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The market value of decomposed carbon emissions

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Abstract

We introduce the decomposition of carbon emissions into an expected and an unexpected component and analyze the association between these components and firm value. The expected component captures a firm's average carbon emissions inherent to its business model and operating environment. The unexpected component, meaning the firm-specific deviation from expected carbon emissions, reflects the management's effort and ability to implement carbon management and actively influence carbon emissions. For a sample of US firms operating in carbon-intensive industries, we estimate the expected component using a regression of carbon emissions on firm characteristics and industry. The residual of this regression represents the unexpected component. The results reveal that, on average, investors attach value to both components. While investors consider the expected component to be relevant regardless of assurance, they consider the unexpected component to be more relevant in the presence of assurance. The assurance alleviates credibility concerns about the information content of the unexpected component. Additionally, we confirm the nomological validity of our measure of the unexpected component, as it is negatively related to indicators of better carbon management systems.

KEYWORDS
carbon emissions, decomposition, firm value, value relevance

JEL CLASSIFICATION
C23, G32, M41

1 | INTRODUCTION

Climate change has emerged as a focal challenge for society as scientists warn about serious consequences (e.g., Intergovernmental Panel on Climate Change, 2014), activist groups voice growing public concern about climate change (e.g., Greta Thunberg and the "Skolstrejk för klimatet") and more and more regulations around the world address the issue (The European Parliament & The Council of the European Union, 2003; US Environmental Protection Agency (EPA), 2010). Investors and other stakeholder groups are becoming increasingly aware of the significance of firms' role in climate change. Prior empirical research suggests that investors consider carbon emissions in their decision-making (Cahan et al., 2016; Griffin et al., 2017; Hoepner & Rogelj, 2021; Matsumura et al., 2014). As a basis for evaluating carbon management strategies and their implementation, they put pressure on firms to measure, manage and disclose their carbon emissions. We analyze how the disclosure of carbon emissions aids investors in evaluating a firm's carbon management.

The quantitative nature of carbon emissions as a key performance indicator for carbon performance particularly appeals to investors (Ilinitch et al., 1998). Investors traditionally evaluate a firm's performance by comparing key performance indicators to firms exposed to similar risks (Antle & Smith, 1986). The performance of firms exposed to similar risks conveys information on the average performance to be expected, that is, the benchmark.

Building on this idea, we introduce into the research the decomposition of a firm's carbon emissions into two components: an expected component and an unexpected component. The expected component of carbon emissions provides information about the firm's average carbon emissions that a knowledgeable investor would consider inherent to a firm's business model and its operating environment (i.e., the benchmark carbon emissions). The unexpected component, that is, the firm-specific deviation from benchmark carbon emissions, captures management effort and ability aimed at actively influencing carbon emissions. If a firm's management successfully implements a carbon management system and related practices, the firm will reduce carbon emissions relative to benchmark firms. Investors will integrate information on the components of carbon emissions in their decision-making if they consider this information useful. However, the unexpected component is also affected by discretion, manipulation and measurement error (noise). "Noise" increases the likelihood that the information provided will be of poor quality (i.e., information risk; Francis et al., 2005). If "noise" dominates the information contained in the unexpected component of carbon emissions, investors will refrain from integrating information on this component in their decision-making.

Our empirical analyses are based on a sample of firms operating in carbon-intensive industries that were included in the S&P 500 at least once between 2006 and 2014. Firms operating in carbon-intensive industries such as transportation, electricity and manufacturing are responsible for the majority of carbon emissions.[1] They also differ substantially from firms operating in non-carbon-intensive industries with regard to their carbon management (e.g., Ott et al., 2017). The final sample consists of 1034 firm-year observations for which carbon emissions and all other necessary data are available.

We proceed in two stages to identify and evaluate the two components of carbon emissions. In the first stage, we decompose carbon emissions into the expected component and the unexpected component based on our emissions estimation model. The expected component of carbon emissions is the fitted value from a regression explaining the level of total carbon emissions. Our evidence suggests that the basic firm characteristics of total assets; intensity of property, plant and equipment; capital expenditures; gross margin and a firm's industry affiliation explain the

[1] The Inventory of US Greenhouse Gas Emissions and Sinks established by the EPA shows that the major sources of man-made carbon emissions in the United States in 2019 are transportation activities (29% of carbon emissions), electricity generation (25%) and manufacturing activities (23%; EPA, 2021).

carbon emissions reasonably well. The residual of this regression (i.e., the firm-specific deviation from the expected component) is the unexpected component of carbon emissions.

In the second stage, we evaluate the usefulness of our decomposition into the two components of carbon emissions. First and foremost, we analyze the association between the two components and firm value. Building on Ohlson-type valuation models applied in prior empirical research (e.g., Barth & Clinch, 2009; Campbell et al., 2003), we define firm value as a function of total assets, total liabilities, earnings and additional information about carbon emissions. We provide evidence that investors integrate information about carbon emissions into their decision-making because the firm value is significantly negatively associated with both the expected component and the unexpected component. Our findings also suggest that the accuracy of the expected component appears to be innate and not dependent on assurance. However, assurance contributes to increased accuracy and thus higher usefulness of the information contained in the unexpected component. Moreover, we report evidence supporting the notion that the unexpected component captures management effort and ability.

This paper makes several contributions to the research. First, we contribute to research on the capital market effects of environmental performance in general and carbon emissions in particular. We introduce the decomposition into the expected component and the unexpected component of carbon emissions into the research. Thereby, we expand on Griffin et al. (2017), who attempt to estimate carbon emissions and Clarkson et al. (2015), who distinguish between carbon emission allowances provided via the European Union's Emission Trading Scheme (EU ETS) and carbon emissions deviating therefrom. For our decomposition, we exploit only basic firm characteristics, which makes it generally applicable. Additionally, our decomposition provides useful information about the influence of firms' carbon management on firm value.

Second, we contribute to research investigating the valuation of information risk, which criticizes the poor quality of information about carbon emissions because measurements often rely on estimates (Andrew & Cortese, 2011; Busch et al., 2022; Matsumura et al., 2014). We isolate the component most influenced by "noise" (i.e., the unexpected component). Our results suggest that despite the existence of "noise," the unexpected component also contains information useful to investors.

Third, we contribute to research that investigates carbon management. Ilinitch et al. (1998) note that we need a better understanding of the available measures for environmental performance. The expected component and the unexpected component of carbon emissions allow investors and other stakeholders to interpret carbon performance better.

Section 2 introduces carbon emissions as a key performance indicator for carbon performance, reviews the related empirical literature and develops the hypotheses. Section 3 describes the sample and introduces the research design. Section 4 examines whether the expected component and the unexpected component capture different aspects of carbon management. Section 5 presents additional analyses and robustness checks. Section 6 concludes.

2 | CARBON EMISSIONS AND THEIR COMPONENTS

2.1 | Carbon emissions

Carbon performance reflects the quality of a firm's carbon management strategy and the implementation of related practices (Alexander & Buchholz, 1978). Following ISO 14001:2015 (International Organization for Standardization [ISO], 2015), carbon emissions refer to the measurable results of a firm's management of the carbon aspects of activities, processes, products, services and systems. If a firm reduces its carbon emissions, its carbon performance will improve.

The Greenhouse Gas Protocol (GHG Protocol) distinguishes between direct and indirect carbon emissions (Ranganathan et al., 2004).[2] While direct carbon emissions occur at sources owned or controlled by the firm, indirect carbon emissions are a consequence of the firm's activities but occur at sources owned or controlled by another firm. The GHG Protocol, which was developed in partnership with industry experts, provides guidance on its website on the measurement of carbon emissions. However, its use as a measurement tool is not mandatory (Andrew & Cortese, 2011).

2.2 | Decomposition of a firm's carbon emissions

Investors traditionally evaluate a firm's performance by comparing key performance indicators of firms exposed to similar risks (Antle & Smith, 1986). The performance of other firms conveys information on the average performance that may serve as a benchmark. Building on this idea, we decompose a firm's carbon emissions into an expected component and an unexpected component. The expected component reveals the firm's average carbon emissions that a knowledgeable investor would expect from firms that are similar in terms of their business model and operating environment. The structure of a firm's assets (i.e., how a firm creates value) and the industry in which it operates are the results of strategic decisions that cannot be changed in the short term without considerable effort. Thus, the expected component represents the benchmark that is compared with the firm-specific carbon emissions. Similarly, Griffin et al. (2017) estimate the carbon emissions of firms that do not voluntarily disclose this information. Clarkson et al. (2015) distinguish firms' carbon emissions into the carbon emissions allowed under the EU ETS (i.e., carbon emission allowances) and those that differ from them.

Two firms operating under the same business conditions differ with regard to each firm's organizational capabilities. Organizational capabilities are coordinating mechanisms that assist in using a firm's assets efficiently (Day, 1994). They are difficult to imitate because they depend on a combination of management effort and ability (Barney, 1991; Teece et al., 1997). The unexpected component is the deviation of the firm-specific carbon emissions from the benchmark carbon emissions. Thus, this component reflects the effort and ability of a firm's management to implement carbon management and influence its carbon emissions. By putting more effort into implementing a carbon management system and related practices, the management can achieve a lower level of carbon emissions than other firms with similar characteristics. If it sets other priorities, the management can also accept higher than average carbon emissions.

2.3 | Valuation of a firm's carbon emissions

Carbon emissions, similar to other aspects of environmental performance, are typically not recognized in firms' financial statements but may influence both future revenues and costs (Ilinitch et al., 1998; Klassen & McLaughlin, 1996). A firm with a high level of carbon emissions may face higher future costs due to necessary investments in implementing less carbon-intensive production technologies and processes (i.e., carbon adaptation, innovation and mitigation) and developing less carbon-intensive goods and services. Other future costs include the impact of future regulations, taxes, government decrees and litigation exposure. Thus, a decrease in carbon emissions is expected to translate into future cost savings and a reduction in future environmental liabilities (Hassel et al., 2005; Reinhardt, 1999). Furthermore, customers may prefer firms with lower carbon emissions, resulting in higher future revenues (Klassen & McLaughlin, 1996).

