Carbon Neutrality

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Firms and climate change: a review of carbon risk in corporate finance

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Abstract

This paper provides an overview of financial economics-based research on carbon risk with an emphasis on corporate finance. In the corporate finance literature, carbon risk refers to the impact of society's transition to a low-carbon economy on firm value due to tightening regulations, changing consumer preferences, reputational damage, etc. We focus on the links between carbon risk and different firm performance factors, such as firm risk, cost of capital, financial performance, firm value, and corporate decisions. Although research on carbon risk is still emerging in the corporate finance field, the amount of literature on this topic has been increasing, especially in the last 2 years. We find that some results are robust, while others are mixed. This indicates that conflicting hypotheses still exist, leading to a need for more in-depth exploration.

Keywords: Carbon risk, Carbon emissions, Climate change, Corporate finance

1 Introduction

Firms' carbon performance has become increasingly important in recent years due to concerns about global warming linked to carbon dioxide emissions from human activities. The Intergovernmental Panel on Climate Change (IPCC) stated in "Climate Change 2021: The Physical Science Basis" that the increase in the average global temperature is unequivocally due to human influence.[1] To limit anthropogenic climate factors, in December 2015 at the COP 21 in France, representatives from more than 190 nations signed the Paris Agreement (PA) and committed to limiting global warming to "well below 2 °C" above pre-industrial levels. In practice, many jurisdictions have already introduced carbon pricing mechanisms to reduce carbon emissions,[2] such as carbon trading and carbon taxes. Specifically, 25 countries have implemented carbon taxes (e.g., Canada, the U.K., Germany, Finland, and Singapore), and 36 countries have adopted carbon emissions trading schemes (e.g., the E.U., the U.S., Korea, and China).

These policy efforts to curb carbon emissions raise questions of whether firms will be affected by carbon risk. Which types of firms are most vulnerable to such policies? Will the effects on firm performance be positive or negative? To answer these questions, this study reviews the corporate finance research focusing on carbon risk issues. Although it is closely related to our study and important, we do not review the extensive literature on climate change or climate risk. Moreover, to keep the review to a manageable length, we limit the scope of this paper to the corporate finance literature that relates to the questions we are addressing.

We begin our review by clarifying the definition and scopes of carbon emissions and carbon risk and assessing the current state of carbon information disclosure and data availability. We then review how firm risk may be related to carbon risk exposure, followed by an analysis of the literature on whether and how carbon risk influences firms' cost of capital. Moreover, we summarize the relationship between carbon risk and firm performance or firm value. We also review whether

[1] https://www.ipcc.ch/report/ar6/wg1/#SPM
[2] https://carbonpricingdashboard.worldbank.org/

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carbon risk has an impact on firm behaviour. Finally, we conclude with a discussion of unanswered questions and present potential areas for further research.

2 Definition, measurement, and data availability

2.1 Definition and scope

In the corporate finance literature, carbon risk usually refers to the impact of society's transition to a low-carbon economy on firm value due to extensive policy, legal, technology, market and reputation changes. Carbon risk is a transition risk. Firms face carbon risk because of their carbon-intensive production process under a low-carbon transition, not because they are exposed to a certain physical climate risk (rising sea levels, for instance). Some scholars offer definitions of carbon risk. For example, Hoffmann and Busch [1] consider carbon risk 'any corporate risk related to climate change or the use of fossil fuels'. Ehlers et al. [2] define carbon risk as 'the potential financial impact of tightening carbon emissions policies'.Trinks et al. [3] refer to carbon risk as regulatory and market risks incurred by high-emission firms during the transition from a high-carbon to a low-carbon production system. Nguyen and Phan [4] define carbon risk as a firm's financial vulnerability to the transition away from a fossil fuel-based to a lower-carbon economy. In the past, high emitters could externalize the cost of their carbon emissions and thus were not exposed to carbon risk. With an increasing number of carbon reduction initiatives being undertaken, however, firms are required to internalize the cost of carbon emissions, making carbon risk a core business consideration [5].

