sustainable Finance Hub, USA. E-mail: shuqingao@fas.harvard.edu, gaoshuqin@pku.edu.cn

Received: December 9, 2024 Accepted: January 10, 2025 Online Published: January 22, 2025

doi:10.5430/ijfr.v16n1p1 URL: https://doi.org/10.5430/ijfr.v16n1p1

Abstract

This research explores climate related financial risk disclosure by quantifying climate related transition risk and physical risk, creating cost-benefit analysis for businesses, industries and financial institutions with business as usual model (BAU) and alternative models of an updated carbon emission reduction scheme, constructing carbon emission-induced cost function and benefit function models, as well as multi-dimensional climate damage function models. This research integrates frameworks based on carbon shadow price, carbon emission abatement costs and climate damage costs, social costs of carbon with climate change scenarios for assessing climate financial risk, as well as its asymmetric and nonlinear impact on financial equilibrium. The heterogeneity of climate financial risk scenarios are built up on implementing national determined commitment (NDC) for a predefined temperature target 1.5-2 ^{0}C above pre-industrial levels under carbon neutrality target of Paris climate agreement and the United Nations Framework Convention on Climate Change (UNFCCC). The model functions, selected parameters and cost-benefit simulation construct a cost-effective optimal pathway for driving future carbon emissions reduction and building climate resilience to manage and mitigate climate related financial risk.

Keywords: climate finance risk, carbon price, carbon shadow price, carbon abatement cost, social cost of carbon, financial solvency, financial liquidity, financial equiulibrium, climate finance scenarios

1. Introduction

Global climate change has been inducing great risk and huge uncertainty for financial institutions and businesses, exacerbating social-economic damage costs and generating new carbon emission abatement costs across different industries and businesses. There is extensive and mounting evidence that climate financial risks are real and may reconstruct financial equilibrium and impact on financial liquidity and solvency over the short, medium and long term. The bankruptcy of the major Californian utility PG&E was dubbed “the first climate-change bankruptcy” by the Wall Street Journal (Russell Gold 2019). The Stern Review of the Economics of Climate Change (Stern 2006) concluded that if no climate mitigation action is taken, the overall costs and risks of global climate change will be equivalent to losing at least 5% of global Gross Domestic Product (GDP) each year, now and forever. The associated uncertainties with carbon abatement costs and transition risk are very high, but the annual increase in the damage cost is relatively well constrained with each additional year of delay in implementing mitigation costing an additional 0.3-0.9 trillion dollars in total discounted future mitigation costs (Benjamin M. Sanderson & Brain C. O Neill, 2020). If the 2 ℃ target is to be ultimately met, conditions leading to damages or mitigation costs turn out to be unexpectedly high. That said we are paying the cost of delay in adopting a cost-effective decarbonization pathway to mitigating climate change risk every day.

Many industries and businesses are likely more affected by both climate transition risk and physical risk. The potential disruption of industry operation, market demand and supply chains, as well as the financial implications from climate disaster has driven substantial financial losses, it has also triggered financial insolvency and low liquidity ratio problem. Therefore, it is significant and urgent to disclose real and potential impacts of climate risk on the financial equilibrium. Financial sector reform needs to mobilize and catalyze the capital flow toward low-carbon climate resilient investment for environmental and social governance concerns, allocate financial resources for climate resilience capacity building across businesses and financial institutions.

In 2017 the Financial Stability Board pushed for greater disclosure via an international initiative: The Task Force on Climate-related Financial Disclosures (TCFD). June 29, 2017, the Financial Stability Board's TCFD made the recommendation of climate and environmental disclosures and their associated risks into credit ratings more consistent and transparent for G20 summit. (Note 1) In 2017 the TCFD required the voluntary climate-related financial disclosures for building sustainable finance and reforming the financial sector, it aims to prioritize investment in clean energy, resource-efficient projects, green products and climate innovation, accelerate the growing trend towards climate resilience low-carbon investment. Climate and green sectors have already provided enormous investment opportunities, with more than $1 trillion flowing into climate-related projects worldwide (World Bank Report 2021), and climate investment could provide up to $23 trillion new opportunities in emerging market by 2030. (World Bank Report 2021)

In 2020 the TCFD requires businesses, industries and financial institutions to be mandatory to report but voluntary to disclose its CO_2 emission reduction plan. The TCFD aims to incentivize all businesses and financial institutions to channel and deploy financial resources toward low-carbon climate resilience investment to offset or reduce climate-related risks: Businesses and industries, shareholders generally have an obligation to disclose climate related financial information; Investors, lenders, and insurers need to make informed capital allocations to mitigate climate change risk; Regulators and macro-prudential supervisors need to manage the impact of climate risks on the financial equilibrium and the financial system potential exposures to climate transition and physical risk; Government and regulators need to identify and mitigate potential climate risk and improve climate resilience.

1.1 Literature Review

There is a big gap concerning integrating climate transition risk and physical risk into financial planning and strategies management for businesses, industries and financial institutions piloting the TCFD in the international literature. David M. Silk, Sabastian V. Niles, and Carmen X. (2020) pointed out that the TCFD serves as a guideline and benchmark framework for corporates to manage climate responsibilities. Christine Robinson, Deb DeHaas, Debbie McCormack, Jennifer Burns, Kristen Sullivan, Maureen Bujno (2020) Explore that organizations need to develop climate-related financial disclosures, as well as supplemental guidance for specific sectors. Renard Siew (Aug. 2020) highlights the common challenges faced by the property and construction industry in implementing the TCFD. David Wei and Giulio Berruti (2019) pointed out the important governance and strategy, risk management for implementing the TCFD. Betty M. Huber and Paula H. Simpkins (2020) pointed out that the largest increase in disclosure of climate related financial risk was related to how to identify, assess and manage climate-related risk. Robert G. Eccles & Michael P. Krzus (2019) evaluates difficulties and feasibilities for companies to implement the recommendations of the TCFD. Ian Edwards and Kiri Yapp (2020) discussed the TCFD limitations to drive climate action in public sector. However, above debate from either scholars or businesses consultants hasn’t quantified the climate finance risk, they also didn’t build climate cost and benefit function model to monetize the climate related financial risk.

Some scholars analyze uncertainties associated with Green House Gas (GHG) emission to policy and economy. Zvi Adar and James M. Griffin (1976) compares the relative efficiencies of pollution taxes, pollution standards when the marginal damage function or marginal abatement cost are subject to uncertainties. Weitzman, M.L. (1974) explores the correlations of prices vs quantities with uncertainty of marginal cost. Stavins, R. (1996) discussed the correlation of price instrument and quantity and the simultaneous uncertainty in benefits and cost for environmental protection; Roberts, M.J. and M. Spence (1976) discussed price of subsidies and license for marginal cost and benefit function. This research considers the above discussion and integrates uncertainty into damage function, cost and benefit function of climate financial risk analysis framework, monetizing the climate related physical and transition risk and impact on the financial equilibrium as the proxy of general economic-social-environmental impact of global climate change.

1.2 Research Questions

How to manage the climate related financial risk for transition to a low-carbon future and mitigate its climate financial risk exposures? How to monetize climate-related financial transition risk and physical risk? What are the disclosure portfolios to implement the TCFD? How to incentive financial resources to mitigate climate related financial risk?

1.3 Research Methods

There is a large number of research methodologies supporting the TCFD-compliance scenario analysis: some common core datasets, modelling components and methods for climate related financial valuation. (Note 2) This research explores some quantitative models to quantify the climate financial risk, illustrates potential pathways to reduce climate financial risk and its impact on financial equilibrium, evaluating the potential resilience of their financial equilibrium to a range of climate mitigation and adaptation scenarios. A multiple-statistical damage function, cost and benefit function models will be constructed to explore the relationship between climate change scenarios, GHG emissions scenarios, carbon pricing policy and climate related financial risk.

The analytical framework of climate related financial risk scenarios is based on the transition risk scenarios, the physical hazard scenarios and chronic damage functions, determining a disclosure portfolio as the indicators of climate financial risk. Data-driven forward-looking physical risk scenarios are constituted by empirical evidence from local meteorological bureau and hydrometric station, these empirical data show the extreme weather events scenarios. The social cost of carbon is used to examining the social-economic-environmental damage from the chronic changes in temperature and precipitation induced by the anthropogenic GHG emissions, that said social cost of carbon measures the present value of future economic damage caused by each additional ton of carbon emission, but the current social cost of carbon is too low to reflect GHG environmental externalities impact. climate disaster impact on the financial-economic activities will be calculated based a micro-econometric modelling of climate scenarios.