[2] For carbon accounting purposes, the GHG Protocol introduces the concept of scopes of carbon emissions. Scope 1 carbon emissions cover all direct carbon emissions. Indirect carbon emissions are broken down into Scope 2 carbon emissions, which result from a firm's consumption of purchased electricity, heat or steam, and Scope 3 carbon emissions, which include all indirect carbon emissions other than Scope 2 carbon emissions.

Investors use all available information on carbon emissions to form unbiased expectations of a firm's future cash flows and determine its firm value. Even if capital markets are not always efficient, investors who know about these inefficiencies make them more efficient by exploiting their information advantages. Because a high (low) level of carbon emissions incurs higher (lower) future costs and results in lower (higher) future revenues, we expect a negative relation between carbon emissions and firm value. Prior research also suggests that investors assign a higher value to firms with a lower level of carbon emissions than to firms with a higher level (Chapple et al., 2013; Griffin et al., 2017; Matsumura et al., 2014).

The usefulness of a performance measure for determining firm value is related to the extent to which it contains information on the efficiency and effectiveness of the management's strategy and the implementation of related practices (Cook et al., 2019; Melnyk et al., 2014). A performance measure with a higher signal-to-noise ratio will influence firm value more than a performance measure that contains considerably more "noise." Both components of carbon emissions are assumed to be reliable and meaningful measures of carbon management. However, some specific attributes distinguish the two components of carbon emissions.

The expected component reflects a firm's carbon management strategy to the extent that it impacts the business model and the operating environment. Such impacts would have considerable long-term consequences for firms, likely exceeding the tenure of their management. The management can make decisions that change the firm's business model and shift the firm into a different operating environment and, consequently, change the firm's carbon management strategy. However, this type of change would occur gradually over a longer period. Overall, information about the efficiency and effectiveness of a firm's carbon management strategy reflected by the expected component may aid in determining the firm's value. However, pursuing an unspecified carbon management strategy does not necessarily guarantee success (Wood, 1991).

The unexpected component of carbon emissions provides insights into the organizational capabilities representing a combination of management effort and ability with regard to the reduction of carbon emissions. Organizational capabilities such as the successful implementation of a carbon management system and related practices create competitive advantages that result in cost savings and revenue increases and thus explain future cash flows (Aragón-Correa & Sharma, 2003; Hart, 1995; Hart & Dowell, 2011). A firm with an expectedly low level of carbon emissions may not need the most elaborate carbon management system. However, if a firm intends to imitate a more successful firm (i.e., a firm with lower-than-expected carbon emissions), its management will need to exert considerably more effort and/or possess a much better ability to implement a carbon management system and related practices (Ilinitch et al., 1998). Overall, the unexpected component of carbon emissions, which is argued to capture the management's effort and ability to implement a carbon management system and related practices, will likely be related to firm value.

The unexpected component also reflects discretion, manipulation and measurement error (noise). In the absence of mandatory regulations, firms provide information on carbon emissions on a voluntary basis. Ott et al. (2017) find that firms' disclosure decisions regarding the Carbon Disclosure Project (CDP) are relatively stable over time. Firms that decide to provide this type of information once are more likely to provide information of this nature again in the future, thereby implicitly increasing the reliability of this type of information. Since 2010, US firms have been required to publish the carbon emissions of their carbon-intensive facilities (EPA, 2010). Some firms also operate in countries where the publication of carbon emissions was mandatory before 2010 (e.g., carbon emissions data on the facility level demanded by the EU ETS). In the presence of mandatory disclosure, the frequency of disclosure and the proportion of disclosing firms are higher, so it is reasonable to assume that firms have more experience in measuring carbon emissions. However, even in this case, the measurement error can be substantial. Matsumura et al. (2014) draw attention to the fact that the measurement of carbon emissions is complex. While mandatory schemes for carbon disclosure typically demand disclosure on the facility level, the firm's total carbon emissions cannot be easily derived from this information (e.g., no disclosure for facilities outside the scope of application of the mandatory disclosure scheme; EPA, 2010; Griffin et al., 2017). Moreover, firms can still choose the carbon measurement methods they apply at the firm level. In the CDP 2015 questionnaire, the firms name more than 50 different carbon measurement methods. Andrew and Cortese (2011) bemoan that the heterogeneous use of carbon measurement methods inhibits the comparability and reliability of the information on carbon emissions even within the same industry. In addition, information on carbon emissions often remains unassured, which may cause investors to doubt the reliability of carbon measurement methods and the reported information based thereon (Fuhrmann et al., 2017). In sum, the measurement of carbon emissions can be subject to discretion and manipulation, and their disclosure subject to misreporting and misinterpretation.

We expect both the expected component and the unexpected component of carbon emissions to contain information useful for investors' firm valuation because they capture aspects of a firm's carbon management and are thus indicative of a firm's future cash flows. We assume that "noise" is uncorrelated with the expected component but likely affects the unexpected component. A lack of reliability due to the "noise" associated with measuring carbon emissions may affect the extent to which investors consider this type of information in firm valuation. If investors are aware of high levels of "noise," then the unexpected component will not be as useful for firm valuation as the expected component. Therefore, we formulate the following hypotheses:

H1: *The expected component of carbon emissions is negatively associated with firm value.*
H2: *The unexpected component of carbon emissions is negatively associated with firm value.*

3 | RESEARCH DESIGN

3.1 | Sample description

For our analyses, we focus on a sample that consists of all firms operating in carbon-intensive industries included in the S&P 500 at least once during the years 2006 through 2014. Carbon-intensive industries are responsible for the majority of carbon emissions and thus contribute significantly to climate change. Firms operating in carbon-intensive industries are increasingly in the focus of public attention (e.g., Greta Thunberg and the "Skolstrejk för klimatet"), and regulatory pressure on these firms has also been increasing in recent years (The European Parliament & The Council of the European Union, 2003; US EPA, 2010). Thus, reducing carbon emissions is becoming an increasing strategic challenge for these firms. Not surprisingly, these firms differ substantially from firms operating in non-carbon-intensive industries with regard to their carbon management strategies and the implementation of related practices, which in turn affects the relationship between carbon emissions and firm value (e.g., Matsumura et al., 2014; Ott et al., 2017).

For the identification of carbon-intensive industries, we rely on the Environmental Protection Agency's (EPA) understanding established in its regulation on "Mandatory Reporting of Greenhouse Gases" (EPA, 2010).[3] To identify the facilities required to report their carbon emissions to the EPA, the EPA explicitly lists the industries subject to its regulation. Although the EPA could be criticized for possibly not including all carbon-intensive industries in the list (e.g., for political reasons), the industries included can be classified as carbon-intensive. Moreover, regulation by a US government agency creates significant pressure on the industries it targets. Even if it only requires the reporting of carbon emissions and is not directly linked to emission trading schemes or carbon taxes, the risk for more extensive regulation cannot be ruled out in the future. Furthermore, it raises investors' sensitivity to the climate change-related risks for the targeted industries.

In line with prior empirical research (Griffin et al., 2017; Matsumura et al., 2014), we measure a firm's total carbon emissions as the sum of the firm's direct (Scope 1) and indirect (Scope 2) carbon emissions. Similar to Griffin et al. (2017), we hand-collected carbon emissions data from CDP's S&P 500 reports. As suggested by Matsumura et al. (2014), we verified the data based on the CDP's firm-individual data and added carbon emissions as reported in the

[3] In Section 5.3, we discuss the results of the same analyses considering an alternative identification of carbon-intensive industries and including all S&P 500 firms. We find directionally consistent but generally less significant results.

TABLE 1 Sample selection

Description	Firms	Firm years
Number of firms that were a constituent of the S&P 500 at least once between 2006 and 2014	710	6390
Deleted firms from non-carbon-intensive industries	(445)	(4005)
Number of firms operating in carbon-intensive industries	265	2385
Deleted firms because of less than 2 consecutive firm years of firm value and financial data	(33)	(297)
Deleted firm years because of less than 2 consecutive firm years of firm value and financial data	(0)	(242)
Deleted firms because of no disclosure of carbon emissions	(64)	(576)
Deleted firm years because of no disclosure of carbon emissions	(0)	(236)
Final sample	168	1034

Thomson Reuters Asset4 database. Thus, we are confident that we have considered all the carbon emissions data available through different disclosure channels for the sample firms.

We need at least two consecutive years of available carbon emissions data because of our empirical research design for the estimation of carbon emissions. We also collect financial and non-financial data from the databases Compustat and Thomson Reuters Asset4. Table 1 reports how data availability affects our sample size. The final sample of our paper includes 1034 firm-year observations for which carbon emissions data and all other data are available.

3.2 | Emissions estimation model

The performance of similar firms gives an indication of the average performance to be expected from the firm of interest. Building on this idea, we decompose the firm's carbon emissions into the expected component and the unexpected component in the first stage of our analysis. We determine the expected component based on the following regression model:

$$\begin{aligned}\left(\mathrm{CO2\_REPORTED}_{i,t+1}\right) = {} & \alpha_0 + \alpha_1 \ln\left(\mathrm{ASSETS}_{i,t}\right) + \alpha_2 \mathrm{PPE\_INT}_{i,t} + \alpha_3 \mathrm{CAPX\_INT}_{i,t} \\ & + \alpha_4 \mathrm{PPE\_AGE}_{i,t} + \alpha_5 \mathrm{GROSSMAR}_{i,t} + \mathrm{INDUSTRY} - \mathrm{CONTROLS}_i + \varepsilon_{1,i,t}. \end{aligned} \tag{1}$$

The dependent variable *CO2_REPORTED* is either the direct (*CO2_DIRECT*), indirect (*CO2_INDIRECT*) or total (*CO2_TOTAL*) carbon emissions of firm *i* in year $t + 1$. To increase the accuracy of the estimation, we apply separate estimation models for direct and indirect carbon emissions whenever possible. This approach allows assigning different weights to the determinants of direct and indirect carbon emissions because their coefficients can vary freely in two separate models. We also apply an estimation model based on total carbon emissions. We use the resulting estimates only in cases in which direct and/or indirect carbon emissions are unavailable.