In practice, carbon emissions are used to identify whether firms' production process is carbon intensive. Carbon emissions generally come from fossil fuel consumption, agriculture, deforestation, production processes (e.g., cement manufacturing), and refrigerant gas usage. According to the GHG Protocol, carbon emissions are grouped into direct emissions and indirect emissions based on firms' operations and economic activities. Specifically, direct emissions (scope 1) are associated with the combustion of fossil fuels or the processing of chemicals and materials from sources owned or controlled by a firm. Indirect emissions refer to emissions from purchased electricity, heat, or steam (scope 2) as well as emissions from all other value chains, such as product use, purchased materials, outsourced activities, and waste disposal (scope 3).

2.2 Measurement and data availability

In reviewing previous studies, we find two types of approaches to measuring corporate carbon risk. One methodology is based on carbon emissions, including carbon emissions level (scope 1, scope 2, scope 3, or total) and carbon emission intensity (the ratio of carbon emissions to sales revenue). There is a general assumption, which is tested by many empirical studies, that the higher the level of emissions is, the higher the risk. It is thus obvious to raise the question of whether carbon emissions (performance) are a good proxy for carbon risk. According to the Taskforce on Climate-related Financial Disclosure (TCFD),[3] transitioning to a low-carbon economy entails changes in policy, legislation, technology and markets, and these changes may have financial impacts on high emitters. Therefore, we consider carbon emissions (performance) as a good proxy for carbon risk only if firms are located in a jurisdiction with more stringent climate regulations. Another group of studies uses good corporate carbon performance as a proxy for low carbon risk, including emission reduction and carbon efficiency. Specifically, emission reduction is the change in carbon emissions between two or more years. Carbon efficiency is the extent to which a firm's output level is produced with lower carbon emissions relative to industry rivals [6]. Moreover, since carbon disclosure is the first step in addressing climate-related issues, it is worth identifying whether carbon disclosure is a good measure of risk. As mentioned above, carbon risk refers to the impact of society's transition to a low-carbon economy on firm value. In contrast, carbon disclosure refers to the practice of firms reporting their carbon emissions, which can reduce information asymmetry but cannot reduce carbon risk. Therefore, carbon risk and carbon disclosure are two different concepts, as an honest firm could be either high-risk or low-risk.

One challenge in measuring carbon risk is obtaining firm-level carbon emissions information, which is not usually disclosed in firms' financial statements and is not mandated by most financial regulators [7]. Additionally, there are still no uniform disclosure standards or accounting methods for carbon emissions. Scholars and investors usually obtain information from data providers that follow the Greenhouse Gas Protocol and provide firm-level carbon emissions data. For example, CDP (formerly known as the Carbon Disclosure Project), established by institutional investors who were concerned about transition climate risks, invites large global firms to voluntarily disclose carbon information every year. Firms need to fill out a questionnaire that captures information on firms' direct and indirect carbon emissions. Other data providers, such as Trucost, MSCI, Thomson Reuters, Sustainalytics, Bloomberg, and ISS, rely on CDP data and supplement it with other data sources to finally form corporate-level carbon emissions data. These data provide a basis for follow-up empirical research.

[3] https://www.fsb-tcfd.org/publications/

3 Carbon and firm risk

Empirical work that explores whether firms' carbon risk influences risk-related metrics in the equity market is limited. Trinks et al. [6] estimate carbon efficiency that reflects firms' carbon emission levels relative to their most efficient peers with comparable production structures. They find that carbon-efficient firms have significantly lower systemic risk but not lower total risk. Xue et al. [8] find that U.K. firms with good environmental management performance, such as emission reduction performance monitoring, can effectively reduce their idiosyncratic and total risks. However, the authors do not find a significant impact of carbon intensity on firm risks.

