Strategic Investment to Mitigate Transition Risks

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Abstract

This paper investigates strategic investments needed to mitigate transition risks, particularly focusing on sectors significantly impacted by the shift to a low-carbon economy. It emphasizes the importance of tailored sector-specific strategies and the role of government interventions, such as carbon taxes and subsidies, in shaping corporate behavior. In providing a multi-period framework, this paper evaluates the economic and operational trade-offs companies face under four various decarbonization scenarios—immediate, quick, slow, and no transitions. The analysis provides practical insights for both policymakers and business leaders, demonstrating how regulatory frameworks and strategic investments can be aligned to manage transition risks while optimizing long-term sustainability effectively. The findings contribute to a deeper understanding of the economic impacts of regulatory policies and offer a comprehensive framework to navigate the complexities of transitioning to a low-carbon economy.

Keywords: Transition Risk, Low-Carbon Economy, Government Intervention, Decarbonization Scenarios.

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1 Introduction

1.1 Climate Risks

Mitigating climate change necessitates a swift and comprehensive decarbonization of the global economy. Climate change is already posing serious threats to society by altering extreme weather patterns and damaging vital ecosystems. Current leading climate models predict that without immediate action, catastrophic outcomes could emerge from nonlinear climate dynamics. Nonlinear behavior means that a small increase in temperature could trigger large, sudden, and possibly irreversible changes, such as the rapid melting of polar ice sheets or the collapse of entire ecosystems, which represent critical tipping points in Earth's systems (Lenton et al. (2008)). The 2015 Paris Agreement highlights the urgency of preventing such consequences, aiming at limiting global temperature rise to well below 2°C above pre-industrial levels. This goal seeks to mitigate the most severe impacts of climate change, even though significant climate variability would likely persist (Holden et al. (2018)). To prevent global temperatures from rising more than 1.5°C, evidence from the Intergovernmental Panel on Climate Change (IPCC) suggests that achieving net-zero carbon emissions by the middle of the century is crucial. As a result, many governments and local authorities have already begun implementing legislation mandating carbon neutrality by or before this target date.

Achieving rapid decarbonization, however, is no small feat. It requires substantial structural transformations across various sectors. Some industries will need to dramatically scale up their production and market presence, while others will have to overhaul their technological foundations—or, in some cases, shrink or even phase out entirely. The most impacted sectors include those involved in the extraction and distribution of fossil fuels, as well as industries that rely heavily on fossil fuels for production, such as steel and cement manufacturing. These sectors represent a significant portion of the global economy. In certain areas, such as power generation, low-carbon alternatives are increasingly becoming more competitive with traditional energy sources. Furthermore, the electrification of end-use technologies, including passenger transportation, offers promising decarbonization pathways (Kober et al. (2020)). However, in industries such as steel production and air travel, progress is still in its infancy, and a large number of companies lack the strategic planning necessary to effectively navigate the transition to a low-carbon economy (Dietz et al. (2020)).

The risks posed by climate change are reflected in many aspects. Climate risk, including physical and transition risks, has become a key and complex topic within the broader conversation on environmental sustainability. This has been further highlighted by Carney (2015). Physical risk refers to the direct consequences of climate change, such as extreme

weather events, rising sea levels, and ecosystem disruptions. These risks pose direct threats to businesses, infrastructure, and communities. Transition risk, on the other hand, arises from the global shift towards a low-carbon economy. This shift is driven by evolving regulations, technological progress, and changing societal expectations. As societies grapple with environmental vulnerabilities and economic changes, it becomes essential to explore climate risk in depth. A strategic response from policymakers, businesses, and investors is necessary to build resilience and create sustainable pathways forward.

Additionally, climate change can also impact asset prices through both physical and transition risks, as detailed in Cisagara (2024). Physical risks result in financial losses or increased costs due to chronic and acute climate events. Transition risks, meanwhile, stem from the adjustments required to move towards a low-carbon economy. These risks are typically triggered by changes in climate policy, technological innovations, and shifts in public preferences.

This paper will strategically prioritize the investigation of transition risk over physical risk for two reasons. Firstly, physical risks are often caused by unforeseen natural events, making them more unpredictable and harder to mitigate. In contrast, transition risks stem from planned, deliberate shifts towards a low-carbon economy, allowing for more effective strategic interventions and proactive measures. Secondly, there is a noticeable gap in the existing literature in modeling the transition risk, with relatively few studies developing robust quantitative models to measure the financial impact of transition risk on the economy. This paper aims at filling that gap by creating corresponding models to assess transition risk and provide insights for industries navigating the shift to a sustainable economy.

1.2 Understanding Transition Risk

Transition risk refers to the financial risks that arise from the process of shifting towards a low-carbon economy, leading to significant structural changes in key industries and markets. As governments and institutions implement policies such as carbon taxes or renewable energy incentives to reduce carbon emissions, businesses heavily reliant on fossil fuels face mounting challenges of adapting to stricter regulations, transitioning to cleaner technologies, and maintaining profitability in a low-carbon economy. These industries must either rapidly transform their operations or face potential decline, with risks including reduced competitiveness, loss of market share, or even bankruptcy for firms that fail to transition effectively (Lazard (2020)). This transformation affects not only energy-intensive sectors but also industries involved in production, transportation, and logistics that depend on fossil fuels. Sectors like steel, aviation, and heavy manufacturing encounter particular obstacles as low-carbon alternatives remain underdeveloped or economically less viable compared to

traditional energy sources. Firms in these sectors may face significant costs from investing in new technologies or risk incurring regulatory penalties for failing to meet emissions standards (Dietz et al. (2020)).

A critical element of transition risk is the uneven pace of adaptation across industries, where by adaptation, we specifically mean the shift towards low-carbon technologies and practices. While power generation has seen progress with renewable energy adoption, other sectors lag behind due to the lack of cost-effective alternatives. The speed of adaptation is influenced by both technological advancements and regulatory developments, yet policies aimed at mitigating climate change are not always consistent or predictable. This policy uncertainty creates challenges for companies planning long-term investments, as future regulations may impact their operations in unforeseen ways (Holden et al. (2018)). As a result, financial institutions exposed to high-emission sectors may face increased credit risk, potentially leading to broader systemic challenges if a significant portion of the economy struggles to transition to a low-carbon model. Furthermore, investors are increasingly integrating climate risks into their portfolios, which could lead to higher borrowing costs and reduced access to capital for firms that are slow to adapt (Bolton and Kacperczyk (2021)).

The global response to climate change, particularly through major agreements such as the Paris Agreement, has intensified the need for regulatory measures such as carbon taxes and emissions trading schemes. While such policies are critical for reducing future climate risks, their rapid implementation creates transitional challenges for certain sectors and the financial system as a whole (Bank of England (2018)). In this context, the shift towards a low-carbon economy, characterized by renewable energy adoption, circular economies, and stringent environmental regulations, represents both significant risks and opportunities for businesses. Companies are now evaluated not only on traditional financial metrics but also on their resilience to low-carbon transition risks (Schulte and Hallstedt (2018)). Thus, it has been suggested that investing in companies that actively adopt sustainability measures is no longer just an ethical choice; it is now a necessary step to protect financial portfolios from the growing risks of the low-carbon transition.

The economic costs, financial impacts, and macroeconomic implications of these transition risks are far-reaching. Firms exposed to climate policy uncertainty may face the risk of stranded assets—investments that can no longer generate returns due to regulatory or market changes—along with increased costs and potential financing constraints. The financial impact of future climate regulation is particularly difficult to quantify, exposing investors to both tail risk and variance risk (Semieniuk et al. (2021)), where tail risk involves the potential for extreme, rare losses, and variance risk reflects increased volatility in asset returns due to regulatory unpredictability. Overall, the low-carbon transition presents a complex

risk landscape, where the pace of policy implementation and technological advancement will determine the resilience of industries and financial systems in the years to come.

1.3 Low-Carbon Transformation: Balancing Benefits and Challenges for Enterprises

Undertaking a low-carbon transformation is now a strategic imperative for businesses looking to align with sustainable practices. This shift offers numerous potential benefits, including cost savings through improved efficiency, the chance to become market leaders, and the ability to foster innovation. These advantages not only reflect environmentally conscious decisions but also contribute to long-term economic stability. For instance, Tesla's early commitment to electric vehicle production allowed it to capitalize on carbon credit sales, generating billions in revenue, which provided a competitive edge and essential funding during its growth phase. Similarly, British Petroleum's (BP's) shift towards renewable energy investments has positioned it favorably as global policies increasingly push for emissions reductions. By investing early in clean energy, BP aims to mitigate future regulatory costs, adapt to shifting consumer preferences, and establish a foothold in the expanding renewables market. However, managing transition risks associated with this shift is complex due to the interplay of economic, political, and technological factors. While some companies are making progress in decarbonizing their operations, others are still struggling due to limited resources or a lack of strategic foresight. This disparity is problematic because it creates varying levels of risk exposure across industries and markets, which can lead to unequal competitive advantages, market instability, and slower overall progress in achieving global climate goals.

Moreover, the interconnected nature of global supply chains means that transition risks in one sector can have widespread effects throughout the economy (NGFS (2019)). For instance, rising energy costs can increase production expenses for manufacturing industries, which in turn influences product pricing and consumer demand. Policymakers face the difficult task of balancing climate action with minimizing economic disruption, adding uncertainty for businesses. The unpredictable nature of future regulations—whether stricter or more lenient—creates challenges for companies trying to plan long-term investments (Schulte and Hallstedt (2018)). This regulatory uncertainty also contributes to market volatility as firms attempt to navigate the evolving policy landscape.

In addition to regulatory challenges, businesses face significant financial hurdles when adopting sustainable technologies and practices. The high upfront or sunk costs associated with these investments can strain economic resources and negatively impact short-term profits. For some companies, particularly those in capital-intensive industries, the costs as-

sociated with transitioning to low-carbon technologies can also increase credit risk. This is an issue because as companies take on more debt to finance these transitions, their ability to repay loans may become uncertain if the returns on investment are delayed or underperform. Furthermore, the rapid pace of technological advancement in the low-carbon sector can introduce additional risks. Investments made today may quickly become obsolete or less cost-effective as newer technologies emerge, leading to potential financial and technological losses.

Given these challenges, businesses must approach the low-carbon transition carefully, weighing the potential benefits against the associated potential costs. Striking the right balance between cost savings, market positioning, and innovation is critical for achieving a successful transformation to a low-carbon economy. Developing a practical and effective analytical framework to guide low-carbon transition efforts is essential. In the next section, we will introduce a stylized model aimed at determining the optimal low-carbon transition strategies for various industries. This framework will help explain the dynamics of investment decisions in the context of low-carbon transformation, offering a clearer understanding of how companies can navigate this evolving landscape in the face of uncertainty.

2 Preliminaries and Model Building

2.1 Motivations

2.1.1 Sector-Specific Strategies and Investments in the Low-Carbon Transition

The global push for a low-carbon economy has placed growing pressure on industries, each facing unique challenges and opportunities during this transition period. Although the need for investment in low-carbon technologies is universal, the specific requirements and strategies vary across sectors due to their distinct energy needs, emission levels, and operational processes.

The energy sector, particularly utilities, is one of the most crucial areas for low-carbon investment. Utilities, which generate and supply electricity to households and industries, have traditionally relied on fossil fuels, such as coal and natural gas, as primary energy sources. This has made them significant contributors to global greenhouse gas (GHG) emissions. As the transition to renewable energy sources, such as solar, wind, and hydroelectric power, becomes increasingly urgent for governments, businesses, and society at large, substantial investments by both the public and private sectors are required. These include upgrading existing infrastructure, modernizing grids, and advancing energy storage technologies to ensure efficient and reliable integration of renewable energy, as noted by Boyd (2013). For example, grid modernization and development of energy storage technologies are key factors

in ensuring that intermittent renewable energy sources can consistently meet demand from both residential and industrial consumers.