The expected component reflects the average carbon emissions that a knowledgeable investor would expect based on a firm's business model and its operating environment. Prior research suggests that the firm's size; the intensity and age of its property, plant and equipment; its capital expenditures; its gross margin and the industry in which it operates explain the expected level of carbon emissions (e.g., Clarkson et al., 2008; Downar et al., 2021; Goldhammer et al., 2017; Griffin et al., 2017; Nguyen et al., 2021).[4] These firm characteristics, which reflect a firm's

[4] To enable a universal applicability of the emissions estimation model, we rely on a parsimonious choice of explanatory variables to estimate the carbon emissions. In Section 5.3, we discuss additional explanatory variables as well as alternative estimation approaches.

business model and its operating environment, are the result of strategic decisions (i.e., carbon management strategy), which are unlikely to considerably change in the short term. We include firm size, measured as the natural logarithm of *ASSETS*, because larger firms are more likely to generate more carbon emissions due to their larger production capacities and volumes (Nguyen et al., 2021). Firms of the same size also differ in their levels of carbon emissions because they have different business models. We consider the intensity of gross property, plant and equipment (*PPE_INT*) because a business model relying on a larger proportion of firm-owned production facilities is expected to generate more carbon emissions (Downar et al., 2021; Goldhammer et al., 2017). *PPE_INT* is measured as the gross value of property, plant and equipment divided by total assets. By using gross values to measure *PPE_INT*, we mitigate differences resulting from varying depreciation methods or different useful lives. New production facilities are likely to be more efficient, resulting in relatively lower levels of carbon emissions. Therefore, higher investments in new machines (*CAPX_INT*) are expected to be accompanied by lower total carbon emissions (Clarkson et al., 2008; Griffin et al., 2017). We measure *CAPX_INT* as capital expenditures divided by total assets. Older production facilities are likely to generate more carbon emissions than newer ones. Thus, the age of the property, plant and equipment (*PPE_AGE*) is indicative of carbon emissions (Clarkson et al., 2008). We calculate *PPE_AGE* as the difference between the gross and net value of property, plant and equipment divided by the depreciation. The profitability captures a firm's market pressures and/or slack resources. On the one hand, higher profitability indicates less competition in a firm's main sales markets, indicating little pressure for a firm to pursue carbon-reducing investments to differentiate itself from its competitors. On the other hand, higher profitability indicates that a firm has sufficient resources to implement carbon-reducing activities. We capture profitability by measuring gross margin (*GROSSMAR*) as one minus the ratio of cost of goods sold to total revenues (Griffin et al., 2017; Nguyen et al., 2021). The industry-fixed effects (*INDUSTRY-CONTROLS*), based on two-digit SIC (Standard Industrial Classification) codes, control for the production technologies and processes of individual industries that do not vary within industries. They also capture the heterogeneous use of carbon measurement methods in different industries. Table 2 summarizes the measurement and data sources for all variables of the emissions estimation model.

As we focus on firms from carbon-intensive industries, we expect their business models to be strongly reflected in the direct carbon emissions that occur at sources owned or controlled by the firm. Therefore, we expect the emission estimation model to have higher explanatory power for direct carbon emissions as the dependent variable than for indirect carbon emissions.

We apply year-specific emissions estimation models. For each year, we estimate the carbon emissions, including all firm-year observations up to this year. To illustrate, the estimation of carbon emissions for 2006 is based on the explanatory variables capturing the firm's business model and the operating environment in 2005. For the estimation of carbon emissions for 2007, we additionally include the carbon emissions for 2007 and the explanatory variables from 2006. Thus, the emissions estimation model for 2007 regresses carbon emissions from 2006 and 2007 on the explanatory variables from 2005 and 2006. By including the maximum number of available firm-year observations for each year, this approach reflects the available information in the year of the estimation and increases the stability of the estimations.

The expected component of carbon emissions (*CO2_EXPECTED*) represents the benchmark, that is, the average carbon emissions to be expected from firms, which are similar to each other in terms of their business model and operating environment. We use the coefficients of the emissions estimation model to estimate *CO2_EXPECTED*. If the coefficients of the separate emissions estimation model based on direct and indirect carbon emissions are available, *CO2_EXPECTED* is the sum of the estimated direct carbon emissions and the estimated indirect carbon emissions. Otherwise, *CO_EXPECTED* corresponds to the estimated total carbon emissions. Negative values of *CO2_EXPECTED* are set equal to zero.[5]

[5] We use zero as a cutoff value because carbon emissions cannot be lower than zero. However, to ensure the robustness of our results, we investigated the results of the firm valuation model for the alternative of allowing negative values for *CO2_EXPECTED*. Although the sizes of some coefficients became smaller, the signs remained unchanged, and the significance levels remained virtually the same for *CO2_EXPECTED* and *CO2_UNEXPECTED*.

TABLE 2 Variables, measurements and data sources

Variable	Description	Measurement	Data source
FIRM_VALUE	Firm value	Number of shares outstanding multiplied by the price per share at the end of the calendar year (*csho* * *prcc_c*)	Compustat
CO2_TOTAL	Total carbon emissions	Sum of direct (Scope 1) and indirect (Scope 2) carbon emissions	Carbon Disclosure Project (CDP), complemented by Thomson Reuters Asset4
CO2_DIRECT	Direct carbon emissions	Direct (Scope 1) carbon emissions	CDP, complemented by Thomson Reuters Asset4
CO2_INDIRECT	Indirect carbon emissions	Indirect (Scope 2) carbon emissions	CDP, complemented by Thomson Reuters Asset4
CO2_EXPECTED	Expected component of carbon emissions	Based on emissions estimation model (1)	Our calculation
CO2_UNEXPECTED	Unexpected component of carbon emissions	*CO2_TOTAL* – *CO2_EXPECTED*	Our calculation
ASSURANCE	Assurance of carbon emissions	Equals one if the firm reported the verification/assurance status of its direct (Scope 1) and/or indirect (Scope 2) carbon emissions as complete or under way and is 0 otherwise	CDP
ASSETS	Total assets	Total assets (*at*)	Compustat
CAPX_INT	Intensity of capital expenditures	Capital expenditures divided by total assets (*capx/at*)	Compustat
EARNINGS	Operating income	Operating income after depreciation (*oiadp*)	Compustat
GROSSMAR	Gross margin	One minus the ratio of cost of goods sold to total revenues (1 – *cogs/revt*)	Compustat
LIABILITIES	Total liabilities	Total liability (*lt*)	Compustat
PPE_AGE	Age of property, plant and equipment	Difference of gross value of property, plant and equipment minus net value of property, plant and equipment, divided by yearly depreciation (*ppegt* – *ppent*)/*dp*)	Compustat
PPE_INT	Intensity of property, plant and equipment	Gross value of property, plant and equipment divided by total assets (*ppegt/at*)	Compustat

The unexpected component of carbon emissions (*CO2_UNEXPECTED*) reflects the effort and ability of a firm's management to implement carbon management and influence the firm's carbon emissions (compared to a similar firm). *CO2_UNEXPECTED* is the firm-specific deviation of the sum of reported direct and indirect carbon emissions (or reported total carbon emissions, if direct and indirect carbon emissions are unavailable) from *CO2_EXPECTED*:

$$\text{CO2\_UNEXPECTED}_{i,t} = \text{CO2\_TOTAL}_{i,t} - \text{CO2\_EXPECTED}_{i,t}. \tag{2}$$

Negative values of *CO2_UNEXPECTED* indicate that management efforts and abilities contribute to reducing a firm's carbon emissions to a lower level than would be expected from similar firms based on the emissions estimation model (i.e., superior carbon management). If the firm's management puts less effort into implementing a carbon management strategy and related practices, a firm's actual level of carbon emissions will exceed the expected level of carbon emissions, and *CO2_UNEXPECTED* will assume a positive value (i.e., inferior carbon management). As we explained above, this component also captures noise.

3.3 | Firm valuation model

In the second stage of our analysis, we analyze the usefulness of the distinction between the expected component and the unexpected component of carbon emissions by exploring their relation to firm value based on an Ohlson-type valuation model:

$$\begin{aligned} \text{FIRM\_VALUE}_{i,t} = {} & b_0 + b_1\text{CO2\_EXPECTED}_{i,t} + b_2\text{CO2\_UNEXPECTED}_{i,t} + b_3\text{ASSURANCE}_{i,t} \\ & + b_4\text{ASSETS}_{i,t} + b_5\text{LIABILITIES}_{i,t} + b_6\text{EARNINGS}_{i,t} \\ & + \text{INDUSTRY} - \text{CONTROLS} + \text{YEAR} - \text{CONTROLS} + \varepsilon_{2i,t} \end{aligned} \tag{3a}$$

Ohlson-type valuation models have been used in prior empirical accounting research examining the association between carbon emissions and firm value (Griffin et al., 2017; Matsumura et al., 2014). Barth and Clinch (2009) find that unscaled variables are least impacted by scaling effects in the accounting context. Thus, we measure firm value (*FIRM_VALUE*) as the market value of common equity (in USD millions). Following Barth and Clinch (2009), we include total assets (*ASSETS*) and total liabilities (*LIABILITIES*) in the firm valuation model. We expect *ASSETS* to have a positive sign and *LIABILITIES* to have a negative sign. Operating income (*EARNINGS*) is included in the model because capital markets value more profitable firms higher than less profitable firms (Matsumura et al., 2014). Therefore, we expect a positive sign for *EARNINGS*.