Several studies use default risk as a measure of firm risk and confirm a positive correlation between carbon risk and default probability. Specifically, Capasso et al. [9] investigate the influence of carbon risk exposure on corporate default risk with a sample of Bloomberg Barclays Aggregate Corporate Index constituents from 2007 to 2017. They find that high carbon emissions and high carbon intensity of a firm can lead to increased default risk, especially after the adoption of the Paris Agreement. In related work, Kabir et al. [10] analyse the relationship between carbon emissions and default risk with a broader and more representative sample of 2785 firms worldwide from 2004 to 2018. They also show a significant positive impact of carbon emissions on firms' default risk, indicating that firms with greater carbon risk exposure are more likely to default on their debts. The impact is stronger for firms in carbon-intensive industries and highly environmentally conscious economies. Moreover, announcing environmental initiatives and setting emission targets can diminish the effect of carbon risk on corporate default risk, while involvement in environmental scandals can aggravate the impact. From another perspective, Duong et al. [11] use 13 indicators to evaluate firms' carbon risk management score and find a significant negative correlation between the score and credit default swap spread, indicating that investors believe that good carbon risk management is effective in reducing the probability of default. Interestingly, firms' default probability can also positively affect their emission levels, as firms with financial constraints and high default probabilities are less enthusiastic about keeping up with national environmental strategies [12].

In addition to suggesting associations or causal relations, many of these studies help explain why firms' carbon risk positively relates to their default risk (e.g., Kabir et al. [10]). First, in the transition to a low-carbon economy, new regulations are enacted and enforced. Firms with higher carbon risks are more likely to be subject to substantial regulatory pressure, resulting in increased abatement and compliance costs. Second, high carbon emitters may suffer from reputational risk due to the increased environmental consciousness of their stakeholders, leading to further loss of revenue. Third, investors and lenders charge a carbon risk premium to high emitters as compensation, thus increasing the funding costs of emitters. Hence, reduced revenues and increased costs amplify firms' default probability.

4 Carbon risk and cost of capital

When analysing the impact of carbon risk on the cost of capital, researchers generally consider two perspectives: the cost of equity and the cost of debt [13].

4.1 Carbon risk and cost of equity capital

One group of studies examine the differences in stock returns between firms with high and low carbon emissions. The predominant view is that investors require returns proportional to the predicted level of risk. Since the low-carbon transition of the whole economy creates increasing regulatory and market risks for high-emitting firms, financial investors demand compensation for such risks and thus raise the cost of equity capital for high carbon emitters [3]. Some empirical studies support this view. For example, Oestreich and Tsiakas [14] observe a carbon premium on the German stock market, with firms that received free carbon allowances outperforming other firms. Bolton and Kacperczyk [15] find that U.S. firms with higher carbon emissions (and changes in emissions) have higher stock returns, and they suggest that the carbon premium cannot be explained by differences in unexpected profitability or other well-known risk factors.

However, the carbon premium is not always proven. Some studies find a carbon alpha. For example, In et al. [16] construct a carbon efficient-minus-inefficient portfolio based on firm-level carbon emission intensity. They confirm that firms with low carbon intensity outperform high emitters since 2010. Bernardini et al. [17] focus on European electric utilities and find that a portfolio that is long in firms with low carbon emission intensity and short in those with high carbon emission intensity generates positive risk-adjusted returns (alpha) from 2012 to 2016. Moreover, Ggrgen et al. [18] argue that there is no carbon risk premium, although carbon risk can explain systematic variation in returns. There are two possible reasons why investors do not price carbon risk. First, they do not know how to interpret or evaluate information related to carbon risk. Second, they see carbon information as immaterial and do not believe that carbon risk will affect firms' reputation or competitive advantage [19].

Another group of studies directly analyses the correlation between carbon risk and the cost of equity capital. Trinks et al. [3] show a significant positive impact of

firms' carbon intensity on their cost of equity capital. They find that the impact is more pronounced where carbon risk is a prominent issue, such as in high-emitting sectors and firms under carbon pricing regulations. Bui et al. [20] also indicate that carbon intensity is positively associated with the cost of equity capital and that the correlation can be mitigated through extensive carbon disclosure. The authors explain that the reason is that disclosure provides investors with more information and reduces their estimates of high emitters' risk, thus cutting the required premium. This argument is supported by Albarrak et al. [21], who find that disseminating carbon information through Twitter can significantly decrease firms' cost of equity. Similarly, Kim et al. [22] find a significant positive relationship between carbon intensity and the cost of equity capital for Korean firms. Unlike Bui et al. [20], they believe the effects are no different between firms that voluntarily disclose their sustainability reports and those that do not.

In summary, researchers in this field use different methods and metrics to examine whether carbon risk is fully integrated by investors. Although most studies confirm that carbon risk significantly increases the cost of equity, there are inconsistencies in research conclusions. In Table 1, we present the results of each article.