The transportation sector is another major contributor to carbon emissions, primarily through the burning of fossil fuels in vehicles. According to Tyfield (2013), transitioning this sector to a sustainable, low-carbon future requires a substantial amount of investment in electric vehicles (EVs), public transportation infrastructure, and alternative fuels such as hydrogen. In addition, advancements in battery technology, expansion of EV charging networks, and supportive public policies are essential to encourage the rapid adoption of EVs and effectively decarbonize transportation. For instance, the global adoption of EVs has been steadily increasing, with countries such as Norway leading the way, where over 50% of new car sales are electric cars.

Industries such as manufacturing, steel production, and chemical processing are highly energy-intensive and have traditionally relied on fossil fuels for processing heat and feedstock. Transitioning these sectors toward low-carbon alternatives, such as electrification, hydrogen-based processes, or bio-based feedstocks, necessitates a substantial amount of capital investment. The adoption of carbon capture and utilization/storage (CCUS) technologies, which involve capturing carbon dioxide emissions from industrial processes and either storing it underground or using it in products, along with improving energy efficiency, are additional strategies that can significantly reduce emissions. The steel industry, for instance, is exploring hydrogen-based technologies to replace traditional coal-based methods of production. This transition, though capital-intensive, can help lower the sector's overall carbon footprint.

Agriculture and land use are other critical areas for low-carbon transition, as they are significant sources of GHG emissions. Livestock production, fertilizer use, and deforestation are among the primary contributors to emissions in this sector. Investing in sustainable agricultural practices, such as regenerative farming, agroforestry, and precision agriculture, can enhance carbon sequestration and reduce emissions, as discussed by van Veelen (2021) and Norse (2012). Protecting natural ecosystems like forests and wetlands also plays a vital role in capturing carbon and preserving biodiversity, where by biodiversity we mean the variety of plant and animal species within an ecosystem. For instance, Brazil's efforts to reduce deforestation in the Amazon have yielded measurable reductions in carbon emissions.

While the transition to a low-carbon economy is imperative, it comes with a substantial amount of costs. Estimates from McKinsey (2021a) suggest that global spending on physical assets for a net-zero transition could reach approximately $275 trillion by 2050, or about $9.2 trillion annually. The energy sector, in particular, will need to transform existing infrastructure to support cleaner energy generation and distribution, and adopt low-emission

technologies like renewable energy, carbon capture, and biofuels, all of which involve a substantial amount of investment. Conversely, sectors such as the service industry, with lower emissions intensity, may require comparatively a small amount of investment. It is essential to recognize different amounts of investment are needed across different sectors. For example, utilities and manufacturing require large-scale investments to decarbonize, while the service sector may need fewer capital to achieve sustainability goals. Sector-specific strategies and tailored investment plans are therefore critical to achieving optimal outcomes, as highlighted by McKinsey (2021b) and BlackRock (2024).

2.1.2 Balancing Costs and Benefits of Low-Carbon Transition

Investing in the low-carbon transition confers great benefits across various industries by driving long-term sustainability, reducing regulatory risks, and enhancing competitive positioning. For energy-intensive industries such as manufacturing and transportation, reducing carbon emissions can lead to cost savings through improved energy efficiency and reduced fuel expenses. In the financial sector, supporting low-carbon initiatives can mitigate portfolio risks linked to climate change, while at the same time also opening new investment opportunities in green technologies and sustainable businesses. Industries such as real estate and construction benefit by developing energy-efficient buildings that attract environmentally conscious tenants, boosting property value. Additionally, adopting low-carbon strategies can enhance the brand reputation for corporate responsibility and environmental stewardship, meet evolving consumer preferences for sustainability, and ensure compliance with future climate regulations, positioning companies for growth in a low-carbon economy. However, the upfront costs of adopting cleaner technologies can strain businesses, particularly if the returns on investment are not immediate. For example, investing in renewable energy infrastructure may tie up capital that could otherwise be used for business expansion or other needs.

Companies must carefully balance the costs and benefits of low-carbon investments. This involves determining the optimal investment ratio, which refers to the proportion of financial resources allocated to low-carbon initiatives relative to total investments. Companies that can effectively manage financial risks and seize the long-term benefits of low-carbon investments will likely be able to strengthen their competitiveness and resilience in a rapidly evolving global economy.

Given these considerations, this paper proposes a stylized analytical framework to determine the optimal low-carbon transition strategy across different sectors. The framework aims at capturing the unique underlying dynamics and investment needs of each sector, helping industries navigate the complexities of transitioning toward a sustainable, low-carbon future.

8

2.2 Variables Descriptions

The parameters and variables in this framework are introduced with the aim of replicating the dynamics of low-carbon transition investments and their effects on various industry operations, offering insights into investment strategies. Below, we provide a detailed description of each variable and parameter.

Selling price per unit (p): This parameter represents the price at which the product of interest is sold in the market. Taking the selling price into consideration is to describe and quantify the revenue. In the context of low-carbon transition, businesses may find opportunities to increase prices for eco-friendly products due to an increased consumer demand for sustainability. For instance, Tesla's Model 3 and other EVs are often priced higher than traditional internal combustion engine vehicles (ICEs), yet some consumers are willing to pay the premiums for the environmental advantages.

Production Cost per unit (c): Production cost per unit includes all expenses incurred in manufacturing each unit, such as raw materials, labor, and energy. Analyzing production costs is essential to evaluating profitability. A study by Siddique and Sultana (2018) found that switching to sustainable sourcing practices initially raised production costs due to the adoption of cleaner and more expensive technologies, but long-term benefits such as energy savings and brand value will outweigh the initial investment.

Selling Profit per unit ($p - c$): This parameter reflects the profit earned from each unit sold, determined by subtracting production costs from the selling price. It captures the direct profitability of the product after accounting for costs. Profit is the primary goal for a company when making decisions, as it ensures financial viability and supports long-term growth, influencing how much of the company's revenue can be allocated toward investments, including those for sustainable transitions.

Total Asset (A): Total asset represents all financial resources available to a company, encompassing both current and long-term assets. This metric is essential for evaluating the company's capacity to invest in production and growth opportunities, providing insight into the scale and potential of the business. Research indicates that firms with larger asset bases are more inclined to invest significantly in sustainability initiatives, as they can support longer investment horizons and absorb higher upfront costs associated with such projects (Eccles et al. (2014)). For example, Amazon has invested $2 billion in renewable energy through its Climate Pledge Fund, leveraging its extensive financial resources to lead in corporate sustainability (Amazon (2020)). Consequently, total assets not only reflect a company's financial strength but also its commitment to sustainable practices and long-term value creation.

Transition Investment Ratio (α): The Transition Investment Ratio is a critical met-

ric in our model, measuring the proportion of total assets allocated to low-carbon initiatives. This ratio is essential as it reflects a company's commitment to sustainability and its responsiveness to market dynamics and regulatory pressures. By strategically adjusting this ratio, businesses can enhance their reputation and mitigate risks associated with climate-related regulations and consumer preferences. Our primary goal with this framework is to identify the optimal transition investment ratio that balances financial performance with sustainability objectives, ensuring that companies thrive economically while still contributing positively to the environment.

Practically, the Transition Investment Ratio offers insights into how effectively a company aligns its financial resources with sustainability goals. A higher ratio signifies a greater investment in low-carbon initiatives, leading to long-term cost savings and competitive advantages. For instance, IKEA's allocation of over 3 billion pounds toward renewable energy infrastructure exemplifies the benefits of a strategic adjustment in this ratio (IKEA (2020)). By investing in solar and wind energy projects, IKEA not only reduced its operational reliance on fossil fuels but also achieved improved operational efficiency and lower carbon emissions. Improved operational efficiency can manifest in reduced energy costs, as renewable energy sources often lead to lower utility bills. IKEA's renewable energy infrastructure allows it to produce a substantial portion of its energy needs in a sustainable manner, ultimately lowering the company's operational costs and enhancing its energy independence. Additionally, the transition to renewable energy directly impacts carbon emissions, as utilizing solar and wind energy decreases IKEA's greenhouse gas footprint. This shift aligns with regulatory expectations and resonates with consumers who favor environmentally responsible brands. Thus, the Transition Investment Ratio is pivotal in our model, encapsulating the strategic allocation of resources toward sustainability and driving both operational efficiency and lower carbon emissions.

Enterprise Low-carbon Production Efficiency Coefficient (k): This coefficient measures the improvement in production efficiency of the firm resulting from low-carbon initiatives, with a value greater than 1 indicating a gain in efficiency due to cleaner technologies. In our framework, we assume a higher value of k signifies greater production efficiency of the firm after investing in the transition to sustainable practices. For instance, Siemens reported a remarkable 20% increase in production efficiency after transitioning from traditional fossil fuel-based energy to renewable energy sources and incorporating energy-efficient manufacturing technologies (AG (2019)). This transition not only reduced their carbon footprint but also streamlined their operations, demonstrating that investments in sustainability can yield great returns in efficiency.

Original Productivity Coefficient (β): The value of this coefficient ranges between

0 and 1. A lower value indicates that, given a fixed amount of raw materials, the firm's production efficiency is relatively low, resulting in fewer products being produced per unit of input, which reflects suboptimal resource utilization. Conversely, a value closer to 1 suggests higher efficiency in material utilization, allowing the enterprise to produce more output with the same raw material input, indicating both optimized resource allocation and production process efficiency. Changes in this coefficient can thus reflect the current production efficiency of the enterprise and offer insights into potential improvements under low-carbon transition strategies. There is evidence to suggest that many firms that start with below-average efficiency have successfully turned their operations around after investing in cleaner technologies. Research in Weng et al. (2015) indicates that companies in the regions with lower initial productivity often experience the most significant gains when transitioning to more efficient, low-carbon systems. By enhancing productivity through sustainable practices, these firms not only improve their operational performance but also position themselves for greater profitability in the long run. Thus, the firms with lower β values should prioritize upgrades to enhance productivity and better align with sustainability goals.

Carbon Price (B): The carbon price signifies the cost of emissions imposed by regulatory frameworks and is essential to a company's profitability. This price is sensitive to regulatory or policy changes, with high carbon prices creating significant financial pressure on firms to reduce emissions. When the market carbon price is elevated, it can substantially diminish a company's profit margins, compelling businesses to reassess their operational strategies. In response to these challenges, companies are incentivized to invest in cleaner technologies and adopt sustainable practices to mitigate their carbon liabilities. As firms strive to maintain profitability while adhering to environmental regulations, understanding and managing the implications of carbon pricing becomes crucial for their long-term success.

Carbon Intensity (I): Carbon intensity refers to the amount of carbon dioxide (CO_2) emissions produced per unit of output, typically measured in terms of emissions per product manufactured or per unit of energy consumed. It serves as a critical metric for companies transitioning to low-carbon production, as reducing carbon intensity is essential for minimizing environmental impact while maintaining operational efficiency.

In the literature, carbon intensity is usually defined as a measure of the environmental performance of a company's production processes. For instance, the IPCC emphasizes that carbon intensity is a key indicator of how effectively an organization utilizes resources and minimizes emissions in its operations (Change et al. (2014)). Similarly, the World Resources Institute (WRI) defines carbon intensity as a means to assess the relationship between output and emissions, allowing for comparisons across industries and over time (Institute (2015)). In addition, carbon intensity is defined more specifically as the ratio of expected annual

emissions to expected revenue in Fang et al. (2019). This formulation highlights the firm's contribution to climate change per unit of revenue, thus linking environmental impact directly to economic output and enabling the pricing of emissions-related risks in financial evaluations.

Flow and Interaction Between Variables: The interaction between these variables provides a comprehensive framework for assessing the financial, operational, and environmental trade-offs involved in a low-carbon transition. For example, increasing the transition investment ratio (α) may initially raise firm's production costs (c), but this can lead to greater efficiency (k) and reduced carbon intensity (I) for the firm over time. Firms in markets with high carbon prices (B) are more likely to invest in low-carbon technologies, seeing long-term benefits from both regulatory compliance and enhanced profitability through premium pricing and consumer demand for sustainable products. By considering these variables, companies can strategically navigate the low-carbon transition, balancing short-term financial considerations with long-term environmental and competitive advantages. This paper will build the analytical framework based on these parameters and variables in the following parts.