In this research the transition risk is quantified by exploring the cost and benefits in de-carbonization transition process to meet the countries' national emissions reductions target and low carbon economy transition criteria. Multiple forward-looking data-driven scenarios will be used for assessing climate-related financial transition risk, integrating the TCFD scenario into the industry and businesses' financial (financial risk metrics, ratings etc.) plan to mitigating and monitoring carbon footprint, exploring climate stressed financial economic losses under different carbon emission reduction scenarios. The carbon pricing and emission abatement cost serve as the proxy to translate the climate related transition risk to financial value. Climate policy, energy performance and low-carbon disruptive technology, market change scenarios (Note 3) with a range of GHG emission scenarios, and carbon pricing system together construct an analytical framework for assessing climate related financial transition risk.

This research performs a cost-benefit analysis, integrating carbon emissions offset schemes with carbon abatement costs, social cost of carbon (Note 4) including the social cost of methane and nitrous oxide, discount rate and carbon shadow price etc., quantifying and comparing the total costs vs total expected benefits to predict the climate related transition financial risk. A benefit-cost ratio may also be computed to summarize the correlation between the relative costs and benefits for climate related financial risk elasticity assessment.

1.4 Research Assumptions and Climate Related Financial Exposure Portfolios Parameters

This research hypothesizes that in 2020 all industry and business mandatorily need to set a carbon emission reduction scheme to meet the limiting carbon emission threshold required by the sustainable low-carbon climate-resilient economy model addressing to the Intended National Determined Contribution (NDC) to the carbon neutrality target by 2050 and the TCFD recommendations. It is required to allocate financial resources to adjust its business model to climate-resilient low-carbon sustainable business models, mitigating and managing climate related financial risk.

To monetize and quantify climate related financial risk, this research also hypothesizes that the carbon abatement cost and building climate resilience cost are different from the benefit of reducing carbon emission given the Nationally Determined Commitment (NDC) to carbon neutrality target by 2050 is implemented. The differences of cost and benefit from reducing carbon emissions show the elasticity curve for the potential climate-related transition risk and physical risk.

This research will examine climate related financial risk disclosure portfolios including a series of parameters: carbon abatement cost, carbon shadow price, carbon permit and allowance price, proposed carbon abatement quantity, the carbon emission standards GDP per unit and real carbon emission quantity (Note 5), climate policy including energy mix and efficiency criteria, energy tax, carbon tax, low-carbon technology cost and carbon emission trade price curve, economic losses from climate disaster scenarios, chronic social-economic damage cost from GHG emission concentration in atmosphere etc.. These financial exposure parameters are attributed to huge uncertainties associated with global climate change and GHG emission reduction targets. Thus, in this research the economic tools of carbon pricing: carbon shadow price, carbon abatement cost and carbon social cost will be applied to test the uncertainties associated with climate damage function, climate cost and benefit function.

1.5 Research Objectives and Structure

This research aims to disclose climate related financial risk for decision makers and investors in the financial institutions, industries and businesses, incentivizing financial allocations to facilitate the investment and businesses transition to a more sustainable, low-carbon resilient development model. This research structure is as the following concrete:

The first part of this research develops a conceptual framework to incorporate climate-related risk disclosure into the financial decision-making process, enabling policy makers and stakeholders to thoroughly understand the concentrations of carbon bubble in the financial sector and the financial system's exposures to climate-related risks. The second part of this research provides a rigorous assessment to quantify the financial potential exposures to the climate-related transition risk and physical risks, establish strong climate-related financial risk measurement modelling and tools. The last part of this research explores a climate damage function, benefit and cost function to explain how to effectively manage climate related financial risk to build climate related financial resilience.

2. Climate Related Financial Exposure: Physical Risk and Transition Risk

2.1 Climate Related Transition Risk and Physical Risk

Climate-related transition risk includes the uncertainty associated with climate policies, market changes and low carbon technologies adoption including renewables, carbon capture, utilization and storage technology, environmental tax and carbon pricing policy, energy efficiency and energy mix criteria etc. This will inevitably impact the production operations, input cost, present value chain, future value chain and gross value added growth, market consumption preference, financial liquidity and strategic planning framework in all industries and businesses.

The growing climate physical risks refer to extreme weather events, chronic temperature and precipitation changes induced by anthropogenic GHG emission concentration in atmosphere, rising sea levels, changing weather patterns and more frequent or intense droughts, floods, and storms etc.. These all can generate serious financial economic losses and assets damage from disruption of the entire value chain and operation: including damage for facilities and property, supply chains, employees and financial capital market volatility etc. (Shuqin Gao 2024). The chronic change in temperature and precipitation change agricultural productivity, biodiversity and ecosystem, decline in human health and labor productivity etc.

2.2 Climate Related Financial Risk

2.2.1 Climate Related Financial Physical Risk

Climate related financial physical risk (Note 6) means financial exposure to the impacts of extreme weather and climate disasters, as well as the damage cost triggered by the chronic change in temperature and precipitation induced by anthropogenic GHG emission. Apparently, the growing physical risks of the increased extreme weather events will generate huge financial losses and abrupt disruption for businesses, triggering substantial property damage and assets losses by disrupting operations, supply chain and market demand. Therefore, financial sector reform is required to facilitate the financial allocation for further climate mitigation and adaptation, in order to build climate resilience capacity at the scale and speed needed to prevent, reduce or offset the climate related financial physical risk. Climate meteorological data and the GHG emission quantity evaluating climate sensitivity level serve as the climate related physical risk drivers, these need to be incorporated into financial borrower’s analysis, insurance, investment and climate resilience capacity building concern.

2.2.2 Climate-related Financial Transition Risk

The financial exposure to the uncertainty due to introducing or implementing new climate policies, low carbon market regulation and innovation policy formulates the climate related financial transition risk. It is based on modeling how climate policy, market and innovation regarding energy mix and GHG emissions interact with business operations and revenues among other key factors in the short, medium and long term. These parameters can reflect a faster or slower transition depending on the dynamic changes of key parameters: the low-carbon technology adaptation, development and deployment; changes and timing of key policies like energy mix and efficiency; the implementation of carbon tax and carbon prices reflect its environmental effectiveness and economic efficiency etc.

In constructing a scenario about the potential impact of the transition to a low-carbon and climate resilient model a number of published scenarios are available, that lay out various plausible pathways to a particular CO_2 emission reduction level. These scenarios have varying assumptions associated with uncertainties about the timing of policy changes, market consumption preference change, low-carbon technology adoption, changes in energy mix, and other factors to achieve a low-carbon climate resilient sustainable economy (Note 7).

In implementing a rigorous climate-related scenario analysis process, a range of hypothetical outcomes will be evaluated by considering a variety of existing publicly available scenarios: A 2 ℃ scenario and other climate-related transition scenarios to climate-resilient low carbon economy related to the NDC under the UNFCCC (Note 8) for assessing the GHG emissions reduction, Global Carbon project (provides information on the global carbon cycle, including its biophysical and human dimensions and the interactions between them, as well as carbon and methane budgets and trends) will be considered in this research. (U.S.E.A CREAT, 2022)

This research on climate financial transition risk specifically monetizes the impact of carbon emission and emission reduction for businesses and industries, financial institutions. This is a corporate-based carbon emission calculation that is different from the national level carbon calculation methodologies to the NDC for the Paris agreement target. Therefore, market-based and location-based carbon emission calculation methods is used for calculating the proposed corporate carbon emissions in this research (Note 9), assessing a range of financial risks associated with various carbon reduction scenarios, exploring the carbon footprint and investment portfolios to allocating financial resources.

3. Assessing the Potential Financial Exposures to the Climate Related Financial Risks

3.1 Climate Related Financial Transition Risk Exposure

3.1.1 Climate Related Financial Transition Risk and Investment Portfolios

A range of plausible climate-related transition risk scenarios based on a coherent and internally consistent set of assumptions about key parameters: discount rate, technological change, carbon price or tax, carbon shadow prices, policy and regulation changes, energy performance and carbon marginal abatement cost (Note 10), annual cumulative GHG emission reduction quantity and annual cumulative GHG emission quantity etc. In addition, Policies supporting the low-carbon transition have reduced market demand for higher carbon products/commodities, increasing demand for energy-efficient lower-carbon products and services, policy and regulation have also increased input/operation costs for high carbon economic activities and operations, as well as the risk of loss of trust and confidence in management and market demand for high carbon product. The climate policy and low-carbon innovation trigger market value chain and market demand change, high carbon intensity product and service will be less consumed due to environmental harm, environmental regulations and the increased input cost.