4.2 Carbon risk and cost of debt

Concerning the links between carbon risk and the cost of debt, most of the research is based on agency theory, according to which agency problems arise when the expectations of lenders and borrowers for carbon-intensive projects are not aligned. Specifically, if a carbon-intensive project is successful, shareholders will benefit from most of the profits, while lenders will bear most of the costs if it is not successful. Moreover, from the literature we review in the previous section, we indeed find that an increase in carbon risk can increase firms' default risk and credit risk [10, 23]. Therefore, firms with high carbon risk will be charged higher interests as lenders need to compensate for the increased cash flow uncertainty, default risk, and reputational risk [24–26].

In empirical analyses, although the existing literature confirms the positive correlation between carbon risk and cost of debt, discrepancies exist in the findings to some extent. Delis et al. [27] examine the syndicated loan market and compare the loan rate between fossil fuel and non-fossil fuel firms with a global sample. They show that only after the adoption of the Paris Agreement have banks started to price the stranded fossil fuel reserves risk, leading to an increase in the cost of credit for fossil fuel firms. Relatedly, Ehlers et al. [2] study whether banks price carbon risk across all sectors to reflect a broader phenomenon beyond a specific sector. They also find a significant carbon premium in the syndicated loan market after the adoption of the Paris Agreement, although it is relatively low, at approximately 3–4 basis points. Interestingly, they confirm that the premium exists only for direct carbon emissions (scope 1), suggesting that banks are less concerned about firms' whole carbon footprint than their direct emissions. In summary, both studies show that banks did not start pricing carbon risk until the Paris Agreement. Relative to them, Kleimeier and Viehs [28] find that carbon emissions, arising either from scope 1 or scope 2, had a significant positive effect on loan spreads before the adoption of the Paris Agreement. They also find that for opaque firms, voluntary disclosure can significantly lower bank loan spreads. However, for transparent firms,

Table 1 Carbon risk and cost of equity

Carbon risk	Cost of equity	Sign	Sample	Time period	Citation
carbon emission allowances	stock returns	+	German	2003–2012	Oestreich and Tsiakas [14]
carbon emissions and changes in emissions	stock returns	+	U.S.	2005–2017	Bolton and Kacperczyk [15]
carbon intensity	stock returns	–	U.S.	2005–2015	In et al. [16]
carbon intensity	stock returns	–	E.U.	2008–2016	Bernardini et al. [17]
performance in carbon and transition-related issues	stock returns	/	Global	2010–2017	Ggrgen et al. [18]
carbon intensity	cost of equity based on CAPM	+	Global	2008–2016	Trinks et al. [3]
carbon intensity	cost of equity based on Ohlson and Juettner-Nauroth's (2005) model and Eason's (2004) model	+	Korean	2007–2011	Kim et al. [22]
carbon intensity	cost of equity based on Easton's (2004) model	+	Global	2010–2015	Bui et al. [20]

voluntary disclosure has no impact. This result is consistent with the findings that reduced information asymmetries can lead to a lower cost of capital (e.g., [29]). The reasons for the differences in conclusions may be the differences between sample firms. Although both Ehlers et al. [2] and Kleimeier and Viehs [28] use firm-level carbon emissions as a proxy of carbon risk, Kleimeier and Viehs [28] cover firms that respond to CDP, and Ehlers et al. [2] cover sample firms in the Trucost database, which includes not only firms that disclose their carbon emissions but also firms whose emissions are estimated through an input-output model. In addition, the authors use different methodologies to calculate firms' emissions levels. Kleimeier and Viehs [28] use industry- and firm-size-adjusted carbon emissions, and Ehlers et al. [2] measure carbon risk as annual carbon emissions over annual revenues. The differences in their results may also be driven by different sample periods. Specifically, Ehlers et al. [2] use the years 2006 to 2015 to denote the pre-Paris Agreement period, and Kleimeier and Viehs [28] cover the years 2007 to 2013. Quiet differently, Delis et al. [27] classify high- and low-risk firms based on whether they have fossil fuel reserves.