In summary, the variables and associated parameters of the analytical framework are described in Table 1.

Notation	Description
p	Selling Price per unit
c	Production Cost per unit
$p - c$	Selling Profit per unit
A	Total Asset
α	Transition Investment Ratio
k	Enterprise Low-carbon Production Efficiency Coefficient
β	Original Productivity Coefficient
B	Carbon Price
I	Carbon Intensity

Table 1: Notations Description Table

2.3 Optimal Transition Investment Ratio without Government Intervention

The transition towards a low-carbon economy presents a complex challenge for enterprises, acting as a double-edged sword with respect to both arising opportunities and costs. While embracing low-carbon transformation holds the promise of environmental sustainability and enhanced competitiveness, it also entails a substantial amount of financial investments and

operational adjustments. For many enterprises, particularly those operating in carbon-intensive industries, the costs associated with transitioning to cleaner technologies and sustainable practices can be daunting. These costs may include investments in renewable energy infrastructure, efficiency upgrades, and emission reduction measures, all of which require a substantial amount of capital expenditure and major operational restructuring in order to embark on the transition path.

As a result, some companies may hesitate to fully commit to low-carbon transformation, fearing the resulting financial burden and potential disruptions to their existing business models. This reluctant proclivity to adopt green practices could undermine firm's progress towards sustainability goals and exacerbate environmental challenges. In such cases, the role of government intervention becomes relevant in incentivizing and regulating enterprises' low-carbon transformation efforts.

Governments possess the ability to influence corporate behavior through various policy instruments, including subsidies, tax incentives, and regulatory measures. By introducing targeted subsidies or tax breaks for low-carbon investments, governments can help alleviate the financial barriers faced by enterprises and encourage them to pursue sustainable practices. These financial incentives can offset the upfront costs of transitioning to cleaner technologies and provide companies with the necessary resources to invest in green initiatives.

Furthermore, governments can enact regulatory policies that mandate emission reductions, promote energy efficiency, and set emissions targets for industries. By establishing clear and enforceable regulations, governments create a framework that incentivizes companies to prioritize low-carbon transformation and align their business strategies with broader environmental objectives. Regulatory measures can also level the playing field for all companies by imposing costs on carbon emissions and internalizing the externalities associated with pollution, thereby encouraging companies to internalize the true costs of their environmental impact.

Hence, this section aims at analyzing and delineating the optimal low-carbon transition investment strategies for companies, considering both scenarios with and without external government intervention. By comparing these two approaches separately, we hope to elucidate the efficacy and implications of different pathways toward sustainable transformation within the corporate landscape and to provide valuable insights and suggestions for policymakers, such as government entities, to better support and incentivize effective low-carbon strategies in the corporate sector.

2.3.1 Model Building

Maximizing profit holds a paramount position among the objectives of any company. This strategic action emanates from the foundational principle that profit arises from the difference between total revenue and total costs. Therefore, to effectively navigate and optimize profit margins, it becomes indispensable to dissect the constituents of both total revenue and total costs.

In our framework, total revenue is represented by the unit selling price per unit of the product (denoted as p) multiplied by the total production volume. The total production volume is represented by $2 \cdot \text{Sigmoid}(\alpha k) \cdot [(1-\alpha) \cdot A]^{\beta}$, where $\text{Sigmoid}(\alpha k) = \frac{1}{1+e^{-\alpha k}}$. This formulation integrates several key parameters: the transition investment ratio (α), indicating the allocation of total assets towards low-carbon initiatives; the enterprise low-carbon production efficiency coefficient (k), denoting the effectiveness of transitioning to cleaner technologies; and the original productivity coefficient (β), reflecting the baseline production efficiency. The sigmoid function encapsulates the joint impact of transition investments and the firm's production efficiency on production volume, ensuring a realistic representation of the firm's saturation effects. Meanwhile, the term $(1-\alpha) \cdot A$ captures the portion of the firm's total assets available for production activities, adjusted by the original productivity coefficient β to reflect the company's inherent efficiency before investing in the low-carbon transition. Thu, the term $[(1-\alpha) \cdot A]^{\beta}$ represents the firm's total production volume before investing in low-carbon transition. Simultaneously, the firm allocates a portion α of its total assets A towards the low-carbon transition investment. This investment is expected to enhance production efficiency, leading to an overall increase in production volume by a factor of $2 \cdot \text{Sigmoid}(\alpha k)$. By combining these various elements, the formula provides a greater understanding of how strategic decisions regarding transition investments and production efficiency influence the overall production capacity of the company.

Although the sigmoid function is customarily not utilized as part of a production function, we employ it in our framework to depict the anticipated upward trajectory of total production volume as both α and k increase. This choice is informed by our expectation of production growth in response to heightened transition investments and enhanced production efficiency of the firm. Additionally, the sigmoid function exhibits a slight decrease at its margins, which corresponds to our understanding of production dynamics. Notably, we introduce a scaling factor of '2' at the beginning of the sigmoid function. This adjustment is made to ensure that the sigmoid's baseline value remains at least 0.5 when the input (αk) exceeds 0 in our model. By multiplying the sigmoid by '2', we normalize its baseline rate to 1, resulting in a more pronounced increase above 1 as the values of α (Transition Investment Ratio) or k (Enterprise Low-carbon Production Efficiency Coefficient) rise. This modification aligns

14

with our expectations.

Based on the descriptions provided above, we can formulate the expression for 'Revenue' in the framework as follows:

$$
\begin{aligned}
\text{Revenue} &= \text{Selling Price per unit} \times \text{Unit Amount} \\
&= p \times \left\{ 2 \cdot \text{Sigmoid}(\alpha k) \cdot [(1 - \alpha) \cdot A]^{\beta} \right\} \\
&= p \times \left\{ \left(\frac{2}{1 + e^{-\alpha k}} \right) \cdot [(1 - \alpha) \cdot A]^{\beta} \right\}
\end{aligned}
\tag{2.1}
$$

Next, we address the 'Cost' component of the framework, which comprises both the 'Production Cost' and the 'Carbon Cost'. Denote 'c' as the production cost per unit. The production cost can then be expressed as 'c' multiplied by the unit amount (equivalent to the unit amount in the revenue part). Additionally, we incorporate the carbon cost in our framework, which is calculated as the product of the 'Carbon Intensity', the unit amount, and the 'Carbon Price'. Here, the 'Carbon Intensity' is defined as $\left(2 - \frac{2}{1+e^{-\alpha k}} \right)$, a value ranging from 0 to 1. When αk is zero (signifying no transition investment), the carbon intensity reaches its highest level of 1. Conversely, as transition investment increases, the carbon intensity decreases, indicating a reduction in emissions due to greater transition efforts. As mentioned, we define 'Carbon Intensity' as the 'Carbon Emission' divided by the total production volume, aligning with the traditional understanding of 'Carbon Intensity' discussed earlier. Based on these considerations, we can formulate the 'Cost' component in the framework as follows:

$$
\begin{aligned}
\text{Cost} &= \text{Production Cost} + \text{Carbon Cost} \\
&= \text{Production Cost Per Unit} \times \text{Unit} + \underbrace{\text{Carbon Intensity} \times \text{Unit}}_{\text{Carbon Emission}} \times \text{Carbon Price} \\
&= c \cdot \left\{ \left(\frac{2}{1 + e^{-\alpha k}} \right) \cdot [(1 - \alpha) \cdot A]^{\beta} \right\} \\
&\quad + \left(2 - \frac{2}{1 + e^{-\alpha k}} \right) \cdot \left\{ \left(\frac{2}{1 + e^{-\alpha k}} \right) \cdot [(1 - \alpha) \cdot A]^{\beta} \right\} \cdot B
\end{aligned}
\tag{2.2}
$$

Thus, the total profit π is calculated as:

$$
\begin{aligned}
\pi &= \text{Revenue} - \text{Cost} \\
&= \left[p - c - \left(\frac{2e^{-\alpha k}}{1 + e^{-\alpha k}} \right) \times B \right] \times \left[\frac{2}{1 + e^{-\alpha k}} \times [(1 - \alpha) \times A]^{\beta} \right]
\end{aligned}
\tag{2.3}
$$

To determine the optimal value of α under various conditions, we begin by taking the first-order derivative of the total profit with respect to α. This yields a necessary first-order condition (FOC) as follows:

$$\frac{2((1-\alpha)A)^{\beta}\left(-\frac{2Be^{\alpha(-k)}}{e^{\alpha(-k)}+1}-c+p\right)}{e^{\alpha(-k)}+1}=0 \tag{2.4}$$

This equation helps us identify potential critical points of maximizing the Equation 2.3. To further analyze these points, specifically to assess their convexity and determine whether they are minima, maxima, or saddle points arising from the formulation of the model, we compute the second-order derivative with respect to α. The resulting second-order condition (SOC) is used to evaluate the nature of these critical points.

$$\frac{1}{(\alpha-1)^2\left(e^{\alpha k}+1\right)^3}2\alpha e^{\alpha k}(A-\alpha A)^{\beta}\left(-(\alpha-1)^2 k^2\left(e^{\alpha k}-1\right)\right.$$
$$\left.+(\beta-1)\beta\left(e^{\alpha k}+1\right)^2+2(\alpha-1)\beta k\left(e^{\alpha k}+1\right)\right) \tag{2.5}$$

From the analysis of the second derivative, we observe that the value is less than 0 when α and β are both within the range of (0, 1). Consequently, the optimal value of α maximizes profit, aligning with the expectations set by the problem.

Our first objective is to understand how changes in specific parameters affect the optimal transition investment ratio. For instance, we aim at analyzing how the optimal value of α adjusts when the carbon price (B) increases from 0 to 2. This analysis will elucidate the impact of carbon pricing on the optimal transition investment ratio for the firm. However, explicitly expressing α in terms of other parameters analytically is challenging based on the FOC due to several inherent complexities. The equation features exponential terms such as $e^{\alpha(-k)}$, which complicate the isolation of α since these terms do not simplify easily into a linear or polynomial form. Additionally, the equation includes a combination of linear and non-linear terms involving multiple parameters $(A, B, c, p, \beta, \text{ and } k)$, further complicating the process. The presence of α in both the numerator and the denominator within the fractional expressions adds another layer of difficulty. Therefore, we will resort to numerical methods to demonstrate how the optimal transition investment ratio of the firm varies in response to incremental parameter changes.

2.3.2 Numerical Study

In this subsection, we conduct a detailed numerical analysis of each critical parameter affecting the optimal transition investment ratio (α). Recall the optimal transition investment ratio represents the proportion of firm's financial resources allocated towards its low-carbon initiatives relative to its total investment. A key variable is a specific variable within our framework that we systematically vary to observe its impact on the optimal α. By focusing on one variable at a time, we can isolate its effect and gain deeper insights into its role within the overall system. This is known in Economics as a comparative static exercise.

While holding all other variables constant, we determine the optimal value of α for a range of values of a specific key variable. We then graphically represent the relationship between this key variable and the optimal α. Additionally, we will present the maximum profit achievable for different values of the key variable. This approach allows us to visualize how changes in one variable influence both the optimal investment decision and the profitability of the company.

The baseline values of the variables in the framework are provided in Table 2. These values are set within a reasonable range for illustrative purposes and can be adjusted by readers interested in exploring scenarios across different industries. Building on this foundation, we will systematically vary one variable at a time to different values and analyze the resultant changes in the value of optimal α.

Variable Name	Description	Baseline Value
p	Selling Price per unit	3.6
c	Production Cost per unit	1.6
$p - c$	Selling Profit per unit	2
A	Total Asset	100
k	Enterprise Low-carbon Production Efficiency Coefficient	2
β	Original Productivity Coefficient	0.8
B	Carbon Price	1

Table 2: Baseline Parameters for Analysis

From Figure 1 to Figure 4, the left plot illustrates how changes in the key variable affect the optimal transition investment ratio, aiming to maximize profit under each scenario. The right plot shows the corresponding maximum profit achieved under the optimal transition investment as the key variable changes. We will explain each figure in detail below.