This research will develop multiple scenarios with respect to assessing and quantifying the impact of the climate related financial transition risk:

Model 1

Given the NDC to net zero carbon emission target by 2050 is implemented, assuming that there is not a carbon emission trade scheme and carbon offset mechanism in the designated jurisdiction. This research proposes the annual cumulative GHG emission quantity=ACGc(t), denotes annual cumulative GHG reduction=ACGr(t), regulatory annual cumulative GHG emission reduction quantity=ACGrr(t), ACGrr(t) is very impacted by the carbon intensity annual GDP per unit, denotes the carbon shadow price /per ton =(Csp).The projected life cycle time=Time (Ty), Marginal carbon abatement cost=Cmag,

Carbon price / tax/per ton= C_t, Discount rate=D^r

$$\text{Csp}= \frac{C_t}{1-D^r}$$

The climate related transition financial risk= Carbon bubble reflects in a project life cycle time frame:

Cost= ACGc(t) x Csp($) x T(y) + ACGr (t) x Cmag ($) x T(y)

Financial Climate transition risk (FCtrisk) portfolios including: Policy Regulation (Energy Mix+ Energy efficiency)+ Innovation including carbon capture, utilization and storage technology (CCUST) and biofuel biochar etc. (BCCT), GHG emission reduction standards. This research denotes that carbon marginal abatement cost includes the innovation and energy transition cost.

Annual cumulative GHG emission reduction quantity= ACGr (t)

FCtrisk benefit = [ACGr (t)- ACGrr(t)] x Csp x T(y)

Annual cumulative GHG emission quantity=ACGc(t)

Benefit from GHG emission reduction=[ACGr(t)- ACGrr(t)]x Csp($) X T(y)

Cost from GHG emission reduction=ACGr(t) x Cmag($) x T(y) + ACGc(t) x Csp($) x T(y)

Ctrisk = Ctrisk Cost - Ctrisk benefit=

ACGr(t)x Cmag X T(y) + ACGc(t)x Csp X T(y) – [ACGr(t)- ACGrr(t)] x Csp x T(y)

In order to assess the impact of energy mix on a set of representative financial exposures to the climate transition risk scenarios, it is necessary to assess the impact of some metrics such as limiting GHG emissions (Cea) and net zero carbon emission target by 2050 on the energy transition portfolio development, energy efficiency standard tax and energy tax (Et), annual energy consumption amount (Eq), carbon remove technology cost (T$), energy consumption amount, GHG emission marginal abatement cost, carbon shadow price (Csp), power efficiency tax (Pt) and power annual consumption amount (Pq). With regard to sustainable energy transition scenarios: International Renewable Energy Agency (IRENA) (2016) (Note 11) Remap focuses on renewable power technologies, but also clean power innovation transition in heating, cooling, and transport (ETP 2015). Transition scenarios and their underlying assumptions include IEA WEO 450 Scenario, ETP 2DS Scenario, Deep Decarbonization Pathways Project (DDPP), IEA ETP (2015) etc. (Note 12). In the above scenarios analyses, climate related transition risk portfolios require specific consideration and standardization, international standard industrial classification (ISIC) heterogeneous factors (power generation, transmission and distribution) metric and indicators to monitor the vulnerabilities of businesses to global climate change transition risk and environment externality.

Model 2

Assumes that the projected carbon reductions scheme or offset mechanism meets or under the regulatory benchmark, there is a carbon trade scheme and offset mechanism in the designated jurisdictions. The cost and benefit is calculated as follows:

Benefits=[ACGr(t) - ACGrr(t)] x Csp x T(y)

Ctrisk Cost=Cmag x ACGr(t) x T (y) + ACGc(t) x Csp($) x T(y)

Ctrisk Cost= Cost for energy regulation (Energy Mix + Energy efficiency + Power efficiency etc)+ cost for Innovation (CCUST + BCCT).

Risk = 0, Benefit=Cost

Classifying Cost: Abatement Cost =Cmag x ACCr x T(y)

Energy tax cost =Et x Eq x T(y)+T$+ Pt x Pq x T(y)

Total cost= Cmag x ACCr x T (y) + Et x Eq x T(y) + T$ + Pt x Pq x T(y)

Classifying Benefit:

Benefits=[ACCr(t) - ACGrr(t)] x Csp x T (y) – (Pt x Pq x Tax+ Et x Tax) x T(y) - T$

BAU model: The projected carbon emissions reduction scheme takes the BAU model, the CO2 abatement is lower than the regulatory benchmark. According to the regulation criteria, projects need to pay an extra tax for energy mix and efficiency, power efficiency tax, as well as purchase extra carbon credit. The project was designed with the BAU carbon emission reduction scheme, After 2020 the BAU project should be gradually phased out and need accelerate carbon emission reduction.

This research denotes the regulatory annual cumulative carbon emission standard=ACCErr, carbon credit price=$\$C^{cp}$

Portfolios ($) = Benefits- abatement cost-Tax for energy mix and efficiency- power efficiency tax- carbon emission allowance x [ACCc (T)-ACCEs]x T(y),

Risk>0

Ctrisk Cost =Cmag x ACCr x T(y) + Et xEq x T(y)+T$+ Pt x Pq x T (y)+ $\$C^{cp}$ x [ACCc (T)-ACCEr]x T(y),

Ctrisk Benefits =[ACCr x T(y)- ACGrr(t)] x Csp –Pt x Pq x T(y)-Et x Eq x T(y)- $\$C^{cp}$ x [ACCc (T)-ACCEr]x T(y)

Model 3

Assuming that the projected carbon emissions reduction and offsetting scheme exceeds the regulatory benchmark, this scenario will get extra carbon emission reductions benefits by selling its extra carbon credit in the carbon trade market. This project will get financial preferential support and government environment reward credit support, the climate related financial risk for this model is negative. The benefit and cost is calculated as follows:

Portfolios ($) = Benefits- abatement cost + $\$C^{cp}$ x [ACCc (T)- ACCErr] x T (y)

Risk < 0

GHG abatement Cost =Cmag x ACCr(t) x T(y)

Tax cost = Et x Eq x T (y) +T$+ Pt x Pq x T(y)

Benefits = ACCr (t) x T(y) x Csp + $\$C^{cp}$ x [ACCEs -ACCc (T)] x T(y)

Climate related financial transition risk and investment portfolios drive and facilitate financial allocation to low (de)-carbon sustainable businesses, the climate related financial transition risk $can\ reach\ \leq 0$. lenders and investors also will calculate the carbon emission reduction and offsetting scheme into the projected financial portfolios scheme. Regulators and banks need to set up the appropriate criteria and metrics for energy mix and efficiency to support the NDC for the net zero carbon emission target. Through improving energy performance and reducing GHG emissions, de-carbonization technological solution and market-based solution (CTS) to pursue sustainable business models and reduce climate financial risk. When the climate related financial transition risk >0, regulators, financiers and lenders will gradually phase out this high climate financial risk model and high carbon emission model.

3.2 Climate Related Financial Physical Risk

The increased anthropogenic GHG emission in the atmosphere induces the chronic changes in temperature and precipitation. These long term chronic climate changes will trigger more frequent and severe extreme weather events. The chronic climate change and extreme weather disaster has increased business interruption and damage across operations and supply chains with negative outcome for input costs, revenues, added value chain, labor safety and productivity, biodiversity and ecosystem, capital market and insurance etc.

3.2.1 Climate-related Financial Physical Risk Scenarios

The climate-related financial physical risk comes either through persistent, chronic long-term shift in climate patterns (sustained higher temperatures and precipitation) or the increased specific extreme weather perils (storms, cyclones, hurricanes etc.), which subsequently trigger direct physical damage to assets and impact on supply chain disruption and operation. (Shuqin Gao, 2024). Climate-related financial physical risk scenarios show the social-economic cost of chronic climate damages and the financial-economic losses from the climate hazard environmental externalities.

This research determines and selects the climate hazard according to local geospatial empirical record. The Intergovernmental Panel on Climate Change (IPCC) scenarios based on Representative Concentration Pathways (RCP) reflect (IPCC Report 2015) (Note 13) a range of GHG emissions concentration pathways and consequent outcomes resulting in incremental global temperature and precipitation change. This research applies this model and considering a range of climate data and parameters, which drive the climate physical risk impacts (storm and hurricanes etc.) When undertaking climate related physical risk scenario analysis, the IPCC RCP (Note 14) modeling scenario data and the publicly available climate related physical scenarios (Note 15) are used to develop the industry-businesses' climate tools to mapping out climate impact, assessing the interactions between the business with climate variables to reflect the climate impact on the business's output, assess the broad financial consequences of climate physical risk.