Another group of studies is based on specific countries. Chen and Silva Gao [24] focus on the U.S. bond market and find a significant positive correlation between the emissions rate and yield-to-maturity spreads for the electric utilities sector. More recently, Jung et al. [25] confirm a significant and positive relationship between historical carbon intensity (measured as scope 1 emissions divided by sales revenue) and cost of debt for Australian firms that fail to respond to the CDP between 2009 and 2013. Interestingly, the penalty of the increased costs can be negated if firms demonstrate carbon risk awareness. In addition, using a sample of Canadian firms between 2012 and 2015, Maaloul [30] finds that both total carbon emissions and emissions intensity can increase the cost of debt. Kumar and Firoz [31] investigate Indian firms during 2011 to 2014 and find that firms with higher direct carbon emissions levels have a higher cost of debt. However, instead of finding a positive link between carbon risk and cost of debt, Zhou et al. [26] come to a different conclusion. They show that the relationship between carbon risk and cost of debt is U-shaped for Chinese private firms in high-carbon industries. The difference in the results may be due to the difference in carbon risk estimation. Zhou et al. [26] define carbon risk as an ordinal variable based on the penalties that firms incur for carbon emissions, while other studies in this field prefer to define carbon risk using carbon emissions or carbon intensity.

In summary, authors in this area have employed different measures of carbon risk and cost of debt to analyse the relations between the two concepts and have come to roughly the same conclusion: that carbon risk increases firms' cost of debt. In Table 2, we outline how risk and cost are measured in each article along with the direction of the estimated relationship, sample selection, time period, and article citation.

5 Carbon risk, financial performance, and firm value

This section reviews the literature on the effect of carbon risk on firms' financial performance and value. Financial performance and value are usually measured in two ways: accounting-based performance (e.g., ROA, ROE) and market-based performance (e.g., stock returns, market value, Tobin's q). Since we discussed the relationship between carbon emissions and stock returns in Section 4.1, we will not do so again in this section.

In traditional corporate finance theory, firms' only goal is to maximize shareholder value. Activities to reduce environmental damage incur additional costs and put firms at a competitive disadvantage [32]. However, as proven by related literature, some economic mechanisms can drive a positive correlation between carbon performance and firm value [33]. First, according to the Porter hypothesis, although environmental regulation may involve additional costs, it can also provide an impetus for firms' R&D and encourage firms to use new technologies to increase their production and profits [34]. Second, firms' involvement in carbon reduction activities can enhance their reputation, give them a competitive advantage and ultimately lead to a win-win situation for both carbon and financial performance. Furthermore, investors may give higher valuations to firms with better carbon performance due to their environmental preferences [35].

In empirical analyses, most studies have confirmed a negative effect of carbon risk on firm performance and value. Busch and Lewandowski [33] conducted a meta-analysis of 32 studies between 2010 and 2016 and suggest that carbon emissions are negatively correlated with firms' financial performance. Nguyen [36] finds that Australian polluters (firms in carbon-intensive industries) have a higher probability of negative net income, a lower Tobin's q, and a lower ROE than non-polluters. With 362 Japanese firms from 2003 to 2010, Lee et al. [37] find that carbon emissions significantly decrease firms' Tobin's q and ROA. From different perspectives but reaching a consistent conclusion, Trinks et al. [6] find superior short-term profitability (ROA) in carbon-efficient firms based on a global sample of 1572 firms from 2009 to 2017. Busch and Hoffmann [38] confirm that firms with superior corporate environmental performance (lower carbon intensity) have significantly higher Tobin's q. Taking Chinese manufacturing

Table 2 Carbon risk and cost of debt

Carbon risk	Cost of debt	Sign	Sample	Time period	Citation
carbon intensity (scope 1 emissions relative to revenue)	loan margins	+	global	after PA (2015)	Ehlers et al. [2]
fossil fuel firms	loan rate	+	global	after PA (2015)	Delis et al. [27]
industry- and firm-size-adjusted carbon emissions (scope 1 and scope 2)	loan spread	+	global	2007–2013	Kleimeier and Viehs [28]
emissions rate	yield-to-maturity spreads	+	U.S.	2002, 2003, 2006, 2007, 2008	Chen and Silva Gao [24]
carbon intensity (scope 1 emissions relative to sales revenue)	interest expense divided by the two-year average interest-bearing debt	+	Australia	2009–2013	Jung et al. [25]
total carbon emissions / carbon intensity	weighted average cost of debt for the security	+	Canada	2012–2015	Maaloul [30]
carbon emissions (scope 1)	total interest divided by total long-term debt	+	India	2011–2014	Kumar and Firoz [31]
an ordinal variable based on the punishment due to carbon emission	interest expense divided by average interest-bearing debt	U	China	2011–2015	Zhou et al. [26]