We extend previous models, which establish the association between environmental performance and firm value (Griffin et al., 2017; Matsumura et al., 2014), as follows: We decompose carbon emissions into the expected component (*CO2_EXPECTED*) and the unexpected component (*CO2_UNEXPECTED*). According to the hypotheses, we expect the components to convey useful information and thus to observe significantly negative coefficients for both *CO2_EXPECTED* (H1) and *CO2_UNEXPECTED* (H2). It is important to note that *CO2_UNEXPECTED* not only conveys useful information about management effort and ability but also captures "noise" related to the reporting of carbon emissions. If *CO2_UNEXPECTED* captures only "noise," investors will not consider this component in firm valuation. Assurance is typically argued to increase the credibility of the non-financial information disclosed (Fuhrmann et al., 2017; Simnett et al., 2009). Where assured non-financial information is available, the level of discretion, manipulation and measurement error (noise) related to the reporting of carbon emissions is reduced. We add a binary control variable to capture whether a firm indicated that its reported carbon emissions had been assured (*ASSURANCE*). Only 20.4% of the firms had their carbon emissions assured in our final sample.

We control for industry-level characteristics (*INDUSTRY_CONTROLS*) by including industry-fixed effects based on two-digit SIC codes. We also include time-fixed effects for each year of our analysis (*YEAR_CONTROLS)* to capture macroeconomic developments such as oil price changes. Table 2 explains the variable measurements and data sources in detail.

TABLE 3 Descriptive statistics

Variable	Mean	St. dev.	5%	Median	95%
FIRM_VALUE	32,797.430	42,435.020	3241.531	17,411.010	140,290.100
CO2_TOTAL	14,993.720	26,981.630	90.616	3853.984	68,005.000
CO2_DIRECT#	13,307.080	25,998.270	12.487	2611.251	62,650.460
CO2_INDIRECT#	1441.189	2419.601	37.797	564.034	7570.000
CO2_EXPECTED	13,680.440	23,981.400	98.995	3952.341	60,457.850
CO2_UNEXPECTED	1313.289	17,656.970	−19,238.390	−16.222	31,233.300
ASSURANCE	0.204	0.403	0.000	0.000	1.000
ASSETS	33,544.160	34,389.950	3767.000	23,165.210	113,644.000
CAPX_INT	0.060	0.045	0.012	0.051	0.143
EARNINGS	3153.203	4092.775	140.000	1831.686	13,859.000
GROSSMAR	0.390	0.209	0.117	0.340	0.814
LIABILITIES	20,808.000	20,026.170	1943.999	14,329.000	66,733.000
PPE_AGE	7.966	3.560	2.527	7.779	13.986
PPE_INT	0.739	0.381	0.174	0.778	1.251

Note: The table reports descriptive statistics for the dependent and independent variables applied in the emissions estimation model (1) and the firm valuation models (3a and 3b; $N = 1034$). Table 2 summarizes the variable definitions.
#The number of observations is reduced to 943 for *CO2_DIRECT* and to 853 for *CO2_INDIRECT*.

Finally, we expand model (3a) by interacting *ASSURANCE* with *CO2_EXPECTED* and *CO2_UNEXPECTED*. *CO2_EXPECTED* is not expected to vary in interaction with *ASSURANCE*. It does not need to be assured to be credible because it can be verified based on externally available information on a firm's business model and its operating environment. As noise is, by design, captured by *CO2_UNEXPECTED*, we expect a significant firm-value effect of *CO2_UNEXPECTED* in interaction with *ASSURANCE*. The expanded model is as follows:

$$\begin{aligned} \mathrm{FIRM\_VALUE}_{i,t} = {} & \gamma_0 + \gamma_1 \mathrm{CO2\_EXPECTED}_{i,t} + \gamma_2 \mathrm{CO2\_UNEXPECTED}_{i,t} + \gamma_3 \mathrm{ASSURANCE}_{i,t} \\ & + \gamma_4 \mathrm{CO2\_EXPECTED}_{i,t}{}^{*}\mathrm{ASSURANCE}_{i,t} + \gamma_5 \mathrm{CO2\_UNEXPECTED}_{i,t}{}^{*}\mathrm{ASSURANCE}_{i,t} \\ & + \gamma_6 \mathrm{ASSETS}_{i,t} + \gamma_7 \mathrm{LIABILITIES}_{i,t} + \gamma_8 \mathrm{EARNINGS}_{i,t} \\ & + \mathrm{INDUSTRY} - \mathrm{CONTROLS} + \mathrm{YEAR} - \mathrm{CONTROLS} + \varepsilon_{3i,t}. \end{aligned} \tag{3b}$$

4 | RESULTS AND DISCUSSION

4.1 | Descriptive statistics

Table 3 reports descriptive statistics. The firms in our sample generate 14,994 thousand metric tons of carbon emissions on average.[6] The mean values of *CO2_EXPECTED* amount to 13,680 thousand metric tons and *CO2_UNEXPECTED* to 1313 thousand metric tons. Since *CO2_UNEXPECTED* is defined as the residual of the emissions estimation model (1), *CO2_UNEXPECTED* is expected to have a mean close to zero.

[6] The level of carbon emissions that firms in our final sample generate on average is lower than that reported by Matsumura et al. (2014). The lower level of carbon emissions in our sample might be attributable to a decrease in carbon emissions over time. For instance, if we restrict our sample period to the period before 2010, we also find a considerably larger value of 17,684 thousand metric tons of carbon emissions on average generated by the firms in our sample (not reported).

Table 4 reports the correlation matrix with Pearson and Spearman correlation coefficients. We find a positive correlation between *CO2_TOTAL* and *FIRM_VALUE* (Pearson: 0.173, $p < 0.01$; Spearman: 0.118, $p < 0.01$). This is less surprising because larger firms generally generate more carbon emissions. The size effect dominates the firm value effect in the correlation analysis. We control for the size effect in the firm valuation model (3a and 3b) and then expect *CO2_TOTAL* to be negatively associated with *FIRM_VALUE*.

4.2 | Emissions estimation model

Table 5 reports the emissions estimation model (1) applied to calculate *CO2_EXPECTED* and *CO2_UNEXPECTED*. Panel A presents the results of the emissions estimation model with total carbon emissions as the dependent variable. The *F*-statistics suggest that the emissions estimation model provides overall significant results ($p < 0.01$). The adjusted R^2s of the models that estimate total carbon emissions range between 0.739 and 0.891. A firm's business model and its operating environment explain a considerable amount of the variance of its carbon emissions. The high explanatory power of the regression supports our argument that we can meaningfully decompose a firm's carbon emissions into the expected component and the unexpected component.

Focusing on the most comprehensive sample for the emissions estimation model with total carbon emissions as the dependent variable (Panel A: Year 2014), we find that the natural logarithm of *CO2_TOTAL* is positively associated with the natural logarithm of *ASSETS* (coefficient 0.913, $p < 0.01$) and *PPE_INT* (3.072, $p < 0.01$). As expected, larger firms with a higher intensity of property, plant and equipment tend to generate more carbon emissions. An increase in total assets of 1% results in an average increase in total carbon emissions of about 0.913%. Considering the average value for total carbon emissions (14,993.720 thousand metric tons), an increase in the intensity of property, plant and equipment of one percentage point is associated with an average increase in total carbon emissions of 467.756 thousand metric tons (= e^[ln(14,993.720) + 0.01 * 3.072] – 14,993.720). We also observe that the natural logarithm of *CO2_TOTAL* is negatively associated with *CAPX_INT* (−8.776, $p < 0.01$) and *GROSSMAR* (−2.433, $p < 0.01$). Firms investing more heavily in new property, plant and equipment and firms with higher profitability appear to be better able to decrease their levels of carbon emissions. While a one percentage point increase in the intensity of capital expenditures is related to an average decrease in total carbon emissions of 1259.762 thousand metric tons, a one percentage point increase in the gross margin is related to an average decrease in total carbon emissions of 360.395 thousand metric tons. *PPE_AGE* shows no significant association with the level of carbon emissions (−0.007, $p > 0.1$). In contrast to our expectation, older property, plant and equipment are not accompanied by more carbon emissions.

The results of the emissions estimation model for direct carbon emissions (Panel B) are very similar to the results of the emissions estimation model for total carbon emissions (Panel A), whereas the results of the emissions estimation model for indirect carbon emissions (Panel C) are somewhat weaker. While the adjusted R^2s of the models estimating direct carbon emissions range between 0.783 and 0.897 (Panel B), the adjusted R^2s of the model estimating indirect carbon emissions range between 0.637 and 0.732 (Panel C). Obviously, the variables capturing firm characteristics better explain direct carbon emissions than indirect carbon emissions. While direct carbon emissions occur at sources owned and controlled by the firm, indirect carbon emissions are caused by the firm's consumption of electricity and heating. Similar to the results for total carbon emissions as the dependent variable, the natural logarithm of total assets (*ASSETS*: 1.116, $p < 0.01$), the intensity of property, plant and equipment (*PPE_INT*: 3.336, $p < 0.01$), the intensity of capital expenditures (*CAPX_INT*: −7.789, $p < 0.01$) and the gross margin (*GROSSMAR*: −2.557, $p < 0.01$) are significant in estimating the level of direct carbon emissions (Panel B: Year 2014). However, when estimating the level of indirect carbon emissions (Panel C: Year 2014), only the natural logarithm of total assets (*ASSETS*: 0.916, $p < 0.01$), the intensity of property, plant and equipment (*PPE_INT*: 2.363, $p < 0.01$) and the gross margin (*GROSSMAR*: −2.095, $p < 0.05$) remain significant. Comparing the significant variables in both models, we observe some differences. A 1% increase in total assets is related to a 1.116% increase in direct carbon emissions and a 0.913% increase in indirect carbon emissions. Considering the average values for total assets (USD 33,544.160 million), direct carbon emissions (13,307.080