In this research two steps are used to quantify climate related financial physical risk: the first step is to estimate the chronic social-economic environmental damage cost attributable to anthropogenic GHG emission concentration in the atmosphere. The second step is to quantify the financial-economic losses associated with the local extreme weather events. The calculations of damage cost from climate change physical risk is included two parts, this two steps was widely discussed between author and some experts at Harvard Kennedy School Energy Environment and Economics center. These two steps assessment also adopted in other research paper on damage cost from climate physical risk (David J. Frame, Suzanne M. Rosier Ilan Noy. 2020). Obviously, there is scientific consensus among publications on climate change physical risk including anthropogenic GHG emission, Chronic increased frequency and severity in temperature and precipitation, extremely weather disaster.

3.2.2 Climate Related Financial Chronic Risk

This reflects the financial exposure to chronic climate damage, the social-economic and environmental outcome from chronic global temperature warming, precipitation and humidity change, sea level rise. The social cost of carbon (SCC) is used to evaluate the climate social-economic damage but the ecosystem service is omitted. Global studies show that SCC ranges from approximately US$10 per tCO_2 to as much as US$1,000 per tCO_2 (Bansal, R., Kiku, D. & Ochoa, M. 2016, Nordhaus, W. 2014, Pindyck, R. S. 2016). However, the current SCC is very low to reflect the external cost of GHG emission, this is determined by the GDP, population and climate change scenarios, discount rate, GHG emission projections and the meteorological historical trajectory. A low SCC makes a policy seemingly cost more than the benefits ultimately will be delived. Theoretically, the SCC should increase over time because the natural and social-economic systems will become more stressed as the impacts of climate change accumulated until reaching the net-zero GHG emission. In the U.S the interim SCC has yet to be finalized or incorporated into regulations. The SCC would be offset by federal agencies through expansive regulations from the general equilibrium perspective. The current social cost of carbon value omits various impacts of climate change chronic damage. Current assessments models of climate chronic damage, in particular the Integrated assessment models do not include all of the important physical, ecological, and economic impacts of climate change. The short term and long term chronic climate change damage cost assessments are heterogeneous across different sectors, this is also very impact by the sector's adaptive capacity and resilience capacity.

3.2.3 Climate Hazard Financial Physical Risk and Investment Portfolios

Anthropogenic GHG emission induces the persistent chronic change in precipitation & temperatures resulting in more frequent and severe extreme weather events, water scarcity and droughts etc., this triggers serious impact on industry and businesses: damage to production operation, supply chain and facilities infrastructure, market demand and price, workforce safety, capital market volatility and liquidity etc., this also triggers more volatile yield on the corporate debt and loans, possible changes in stock valuation, balance sheet and revenues, income etc..

In order to assess business and industry future vulnerability to climate hazards, this research makes a micro-prudential climate-risk classification: estimating impacts on the entire value chain including damaging impact on operations, supply chain as well as market demand changes induced by the climate hazards, calculating the financial-economic losses in the whole value chain: physical assets and the workforce, as well as the capital market's exposure and response to the weather disaster. Stock and asset price decline during climate hazard period, capital liquidity is slow down, the supply chain disruption usually trigger upstream commodity price rise given ignoring the inflation and market speculation impact, input cost and the added value output price will subsequently rise, labor productivity usually decline and expenditures for labor insurance safety will be increased, this analysis will be applied to the whole value chain, revenues and earnings income across extreme weather timing and geographic frame. The extreme weather scenarios will be formulated by the disaster severity including temperature, precipitation, wind speed, time framing and geographic distribution etc.

3.2.4 Classifying Financial-economic Losses in Entire Value Chain

The heterogeneous empirical meteorological data across geographical jurisdictions and sectors suggest different uncertainty of climate financial physical risk across different sectors, this also changes in different time frames during the climate hazard period. Therefore, this research simulates a generally static impact from climate hazard on a stochastic industry and businesses process:

This research denotes Process Operation=PO, Supply chain=Sc, Infrastructure facility including equipment and machine =If, Market demand and Price=Mdp, Workforce=Wf, Portfolios=P. Capital Stock Market volatility = Smv,

P=PO + Sc + If + Mdp + Wf + Smv

Monetizing financial-economic losses in entire value chain: Σ^{h}

Infrastructure facility damage value= Ifdv, Supply chain price volatility=Scv,

Market demand slow down during and after climate hazard=MdpVc

Process operation value change based on input price rising=PoVc

Market value change based on the reduced market demand and slow consumption liquidity

Workforce damage value=WfDv including negative impact on labor productivity + expenditures for insurance for Labor damage

Stock capital market value change based on assets price decline and liquidity slow down= Smvc,

The total economic-financial losses from climate hazards: Σ^{h}

Σ^{h} =MP= ScV+ PoVc+ IfDv+ MdpVc + WfDv+Smvc

We assume the total damage cost from the chronic climate change: Σ^{c}

The climate financial physical risk=Σ^{h+c}

damage cost from climate hazard + damage cost from chronic climate change

$$\Sigma^{h+c} = \Sigma^{h} + \Sigma^{c}$$

The climate chronic damage cost and the climate hazard damage cost determine the climate physical financial risk exposure. Thus, the empirical backward-looking local meteorological data shows the historical climate sensitivity trajectory and indicates the future climate hazard vulnerability. However, the forward-looking GHG data determines the social-economic damage cost from the chronic climate change. Thus, the countermeasures for mitigating climate financial physical risk are to increase climate adaptive capability and build climate resilience, abating GHG emission, shifting to low-carbon production and consumption, increasing low-carbon innovation adoption and deployment etc.

Furthermore, for banks and insurance companies, climate financial physical risk increases credit risk from deterioration in the credit worthiness of clients corporate, impacting on yields, price volatility, finance liquidity and solvency; For Central Bank and regulators, Climate financial physical risk can destabilize public financial volatility and slow down financial liquidity, undermine financial solvency. Therefore, it is urgent to build a disaster financial pool and index to increase climate adaptive capacity and resilience, managing natural disaster prevention and recovery to ensure against extreme weather damage and minimize climate financial physical risk exposure.

4. Climate Related Financial Risk Managing, Mitigating and Monitoring

The previous two chapters explore financial exposure and investment portfolios to climate-related transition risk and physical risk, building GHG emission data and climate meteorological data driven models for quantifying the climate related financial physical risk and transition risk. This analysis shows the climate related financial risk function and damage function. Thus, business and industry need to integrate climate-related transition risk and physical risk models into their financial risk management frameworks and decision making process, establishing climate related financial risk management planning and strategy, producing climate related financial risk disclosure, identifying and developing climate-related high-quality financial disclosure standard and metrics, implementing the Financial Stability Board's TCFD recommendations.

4.1 Managing Climate Related Financial Risk

The data-driven scenario-based climate-related financial risk analysis investigates possible ramifications of global climate change on financial institutions, businesses and industries, it requires to estimate the future GHG (including carbon equivalent GHG density level, patterns of adoption of efficient and low-carbon innovation, energy performance etc.) emission to quantify the effects of such drivers on financial equilibrium and liquidity, analyzing the vulnerability of businesses and industries to the global climate change, changing BAU financial expenditure plans to de-carbonization model, retiring carbon intensive physical assets and entering to low-carbon productions' markets, developing climate resilience capacity.

In particular, businesses and industries are encouraged to disclose the specific approach for building their own de-carbonization footprint (e.g., adoption and deployment of key de-carbonization technologies, climate policy implementation and timing plans). It will be essential for an organization to disclose the sensitivity of various assumptions of the carbon footprint and managing carbon bubble parameters such as carbon emission quantity, energy performance, institutional internal carbon pricing mechanism and internal carbon budget etc. Climate related physical risk is directly triggered by the chronic change in temperature and precipitation due to anthropogenic GHG emission, as well as the increased frequency and severity of extreme weather events. There is much empirical evidence on this, but there is still a need to calculate the impact of future potential extreme weather events on revenue, future added value output and physical assets damage. Businesses and industry need to incorporate financial allocation plans with a resilience capacity building strategy, considering climate risk in their investment portfolios and engagement strategies, allocating financial resources to climate-resilience low-carbon investment and towards building counter-risk strategic portfolios, reducing investment portfolios exposure to the climate physical risk and carbon intensive sector, support climate adaptation and mitigation.

4.2 Climate Financial Transition Risk and Carbon Function System: Cost and Benefit

Climate related transition risk is driven by climate policy and low-carbon innovation disrupting financial equilibrium: improving energy performance and de-carbonization portfolio through policy change, including carbon pricing, CCUST adoption, developing and deploying low-carbon technologies like biofuels and bio char, new propulsion system, new airframe design to paving the net zero carbon emission footprint.

Monetizing climate related financial transition risk depends on the carbon abatement cost, emission quantity and carbon shadow price, time framing etc. For the BAU Model, fossil fuel price and the cost for purchasing carbon credit will be increased due to the carbon price upwards trend. Thus, GHG functions are the interface between global climate change and the businesses and industry; therefore, financial institutions, businesses and industries need to integrate the carbon reduction scheme with operation cost and financial expenditures for its climate related financial transition risk and revenues evaluation, incorporating carbon offset scheme and climate indicators into business functions scenarios.