Relationship Between Profit Margin ($p - c$) and Optimal Alpha (Figure 1)

Figure 1 reveals a distinctive pattern where the optimal value of alpha for the firm remains high and constant initially, even when the selling profit per unit is very low or negative, suggesting a strategic focus on substantial investments in machinery upgrades or efficiency improvements during periods of low profitability. This high investment level, indicated by a stable high value of alpha, which is likely to reflect a counterintuitive but proactive approach: companies invest heavily during financially challenging times to enhance production efficiency and reduce operational costs, aiming at setting the groundwork for future competitiveness and sustainability.

As the selling profit per unit begins to increase for the firm, the optimal value of alpha sharply declines, indicating that further heavy investments in transformation by the firm are no longer necessary. The decrease in the value of alpha suggests that the earlier investments by the firm have begun to yield improved operational efficiencies and higher profits, reducing

17

the need for continued high expenditure in transformations. This strategic shift emphasizes a dynamic financial strategy where initial heavy investments by the firm during low-profit periods are scaled back as profitability improves, aligning the investment levels of the firm with the diminishing marginal benefits of further transformations.
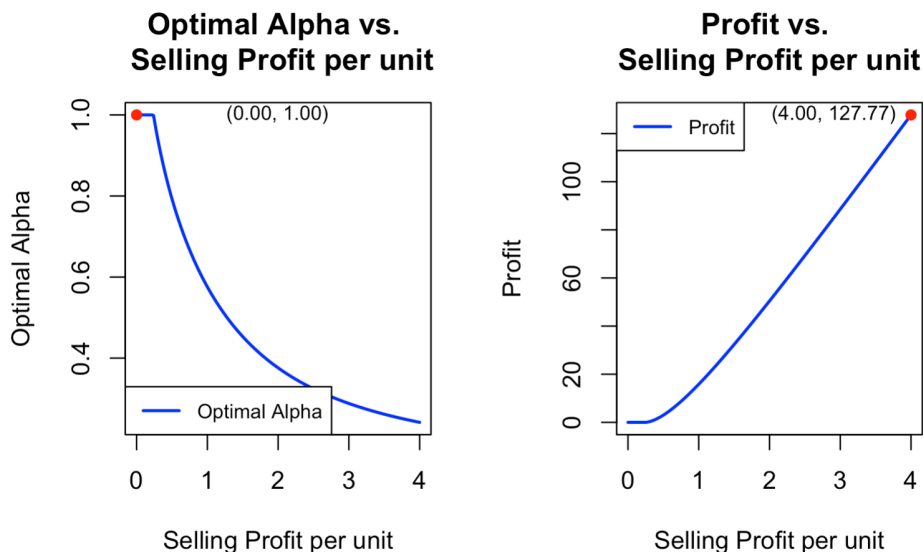

Figure 1: Optimal Level of Alpha and Profit Graph w.r.t. $p - c$

Effect of Increasing Carbon Prices (B) on Optimal Alpha (Figure 2)

As shown in Figure 2, when the carbon pricing variable B increases, it raises operational costs for the firm due to higher carbon taxes. In response, the optimal investment ratio α also increases, as shown in the left plot. This adjustment indicates a strategic move by the firm to allocate more resources towards low-carbon transition initiatives, which enhances production efficiency and reduces carbon emissions, thereby helping to offset the financial burden imposed by the carbon tax.

However, the right plot shows that despite these adjustments, a higher carbon tax still leads to a reduction in overall profit. Even with an optimal increase in the low-carbon investment ratio α, the profit trend declines as B increases. This underscores the financial impact of rising carbon costs on the firm. Nonetheless, by investing strategically in low-carbon transition, the firm can mitigate the extent of this profit decrease, cushioning some of the adverse effects of carbon pricing. In essence, while higher carbon taxes inevitably compress profits, allocating resources towards reducing the carbon footprint can help alleviate the downward pressure on profitability, offering a partial buffer against the increasing tax burden.

Impact of Efficiency Parameter (k) on Optimal Alpha and Profit (Figure 3)

Combining insights from both plots in Figure 3, we can observe that as the efficiency parameter k increases, profit consistently rises, while the optimal investment ratio α peaks
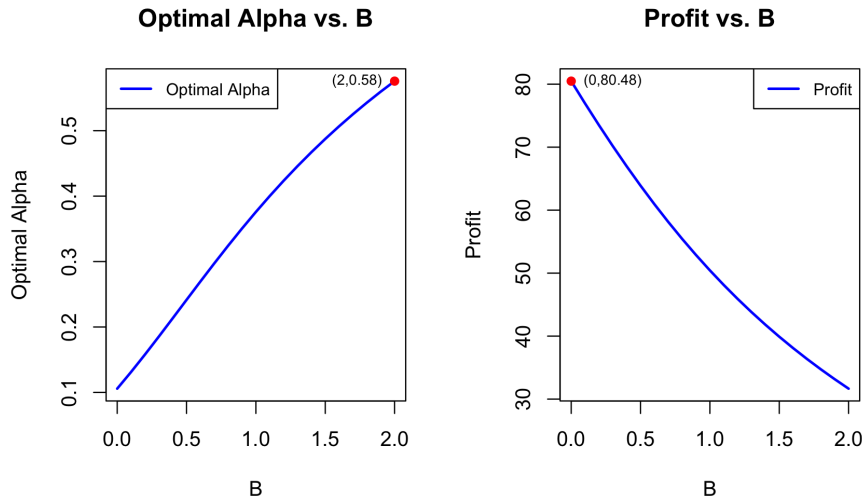
Figure 2: Optimal Level of Alpha and Profit Graph w.r.t. B

around $k \approx 3.1$ and then gradually declines. This suggests that although higher k values are beneficial for the company's profitability, it does not require continuously increasing the investment ratio in low-carbon initiatives. Initially, when k is low, the marginal benefit from efficiency gains is high, encouraging a higher allocation to low-carbon investments. However, as k grows, the marginal efficiency gains diminish, making it less necessary to maintain a high α. At higher k values, profits continue to increase due to the enhanced production efficiency achieved by prior investments, allowing the company to reduce the investment ratio α while still benefiting from increased profits.
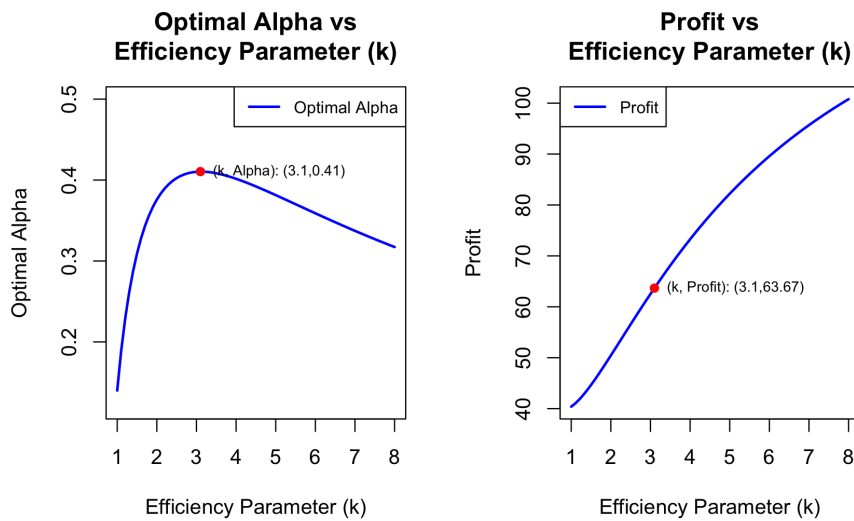

Figure 3: Optimal Level of Alpha and Profit Graph w.r.t. k

19

Influence of Original Productivity Coefficient (β) on Optimal Alpha and Profit (Figure 4)

The plots in Figure 4 demonstrate that as the Original Productivity Coefficient (β) increases, profit grows exponentially while the optimal transition investment ratio (α) declines. A higher β indicates strong baseline productivity, reducing the need for extensive low-carbon investments since the firm's production efficiency is already high. This makes the additional benefits from low-carbon investments less significant, allowing the firm to allocate fewer resources to α. The exponential growth in profit with rising β highlights the significant impact of inherent productivity on profitability, as firms with high baseline efficiency can achieve substantial profits without heavy investment in low-carbon initiatives. The decrease in optimal α reflects diminishing marginal returns on low-carbon investments for high-β firms, where the benefits of further investment in α are minimal.
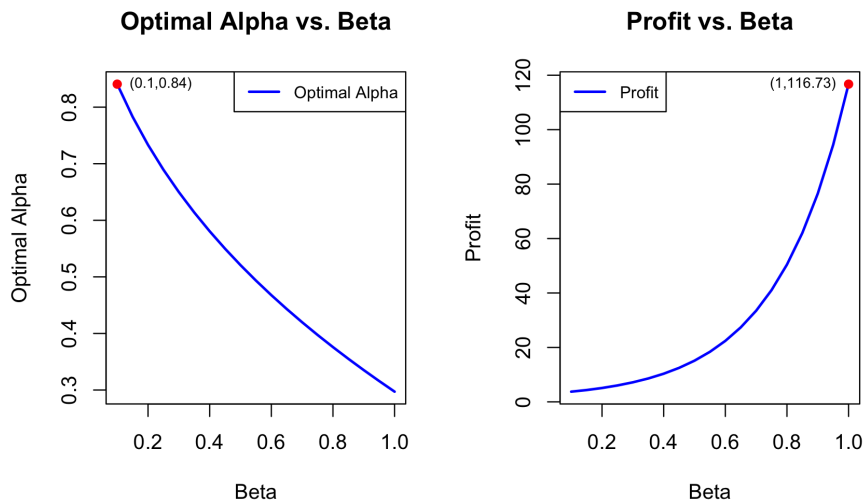

Figure 4: Optimal Level of Alpha and Profit Graph w.r.t. β

2.3.3 Sensitivity Analysis

The sensitivity analysis was conducted to evaluate the impact of variations in critical parameters on the optimal alpha, maximum objective value, and profit change rate. The parameters scrutinized include the enterprise low-carbon production efficiency coefficient (k), production cost per unit (c), original productivity coefficient (β), and carbon price per unit (B). Adjustments for each parameter were performed at $\pm 10\%$ and $\pm 50\%$ based on the baseline values in Table 2, except for β, where the upper limit was constrained to 1.00 due to inherent limitations. The results are concluded in the Table 3 and the analysis of each parameter is presented below.

k (Enterprise Low-carbon Production Efficiency Coefficient)					
Parameter Value	1.0	1.8	2.0	2.2	3.0
Optimal Alpha	0.1399250	0.3560002	0.3758660	0.3896782	0.4102122
Max Objective Value	40.38998	48.03570	50.43508	52.88084	62.52014
Alpha Change Rate (%)	-62.77263	-5.285352	0.000000	3.674763	9.137887
Profit Change Rate (%)	-19.916887	-4.757367	0.000000	4.849314	23.961613
c (Production Cost Per Unit)					
Parameter Value	0.80	1.44	1.60	1.76	2.40
Optimal Alpha	0.3011413	0.3571930	0.3758660	0.3970913	0.5191683
Max Objective Value	80.82201	56.40787	50.43508	44.53826	22.16245
Alpha Change Rate (%)	-19.880685	-4.967987	0.000000	5.647027	38.125899
Profit Change Rate (%)	60.249582	11.842530	0.000000	-11.69191	-56.05747
β (Original Productivity Coefficient)					
Parameter Value	0.40	0.72	0.80	0.88	1.00
Optimal Alpha	0.5806144	0.4107206	0.3758660	0.3430713	0.2971025
Max Objective Value	10.33973	36.31521	50.43508	70.34946	116.72607
Alpha Change Rate (%)	54.473780	9.273146	0.000000	-8.725114	-20.955217
Profit Change Rate (%)	-79.49894	-27.99613	0.000000	39.48516	131.43825
B (Carbon Price Per Unit)					
Parameter Value	0.5	0.9	1.0	1.1	1.5
Optimal Alpha	0.2414888	0.3505336	0.3758660	0.4002088	0.4874011
Max Objective Value	63.88578	52.87325	50.43508	48.11505	39.90827
Alpha Change Rate (%)	-35.751365	-6.739751	0.000000	6.476445	29.674174
Profit Change Rate (%)	26.669326	4.834262	0.000000	-4.600030	-20.871997

Table 3: Sensitivity Analysis Results

Enterprise Low-Carbon Production Efficiency Coefficient (k) :

The sensitivity analysis for k reveals that as k increases from 1.0 to 3.0, the optimal alpha rises from 0.14 to 0.41, which indicates that improving a firm's low-carbon production efficiency encourages a larger investment by the firm in low-carbon technologies. This trend is further reflected in the maximum objective value, which grows from 40.39 to 62.52, showing that better firm's efficiency leads to higher profitability for the firm. These results highlight a strong connection between firm's low-carbon production efficiency and its profitability.