companies as research subjects, Yan et al. [34] also find that good corporate carbon performance contributes to higher Tobin's q. In addition, they find that the effect is more prominent for firms that disclose carbon information.

Another group of studies confirms the negative correlation between carbon risk and market value. Griffin et al. [39] suggest that carbon emissions impose a market-implied equity discount of $79 per ton for the median S&P 500 firm, which is approximately 0.5% of market capitalization. Matsumura et al. [40] argue that capital markets price carbon risk and penalize firms for their carbon emissions, with an average reduction of $212,000 in firm value for each additional thousand metric tonnes of carbon emissions. Clarkson et al. [5] suggest a significant negative correlation between carbon emissions and market value. Moreover, they point out that carbon emissions can affect firm valuation only for firms whose emissions exceed their carbon allowance, and the negative effect can be mitigated if firms have lower carbon intensity than their industry rivals. Choi and Luo [41] analyse the 500 largest firms in the FTSE Global Equity Index Series between 2008 and 2015 and find that firms' carbon emissions are significantly and negatively correlated with their market value. They further show that the negative effect of carbon emissions is more pronounced for firms in countries with national carbon trading schemes and strict environmental regulations. Saka and Oshika [42] study the Japanese market and reach a similar conclusion: that carbon emissions have a significant negative correlation with the market value of equity.

However, other literature suggests that the relationship between carbon performance and financial performance is non-linear. For example, Misani and Pogutz [43] suggest an inverted U-shaped relationship, finding that firms have the highest Tobin's q when their carbon performance (negative industry-adjusted carbon intensity) is intermediate. In addition, Tatsuo [44], Trumpp and Guenther [45], and Lewandowski [46] suggest a curvilinear relationship between carbon emissions (carbon performance) and financial performance.

In short, scholars have not yet reached an agreement on the relationship between carbon risk and corporate performance (value). Most, but not all, studies suggest a negative correlation between firms' carbon risk and financial performance or firm value. However, even among studies that reach similar overall conclusions, some are inconsistent in their detailed results. For example, Busch and Hoffmann [38] find that firms' carbon intensity has a significant negative relationship with their Tobin's q but has no significant correlation with their ROA or ROE. In contrast, Lee et al. [37] find that carbon emissions significantly decrease both Tobin's q and ROA. In general, the reasons for the differences in findings may be the differences in methodologies, such as whether and how to solve reverse causality and other sources of endogeneity. Another issue that needs to be investigated is whether differences in findings are due to differences in measurement choices. As stated by Busch and Lewandowski [33], carbon risk based on relative emissions can significantly influence firms' financial performance, whereas that measured by absolute emissions is not related to financial performance. Moreover, carbon performance appears to have a stronger connection with financial performance based on market measures than based on accounting measures. Table 3 details the measurement indicators of carbon risk and firm performance (value) in each article and indicates the correlations between them.

6 Carbon risk and corporate decisions

Given that capital markets have taken carbon risk into account, firms are likely to respond by manipulating