Table 1. Carbon (Note 16) reduction function includes the multi-dimensional carbon cost functions and benefits functions model

CO_2 reduction function	**Associated Carbon Offset Scheme**	**Business As Usual (BAU)**
Energy performance and Mix Processing GHG (industry) Carbon scope 1,2, 3 footprint Stranded fossil fuel assets	+Benefit: feed in tariff or tax credit for renewables. reducing CO_2 emission, Carbon credit selling -Cost for energy transition, regressive stranded fossil fuel assets	- Cost: Energy Tax, CO_2 Tax and cost for purchasing carbon credit High stranded fossil fuel assets risk
Resources Efficiency Energy Efficiency +Circle economy	+Benefit High efficiency, saving resources benefit from carbon credit selling -Cost for efficient technologies and de-carbonization innovation Energy resources tax	- Cost: Low efficiency and charge for regulation Cost for purchasing carbon credit, energy and resources tax
De-carbonisation Technologies (CCUST) (BCCT)	+ Benefit from CO_2 trade and carbon credit selling, climate innovation policy. - Cost for innovation adoption and installation, deployment and maintenance	- Cost for purchasing carbon credit
Climate finance transition risk rate: (Cost-Benefit)/Carbon bubble	Cost=capital for innovation +capital for clean energy transition Benefit=carbon credit selling + feed in tariff for renewables. Risk rate curve: the higher cost, the higher risk, high carbon price and feed in tariff result is low risk. Low cost and high carbon price and high feed in tariff for renewables is an optimal policy for promoting carbon emission reduction and reducing climate financial risk rate.	High climate transition financial risk rate
Internal financial liquidity ratio Asymmetric and nonlinear impact	Short term-low liquidity ratio Long term-high liquidity ratio	Short term- less impact on the financial liquidity ratio, under effective climate policy implementing can trigger immediate low liquidity ratio, long term-low liquidity ratio
Financial solvency Asymmetric and nonlinear impact	Short term-mediate solvency problem, long term no solvency problem	Short term no induced solvency problem and long term severe financial solvency problem and abrupt financial risk, high solvency problem

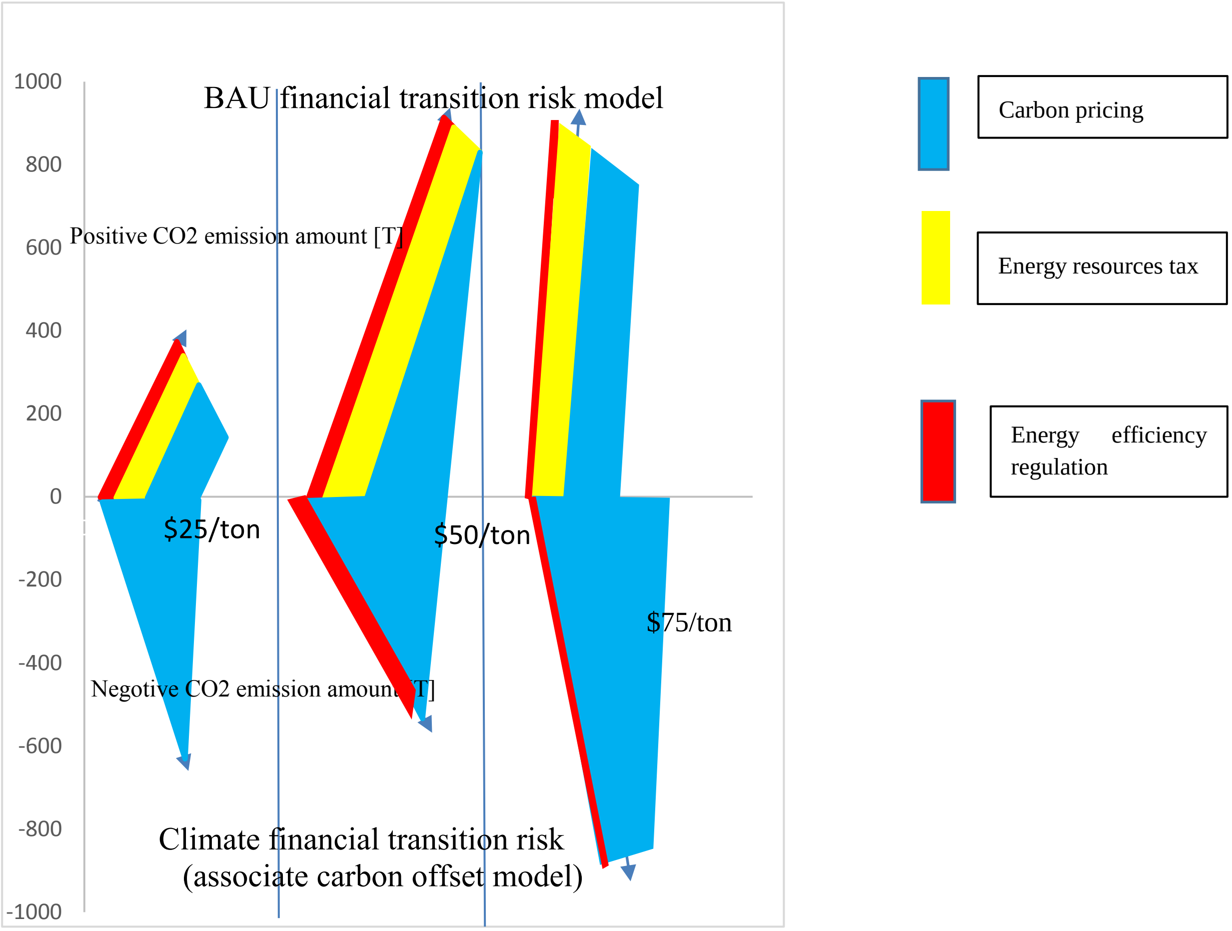

Figure 1. Climate financial transition risk statistical hierarchy simulation

The horizontal axis indicates carbon shadow price $ per ton, author simulates different scenarios by citing the international carbon pricing floor: $25, $50, $75 per ton for least developed countries, emerging market and advanced economy, the vertical axis above horizontal axis represents exact annual carbon emission amount more than the carbon emission regulation, the vertical axis below the horizontal axis represents exact annual carbon emission less than the carbon emission regulation, oblique line indicates the carbon-induced financial transition risk trend and elasticity. The carbon price floor also exist within one country due to carbon pricing and carbon emission trade scheme design, this is an asymmetric and nonlinear impact on financial equilibrium.

The aforementioned analysis (Table 1) shows that reducing climate related transition cost can minimize climate transition financial risk. The transition cost includes GHG abatement cost and low-carbon innovation expenditure, energy transition cost, carbon pricing as well as the expenditure for purchasing carbon credit to offset the GHG emission above the regulation standard. From the long term perspective, the GHG abatement cost and low-carbon innovation investment will get a refund from the carbon emission reduction reward, in particular, the equipment and technological expenditures will remain on the fixed capital balance sheet. The energy transition will induce fossil fuel capital depreciation and the fuel-related human capital depreciation. The cost for purchasing carbon credit and taxing energy resources is determined as the absolute climate transition cost, this is the crucial part determining climate financial exposure and climate financial risk elasticity, the large stranded fuel assets and the stranded human capital will trigger underperforming loans and financial insolvency of businesses and industries. Therefore, all the businesses and industry need to build up the carbon reduction scheme, as the TCFD recommended that carbon emission reduction is a mandatory accountability, it is aimed at addressing total CO_2 emissions above 2020 levels through the purchase of carbon credit from approved carbon reduction projects and the carbon trade market.

Based on the above carbon abatement cost and benefit function, developing a climate financial transition risk statistical hierarchy is crucial to evaluate the elasticity of climate transition financial risk. (Table 1) Carbon pricing and business modeling are key factors to evaluate the elasticity of climate financial transition risk: for the BAU model and a scenario of GHG emission below to the regulation benchmark, the carbon shadow price is in direct proportion to the climate financial risk elasticity, the higher carbon shadow price, the higher climate financial risk. For the new business model with carbon offset scheme, given the GHG emission reduction above or equivalent to regulation benchmark, carbon shadow price is inversely proportional to the climate transition financial risk, the higher CO_2 shadow price, the lower climate financial risk, the climate related financial transition risk can reach to negative level. However, the carbon emission amount always is in direct proportion to the climate financial risk for both BAU and business model with carbon offset scheme. This determines that in any circumstances reducing GHG emissions will help to mitigate the climate financial transition risk.