Moreover, the alpha change rate starts with a large negative value (-62.77%) when $k = 1.0$ and makes a transition to a moderately positive change of 9.14% by $k = 3.0$. Similarly, the firm's profit change rate shifts from a notable loss (-19.92%) at $k = 1.0$ to a relatively large gain (23.96%) at $k = 3.0$. This indicates that as efficiency improves, firms not only increase their levels of investment in cleaner technologies but also experience greater profitability. These results underline the importance of improving low-carbon production efficiency, as it can serve as a key driver for both firm's optimal investment and its profit maximization.

Production Cost Per Unit (c):

As c increases from 0.80 to 2.40, the optimal alpha rises from 0.30 to 0.52, suggesting that firms must invest more to counterbalance higher production costs. However, this comes at the cost of its profitability, as the maximum objective value drops sharply from 80.82 to 22.16, showing that rising production costs significantly undermine a company's profitability potential.

The alpha change rate starts at -19.88% for $c = 0.80$, meaning that lower production costs lead to less investment in low-carbon technology. As c rises, the alpha change rate becomes positive (38.13%), showing that companies need to increase their investments to cope with higher costs. Profit change rates, meanwhile, vary drastically, reaching a peak at 60.25% for $c = 0.80$, followed by a steep decline to -56.06% at $c = 2.40$. This result illustrates the sensitivity of firm's profitability to changes in its production costs and highlights that controlling production costs is crucial for firms whose goal is to sustain profits while investing in low-carbon solutions. If its production costs rise unchecked, the firm may struggle to maintain its profitability, even with optimal investments.

Original Productivity Coefficient (β) :

When it comes to the value of β, the sensitivity analysis overall shows a unique pattern: as β increases from 0.40 to 1.00, the optimal alpha decreases from 0.58 to 0.30. This indicates that as its productivity improves, the firm requires less investment in low-carbon technologies to maintain profitability. Simultaneously, the maximum objective value surges from 10.34 to 116.73, highlighting the substantial impact of productivity on overall profitability of the firm. This result emphasizes that improving productivity not only reduces the required investment by the firm but also dramatically boosts the firm's profit potential.

The change rate of alpha starts at a high level (54.47%) when $\beta = 0.40$ and drops to -20.96% at $\beta = 1.00$, showing that better productivity substantially reduces the need for the firm to increase the level of investment. In terms of profitability, the profit change rate for the firm ranges widely, from -79.50% to a remarkable 131.44%. This further illustrates how vital firm's productivity improvements are for enhancing its profitability. Essentially, better productivity allows firms to generate substantially higher profits with a reduced level of investment, making this an essential factor in optimizing their financial strategies of the firm.

Carbon Price Per Unit (B) :

Finally, the analysis of B shows that as carbon prices increase from 0.50 to 1.50, the optimal alpha rises from 0.24 to 0.49, suggesting that the firm needs to allocate more resources to low-carbon production as carbon prices rise. However, this comes at a cost, as the maximum objective value declines from 63.89 to 39.91, showing that higher carbon prices

can lead to a reduced level of profitability.

The change rate of alpha is consistently negative, starting at -35.75% for $B = 0.50$ and improving slightly to -6.74% at $B = 1.10$, indicating that while increased carbon pricing necessitates the firm to invest more, its negative impact on profitability is relatively moderate. The change rate of the profit peaks at 26.67% for $B = 0.50$ and drops to -20.87% at $B = 1.50$. This suggests that while carbon pricing does affect firm's profitability, the sensitivity is not as severe for the firm compared to other variables. Companies can mitigate the impact of higher carbon prices through improved efficiency and strategic investments in cleaner technologies, ensuring that their profitability does not drastically diminish as carbon prices rise.

In comparing the variables in the framework, it is clear that the original productivity coefficient (β) is by far the most sensitive. Changes in the value of β lead to substantial shifts in the optimal value of alpha, maximum objective value, and the change rate of the profit. The strong relationship between productivity and profitability suggests that firms should prioritize improving productivity to maximize financial outcomes.

Conversely, the carbon price per unit (B) is the least sensitive variable in the framework. While changes in B do affect both the optimal alpha and the profitability, the overall impact for the firm is moderate compared to the other factors. Firms can manage the effects of carbon pricing through strategic investments in cleaner technologies, making it a more controllable factor in its financial performance.

In conclusion, firms should focus heavily on productivity improvements (β) to maximize their profitability while carefully managing their production costs (c) and their low-carbon production efficiency (k) to optimize investments. Carbon pricing (B), while important, presents a more manageable challenge to firms relative to the other factors.

2.3.4   Expanding the One-Period Model to a Multi-Period Model

In our initial analysis, we have focused on a static one-period model to evaluate the impact of transition investment on enterprise profitability. This framework provided basic but useful insights into the immediate effects of various variables on a company's profit. However, real-world scenarios are dynamic in nature and involve changes over multiple periods. Therefore, as a next logical step, we are expanding our previous static framework to a multi-period setting to capture the evolving nature of the variables in the framework and their long-term impacts.

To achieve this, we revise the profit function to account for time dependency, reflecting the changes in key variables in the framework over multiple different periods. The time-dependent profit function is defined as follows:

$$\pi_t = \left[p - c_t - \left(\frac{2e^{-\alpha k_t}}{1 + e^{-\alpha k_t}} \right) \times B_t \right] \times \left[\frac{2}{1 + e^{-\alpha k_t}} \times [(1 - \alpha) \cdot A_t]^{\beta_t} \right] \qquad (2.6)$$

This formulation captures the dynamic nature of transition investments, where p is the selling price per unit (assume p is a constant), c_t is the production cost per unit at time t, α is the transition investment ratio, k_t is the enterprise low-carbon production efficiency coefficient at time t, B_t is the carbon price at time t, and β_t is the original productivity coefficient at time t. By incorporating these time-dependent variables, we can more accurately model the impact of transition investments over multiple periods.

The resulting multi-period objective function can then be expressed as follows:

$$\max \left[\pi_t + g\pi_{t+1} + g^2\pi_{t+2} + \ldots + g^{n-1}\pi_{t+n} \right] \qquad (2.7)$$

where g is the discount factor. This objective function accounts for firm's profits in the current period (π_t) and its discounted future profits (π_{t+1}, π_{t+2}, and so on), providing a more complete view of the impact of transition investments for the firm. The inclusion of future profits, discounted to the present time by the factor g, acknowledges the time value of money, opportunity costs, and inherent risks faced by the company. The discounting factor also acknowledges the uncertainties associated with long-term projections, ensuring a realistic assessment of the enterprise's financial trajectory.

By using this multi-period framework, we aim at finding the optimal value of α that maximizes the overall profit of the firm across multiple periods. The multi-period model is particularly useful for understanding the long-term implications of transition investments for the firm. Transitional investments typically incur immediate costs but generate substantial future benefits for the firm. For example, investments in low-carbon technologies might initially increase production costs for the firm due to the capital expenditure required for new equipment or processes. However, over time, these investments can lead to substantial efficiency gains, cost reductions, and improved regulatory compliance, which enhance future profits of the company.

Short-Term vs. Long-Term Observation:

Our goal is to find the optimal value of α to achieve the maximum objective function value for the firm over different observation periods. For simplicity, we will compare a shorter-term observation (of 3 years) with a longer-term observation (of 6 years).

- Short-Term Observation (3 years): This period allows us to understand the immediate and near-future impacts of transition investments for the firm. It is suitable for enterprises looking for quick wins and immediate adjustments in their strategies.

- Long-Term Observation (6 years): This extended period captures the long-term benefits and potential drawbacks of transition investments faced by the company. It helps the enterprises' plan strategically for sustained growth and ensures compliance with evolving regulations and market conditions.

By comparing these two observation periods, we can evaluate how the optimal value of α varies based on the length of the planning horizon for the company. This comparison will provide important insights into the trade-offs between short-term gains and long-term sustainability, guiding enterprises in making informed decisions about their transitional investments. The numerical exercise will be presented in the next subsection to illustrate these findings.

2.4 Decarbonization Scenario Analysis

2.4.1 Introduction to Decarbonization Scenarios

To illustrate the practical application of our multi-period framework, we examine four decarbonization scenarios by means of a numerical method: Immediate, Quick, Slow, and No Decarbonization. Decarbonization scenarios are strategic frameworks used to explore and analyze the pathways by which industries, economies, and societies can make a transition from high-carbon to low-carbon or carbon-neutral operations. These scenarios are designed to address the urgent need to mitigate climate change by reducing GHG emissions, particularly carbon dioxide (CO2), which is viewed as a major contributor to human-induced global warming. Each decarbonization scenario represents a different approach, pace, and scale of implementing low-carbon technologies, policies, and practices.

By analyzing these different scenarios, we can better understand how different decarbonization strategies impact enterprise profitability over multiple periods and identify the optimal transition investment ratio (α) for each strategy.

Immediate Decarbonization:

In this scenario, significant and immediate investments are made in low-carbon technologies and practices. The goal is to achieve rapid reductions in carbon emissions for the firm as quickly as possible. This approach often involves aggressive regulatory measures, substantial financial incentives, and a rapid deployment of renewable energy sources, energy efficiency improvements, and other carbon reduction technologies by the company. Immediate decarbonization is typically driven by strong political will and societal urgency to address climate change impacts swiftly.

Quick Decarbonization:

Quick Decarbonization involves a fast-paced transition, although not as rapid as the Immediate Decarbonization scenario. Investments in low-carbon technologies are substantial

but spread out over a few years rather than all at once. This scenario aims at balancing the need for substantial emissions reductions with economic and logistical considerations, allowing for a more manageable transition process for the firm. Quick decarbonization often includes accelerated deployment of renewable energy, electrification of transportation, and increased energy efficiency measures by the company.

Slow Decarbonization:

The Slow Decarbonization scenario adopts a more gradual approach to transitioning to a low-carbon economy. Investments and regulatory changes are implemented over a longer period of time, allowing for a smoother transition with less immediate economic disruption. This approach may be motivated by financial constraints, the need for gradual technological adaptation, or political and social considerations by the company. While slower, this scenario still aims at achieving meaningful reductions in carbon emissions, albeit over a longer time frame.

No Decarbonization:

In the No Decarbonization scenario, no substantial efforts are made for the firm to reduce carbon emissions. Industries and societies continue with their current high-carbon practices, leading to minimal changes in carbon intensity and production efficiency. This scenario often results in continued reliance on fossil fuels and can lead to increased carbon emissions over time, exacerbating the adverse impacts of climate change impacts. It is typically considered unsustainable in the long term due to the environmental, economic, and social risks associated with an unchecked force of climate change.