TABLE 4 Correlations table

		(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
(1)	*FIRM_VALUE*		**0.118**	**0.157**	**−0.120**	**0.128**	**0.746**	0.040	**0.859**	**0.275**	**0.642**	**−0.177**	***−0.078***
(2)	*CO2_TOTAL*	**0.173**		**0.909**	**0.235**	0.029	**0.521**	**0.593**	**0.274**	**−0.405**	**0.564**	**0.395**	**0.693**
(3)	*CO2_EXPECTED*	**0.276**	**0.766**		**−0.097**	*0.058*	**0.593**	**0.647**	**0.304**	**−0.398**	**0.632**	**0.437**	**0.747**
(4)	*CO2_UNEXPECTED*	**−0.111**	**0.488**	**−0.188**		**−0.111**	**−0.127**	***−0.066***	***−0.064***	−0.027	**−0.101**	−0.041	**−0.096**
(5)	*ASSURANCE*	**0.106**	0.003	0.040	−0.050		**0.135**	0.046	**0.131**	***0.077***	**0.120**	−0.023	−0.002
(6)	*ASSETS*	**0.849**	**0.427**	**0.505**	−0.033	**0.121**		**0.242**	**0.804**	***−0.062***	**0.963**	−0.057	**0.176**
(7)	*CAPX_INT*	−0.031	**0.179**	**0.333**	**−0.178**	0.023	**0.092**		**0.086**	**−0.140**	**0.212**	**0.265**	**0.771**
(8)	*EARNINGS*	**0.909**	**0.256**	**0.335**	***−0.064***	**0.128**	**0.870**	0.014		**0.106**	**0.742**	**−0.104**	−0.035
(9)	*GROSSMAR*	**0.301**	**−0.265**	**−0.245**	***−0.072***	**0.086**	***0.061***	−0.049	**0.190**		**−0.167**	**−0.331**	**−0.231**
(10)	*LIABILITIES*	**0.724**	**0.463**	**0.507**	0.019	**0.113**	**0.950**	0.050	**0.767**	*−0.061*		0.038	**0.192**
(11)	*PPE_AGE*	**−0.181**	**0.291**	**0.397**	**−0.096**	−0.031	***−0.076***	**0.180**	**−0.135**	**−0.340**	−0.014		**0.542**
(12)	*PPE_INT*	**−0.133**	**0.366**	**0.503**	**−0.125**	−0.004	0.047	**0.717**	***−0.084***	**−0.256**	0.042	**0.552**	

Note: The table reports Pearson (Spearman) correlation coefficients for the independent and dependent variables applied in the emissions estimation model (1) and the firm *valuation* models (3a and 3b; $N = 1034$) below (above) the diagonal. It also reports the significance levels (bold: $p < 0.01$; bold and italics: $p < 0.05$; italics: $p < 0.1$). Table 2 summarizes the variable definitions.

TABLE 5 Estimation of carbon emissions components

Panel A: Estimation of total carbon emissions									
Dependent variable: ln(CO2_TOTAL)	2006	2007	2008	2009	2010	2011	2012	2013	2014
	Coefficient (S.E.)	Coefficient (S.E.)	Coefficient (S.E.)	Coefficient (S.E.)	Coefficient (S.E.)	Coefficient (S.E.)	Coefficient (S.E.)	Coefficient (S.E.)	Coefficient (S.E.)
ln(ASSETS)	0.998	0.994	0.928	0.936	0.958	0.963	0.955	0.934	0.913
	(0.138)***	(0.079)***	(0.071)***	(0.061)***	(0.059)***	(0.055)***	(0.052)***	(0.054)***	(0.056)***
PPE_INT	3.376	3.17	3.638	3.496	3.04	2.998	3.117	3.141	3.072
	(0.872)***	(0.644)***	(0.577)***	(0.502)***	(0.492)***	(0.458)***	(0.434)***	(0.443)***	(0.44)***
CAPX_INT	−4.223	−1.829	−7.172	−10.473	−8.572	−7.432	−7.798	−8.765	−8.776
	(5.357)	(3.489)	(3.22)**	(2.806)***	(2.516)***	(2.3)***	(2.101)***	(2.229)***	(2.391)***
PPE_AGE	0.028	0.028	−0.016	−0.017	−0.001	0.001	−0.008	−0.007	−0.007
	(0.085)	(0.056)	(0.043)	(0.037)	(0.034)	(0.032)	(0.029)	(0.028)	(0.028)
GROSSMAR	−2.18	−2.074	−2.585	−2.33	−2.159	−2.227	−2.35	−2.377	−2.433
	(0.753)***	(0.544)***	(0.44)***	(0.35)***	(0.372)***	(0.33)***	(0.315)***	(0.323)***	(0.34)***
Constant	−6.382	−6.118	−4.157	−4.005	−2.951	−3.042	−2.914	−2.656	−2.400
	(1.344)***	(0.779)***	(0.73)***	(0.641)***	(0.75)***	(0.682)***	(0.63)***	(0.649)***	(0.701)***
Industry controls	YES	YES	YES	YES	YES	YES	YES	YES	YES
N	52	131	231	357	489	627	769	906	1,034
F-statistic	19.580***	60.304***	33.619***	63.253***	92.328***	127.882***	164.154***	188.031***	208.008***
Adjusted R^2	0.861	0.891	0.739	0.786	0.797	0.810	0.817	0.813	0.808

(Continues)

TABLE 5 (Continued)

Panel B: Estimation of direct carbon emissions

Dependent variable: ln(CO2_DIRECT)	2006 Coefficient (S.E.)	2007 Coefficient (S.E.)	2008 Coefficient (S.E.)	2009 Coefficient (S.E.)	2010 Coefficient (S.E.)	2011 Coefficient (S.E.)	2012 Coefficient (S.E.)	2013 Coefficient (S.E.)	2014 Coefficient (S.E.)
ln(ASSETS)	1.343	1.161	1.063	1.088	1.155	1.165	1.158	1.141	1.116
	(0.128)***	(0.102)***	(0.099)***	(0.088)***	(0.082)***	(0.077)***	(0.074)***	(0.074)***	(0.074)***
PPE_INT	2.482	2.353	3.068	3.131	2.972	3.129	3.315	3.342	3.336
	(1.047)**	(0.838)***	(0.688)***	(0.588)***	(0.546)***	(0.502)***	(0.474)***	(0.467)***	(0.461)***
CAPX_INT	−2.565	1.73	−4.178	−7.925	−6.909	−6.795	−7.103	−7.738	−7.789
	(5.321)	(3.999)	(3.423)	(3.065)**	(2.608)***	(2.346)***	(2.25)***	(2.159)***	(2.118)***
PPE_AGE	0.16	0.129	0.058	0.043	0.038	0.029	0.016	0.016	0.014
	(0.095)*	(0.076)*	(0.055)	(0.046)	(0.041)	(0.039)	(0.038)	(0.036)	(0.034)
GROSSMAR	−2.423	−1.849	−2.466	−2.418	−2.378	−2.469	−2.589	−2.56	−2.557
	(0.669)***	(0.639)***	(0.501)***	(0.472)***	(0.517)***	(0.457)***	(0.439)***	(0.43)***	(0.424)***
Constant	−8.096	−5.617	−7.634	−7.508	−6.49	−7.847	−6.52	−6.326	−3.833
	(1.408)***	(1.218)***	(1.08)***	(0.978)***	(0.969)***	(0.927)***	(0.837)***	(0.823)***	(0.891)***
Industry controls	YES	YES	YES	YES	YES	YES	YES	YES	YES
N	46	119	211	329	451	576	702	824	943
F-statistic	26.869***	58.033***	42.996***	76.998***	105.699***	144.490***	176.134***	203.702***	231.265***
Adjusted R^2	0.896	0.897	0.783	0.815	0.823	0.833	0.840	0.838	0.837

(Continues)

TABLE 5 (Continued)

Panel C: Estimation of indirect carbon emissions									
Dependent variable: ln(CO2_INDIRECT)	2006	2007	2008	2009	2010	2011	2012	2013	2014
	Coefficient (S.E.)	Coefficient (S.E.)	Coefficient (S.E.)	Coefficient (S.E.)	Coefficient (S.E.)	Coefficient (S.E.)	Coefficient (S.E.)	Coefficient (S.E.)	Coefficient (S.E.)
ln(ASSETS)	1.145	0.959	0.928	0.96	0.968	0.963	0.943	0.933	0.916
	(0.172)***	(0.089)***	(0.069)***	(0.07)***	(0.071)***	(0.069)***	(0.065)***	(0.065)***	(0.066)***
PPE_INT	5.509	4.663	4.066	3.64	2.804	2.752	2.629	2.461	2.363
	(1.303)***	(0.755)***	(0.628)***	(0.639)***	(0.607)***	(0.59)***	(0.547)***	(0.538)***	(0.526)***
CAPX_INT	−11.662	−7.42	−7.872	−9.35	−5.161	−4.255	−3.097	−3.026	−2.814
	(9.859)	(4.393)*	(3.484)**	(3.303)***	(2.72)*	(2.722)	(2.606)	(2.6)	(2.61)
PPE_AGE	−0.113	−0.102	−0.096	−0.053	−0.018	−0.023	−0.025	−0.020	−0.022
	(0.115)	(0.056)*	(0.045)**	(0.041)	(0.037)	(0.034)	(0.031)	(0.029)	(0.027)
GROSSMAR	−1.37	−1.792	−2.252	−1.637	−1.56	−1.754	−1.925	−2.006	−2.095
	(1.489)	(0.821)**	(0.59)***	(0.433)***	(0.468)***	(0.438)***	(0.427)***	(0.436)***	(0.441)***
Constant	−8.861	−7.953	−4.81	−5.98	−7.575	−3.27	−3.074	−2.688	−2.448
	(2.445)***	(1.166)***	(0.753)***	(0.864)***	(0.795)***	(0.735)***	(0.678)***	(0.687)***	(0.688)***
Industry controls	YES	YES	YES	YES	YES	YES	YES	YES	YES
N	39	101	180	284	394	508	626	740	853
F-statistic	7.028***	16.170***	21.638***	31.507***	40.296***	52.481***	61.505***	68.017***	72.256***
Adjusted R^2	0.717	0.732	0.675	0.672	0.667	0.670	0.670	0.656	0.637

Note: The table reports the results of the ordinary least squares regressions of the emissions estimation model (1) based on observations from 2006 to the year for which the carbon emissions are estimated. The table reports the coefficients, the firm-clustered standard errors and the significance levels (***$p < 0.01$, **$p < 0.05$, *$p < 0.1$). Table 2 summarizes the variable definitions.

thousand metric tons) and indirect carbon emissions (1441.189 thousand metric tons), an increase of USD 1 million in total assets results in an average increase in direct carbon emissions of 0.443 thousand metric tons (= 13,307.080 thousand metric tons × 1.116 × USD 1 million/USD 33,544.160 million) and an average increase in indirect carbon emissions of 0.039 thousand metric tons. The reported coefficients for *GROSSMAR* suggest that an increase in gross margin by one percentage point is related to an average decrease in direct (indirect) carbon emissions of 335.949 thousand metric tons (29.879 thousand metric tons).