4.3 Climate Financial Physical Risk and Its Damage Function

Considering the local climate hazards is based on the local hydro-meteorological empirical data, and incorporating these into climate physical financial risk evaluation models. This research denotes the aggregate chronic climate damage cost =ADsea=Σ^{c} .

Damage cost of local extreme weather disaster in Annual year A and B:

The initial aggregate damage cost of weather disaster=ADcwa

Initial damage cost for supply chain= Dcsca

Initial damage cost for operation and production=Dcopa

Initial damage cost for facilities and physical property=Dcfpa

Initial damage cost for market demand and consumption=Dcmda

Initial damage cost for labor safety=DcLa

Initial damage cost for stock capital and equity, lending=Dcca

Initial damage cost for insurance=Acia (negative)

The aggregate damage cost of weather disaster in Year A

Σ^{ha}=Dcwa= Dcsca + Dcopa + Dcfpa + Dcmda + DcLa + Dcca + Acia

The aggregate damage cost of weather disaster in Year B

Σ^{hb} =ADcwb= Dcscb + Dcopb + Dcfpb + Dcmdb + DcLb + Dccb + Acib

This research uses the midpoint method to calculate the elasticity of damage cost from climate hazard:

$$\Sigma_{h}^{\emptyset} = 100\ x\ \frac{\Sigma^{ha} - \Sigma^{hb}}{\frac{(\Sigma^{ha} + \Sigma^{hb})}{2}}$$

This equation shows the elasticity of climate hazard financial risk exposure in different year. The local metrological volatility, climate sensitivity, climate disaster severity, time frame, geographic distribution, existing climate adaptation capacity and climate resilience together play a central role in evaluating the elasticity of climate hazard financial risk

The aggregate damage cost of climate change=ADccc= Σ^{hc}

The aggregate damage cost of climate change=aggregate chronic damage cost+ aggregate damage cost of weather disaster, ADccc= ADse+ ADcw

$$\Sigma^{hc} = \Sigma^{c} + \Sigma^{h}$$

Elasticity of climate physical financial risk

$$\Sigma_{F}^{\emptyset} = 100\ x\ \frac{(\Sigma^{hcA}) - (\Sigma^{hcB})}{\frac{(\Sigma^{hcA}) + (\Sigma^{hcB})}{2}}$$

Climate financial physical risk reflects financial exposure to extreme weather disaster and chronic climate change, generally including: increased insurance cost, potential reduction in the added value of balance sheet, deteriorating the credit profile, deteriorating lending environment and investment portfolios, reducing value of assets, negative impacts on investment's valuation and related implications on returns of equity, increased input cost and added value output price, negative impact on market value chain and market demand change etc. As the climate physical risk drivers -

climate hazards and temperature and precipitation change, geographic distribution and persistent time, climate adaptation capacity and resilience determine the asymmetric climate sensitivity, climate physical risk drivers and adaptive capability determine the climate vulnerability and financial exposure risk volatility. The following (Table 2) illustrates the relationship between climate disaster index and climate financial physical risk variables. As GHG emission and climate hazards are in the direct proportion to impact the climate financial physical risk, the higher GHG emission, the higher change in temperature and precipitation, the more frequent climate hazards, the higher climate financial physical risk. Thus, reducing GHG emission, increasing climate adaptative and resilience capacity are the direct approach to prevent and reduce climate financial physical risk.

Table 2. Climate disaster assessment and climate financial physical risk exposure indicators equilibrium: + represents direct proportion, and – represents inverse ratio

Damage Climate cost disaster	Labor productivity	Input value	added Value growth	Supply chain	Property and machinery	Capital market volatility	Human capital	Financial liquidity ratio	Financial solvency
Geographic scope Asymmetric	+	+	+	+	+	+	+	+	+
Scale	+	+	+	+	+	+	+	+	+
Severity	+	+	+	+	+	+	+	+	+
Adaptation capability	-	-	-	-	-	-	-	-	-
Persistent time nonlinear	+	+	+	+	+	+	+	+	+
Market resilience	-	-	-	-	-	-	-	-	-
Value chain resilience	-	-	-	-	-	-	-	-	-

4.4 Managing Climate Related Financial Risk: Analyzing Damage Function, Cost Function and Benefit Functions

The above analytical framework for the climate damage function, climate benefit and cost functions shows the fundamental channel to assessing climate related financial risks. It is associated with the following uncertainties: uncertainty with the choice of pollution control (GHG emission reduction) instruments and carbon pricing, uncertainty with the policy instrument, uncertainty about the aggregate marginal abatement cost, uncertainty about the natural capital and human capital depreciation regarding the stranded fossil fuel assets, uncertainty about the chronic environmental social-economic damage cost, uncertainty about damage function and cost stemming from extreme weather events and natural disaster.

The above damage function of climate change shows that climate hazard triggers financial-economic losses along the entire value chain, therefore, building climate resilience capacity is crucial to respond, prevent, mitigate and recover from climate disaster. Government needs to allocate public financial resources to improve climate adaptive and resilience capacity in public infrastructure and local society for preventing, mitigating climate physical risk.

Carbon bubble plays a central role in managing climate-related financial transition risk, it requires to quantify carbon emissions and abatement amount, estimate the future carbon circle and carbon abatement cost, and monetize carbon bubble throughout its entire value chain including carbon scope1-3, taking into account the carbon assets into its financial risk evaluation, promote substantial fundamental structural adjustments to a lower-carbon climate-resilient and resources-efficient business model, financial institutions need to make strategic planning for climate related financial risk identification, assessment and reporting to mitigate climate financial risk.

However, the current carbon price is extremely low, carbon shadow price and social cost failed to internalize the GHG emission environmental externalities, it cannot offset the carbon abatement cost and the chronic social-economic damage cost. Thus, there might not be readily visible signs of the fossil fuel capital depreciation or fossil fuel assets stranded in businesses and industries. The further effective climate policy can trigger fossil fuel related natural capital, human capital, relevant equipment machinery capital dramatically depreciated. This is the largest climate financial transition risk across all the industries, businesses and financial institutions. This requires both public finance and corporate finance to take immediate action to build financial resilience capacity against fossil fuel capital depreciation, prevent future stranded fossil fuel assets.

From the above cost and benefit function analysis this research finds that there are two potential expenditures associated with green financial transition and building sustainable financial system: transition cost for reducing GHG emissions and green investment cost for building climate resilience to mitigating the social-economic-environmental damage cost. These costs trigger asymmetric and non-linear impact on financial equilibrium and liquidity ration across different businesses and geography, as well as the diffiren time frame for transition period and climate hazards timeline. All the industries, businesses and financial institutions need to allocate financial resources for GHG emission reduction and climate resilience building.

The TCFD requires to find a cost-effective approach to implement the regulatory guidance for reduce climate financial risk. It is important to discover several channels for calculating climate-related financial risks to assist investors and businesses' decision makers for making the most efficient allocation of financial resources in light of the potential social-economic damage of climate change. Therefore, financial institutions need to remain a transparency on climate financial risk disclosure, building a robust local, national and internationally consistent climate financial disclosure framework.

Financial institutions, industry and businesses need to assess their financial resilience and financial vulnerability to climate related financial transition risk and physical risk, establishing emergency protective measures, including assessing the damage costs of a future climate disaster, evaluating reimbursable burden, the internal capital adequacy and solvency capability, total deductibles and co−pays for insured losses, uninsured and other expenses (considering inflation and discount rate). Arguably, all industries, businesses and financial institutions have faced the limited capital resource constraints that prevent them from implementing costly green financial reforms. Thus, businesses and financial institutions need to mitigate financial vulnerability and build climate financial resilience to reduce climate transition risk and physical risk, and keep a minimum undesignated fund balance for climate disaster relief.

5. Conclusions

The optimal solution for climate-related financial risk is to exploring the carbon footprint for building the cost-effective decarbonization pathway, taking adaptive measures to build climate resilience capacity. To manage and reduce businesses' exposure to global climate change risk, it is crucial to incorporate the carbon (GHG equivalent) related assets or carbon bubble and the financial capital exposure to climate disaster into financial equilibrium, incentivizing further market-based solutions and de-carbonization innovation solutions, promoting effective climate policy and climate adaptation measure. Indicators such as carbon abatement costs and social costs of carbon, carbon shadow price, carbon pricing and discount rate, energy performance index, carbon emission reduction benefit and emissions reduction rate can be used to estimate the discounted benefits of GHG emission reduction, effectively minimizing climate related financial transition risk. However, the current carbon pricing is too low and failed to precisely reflect and internalize the GHG emission environmental externalities. In light of fossil fuel capital and human capital depreciation, business and financial institutions need an additional climate financial framework like internal carbon pricing mechanism, internal carbon budget and the assessment of internal capital adequacy and solvency to re-construct financial equilibrium. Climate financial transition risk and physical risk can trigger asymmetric and nonlinear impact on financial equilibrium, both can generate serious problems for financial solvency and liquidity. The optimal decarbonization pathway has evolved over the past years, but the cost-benefit simulation with a joint assessment of climate disaster severity and the climate damages cost proposed in this research can be widely used for assessing climate related financial transition risk and physical risk. These models, along with the general equilibrium model can also be used to assessing the climate related public financial risk and fiscal elasticity referring to the National Determined Contribution to carbon neutrality target by 2050 to Paris Agreement.