2.4.2 Variable Changes and Rationale for Each Decarbonization Scenario

To effectively analyze the aforementioned impacts of different decarbonization strategies, it is essential to understand how key variables in the framework evolve under each scenario and the rationale behind these changes. This part delves into the specific modifications of variables such as the enterprise low-carbon production efficiency coefficient (k_t), production cost per unit (c_t), original productivity coefficient (β_t), and carbon price (B_t) for each of the decarbonization scenarios: Immediate, Quick, Slow, and No Decarbonization. By doing so, we can better comprehend the short-term and long-term effects of the transition on firm's profitability and identify the optimal transition investment ratio (α) for the firm in each case.

Immediate Decarbonization:

In the Immediate Decarbonization scenario, enterprises make substantial investments in low-carbon technologies immediately. This aggressive approach aims at achieving rapid decarbonization and substantial reductions in carbon emissions in the shortest possible time.

As a result, the enterprise's low-carbon production efficiency coefficient (k_t) starts at a very high level due to a substantial initial level of investment, reflecting major improvements in production efficiency of the firm. Over time, as the immediate benefits are realized, k_t decreases gradually. The production cost per unit (c_t) of the firm decreases quickly as economies of scale and technological efficiencies are realized from the new low-carbon technologies. The original productivity coefficient (β_t) increases initially due to enhanced production capabilities of the firm but stabilizes over time as the effects of initial investments are more fully integrated. The carbon price (B_t) remains at a very high level due to stricter regulations and market adjustments that favor low-carbon outputs.

Quick Decarbonization:

The Quick Decarbonization scenario involves rapid but slightly less aggressive investments compared to the Immediate scenario. Enterprises aim at achieving substantial decarbonization within a relatively short time frame but spread their investments over a few periods of time to balance costs and benefits. Consequently, the enterprise's low-carbon production efficiency coefficient (k_t) increases quickly but not as sharply as in the case of the Immediate scenario. The efficiency gains are substantial for the firm but spread over a slightly longer period of time. The production cost per unit (c_t) decreases rapidly but not as dramatically, reflecting more moderate cost reductions. The original productivity coefficient (β_t) shows a steady increase due to technological improvements and better resource allocation by the firm. The carbon price (B_t) keeps at a relatively high level, driven by increasing regulatory pressures and market responses.

Slow Decarbonization:

In the Slow Decarbonization scenario, enterprises adopt a gradual approach to transitioning to low-carbon technologies. This approach spreads investments over a longer period of time, allowing enterprises to manage costs and mitigate risks while steadily reducing carbon emissions. As such, the enterprise's low-carbon production efficiency coefficient (k_t) increases slowly, reflecting incremental improvements in production efficiency for the firm as investments are made gradually. The production cost per unit (c_t) decreases steadily but slowly, indicating progressive cost reductions over time. The original productivity coefficient (β_t) shows a gradual increase, correlating with incremental enhancements in productivity as new technologies are adopted by the firm over time. The carbon price (B_t) is set as a relatively low level, aligning with gradual regulatory changes and market adjustments.

No Decarbonization:

The No Decarbonization scenario assumes that enterprises do not make any major investments in low-carbon technologies. Instead, they continue with their current practices, resulting in minimal changes to carbon emissions and production efficiency. Consequently,

there is no need to find the optimal transitional investment ratio under this scenario, as the transitional investment ratio, α, should always be zero.

2.4.3 Numerical Study

By analyzing these different scenarios, we can observe how different levels of investment and urgency in transitioning to low-carbon technologies affect key variables of the framework over time. This analysis helps us understand the trade-offs between immediate costs and long-term benefits, guiding enterprises in making informed decisions about their decarbonization strategies. The goal is to determine the optimal value of α that maximizes the overall profit across multiple periods, ensuring both short-term (3-year observation period) profitability and long-term (6-year observation period) sustainability. We will not consider the scenario of 'No Decarbonization' in this part, as there is no need to determine the optimal transitional investment ratio α under this scenario.

Year	1	2	3	4	5	6
k (Enterprise Low-carbon Production Efficiency Coefficient)						
Immediate	5	4.5	4	3.5	3	2.5
Quick	1.5	5	4.5	4	3.5	3
Slow	2	3	4	5	4.5	4
c (Production Cost Per Unit)						
Immediate	1.6	1.7	1.8	2	2.2	2.4
Quick	2.4	1.6	1.7	1.8	2	2.2
Slow	2.2	1.9	1.6	1.7	1.8	2
β (Original Productivity Coefficient)						
Immediate	0.9	0.85	0.8	0.75	0.72	0.7
Quick	0.6	0.9	0.85	0.8	0.75	0.72
Slow	0.7	0.8	0.9	0.85	0.8	0.75
B (Carbon Price Per Unit)						
Immediate	4	4	4	4	4	4
Quick	3	3	3	3	3	3
Slow	2	2	2	2	2	2

Table 4: Results for Scenario Analysis

Table 4 presents various variables under different scenarios of low-carbon transition for enterprises, focusing on production efficiency, costs, productivity, and carbon pricing.

In the Immediate Transition scenario, enterprises rapidly adopt low-carbon technologies, leading to a substantial increase in firm's production efficiency initially. This efficiency gain diminishes over time due to the fast adaptation rate and potential initial over-investment by the firm, as reflected in the decreasing values of the enterprise's low-carbon production efficiency coefficient k. Production costs per unit rise initially due to high investments in

new technologies, reaching their peak in later years as the benefits of the new technologies become more apparent and grounded. The original productivity coefficient β sees a rapid decrease due to the initial disruption and learning curve of the firm associated with adopting new technologies, eventually stabilizing at a lower level over time. High carbon pricing (B) is a crucial factor in this scenario, as it works to incentivize the rapid adoption of low-carbon technologies to mitigate the associated costs.

In the Quick Transition scenario, enterprises adopt low-carbon technologies at a moderately fast pace. This approach aims at achieving a rapid improvement in production efficiency, though at a slightly slower rate than in the Immediate scenario. As a result, the initial efficiency gains are significant but not as drastic, allowing the enterprise to avoid potential issues related to over-investment. Given the initially low value of k (starting at 1.5), there is an urgent need to enhance production efficiency quickly. To address this, the enterprise makes a transition investment before the second year, resulting in a sharp increase in k to 5 by the second year. This value then gradually declines each subsequent year, reflecting the natural efficiency losses due to wear and tear. Production costs per unit begin at a relatively high level (2.4), creating a strong need for transition investment to reduce costs. With the Quick Decarbonization approach, c drops significantly to 1.6 in the second year. However, it then rises slightly in the following years, likely due to normal depreciation and the ongoing costs associated with maintaining the new technology. Similarly, the original productivity coefficient β starts at a lower level (0.6), emphasizing the necessity for improvement. Due to the transition investment, β reaches a peak of 0.9 in the second year, reflecting increased productivity. Over time, it gradually decreases, aligning with the adaptation phase and the natural reduction in productivity gains. Carbon pricing B is maintained at a high but stable level (3) in the Quick Decarbonization scenario. This provides a continuous incentive for adopting low-carbon technologies, without imposing excessive financial burdens on the firm.

In the Slow Transition scenario, enterprises adopt low-carbon technologies at a gradual pace, resulting in a steady increase in production efficiency without abrupt changes. The Enterprise Low-carbon Production Efficiency Coefficient (k) begins at a modest value of 2 and gradually rises to 5 by the fourth year before leveling off slightly, indicating a more controlled and gradual improvement. This slower adoption rate minimizes the impact of efficiency losses due to wear and tear over time. The Production Cost Per Unit (c) starts relatively high at 2.2 but decreases progressively as the benefits of low-carbon technology adoption become more apparent, reaching a stable level at 1.8 by the final year. Such a pattern reflects slower capital outlays and reduced urgency in operational adjustments, leading to consistent long-term savings. The Original Productivity Coefficient (β) also starts at a low value of 0.7 and improves steadily to a peak of 0.9 in the third year, maintaining

stability thereafter. This steady incline suggests a smoother, less disruptive learning curve associated with gradual integration of new technologies. Finally, the Carbon Price Per Unit (B) remains low at 2 throughout the period, applying gentle pressure on firms to adopt low-carbon technologies while allowing them to adjust at a manageable pace, balancing the transition costs with sustained incentives.

Based on the settings outlined above, the simulation results for both short-period and long-period scenarios are presented in Table 5, which highlight key insights into the optimal transitional investment ratios and corresponding maximum profits of the company for different decarbonization strategies over short and long periods.

	Short-Period		Long-Period	
	Optimal α	Max Profit	Optimal α	Max Profit
Immediate	0.5692	173.0291	0.6216	212.0262
Quick	0.541	158.3299	0.5678	235.1407
Slow	0.4768	131.7251	0.4606	261.1729

Table 5: Optimal Investment Ratio and Max Profit for Short-Period and Long-Period Scenarios

Firstly, the optimal transitional investment ratio (α) decreases progressively from Immediate to Quick to Slow scenarios, for both short-term and long-term periods. The Immediate scenario demands the highest level of investment in low-carbon technologies for the firm to meet rapid decarbonization goals, leading to the highest optimal α. In contrast, the Slow scenario, with its more gradual transition, requires a lower level of investment, resulting in the lowest level of α. The Quick scenario strikes a balance between the two objectives.

Secondly, the maximum profit patterns for the firm differ between the short-term and long-term periods. In the short term, the Immediate decarbonization scenario yields the highest profits for the firm, likely due to early efficiency gains and cost savings from rapid adoption of low-carbon technologies by the firm. However, in the long term, the Quick and Slow scenarios outperform the Immediate scenario in terms of profit. This shift suggests that the high initial costs of immediate decarbonization reduce long-term profitability of the firm, while more gradual transitions allow for sustainable financial planning and higher long-term profits for the firm.

Finally, in the long term, the optimal value of α increases slightly in the Immediate and Quick scenarios, suggesting that rapid decarbonization requires not only significant initial investments but also sustained allocation of resources to maintain low-carbon operations. This reliance on continuous investment highlights the financial burden of a swift transition, where the firm may face increased short-term financial and credit risks due to the need for a high proportion of resources dedicated to transition efforts. Conversely, in the Slow sce-

nario, the value of α decreases slightly, representing a more gradual and balanced investment approach that reduces immediate financial strain while still enabling steady efficiency gains. This comparison implies that firms may benefit from starting their transition investments earlier and at a slower pace, distributing costs more evenly over time. By preparing gradually, firms can reduce the risk of sudden financial pressures, enhancing their financial stability and long-term profitability, as seen in the Slow scenario's potential for higher sustained profits. This approach underscores the strategic advantage of proactively planning for a low-carbon transition to support sustainable development and resilience.

2.5 Optimal Transition Investment Ratio with Government Intervention

Based on the conclusions drawn from the previous subsections, it is evident that in certain scenarios, companies may exhibit a deficiency in transformational investments. In such instances, it becomes especially relevant for the government to undertake steps of market adjustments at both macro and micro levels, employing tools such as subsidies or tax penalties.

Subsidies can serve as a powerful incentive for companies by lowering the financial burden associated with making a transition to low-carbon technologies. These subsidies can take various forms, such as direct financial assistance, tax credits, or grants for research and development in green technologies. By reducing the initial costs, subsidies make low-carbon investments more attractive to companies, thereby accelerating the adoption of sustainable practices. For example, a company might receive a tax credit for every unit of renewable energy produced, which would directly offset its production costs and enhance profitability.

On the other hand, tax penalties act as a deterrent against environmentally harmful practices. By imposing higher taxes on carbon emissions or non-compliant activities, governments can create the risk of a financial disincentive for companies to continue with high-carbon operations. This approach compels businesses to internalize the environmental costs of their actions, thereby encouraging them to seek out more sustainable alternatives. For instance, a carbon tax that increases with the level of emissions will drive companies to innovate and invest in cleaner technologies to minimize their tax liabilities.