4.3 | Firm valuation model

Table 6 presents the results of the firm valuation model, which is of central interest for assessing the usefulness of the decomposition of carbon emissions into its two components. Consistent with prior results for shorter sample periods (Clarkson et al., 2015; Griffin et al., 2017; Matsumura et al., 2014), we also find a negative relationship between total carbon emissions (*CO2_TOTAL*) and firm value (*FIRM_VALUE*) for our sample period from 2006 to 2014 (coefficient: −0.127, $p < 0.01$). In contrast to the correlation analysis, the size effect does not dominate the negative association of carbon emissions and firm value. Investors appear to associate higher (lower) carbon emissions with higher (lower) future costs and/or lower (higher) future revenues and thus regard them as negative (positive) information when determining the firm value. This negative association probably results from the expectation of higher follow-up costs due to the development of less carbon-intensive products and services, investments in less carbon-intensive production technologies and processes, the purchase of carbon emission allowances or the imposition of carbon taxes. Furthermore, firms with lower carbon emissions might increase future revenues due to their customers' preferences for more carbon-friendly products and services (Ilinitch et al., 1998; Klassen & McLaughlin, 1996).

Our results indicate that the firm value decreases by USD 127,000 for each additional thousand metric tons of carbon emissions for firms from carbon-intensive industries. The valuation discount is thus smaller than the valuation discount of USD 182,000 per additional thousand metric tons of carbon emissions reported by Matsumura et al. (2014) for their sample of carbon-intensive industries but higher than the valuation discount of USD 79,000 per additional thousand metric tons of carbon emissions reported by Griffin et al. (2017) and the valuation discount of EUR 39,000 per additional thousand metric tons of carbon emissions reported by Clarkson et al. (2015). In a further analysis, Clarkson et al. (2015) attribute a valuation discount of EUR 75,000 exclusively to the proportion of the firm's carbon emissions not covered by carbon emission allowances that the firms received free of charge under the EU ETS.

Consistent with the hypotheses (H1 and H2), we find both components of carbon emissions to be significantly negatively associated with a firm value (*CO2_EXPECTED*: −0.135, $p < 0.05$; *CO2_UNEXPECTED*: −0.120, $p < 0.01$) in firm valuation model (3a). For each additional thousand metric tons of expected carbon emissions (*CO2_EXPECTED*), the firm value decreases by USD 135,000. This result indicates that a firm's carbon emissions inherent to its business model and operating environment map into firm value. Investors appear to penalize firms with a business model and in an operating environment that is expected to generate higher carbon emissions and reward firms with a business model and in an operating environment that is expected to generate lower carbon emissions.

At first sight, the expected component of carbon emissions might be reminiscent of carbon emission allowances, which are conventionally allocated on the basis of benchmarks. Clarkson et al. (2015) focus primarily on a firm's carbon emissions within the scope of the EU ETS and do not observe a significant valuation discount for the carbon emission allowances. Since firms receive carbon emission allowances free of charge within the scope of the EU ETS, this result may appear less surprising. For those carbon emissions not falling within the scope of the EU ETS and therefore not covered by carbon emission allowances, Clarkson et al. (2015), in turn, observe a significant valuation discount. The US firms in our sample generate their carbon emissions in facilities in the United States and all over the world. Although the United States did not have overarching emission trading schemes in place or imposed carbon taxes during our sample period, our sample firms were confronted with cap-and-trade systems at the state level (i.e., the Regional Greenhouse Gas Initiative in nine states focusing on fossil fuel power plants introduced in 2009 and the

TABLE 6 Firm valuation models including different components of carbon emissions

	Total carbon emissions		*Decomposed carbon emissions*		*Decomposed carbon emissions and assurance*	
Dependent variable: FIRM_VALUE	Coefficient	S.E.	Coefficient	S.E.	Coefficient	S.E.
CO2_TOTAL	−0.127	0.047***				
CO2_EXPECTED			−0.135	0.068**	−0.124	0.048**
CO2_UNEXPECTED			−0.120	0.045***	−0.070	0.035**
ASSURANCE	1449.617	2063.099	1482.658	2052.774	2417.419	2426.988
CO2_EXPECTED × *ASSURANCE*					−0.042	0.084
CO2_UNEXPECTED × *ASSURANCE*					−0.229	0.106**
ASSETS	1.042	0.195***	1.045	0.194***	1.072	0.193***
LIABILITIES	−0.839	0.261***	−0.839	0.260***	−0.864	0.260***
EARNINGS	4.889	0.848***	4.879	0.841***	4.780	0.820***
Constant	−10,661.48	2285.909***	−10,656.48	2293.892***	−11,013.04	2416.339***
Industry controls	YES		YES		YES	
Year controls	YES		YES		YES	
N	1034		1034		1034	
F-statistic	62.982***		60.472***		56.961***	
Adjusted R^2	0.896		0.896		0.897	

Note: The table reports the results of the ordinary least squares regression for firm valuation models (3a and 3b; $N = 1034$). The column "Total emissions" refers to results for a firm valuation model containing an independent variable capturing total carbon emissions (*CO2_TOTAL*). The column "Decomposed carbon emissions" presents results for a firm valuation model containing decomposed variables of total carbon emissions: the expected component (*CO2_EXPECTED*) and the unexpected component (*CO2_UNEXPECTED*). The column "Decomposed carbon emissions and assurance" presents the results for a firm valuation model containing the interaction variables between assurance and the decomposed variables of total carbon emissions. The table reports the coefficients, the firm-clustered standard errors and the significance levels (***$p < 0.01$, **$p < 0.05$, *$p < 0.1$). Table 2 summarizes the variable definitions.

cap-and-trade system in California in effect since 2013). Moreover, initiatives at the federal level (e.g., The American Clean Energy and Security Act of 2009; EPA, 2010) and at the international level (e.g., United Nations Climate Change Conferences) expose the firms to risks because they may lead to higher carbon emissions-related costs in the future. In addition, increasing public attention to climate change may lead to reputational risks for firms with higher carbon emissions, which could result in lower revenues in the future. The valuation discount observed for the expected component appears to reflect such expected financial consequences.

If a firm decreases (increases) the level of carbon emissions further below (above) the expected level of carbon emissions (i.e., the benchmark carbon emissions), the firm value will increase (decrease) by USD 120,000 per additional thousand metric tons of unexpected carbon emissions (*CO2_UNEXPECTED*). The deviation of a firm's carbon emissions from its benchmark carbon emissions can be attributed to management effort and ability. Investors appear to reward firms whose management is committed to and is able to reduce carbon emissions compared to firms that are similar in terms of their business model and operating environment and penalize firms whose management is unwilling or unable to do so. Clarkson et al. (2015) document a valuation discount for allowance shortfalls, that is, the difference between a firm's actual carbon emissions falling under the EU ETS and those covered by related carbon emission allowances. If the carbon emission allowances allocated to the firms free of charge are not sufficient, additional carbon emission allowances must be purchased. Our measure of the unexpected component of carbon emissions differs from the measure for allocation shortfalls of Clarkson et al. (2015) because it reflects the difference between a firm's total carbon emissions, not restricted to those falling under the European Union, and its benchmark carbon emissions.

The coefficients of *CO2_EXPECTED* and *CO2_UNEXPECTED* are relatively similar in size, which indicates that investors apply a similar valuation discount to an additional thousand metric tons of carbon emissions of the expected component and the unexpected component of carbon emissions when determining the firm value. Although the unexpected component of carbon emissions is argued to contain considerably more "noise" due to discretion, manipulation and measurement error related to the reporting of carbon emissions, the investors consider this component to be as relevant as the expected component. In other words, both components of carbon emissions appear to convey information useful to aid investors in estimating future cash flows.

Assurance is an indicator of the credibility of sustainability-related disclosures (Fuhrmann et al., 2017; Simnett et al., 2009). To further analyze the effect of noise, we interact *ASSURANCE* with *CO2_EXPECTED* and *CO2_UNEXPECTED* in the firm valuation model (3b). We find a significant negative coefficient for *CO2_EXPECTED* (–0.124, $p < 0.05$) and an insignificant coefficient for the interaction of *CO2_EXPECTED* with *ASSURANCE* (–0.042, $p > 0.1$). This finding suggests that investors do not need assurance as a credibility signal to consider the information contained in the expected component of carbon emissions in their decision-making. They rely on the information contained in this component because they can easily compare it with that of similar firms and thus indirectly verify it themselves.