Abbreviations

BAU	Business as usual model
UNFCCC	United Nations Framework Convention on Climate Change
GDP	Gross Domestic Product
TCFD	Task Force on Climate-related Financial Disclosures
GHG	Green House Gas
NDC	Nationally Determined Contribution
IPCC	Intergovernmental Panel on Climate Change
RCP	Representative Concentration Pathways

Acknowledgments

This research is dedicated to the memory of Maurits C. Boas Professor Richard Cooper at Harvard Economics Department, who led the book Global Carbon Pricing: The path to Climate cooperation (2017), Author gratefully acknowledges him for all his supervision and support for this research. The author would like to thank Professor Aldy Joseph Edgar from Harvard Kennedy School Energy, Environment and Economics Program for his valuable advices, discussions and suggestions. In undertaking this research, author benefitted from the insights from many individuals with expertise in climate economics, energy economics and carbon pricing, including Professor Rogoff Kenneth from Harvard Economics Department, Professor John P. Holdren and Henry Lee from Harvard Kennedy School Natural Resources and Environment Program. The author would also express sincere gratitude to the International journal's of Financial Research peer reviewers and editors for their valuable comments and suggestions. The views expressed are those of the author and do not necessarily reflect those of their comments.

Authors' contributions

Shuqin Gao is responsible for this research design, analysis, data collection, literature review and climate financial transition risk and physical risk scenario buildings.

Competing interests

The author declares no conflict of interest

Informed consent

Obtained.

Ethics approval

The Publication Ethics Committee of the Sciedu Press.

The journal and publisher adhere to the Core Practices established by the Committee on Publication Ethics (COPE).

Provenance and peer review

Not commissioned; externally double-blind peer reviewed.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Data sharing statement

No additional data are available.

This research was undertaken in 2022.

References

Adar, Z., & Griffin, M. J. (1976). Uncertainty and the choice of pollution control instruments. *Journal of Environmental Economics and Management*, *3*, 178-188.

Bansal, R., Kiku, D., & Ochoa, M. (2016). Price of Long-Run Temperature Shifts in Capital Markets. *National Bureau of Economic Research*, 2016.

Eccles, G. R., & Krzus, P. M. (2019). Implementing the Task Force on climate-related financial disclosure recommendations: An assessment of corporate readiness. *Schmalenbach Business Review, 71,* 287-293.

Edwards, I., & Yapp, K. (2020). Climate-related financial disclosure in the public sector. *Nature Climate Change, 10,* 588-591.

Financial Stability Border Report. (2020). TCFD Releases Third Status Report on the Adoption of Its Climate-Related Disclosure Recommendations. October 30, 2020. Retrieved from https://www.briefinggovernance.com/2020/10/tcfd-releases-third-status-report-on-the-adoption-of-its-climate-related-disclosure-recommendations/

Gao, S.-Q. (2024). An Exogenous Risk in Fiscal-Financial Sustainability: Dynamic Stochastic General Equilibrium Analysis of Climate Physical Risk and Adaptation Cost. *Journal of Risk Financial Management, 17*(6), 244. https://doi.org/10.3390/jrfm17060244

Gold, R. (2019, January). PG&E: The First Climate-Change Bankruptcy, Probably Not the Last. *Wall Street Journal.* Retrieved December 2019, from https://www.wsj.com/articles/pg-e-wildfires-and-the-first-climate-change-bankruptcy-11547820006

Nicholas, S. (2006). The Stern review of the Economics of Climate Change. London School of Economics and Political Sciences, The UK.

Nordhaus, W. (2014). Estimates of the social cost of carbon: concepts and results from the DICE-2013R model and Alternative approaches. *J. Assoc. Environ. Resour. Econ., 1,* 273-312.

Pindyck, R. S. (2016). *The Social Cost of Carbon Revisited.* National Bureau of Economic Research, 2016.

Robinson, C., DeHaas, D., McCormack, D., Burns, J., Sullivan, K., & Bujno, M. (2020, April). The Atmosphere for Climate-Change Disclosure. Retrieved from https://corpgov.law.harvard.edu/2020/04/05/the-atmosphere-for-climate-change-disclosure/

Sanderson, M. B., & Neill, C. O. B. (2020, June). Assessing the costs of historical inaction on climate change, p. 9. Retrieed from http://www.nature.com/scientificreport/

Siew, P. (2020). Briefing: task force for climate financial disclosures (TCFD) for the property and construction industry, August, 2020. *Sustainable Building Journal, 5*(3), 2020. Retrieved from https://www.sustainable-buildingsjournal.org/articles/sbuild/full_html/2020/01/sbuild200001/sbuild200001.html

Silk, M. D., Niles, V. S., & Carmen, X. (2020). Blackrock nudges companies toward a common standard and tcfd/. Retrieved from https://corpgov.law.harvard.edu/2020/01/18/blackrock-nudges-companies-toward-a-common-standard-sasb-tcfd/

Spence, M. (1976). Effluent charges and licenses under uncertainty. *Journal of Public Economics, 5,* 193-208.

Stavins, R. (1996). Correlated uncertainty and policy instrument choice, *Journal of Environmental Economics and Management, 30,* 218-32.

U.S. Environmental Protection Agency. (2022). Climate Resilience Evaluation and Awareness Tool (CREAT). U.S. Geological Survey. “Climate and Land Use Change.” Data and Tools. Retrieved from https://www.epa.gov/crwu/climate-resilience-evaluation-and- awareness-tool

Wei, D. (2019). How to implement the TCFD recommendations: a step-by-step guide, January 14, 2019. Retrieved from https://www.greenbiz.com/article/how-implement-tcfd-recommendations-step-step-guide

Weitzman, M. L. (1974). Prices Vs Quantities. *Review of Economic Studies, 41*(4), 477-91.

World Bank Report. (2021). Climate Investment Opportunities Total $23 Trillion in Emerging Market by 2030, Says Report at the International Financial Corporate and World Bank Group. Retrieved 28 January, 2021, from https://www.ifc.org/wps/wcm/connect/news_ext_content/ifc_external_corporate_site/news+and+events/news/n ew+ifc+report+points+to+%2423+trillion+of+climate-smart+investment+opportunities+in+emerging+markets+by+2030

World Bank Report. (2021). World Bank Group IFC report disclosed that more than $1 trillion investment are flowing into climate- related projects in renewable energy, off-grid solar and energy storage, agribusiness, green buildings, urban.

Notes

Note 1. On July 8, 2017, the Hamburg Action Plan was released following the G20 summit in Hamburg, Germany. This sets out the G20's strategy for achieving strong, sustainable, balanced and inclusive growth. The Action Plan refers to, amongst other things, the recommendations published by the TCFD on June 29, 2017. These recommendations present a voluntary disclosure framework that aims to make it easier to both produce and use climate-related financial disclosures.

Note 2. European climate information Portal (CLIPC) online scenario database for energy GHG mitigation strategies, climate policies consistent with 2 ℃ and IPCC scenarios. Climate Resilience Evaluation and Awareness Tool (CREAT) of the U.S Environmental Protection Agency, risk-assessment to extreme weather events through a better understanding of current and future climate conditions. Creating Resilient Water utilities (CRWU), the UN Environmental Program (UNEP) and Copenhagen Center for energy efficiency's best practice and case studies for energy efficiency improvement. The UN food and agricultural organization's modelling system for agricultural impact of climate change. UNEP FI scenario-based methods for climate risks assessme

Note 3. The IEA Integrated Assessment Models provide plausible consistent pathways toward to a low carbon transition. Climate policy, energy mix, de-carbon-technological and market based solution. CTS. IEA , IREA, Deep Decarbonization Pathways Project, Carbon Trade scheme and TFCFD recommendation in 2020.

Note 4. Social cost of methane and nitrous oxide is very different from social cost of carbon, depending on their harmful effect on environment and human health, also depending on different discount rate. Due to most countries haven’t put the price signal on the methane and nitrous oxide, this research generally uses the social cost of carbon to represent the social cost of GHG.