Governments have a vested interest in incentivizing companies to undertake low-carbon transitions for several important reasons. Firstly, fostering a transition to low-carbon practices aligns with broader environmental and climate goals, mitigating the adverse effects of climate change and reducing overall carbon emissions in the country. Secondly, by encouraging businesses to adopt sustainable practices, governments contribute to the development of a more resilient and environmentally conscious economy. Additionally, promoting low-carbon

transitions enhances a country's global competitiveness by positioning it as a leader in clean and sustainable technologies. This, in turn, attracts environmentally conscious investments, boosts innovation, and creates green jobs, fostering economic growth. Furthermore, by mitigating environmental risks and promoting sustainability, governments aim at improving public health and reduce the strain on healthcare systems in the country. Incentivizing low-carbon transitions therefore reflects a strategic approach to building a more sustainable and prosperous future, where economic development is harmonized with environmental stewardship.

2.5.1 Model Building

In the extended framework below, we categorize government regulatory tools into two groups: one from a macro-economic perspective and the other from a micro-economic perspective. The government acts as an 'invisible hand'. We assume that from a macro-economic perspective, the government subsidizes carbon prices that are too high in the market and taxes carbon prices that are too low in the market. On a micro-economic level, if a company surpasses a specified threshold for carbon emissions, the government levies taxes. Conversely, if a company's total emissions fall below the threshold, the government offers rewards and subsidies to companies, fostering increased enthusiasm for low-carbon transformation initiatives. To introduce the extension model of the the previous framework, additional variables and parameters are introduced to be described in Table 6.

Notation	Description
s_1	Subsidy Rate for High Carbon Price
s_2	Subsidy Rate for Low Carbon Emission
q_1	Tax Rate for Low Carbon Price
q_2	Tax Rate for High Carbon Emission
$pr_1 = Pr(\text{ Carbon Price}(B) \geqslant cp)$	Probability of Subsidy for High Carbon Price
$pr_2 = Pr(\text{ Carbon Emission} \leqslant ce)$	Probability of Subsidy for Low Carbon Emission

Table 6: Variable and Parameter Description for the Extended Framework

Based on these variables and parameters, the expected total profit of the company after government subsidy or tax can be expressed as:

$$
\begin{aligned}
\pi' &= \pi + s_1 \cdot (\text{ Total Unit Amount }) \cdot pr_1 - q_1 \cdot (\text{ Total Unit Amount }) \cdot (1 - pr_1) \\
&\quad + s_2 \cdot (\text{ Carbon Emission }) \cdot pr_2 - q_2 \cdot (\text{Carbon Emission }) \cdot (1 - pr_2) \\
&= \pi + s_1 \cdot \left\{ \left(\frac{2}{1 + e^{-\alpha k}} \right) \cdot [(1 - \alpha) \cdot A]^\beta \right\} \cdot pr_1 - q_1 \cdot \left\{ \left(\frac{2}{1 + e^{-\alpha k}} \right) \cdot [(1 - \alpha) \cdot A]^\beta \right\} \cdot (1 - pr_1) \\
&\quad + s_2 \cdot \left(2 - \frac{2}{1 + e^{-\alpha k}} \right) \cdot \left\{ \left(\frac{2}{1 + e^{-\alpha k}} \right) \cdot [(1 - \alpha) \cdot A]^\beta \right\} \cdot pr_2 \\
&\quad - q_2 \cdot \left(2 - \frac{2}{1 + e^{-\alpha k}} \right) \cdot \left\{ \left(\frac{2}{1 + e^{-\alpha k}} \right) \cdot [(1 - \alpha) \cdot A]^\beta \right\} \cdot (1 - pr_2)
\end{aligned}
$$

$$(2.8)$$

where, the total profit π, excluding government intervention, is calculated as previously shown in Equation 2.3.

2.5.2 Numerical Study

In this subsection, we expand our analysis to explore the impact of government intervention on the optimal transition investment ratio (α) and profitability of the firm, through a revised objective function that incorporates both subsidies and taxes linked to carbon pricing and emissions. The new objective function, π', integrates additional terms representing financial incentives and penalties for the firm based on carbon-related metrics.

Our revised framework considers the following variables and parameters: subsidy rates (s_1 and s_2) for high carbon prices and low carbon emissions, respectively; tax rates (q_1 and q_2) for low carbon prices and high carbon emissions, respectively; and the probabilities (pr_1 and pr_2) of these rates being applied based on carbon price and emission thresholds. These factors are critical for determining the cost-benefit landscape of environmental compliance and sustainable investment, as they directly influence the incentives and penalties faced by firms.

The baseline variables from our previous studies are maintained in this study for consistency, but now we add more variables and parameters to the framework. The baseline values for these new variables are shown in Table 7. Then we systematically vary each of the new variables and parameters individually to observe their effects on the optimal value of α and overall profitability for the firm. Graphical representations will be used to illustrate the relationship between these variables and the resulting economic outcomes, providing clear insights into the dynamics at play for the firm under different policy scenarios.

From Figure 5 to Figure 10, the left plot illustrates how changes in the key variable affect the optimal transition investment ratio, aiming to maximize profit under each scenario. The right plot shows the corresponding maximum profit achieved under the optimal transition investment as the key variable changes. We will explain each figure in detail below.

Notation	Description	Baseline Value
s_1	Subsidy Rate for High Carbon Price	0.8
s_2	Subsidy Rate for Low Carbon Emission	0.8
q_1	Tax Rate for Low Carbon Price	0.6
q_2	Tax Rate for High Carbon Emission	0.6
pr_1	Probability of Subsidy for High Carbon Price	0.5
pr_2	Probability of Subsidy for Low Carbon Emission	0.5

Table 7: New Baseline Values for Analysis

Impact of Probability of High Carbon Price Subsidy (pr_1) on Optimal Alpha and Profit (Figure 5)

As the probability of receiving a subsidy at higher carbon prices (pr_1) increases, the optimal investment ratio (α) for the firm decreases. This suggests that businesses, when expecting financial support through subsidies, feel less pressure to invest heavily in low-carbon technologies. The security provided by expected subsidies reduces the need for extensive investment by the firm in hedging against future regulatory changes or market conditions that favor lower emissions. This also highlights a strategic point for businesses: relying too heavily on subsidies might provide a short-term relief but could risk an insufficient preparation for a future with stricter environmental regulations.

Profit increases alongside higher subsidy probabilities, reinforcing the positive impact of government incentives on financial performance of the firm. For investors, this underscores the appeal of firms with strong expectations of a subsidy support, as subsidies directly enhance profitability of the firm. However, it's essential to remain cautious—companies that over-rely on subsidies may be less motivated to invest in long-term carbon reduction strategies, posing potential risks to the firm as market dynamics or regulations shift.

Impact of Probability of Low Carbon Emission Subsidy (pr_2) on Optimal Alpha and Profit (Figure 6)

As pr_2 rises, it reflects a higher tolerance from the government for carbon emissions, effectively lowering the threshold required for firms to qualify for subsidies. This shift reduces the incentive for companies to invest in low-carbon transitions, as they can now receive financial support with less stringent emissions standards. Consequently, the optimal value of α, which represents the proportion of resources allocated to low-carbon investments, declines. This trend shows that firms are less motivated to prioritize sustainable transitions when subsidies become more accessible without rigorous emission targets.

On the profitability side, a higher pr_2 initially appears to be advantageous. With reduced pressure to invest in transition efforts, firms can allocate fewer resources to low-carbon initiatives, which boosts short-term profits. However, this profit increase may be deceptive,
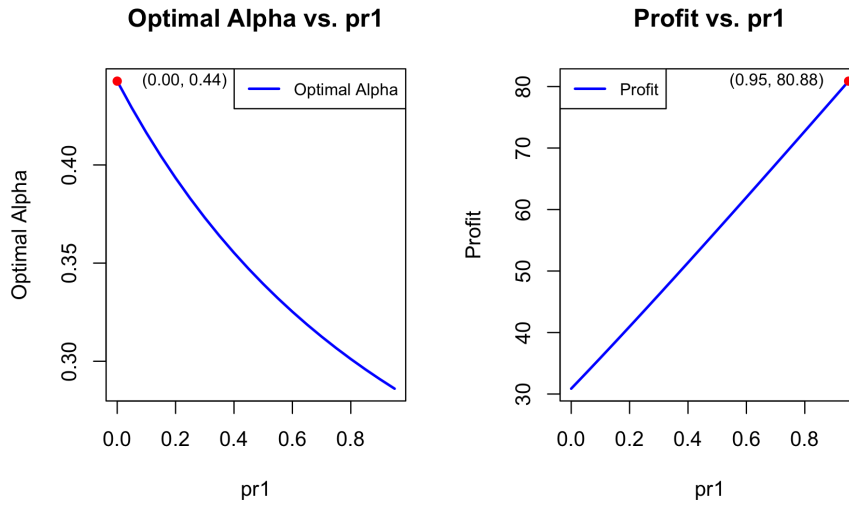
Figure 5: Optimal Level of Alpha and Profit Graph w.r.t. pr_1

as it comes at the expense of long-term resilience. Firms that minimize transition investments now could face significant financial risks if stricter carbon policies are introduced in the future. A sudden regulatory shift would leave them underprepared to adapt, potentially leading to substantial losses. This underscores the trade-off between short-term profit gains and the uncertain long-term stability that comes with underinvesting in sustainable practices.
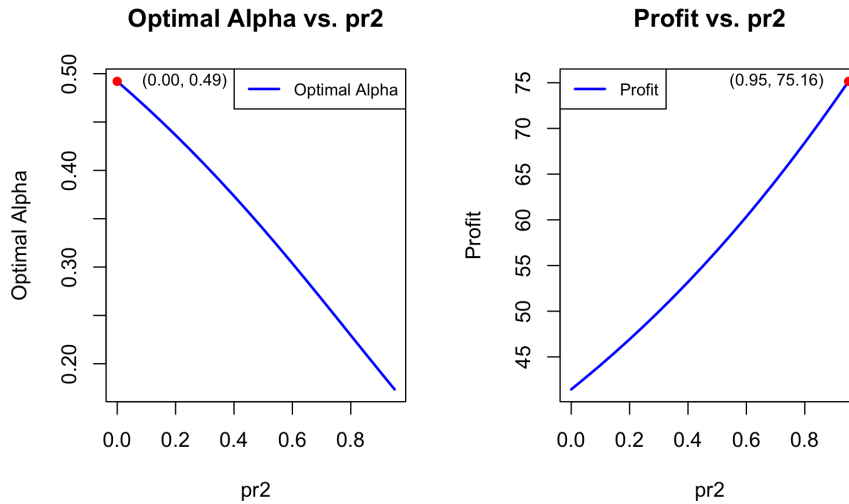
Figure 6: Optimal Level of Alpha and Profit Graph w.r.t. pr_2

Impact of Tax Rates for Low and High Carbon Emissions (q_1 and q_2) on Optimal Alpha and Profit (Figure 7 & Figure 8)

Higher tax rates on low carbon prices (q_1) or high carbon emissions (q_2) push the optimal

value of α higher, indicating that businesses are incentivized to adopt cleaner technologies more aggressively when facing heavier tax burdens. This reflects the practical use of taxes as a tool for driving environmental sustainability—businesses react to them by increasing investments in green technologies to mitigate the financial impact of taxes. However, businesses must be strategic at the same time: while aggressive adoption of low-carbon technologies can reduce future tax liabilities for the firm, over-investing without aligning with long-term sustainability goals could lead to suboptimal resource allocation.