Table 3 Carbon risk, financial performance and firm value

Panel A: Negative effects of carbon risk on firm performance/value				
Carbon indicator	**Firm performance/value**	**Sample**	**Time period**	**Citation**
Whether in carbon-intensive industries	probability of negative net income / Tobin's q / ROE	Australia	2000–2014	Nguyen [36]
carbon intensity (carbon emissions scaled by value of assets)	Tobin's q / ROA	Japan	2003–2010	Lee et al. [37]
- carbon efficiency (carbon emissions relative to those of best-practice peers)	ROA	Global	2009–2017	Trinks et al. [6]
- corporate environmental performance (negative carbon intensity)	Tobin's q	Global	2006	Busch and Hoffmann [38]
- carbon performance (inverse of carbon emissions per unit of revenue)	Tobin's q	China	2009–2017	Yan et al. [34]
carbon emissions (scope 1 and scope 2)	value of common equity per share	U.S.	2006–2012	Griffin et al. [39]
carbon emissions (scope 1, scope 2, and scope 3)	market value of common equity	U.S.	2006–2008	Matsumura et al. [40]
carbon emissions (scope 1, scope 2, and scope 3)	market value of common equity	E.U.	2006–2009	Clarkson et al. [5]
carbon emissions (scope 1, scope 2)	market value of common equity	Global	2008–2015	Choi and Luo [41]
carbon intensity (carbon emissions relative to sales revenue)	market value of equity	Japan	2006–2008	Saka and Oshika [42]
Panel B: Non-linear effects of carbon risk on firm performance/value				
Carbon indicator	**Firm performance/value**	**Sample**	**Time period**	**Citation**
carbon intensity (carbon emissions relative to sales revenue)	ROA / ROE / ROS / ROIC / Tobin's q	Global	2003–2015	Lewandowski [46]
- carbon performance (negative industry-adjusted carbon intensity)	Tobin's q	Global	2007–2013	Misani and Pogutz [43]
- carbon performance (negative carbon intensity)	ROA	Global	2008–2012	Trumpp and Guenther [45]
- carbon performance (inverse of carbon emissions per sales revenue)	ROA	Japan	2006	Tatsuo [44]

Note: "-" represents carbon performance, which is the opposite of carbon risk

certain internal decisions. Recently, some scholars have investigated whether carbon risk exposure shapes firms' financial reporting decisions. Amin et al. [47] investigate whether firms' carbon risk exposure affects managers' earnings management decisions. They find a significant positive relationship between carbon emissions and real earnings management (REM), indicating that managers choose to report strong financial performance to offset the negative impact of high carbon emissions. The authors further find that corporate governance, regional environmental regulations, and institutional investors' investment orientation can influence the relationship. Moreover, Lemma et al. [48] confirm that South African firms with higher carbon risk exposure (carbon intensity) tend to engage in earnings management activities, thus reducing financial reporting quality. Supported by agency theory, Velte [49] finds that carbon performance reduces accrual-based earnings management (ACC) but increases REM. The author argues that managers use carbon strategy as a device to mask earnings behaviour and tend to adopt a hidden earnings management policy by shifting from ACC to more opaque REM.

Another group of studies shows that carbon risk can also affect firms' financial choices. Ngwakwe [50] find that firms prefer to pay higher dividends if they participate in carbon emission reduction plans, indicating that there is a significant positive relationship between firms' carbon emission reduction and their dividends. Similarly, Balachandran and Nguyen [51] investigate the effect of carbon risk on dividend policy for Australian listed firms. The empirical results confirm that firms in high-emitting sectors are less likely to pay dividends and have lower dividend pay-out ratios than low emitters after the ratification of the Kyoto Protocol. They attribute the results to the fact that the higher the carbon risk is, the higher the uncertainty of future returns and, therefore,

the lower the (probability of) dividends. In addition, with the unique tax setting that operates contemporaneously under both imputation and traditional tax systems in Australia, they examine the heterogeneity of the carbon risk effect between the two different tax environments. They find that the significance of the imputation tax environment lies only in the influence of carbon risk on the dividend payout ratio rather than the payout decision.

Taking Australia's ratification of the Kyoto Protocol, again, as an exogenous event, Nguyen and Phan [4] investigate the effect of carbon risk on corporate capital structure. They find that high carbon emitters significantly decreased both book and market leverage after the Kyoto Protocol, especially for financially constrained firms, suggesting that carbon risk is an essential determinant of corporate capital structure. In addition, Bose et al. [52] find that carbon emissions can influence firms' acquisition decisions, with high carbon emitters preferring to acquire foreign firms rather than domestic firms to outsource their carbon risk. Moreover, carbon emissions can influence acquirers' choice only if the targets are in countries with low GDP or weak environmental, regulatory, or governance standards.

7 Future research

The overall literature review finds that the current research on firm and carbon risk is insufficient and that further research in this field is needed. In this section, we discuss the remaining questions in the current research.