Note 5. How to calculate the CO2 emission and CO2 abatement quantity for a project, industry and businesses plan, many specialist refer to the national determined commitment (NDC) required amount. However, this research thinks that the NDC is calculated carbon emission reduction at the national level. TCFD is referred to the certain project of businesses, industry and financial investment. Thus, the carbon-density per GDP can serve as a tool to forecast the CO2 emission reduction requirement and GHG concentration in atmosphere. In addition, the World Resources Institute and World business council for sustainable development co-developed: GHG protocol scope 2 Guidance: An amendment to the GHG Protocol Corporate Standard, P42., A location-based method reflects the average emissions intensity of grids on which energy consumption occurs (using mostly grid-average emission factor data). A market-based method reflects emissions from electricity that companies have purposefully chosen (or their lack of choice). Carbon quantity or carbon equivalent quantity, including methane and nitrous oxide, the methane and nitrous oxide is more harmful for environment and human health, their price is very different from carbon price, however, due to most countries haven’t established pricing system for methane and nitrous oxide, this research generally use carbon and carbon shadow price to evaluate the GHG price. https://ghgprotocol.org/sites/default/files/standards/Scope%202%20Guidance_Final_Sept26.pdf

Note 6. The outputs of climate modelling of physical scenarios will be undertaken within the framework of the IPCC, 1.5-2 ℃ average global warming above pre-industrial level by 2050 Net zero carbon emission concentration in atmosphere. Climate related physical risks cause massive financial losses and disrupt the value chain, market demand changes; Climate related transition risks generate full financial implications for entire value chain in all businesses and industries.

Note 7. IEA WEO current policy and new policies scenarios explicitly model the transition to a lower-carbon economy. Analyzing a range of 2 ℃ and other transition scenarios from the IEA, AAPP, IRENA and Greenpeace, a number of key parameters appear relevant for businesses and industry to consider when constructing, using and assessing various scenarios.

Note 8. Aviation is not included in the UNFCCC ambitious targets, but faces growing pressure to adopt net zero emissions by 2050. The NDCs are built on domestic policy transition for a sound pathway at national level to a low-carbon and climate-resilient economy. The Intended Nationally Determined Contribution Bridge scenarios acknowledge 2 ℃ as a policy objective, IEA 2 ℃ scenario lays out an emissions trajectory consistent with limiting the average global temperature increase to a temperature range around 2 ℃. 2 ℃ Scenario provide a common reference point that is generally aligned with the objectives of the Paris Agreement, UNFCCC, and will support the evaluation of the potential magnitude and timing of transition-related implications. The assumptions about energy mix and energy efficiency metric, publicly available 2 ℃ scenarios and tools, such as International Renewable Energy Agency (IRENA) REmap, Greenpeace Advanced Energy revolution, and Deep De-carbonization Pathways Project (DDPP).

Note 9. A location-based method reflects the average emissions intensity of grids on which energy consumption occurs (using mostly grid-average emission factor data). A market-based method reflects emissions from electricity that companies have purposefully chosen (or their lack of choice). World resources Institute and World business council for sustainable development co-developed: GHG protocol scope 2 Guidance: An amendment to the GHG Protocol Corporate Standard, P42. https://ghgprotocol.org/sites/default/files/standards/Scope%202%20Guidance_Final_Sept26.pdf

Note 10. The optimal price of carbon emission should be equal to the Marginal abatement cost in a perfectly competitive market based on marginal cost theory. But the current carbon price is too low to express the carbon marginal abatement cost and internalize GHG emission environmental externalities. Marginal abatement cost depends on different timeframe, endogenous and exogenous technological improvement and different GHG emission mitigation rate and carbon pricing clmate policy etc.

Note 11. ETP. (2015). Energy Technology Perspectives referring low carbon technology development and deployment, including an energy system development pathway and an emission abatement trajectory consistent with at least a 50% chance of limiting the average global temperature rise to 2 ℃, set the target of cutting CO2 emissions by almost 60% by 2050.

Note 12. Transition scenarios and simulation can be found in the following reports and publications: IRENA. (2016). REmap, Greenpeace Advanced Energy Revolution, IEA WEO Bridge Scenario, IEA WEO INDC Scenario, Source and data visualization: IEA special report: Energy and Climate change and WEO 2014, ETP(Energy technology perspectives) 2016, DDPP 2015 report, IRENA Roadmap for a renewable energy future (2016) and working paper: Synergies between Renewable energy and energy efficiency, Greenpeace Energy revolution (5 th ed), IEA special report: energy and climate change, IEA special report: energy and climate change and data/tables, models: IEA world energy model(WEM), ETP Model, IEA world energy model(WEM), IEA World energy model(WEM) details timeframe: 2012-2040, 2013-2050, 2010-2050, 2010-2030, 2012-2050, 2012-2030, 2012-2030. In designing a 2 ℃ scenario and net zero carbon emissions concentration in atmosphere by 2050, need to consider publicly available scenarios data sets linked to functional tools (e.g., visualizers, calculators, and mapping tools). Deep Decarbonization Pathways Project (DDPs) fills a gap in the climate policy dialogue, in the form of deep decarbonization pathways (DDPs) to reduce emissions, consistent with the 2°C limit. "developed these blueprints for each physical infrastructure, to inform decision makers of the technological and cost requirements of different options for meeting the national emissions reduction goal, in particular carbon remove technologies and sustainable power system transition.

Note 13. IPCC Report. (2015). The IPCC's four RCPs scenarios describe the climate impacts of a range of possible future GHG emissions and consequent trajectories of atmospheric GHG concentrations. The RCP scenarios fix the amount of GHG concentration in the atmosphere and analyze the resulting changes in global temperatures (and other variables such as precipitation) at various timeframe points (i.e., out to 2035, mid-century [2046-65], and end of century [2081-2100]) relative to pre-industrial levels. IPCC Representative Concentration Pathway (RCP) Scenarios: RCP8.5 is the high-emission scenario, consist with a future with no policy changes to reduce emissions, and characterized by increasing GHG emissions that lead to high atmospheric GHG concentrations. IPCC RCP6.0 is a high-to-intermediate emissions scenario where GHG emissions peak at around 2060 and then decline through the rest of the century. Both scenarios are aligned broadly with a current policies or Business-As-Usual Scenario. IPCC RCP4.5 is an intermediate-emissions scenario, consistent with a future relatively ambitious emissions reductions and GHG emissions increasing slightly before starting CIRCA 2040. IPCC RCP2.6 IPCC scenario is in line with the Paris Agreement stated 2 ℃. limit/1.5 ℃ above pre-industrial level, is consistent with ambitious reduction of GHG emissions of the UNFCCC.

Note 14. This research takes IPCC 2C average global warming limit by 2050 to reach Net zero carbon emission concentration in atmosphere. GHG emission concentration in atmosphere trigger the Physical and transition risks. IPCC RCP The IPCC have produced a set of GHG concentration scenarios that result in a range of warming outcomes. This diverse range of models show there are multiple pathways that can limit warming to 2 ℃, including de-carbonizing the power sector by mid-century, electrifying as many energy services as possible, by biofuels and achieving negative emissions in the land-use sector (‘carbon sinks’) by end of the century. The scenarios also highlight efficiency enhancements and behavior changes as a key mitigation strategy. Relevant parameters within IPCC AR RCP for physical risk climate-related: earth surface temperature change, precipitation, water supply and demand sea level change, IPCC 5AR(Assessment report) RCP4.5, IPCC 5AR RCP8.5 assessment of physical risk climate-related impact water risk create high-solution, CO2 emissions pathways and temperature outcomes in IPCC AR5 RCP Scenarios.

Note 15. The UK Climate Impact Program and The U.S interagency Archive of downscaled climate data and information provides an historical and future climatology and hydrology. Global Climate Models consist the assessments of the physical impact of climate change (temperature, precipitation and drought) and associated financial consequences. Global Climate Models, IPCC, climate resilience evaluation and awareness tool, Climate and Land use change and sustainable water tools etc.

Note 16. Greenhouse gas emissions are categorized into three 'Scopes' by the most widely-used international accounting tool, the Greenhouse Gas (GHG) Protocol. Scope 1 covers direct emissions from owned or controlled sources, including operation, vehicle, fugitive and processing GHG. Scope 2 covers indirect emissions from the generation of purchased electricity, steam, heating and cooling consumed by the reporting company. Scope 1 and Scope 2 are the mandatory GHG disclosure. Scope 3 includes all other indirect emissions that occur in a company’s value chain. Carbon emissions share for 81% of overall GHG emissions, and businesses are responsible for a lot of it. The rest of GHG emissions are: methane (10%), nitrous oxide (7%) and fluorinated gases (3%). In this article GHG are categorized into Processing Carbon and Fuel combustion Carbon.