The unexpected component provides information about a firm's relative position, compared to similar firms, which allows conclusions to be drawn about management effort and ability. However, as we explained above, the unexpected component also captures noise related to the reporting of carbon emissions. We find both a significant coefficient for *CO2_UNEXPECTED* (–0.070, $p > 0.05$) and a significant negative coefficient for the interaction of *CO2_UNEXPECTED* with *ASSURANCE* (–0.229, $p < 0.05$). These results reveal a potential credibility issue associated with the unexpected component of carbon emissions. The unexpected component of carbon emissions is taken into account in the valuation, albeit with a certain valuation difference, compared to the expected component, which is probably due to the necessary but missing credibility signal. If the carbon emissions are assured, the firm value increases (decreases) by USD 299,000 for every thousand metric tons of carbon emissions lower (higher) than the expected carbon emissions. This valuation discount is about two times larger than the valuation discount for the expected component (i.e., USD 124,000). Investors seem to take into account that it requires management effort and the ability to reduce carbon emissions below the expected level of carbon emissions. If future carbon emissions measurement and reporting systems become more accurate and reliable, investors will consider the unexpected component of carbon emissions to be even more useful.

Overall, our results indicate that both the expected component and the unexpected component of carbon emissions are relevant for investors. However, the firm valuation model (3b) reveals that investors are more likely to consider the information contained in the unexpected component for firms with more credible disclosures.

5 | ADDITIONAL ANALYSES AND ROBUSTNESS TESTS

5.1 | Determinants of carbon emissions components

On the basis of our analysis, we argue that the two components of carbon emissions reflect different aspects of a firm's carbon management strategy and its implementation. The expected component of carbon emissions captures average carbon emissions due to a firm's business model and its operating environment, while the unexpected component captures management effort and the ability to influence carbon emissions. To assess the nomological validity of our decomposition, we rely on the CDP questionnaire, which also requests data on a firm's management efforts toward reducing carbon emissions. Specifically, we focus on five types of management efforts captured by the CDP questionnaire: (1–Target) Does management set targets for reducing carbon emissions? (2–EMS) Does management establish an environmental management system? (3–Initiative) Does management implement initiatives to reduce carbon emissions? (4–Incentive) Is management incentivized based on carbon emissions? (5–ETS) Does the firm participate in an emissions trading scheme? Some of these management efforts are the sole responsibility of management (e.g., Target, EMS (Environmental Management System)), while others are externally enforced (e.g., ETS). More symbolic management efforts (e.g., Target) create the impression of a change in behavior without necessarily actually changing it (Ashforth & Gibbs, 1990). More substantive management efforts (e.g., Incentive, ETS) focus on concrete actions and manifest in consequences for the management and/or the firm. The CDP has been requesting the respective data since 2009. Therefore, this analysis is restricted to firm-year observations from 2009 through 2014.

First, we separately analyze the five types of management efforts. For *CO2_EXPECTED* and *CO2_UNEXPECTED*, we apply the *t*-test (Wilcoxon rank-sum test) to compare the mean (median) value of the group of firms whose management makes the abovementioned efforts toward reducing carbon emissions with the mean (median) value of the group of firms whose management does not.[7] If the unexpected component of carbon emissions captures management effort and ability as theoretically implied, we will observe lower mean (median) values of *CO2_UNEXPECTED* for the firms whose management is making efforts to reduce carbon emissions, compared to firms without such efforts. We do not expect to observe such differences in the mean (median) values for *CO2_EXPECTED*. For firms participating in an ETS, the mean (median) values for *CO2_EXPECTED* might even be larger because an ETS primarily targets firms in industries with high carbon emissions.

Panel A of Table 7 presents descriptive statistics for *CO2_UNEXPECTED*. For all five types of management efforts, we find that the mean (median) values of *CO2_UNEXPECTED* of the group of firms that report having implemented a particular management effort are lower than the mean (median) values of the group of firms that do not. We also report significant differences in the mean (median) values of *CO2_UNEXPECTED* at the 5% significance level (except for the difference in the mean value for EMS). This finding suggests that not only more substantive management efforts but also more symbolic management efforts are reflected in the unexpected component of carbon emissions. In summary, the results for *CO2_UNEXPECTED* are consistent with our interpretation of the unexpected component of carbon emissions. Increased management efforts and improved abilities are reflected in lower carbon emissions compared to the benchmark carbon emissions.

[7] We also carried out regression analyses, which provide qualitatively similar results. However, due to our research design, we do not need to control for variables capturing the firm's business model and its operating environment anymore. Being the fitted value of the emissions estimation model, *CO2_EXPECTED* is significantly related to these variables. By construction, *CO2_UNEXPECTED* is orthogonal to *CO2_EXPECTED* and, thus, unrelated to these variables.

TABLE 7 Determinants of the components of carbon emissions

Panel A: Subgroup comparison per management indicator variable									
	Subgroup: No (value = 0)				Subgroup: Yes (value = 1)				Sign. difference no > yes
	N	Mean	St. dev.	Median	*N*	Mean	St. dev.	Median	Mean/median
CO2_UNEXPECTED									
Target	435	2199.856	16,393.660	19.033	468	−42.154	18,912.488	−49.247	**/***
EMS	356	1917.159	20,503.171	5.869	547	465.632	15,731.258	−80.385	–/***
Initiative	258	2619.999	15,081.534	32.770	645	405.038	18,710.353	−42.464	**/**
Incentive	347	3210.004	16,259.236	40.669	556	−317.738	18,535.613	−55.674	***/***
Emission Trading Scheme (ETS)	515	2929.749	15,274.381	5.532	388	−1473.226	20,371.213	−234.066	***/***

Panel B: Subgroup comparison per management indicator variable									
	Subgroup: No (value = 0)				Subgroup: Yes (value = 1)				Sign. difference no > yes
	N	Mean	St. dev.	Median	*N*	Mean	St. dev.	Median	Mean/median
CO2_EXPECTED									
Target	435	14,253.636	24,093.591	6219.021	468	12,444.835	22,842.683	2757.782	–/***
EMS	356	9322.355	18,133.246	2484.328	547	15,915.459	26,040.504	5259.437	–/–
Initiative	258	11,680.567	15,504.133	5209.091	645	13,970.432	25,948.070	3171.621	–/–
Incentive	347	12,677.939	18,688.543	5643.834	556	13,714.514	26,003.329	3041.447	–/**
ETS	515	10,462.381	16,620.987	2155.307	388	17,104.094	29,839.908	6916.191	–/–

(Continues)

TABLE 7 (Continued)

Panel C: Subgroup comparison based on management score									
		CO2_UNEXPECTED				*CO2_EXPECTED*			
	N	Mean	St. dev.	Median	Sign. difference subgroups 0 > X mean/median	Mean	St. DEV.	Median	Sign. difference subgroups 0 > X mean/median
MANAGEMENT_SCORE									
0	145	2490.623	13,398.091	40.915		7122.424	10,844.752	3167.436	
1	122	3959.810	18,101.876	19.133	–/–	17,518.113	18,882.538	12,497.440	–/–
2	71	3746.615	13,871.545	5.532	–/–	7119.562	10,786.533	478.386	–/**
3	148	2718.826	20,031.716	−31.272	–/–	13,170.038	24,272.395	2057.957	–/–
4	189	−2131.177	21,199.277	−3.544	**/**	16,892.340	32,815.410	3074.157	–/–
5	228	−757.156	15,908.112	−305.218	**/***	14,066.870	23,567.591	4270.922	–/–
Total	903	1037.884	17,769.441	−23.145		13,316.184	23,457.991	3740.338	

Note: The table reports descriptive statistics of *CO2_UNEXPECTED* (Panel A) and *CO2_EXPECTED* (Panel B) for subgroups of five types of carbon-related management efforts: Target captures whether the firm's management sets carbon emission reduction targets. EMS captures whether the firm's management has established an environmental management system Initiative and captures whether the firm's management has implemented initiatives to reduce carbon emissions. The incentive captures whether the firm's management is incentivized based on carbon emissions. ETS captures whether the firm participates in any emissions trading scheme.

In Panel C, the table reports descriptive statistics of *CO2_UNEXPECTED* and *CO2_EXPECTED* for subgroups based on *MANAGEMENT_SCORE*, which is calculated as the sum of the five types of carbon-related management efforts (i.e., Target, EMS, Initiative, Incentive and ETS).

The table reports the number of observations (*N*), the mean value, standard deviation (st. dev.) and the median value of the corresponding subgroup. In Panels A and B, the column "Sign. difference between subgroups" reports the significance levels (***$p < 0.01$, **$p < 0.05$, *$p < 0.1$) for the difference in mean values (*t*-test) and median values (Wilcoxon rank-sum test) between firms engaging in the respective carbon-related management effort (subgroup: yes) and firms not engaging in this effort (subgroup: no). In Panel C, the column "Sign. difference subgroups 0 > X" reports the significance levels (***$p < 0.01$, **$p < 0.05$, *$p < 0.1$) for the difference in mean values (*t*-test) and median values (Wilcoxon rank-sum test) between the subgroup with *MANAGEMENT_SCORE* equal 0 and the respective subgroup.

Panel B of Table 7 generally reports more ambiguous results for *CO2_EXPECTED* than Panel A for *CO2_UNEXPECTED*. For almost all management efforts, the mean (median) values are not significantly smaller for the group of firms implementing the respective efforts compared to the other group. For firms having implemented an EMS and firms participating in an ETS, the mean (median) values are even higher than for the comparison group. This illustrates that firms with relatively high carbon emissions (due to their business model) are more likely to implement an EMS and to be targeted by an ETS. The results are in line with our arguments that management effort and ability are not captured by the expected component. Overall, the findings for *CO2_EXPECTED* and *CO2_UNEXPECTED* support the nomological validity of the two components of carbon emissions.

Second, we analyze an aggregate score (*MANAGEMENT_SCORE*), which counts the different types of management efforts. *MANAGEMENT_SCORE* ranges from 0, which indicates that a firm reported no particular management effort, to 5, which indicates that a firm reported all five types of management efforts mentioned above. We apply the *t*-test (Wilcoxon rank-sum test) to compare the mean (median) value of the subgroup of firms reporting a certain number of carbon management efforts with the mean (median) value of the subgroup of firms not reporting management efforts.