The first promising direction of research is the objectivity of carbon information disclosure. Carbon emission data are the basis for follow-up research. However, as firms have been voluntarily disclosing their carbon emission information so far, there is no objective and unified disclosure standard; this significantly reduces the consistency and comparability of data. Therefore, future research could be dedicated to developing carbon information disclosure standards and integrating carbon information with finance, accounting, and management fields.

Second, some of the disparate results across the carbon risk literature seem to be related to differences in how carbon risk is measured. For example, some studies define carbon risk as carbon emissions, while others use carbon intensity as a proxy of carbon risk. Similarly, with regard to emissions data, some studies focus on direct carbon emissions, while others use total emissions, including both direct and indirect carbon emissions. Whether differences in the measurement of carbon risk drive the empirical results remains an open question. It is thus obvious to raise the question of which proxy for carbon risk is appropriate. As stated by TCFD, high emitters are exposed to carbon risk as a result of changes in policy, legislation, technology, and markets during the transition to a low-carbon economy. Therefore, there is a need for more in-depth engagement on what carbon risk means and how to choose its proper proxy. For example, most studies directly use firms' carbon emissions as a proxy of carbon risk without considering whether climate change is valued by society. If a high-carbon company is located in a jurisdiction with low climate regulation and therefore does not incur carbon risk, high emissions will be a poor proxy for carbon risk.

Third, while most studies have demonstrated a negative correlation between carbon risk and the cost of equity capital, there is still no consistent conclusion for the carbon premium. Some scholars have even denied the existence of a carbon premium [18]. Thus, reconciling inconsistent findings remains an essential issue to address in future work. For example, there is a need for more evidence on the extent to which different regulatory stringencies in different periods and regions drive the disparate results.

Fourth, with regard to the links between carbon risk and cost of debt, most studies are based on the syndicated loan market (e.g., loan rate) or financial statement information (e.g., interest expense divided by average interest-bearing debt), but only a few studies focus on the bond market. This provides an opportunity for future research on carbon pricing in bond issues.

Fifth, scholars have not yet reached a consistent conclusion regarding the role of carbon risk in firm performance and value. Evidence from different samples proves negative or no linear correlations between them. Although some studies have proven that the differences in these results are due to different measurement indicators, more in-depth exploration is required.

Finally, researchers still need to face the challenge of establishing causal relationships when studying the role of carbon risk in corporate finance. More methodologies are required to address this issue.

8 Conclusion

In this article, we aim to provide a current comprehensive overview of the links between carbon risk and different types of firm performance, such as firm risk, cost of capital (including equity and debt), financial performance, firm value, and corporate decisions. Through the literature review, we find that although the relevant literature has been increasing in the last 2 years and has been gradually moving towards various topics, these fields are still emerging in academic research. Moreover, we have highlighted that research results on some topics are stable and conclusive, but the results on other topics remain debated. For example, while a growing body of

evidence suggests that carbon risk can reduce firm value, this suggestion remains controversial in the literature. Therefore, researchers can further explore these differences to better understand the economic drivers of the results.

The goals of this article are essentially twofold. First, we hope to inform firm managers, policymakers, and investors about the impact of carbon emissions and carbon risk on individual firms, prompting them to pay more attention to carbon risk and carbon information disclosure. Second, we hope to provide readers with a more comprehensive understanding of carbon risk in corporate finance, motivating more research into this important and exciting topic.

Abbreviations

ACC: Accruals-based Earnings Management; CDP: Carbon Disclosure Project; IPCC: Intergovernmental Panel on Climate Change; MVA: Market Value Adjustment; PA: Paris Agreement; REM: Real Earnings Management; ROA: Return on Assets; ROE: Return on Equity; ROIC: Return on Invested Capital; ROS: Return on Sales; TCFD: Taskforce on Climate-related Financial Disclosure

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Authors' contributions

YW conceived of the study, participated in its design and coordination, helped draft the manuscript and revised the work. ZW participated in the study design, performed the literature search, and drafted the manuscript. GZ performed the literature search and drafted the manuscript. All authors read and approved the final manuscript.

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Declarations

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Competing interests

The authors declare that they have no competing interests.

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