On the flip side, profits decrease as taxes rise, which makes high-emission activities less financially attractive for the firm. This highlights the financial risks for companies slow to adopt cleaner practices, reinforcing the need for a more proactive sustainability planning. Investors should be mindful of firms exposed to significant carbon taxes, as their profitability may suffer without adequate mitigation strategies.
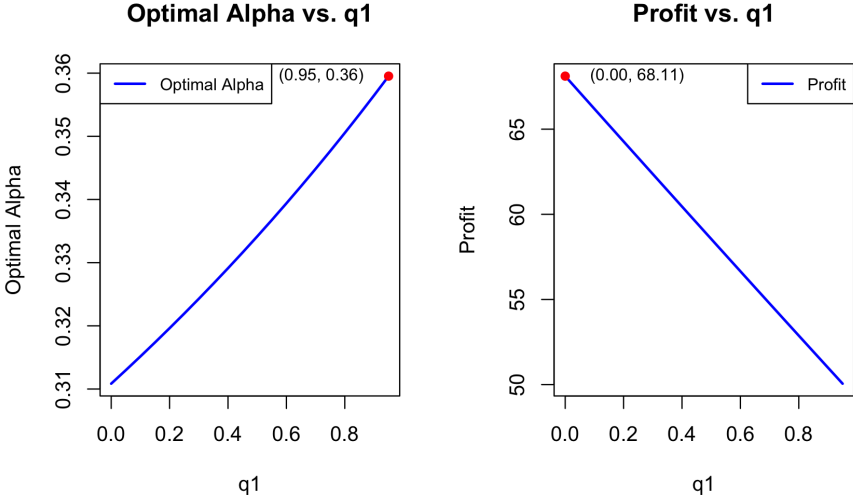

Figure 7: Optimal Level of Alpha and Profit Graph w.r.t. q_1

Impact of Subsidy Rates for High and Low Carbon Scenarios (s_1 and s_2) on Optimal Alpha and Profit (Figure 9 & Figure 10)

An increase in subsidy rates for high carbon price (s_1) or low carbon emission (s_2) scenarios results in a lower optimal value of α, showing that businesses feel less urgency to invest heavily in green technologies when financial incentives make it easier to comply with emission standards. While this may seem beneficial for companies in the short term, there is a risk that such subsidies could slow down the transition to greener technologies if businesses rely too heavily on them without making the necessary levels of investment in long-term sustainability.

Profit increases with higher subsidies, emphasizing the role of financial support in boost-
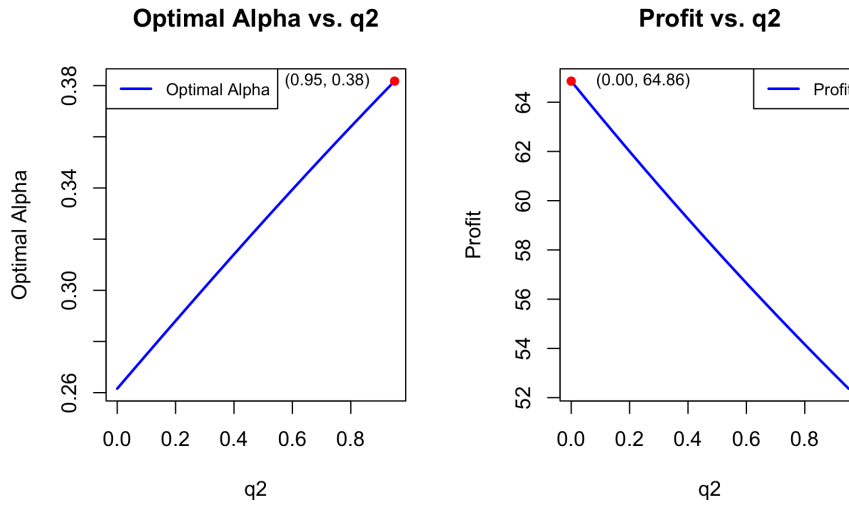
Figure 8: Optimal Level of Alpha and Profit Graph w.r.t. q_2

ing corporate earnings. From an investment perspective, firms with access to a substantial amount of subsidies for meeting environmental standards are likely to be more profitable in the short term, making them more appealing to investors. However, investors should also assess whether these companies are using the subsidy windfall to fund long-term sustainable transformations, as over-reliance on temporary fiscal incentives could pose challenges for the firm in the face of evolving market or regulatory conditions.
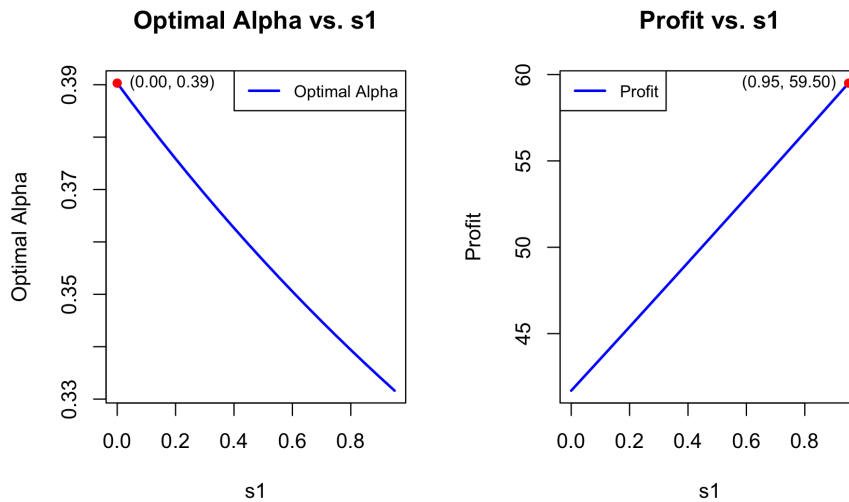

Figure 9: Optimal Level of Alpha and Profit Graph w.r.t. s_1

Policy Recommendations for Effective Low-Carbon Transitions

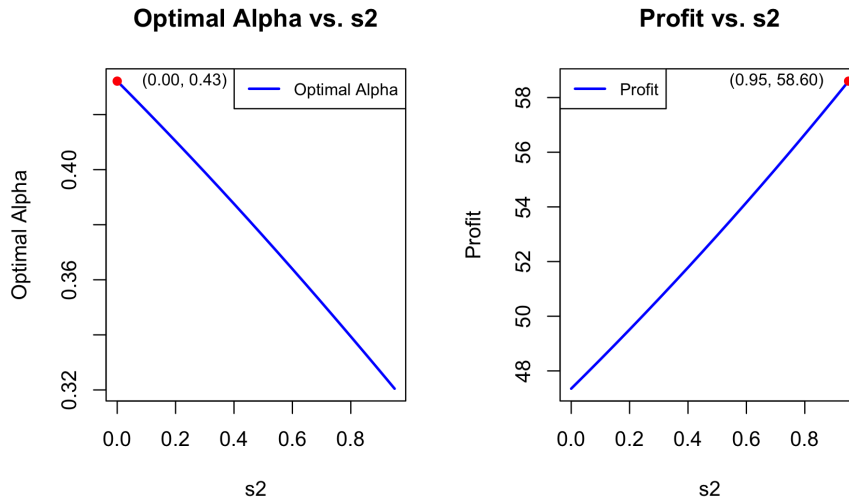Encouraging effective low-carbon transitions requires a sensitive balance between as-

Figure 10: Optimal Level of Alpha and Profit Graph w.r.t. s_2

sertive tax policies and a more targeted, limited subsidy approach. The above numerical analysis suggests several important and practical policy recommendations. While subsidies boost short-term profitability, they do not appear to incentivize long-term investment in low-carbon technologies adequately. This is evident from the decreasing trend in the optimal investment ratio (α) as subsidy probabilities increase. On the other hand, higher emissions taxes consistently drive higher values of α, indicating that tax policies play a more effective role in promoting robust investments in sustainable technologies.

- **Expanding on Tax Strategies:** A more structured and progressive carbon tax regime could enhance low-carbon transitions more effectively. By gradually increasing the cost of higher emissions, such a policy would not only penalize environmentally harmful practices but also provide businesses with the level of predictability they need in order to plan long-term investments in sustainability. This tax strategy could be further refined by introducing tax incentives for specific technologies that deliver substantial carbon reductions. For businesses, the clear financial penalties for high emissions and rewards for investing in sustainable solutions would create a strong motivation to prioritize clean technology adoption, ensuring a smoother and more predictable transition.

- **Reassessing Subsidy Schemes:** A more passive and targeted approach to subsidies is recommended. Direct financial incentives should be limited to sectors of the economy where low-carbon alternatives are not yet economically viable or where early-stage technologies need support to scale. This approach minimizes the risk of companies relying on subsidies for profitability without making a genuine progress toward sustainability. It also encourages firms to seek out real, long-term solutions rather than temporary financial relief. Companies

should anticipate stricter regulatory standards in the future and take a proactive approach to sustainability. Rather than depending on subsidies alone, businesses are advised to prioritize investments in scalable, low-carbon technologies that align with long-term industry trends. Building internal capabilities for sustainable practices and integrating environmental risk assessments into financial planning can help ensure resilience against future regulatory shifts. Additionally, companies should explore partnerships with other industry players or research institutions to advance low-carbon innovations, as these collaborations can reduce costs and accelerate progress toward sustainability goals.

In summary, integrating fiscal policies, such as carbon taxes and subsidies, with broader regulatory measures can amplify their effectiveness with respect to promoting long-term sustainability and reducing emissions. For instance, mandatory carbon emission disclosures and stricter compliance requirements would not only improve transparency but also make tax and subsidy regimes more impactful. Businesses would be incentivized to adopt greener practices both to avoid penalties and to benefit from tax reliefs. This would create a feedback loop where fiscal and regulatory measures reinforce each other, driving a greater amount of corporate investments in sustainability.

Additionally, corporate leaders should adopt a forward-thinking approach, moving beyond short-term financial benefits emanating from current subsidies and tax reliefs. Strategic investments in low-carbon technologies today will prepare businesses for future regulatory shifts, reducing the risk of compliance costs down the line. Companies should conduct detailed cost-benefit analyses that balance immediate economic advantages with future regulatory expectations. Proactively enhancing sustainability measures will not only align businesses with global environmental trends but also provide a competitive edge in an increasingly eco-conscious market. This approach places companies in a better position against stricter regulations in the future and boosts their appeal to environmentally aware consumers.

Finally, investors should closely monitor governmental shifts in environmental policies, as these will impact the profitability and strategic positioning of companies in their portfolios. There is a clear advantage in diversifying investments to include companies with strong environmental strategies or those investing heavily in green technologies. Firms that are better prepared for stringent environmental regulations are more likely to thrive, benefiting from enhanced market reputation and consumer loyalty. Additionally, investors have the potential to influence corporate behavior by advocating for stronger sustainability practices within the companies they support. Active stewardship not only aligns investments with broader environmental goals but also helps mitigate the risks associated with regulatory changes, securing long-term profitability while promoting global sustainability objectives.

3 Conclusions

This paper explores the dynamics of firm's strategic investment decisions that support the transition to a low-carbon economy, focusing on the interplay between government policies and corporate strategies. It reveals how corporations adjust their investment strategies based on anticipated returns and environmental impacts, with a cautious approach prevailing in the absence of government incentives. The analysis highlights that, while long-term sustainability goals are beneficial, they may impose significant short-term financial burdens on companies. When government intervention, through subsidies and taxes, is introduced, corporate behavior shifts dramatically. The findings in this paper show that assertive tax policies on carbon emissions effectively drive firm's investment in sustainable technologies, aligning corporate actions with environmental targets. However, while subsidies enhance short-term profitability of firms, they can lead to a greater reliance on government aid and do not necessarily promote sustained innovation in green technologies.

The study suggests a balanced policy approach—where taxes are used assertively to stimulate investment, and subsidies are applied selectively to avoid dependency. This would encourage corporations to take proactive steps toward sustainability, aligning with long-term environmental goals rather than relying solely on government incentives. For stakeholders, particularly investors, the research underscores the importance of identifying companies that are actively adapting to evolving fiscal and regulatory landscapes. These companies are better positioned to meet future regulatory demands and capitalize on the growing market emphasis on sustainability, offering better long-term returns.

Extending the analytical framework to a multi-period setting under different decarbonization scenarios further reveals how the optimal investment ratio (α) evolves over time. While aggressive early decarbonization yields the highest short-term profits for the firm, slower approaches offer better long-term profitability due to the lower upfront costs. The analysis also shows that sustainable investment in low-carbon technologies is beneficial in the long run, particularly in scenarios involving gradual transitions. In conclusion, this study provides practical insights for policymakers and business leaders on how to promote investments in low-carbon technologies. By implementing a balanced mix of taxes and targeted subsidies, governments can effectively encourage corporate sustainability efforts.

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