Panel C of Table 7 reports detailed results. For *CO2_UNEXPECTED*, we find the lowest mean (median) value for the subgroup of firms with a *MANAGEMENT_SCORE* of 4 (mean: −2131.177 thousand metric tons). Surprisingly, we find the highest mean value not for firms reporting no management efforts at all but for firms with a *MANAGEMENT_SCORE* of 1 (mean: 3959.810 thousand metric tons). We find that mean (median) values of *CO2_UNEXPECTED* are significantly lower for the subgroups with a *MANAGEMENT_SCORE* of 4 and 5, compared to the subgroup with a MANAGEMENT_SCORE of 0. Apparently, firms whose management increases their efforts toward reducing carbon emissions show a significantly lower unexpected component of carbon emissions. For *CO2_EXPECTED*, we do not see such a clear association between management effort and the level of carbon emissions. For example, the second-highest median value of *CO2_EXPECTED* (4270.922) is reported for the subgroup with the highest *MANAGEMENT_SCORE*. In summary, the results suggest that the firm's management effort to reduce carbon emissions maps into the unexpected component.

5.2 | Direct carbon emissions

Prior research analyzing carbon emissions usually focuses on total carbon emissions (Hahn et al., 2015; Matsumura et al., 2014; Ott et al., 2017). However, only direct carbon emissions occur at sources owned or controlled by the firm. Moreover, only direct carbon emissions fall within the scope of most emission trading schemes (e.g., The European Parliament & The Council of the European Union, 2003) or carbon pricing systems such as the Australian carbon pricing mechanism (The Parliament of Australia, 2011). The EPA regulation on "Mandatory Reporting of Greenhouse Gases" also focuses on direct carbon emissions (EPA, 2010). Therefore, direct carbon emissions potentially have a larger impact on future cash flows. Thus, we focus only on direct carbon emissions in this additional analysis. We report the results of the models in Table 8. They indicate that the components of carbon emissions based on direct carbon emissions are negatively associated with firm value. The sizes and significance levels of the coefficients are similar to those in our analysis of total carbon emissions.

5.3 | Robustness tests

We perform a number of (unreported) robustness tests to explore whether and how different research design decisions affect our results. First, we examine different variations of the emissions estimation model because it is central to the differentiation between *CO2_EXPECTED* and *CO2_UNEXPECTED*. We complement our parsimonious selection of explanatory variables in the emissions estimation model by including additional explanatory variables, such as the firm's growth (measured as sales growth or growth in the number of employees), the firm's operating cycle (mea-

TABLE 8 Firm valuation models, including the different components of direct carbon emissions

Dependent variable: *FIRM_VALUE*	*Total direct carbon emissions* Coefficient	S.E.	*Decomposed direct carbon emissions* Coefficient	S.E.	*Decomposed direct carbon emissions and assurance* Coefficient	S.E.
SC1_TOTAL	−0.125	0.051**				
SC1_EXPECTED			−0.126	0.067*	−0.106	0.050**
SC1_UNEXPECTED			−0.123	0.050**	−0.074	0.041*
ASSURANCE	−1187.061	2094.013	−1191.185	2088.293	2052.35	2446.953
SC1_EXPECTED × *ASSURANCE*					−0.055	0.084
SC1_UNEXPECTED × *ASSURANCE*					−0.195	0.115*
ASSETS	1.041	0.198***	1.041	0.198***	1.066	0.196***
LIABILITIES	−0.844	0.268***	−0.844	0.269***	−0.867	0.268***
EARNINGS	4.901	0.869***	4.899	0.861***	4.813	0.848***
Constant	−1369.889	2927.01***	−1380.108	2959.051***	−272.713	3050.695
Industry controls	YES		YES		YES	
Year controls	YES		YES		YES	
N	943		943		943	
F-statistic	277.242***		267.709***		253.119***	
Adjusted R^2	0.895		0.895		0.895	

Note: The table reports the results of the ordinary least squares regression for the firm valuation model (3a and 3b) based on direct carbon emissions only ($N = 943$). The column “Total direct carbon emissions” refers to results for a firm valuation model containing an independent variable capturing total direct carbon emissions (*SC1_TOTAL*). The column “Decomposed direct carbon emissions” presents the results for a firm valuation model containing decomposed variables of total direct carbon emissions: the expected component (*SC1_EXPECTED*) and the unexpected component (*SC1_UNEXPECTED*). The column “Decomposed direct carbon emissions and assurance” presents the results for a firm valuation model containing the interaction variables between assurance and the decomposed variables of total direct carbon emissions. The table reports the coefficients, the firm-clustered standard errors and the significance levels (***$p < 0.01$, **$p < 0.05$, *$p < 0.1$). Table 2 summarizes the variable definitions.

sured as 360 divided by the ratio of sales to the average amount of receivables plus 360 divided by the ratio of cost of goods sold to the average amount of inventories), and the firm's ratio of depreciation to cost of goods sold. Because the additional variables are usually insignificant, the results for the alternative measures for *CO2_EXPECTED* and *CO2_UNEXPECTED* remain unchanged in terms of direction and significance. Instead of capturing industry-fixed effects using two-digit SIC codes, we apply two-digit NAICS codes. The results show negative and significant coefficients for *CO2_EXPECTED* and *CO2_UNEXPECTED*, which supports the robustness of our results. We also replicate Griffin et al.'s (2017) emissions estimation model. In contrast to our parsimonious selection of explanatory variables, we use total revenues, capital expenditures, the ratio of property, plant and equipment to depreciation expenses, intangible assets, gross margin, leverage and industry-indicator variables at the level of GICS industry sectors as explanatory variables. The results for *CO2_EXPECTED* and *CO2_UNEXPECTED* are very similar to our basic analyses in terms of direction and significance. In a final test, we focus only on the industry-specific variations of carbon emissions by excluding all variables capturing basic firm characteristics with the exception of industry-fixed effects. Unsurprisingly, the adjusted R^2s of the emissions estimation models drop to a range between 0.506 and 0.620, which attests that the basic firm characteristics contribute to the explanatory power of the emissions estimation model. However, even when using such a reduced emissions estimation model, our results for the firm valuation model remain qualitatively similar.

Second, we consider three alternatives to the firm valuation model (3a). First, we apply a firm valuation model in which all independent and dependent variables are scaled by common shares outstanding. We find results for the expected component and the unexpected component of carbon emissions that are directionally consistent with the firm valuation model (3a). Both *CO2_EXPECTED* and *CO2_UNEXPECTED* are significantly negatively associated with firm value. The coefficient of *CO2_EXPECTED* is larger than that of *CO2_UNEXPECTED*, but the difference in coefficient size is not significant. Second, we apply a firm valuation model in which firm value, total liabilities, operating income and carbon emissions are divided by total assets, and total assets are substituted by its inverse. Similar to the previous robustness test, the results are consistent with the results of the firm valuation model (3a) in terms of signs and significance. Third, we also test a firm valuation model without industry controls. This addresses concerns that including industry controls in both the emissions estimation model and the firm valuation model could be problematic. However, the results remain very similar, as the coefficients of *CO2_EXPECTED* and *CO2_UNEXPECTED* are negative and significant.

Third, the voluntary management decision to disclose information about carbon emissions might introduce a self-selection bias (Bouten et al., 2012; Matsumura et al., 2014; Ott et al., 2017). A firm might decide to report carbon performance only if it expects positive effects such as a higher firm value. We control for selection bias by implementing a two-step estimation approach as proposed by Heckman (1979). In the first step, we examine which firms are more likely to publish information about their carbon emissions. In the second step, we analyze how firm value varies across the two components of carbon emissions. Overall, our findings do not appear to be impacted by a self-selection bias. The Mills ratio is insignificant, and the results of the two-step estimation approach proposed by Heckman (1979) are consistent with the results for the other analyses presented in Sections 4 and 5.

Fourth, we divide the sample period into three 3-year periods (i.e., 2006–2008; 2009–2011; 2012–2014) to assess whether the coefficients capturing the firm value effects of carbon emissions change over time. As in the analysis for the entire sample period, the coefficients for *CO2_EXPECTED* and *CO2_UNEXPECTED* have the expected negative signs in the firm valuation model and are also significant across the three subsamples. In an additional subsample analysis, we only focus on the years after the financial crisis (i.e., 2010–2014) and find results widely similar to the results for the basic firm valuation model.

Fifth, prior literature suggests that the firm's location may affect the impact of carbon emissions on firm value (Griffin et al., 2021). However, our results do not appear to be significantly different between firms headquartered in a state with cap-and-trade systems (i.e., the nine Regional Greenhouse Gas Initiative states and California) and the others. Similarly, we find no significant differences in the firm value effects of carbon emission components between firms headquartered in Democratic versus Republican-leaning states (based on results of the presidential election in 2008 and 2012).

Sixth, we explore the identification of carbon-intensive industries using self-constructed measures for carbon intensity (e.g., total carbon emissions divided by revenues). We propose two alternatives: (1) We define carbon-intensive industries as those with a median carbon emission intensity larger than the median carbon emission intensity of all firms included in the S&P 500. (2) We classify firm-year observations as carbon-intensive if their carbon emission intensity is larger than the median carbon emission intensity of all firms included in the S&P 500. Unfortunately, such measures are noisy because the denominator (e.g., revenues) does not capture the depth of value-added processes or the actual production volume (e.g., over- vs. underproduction not identifiable by revenues). In addition, there is no agreement among investors on a cutoff value to distinguish between carbon-intensive and non-carbon-intensive industries, making the identification based on any cutoff value somewhat arbitrary. However, even for these somewhat weaker identifications of carbon-intensive industries, we find directionally consistent, although generally less significant, the results for the variables of interest *CO2_EXPECTED* and *CO2_UNEXPECTED*.

Seventh, we consider all firms included in the S&P 500, whether or not they operate in carbon-intensive industries. We find qualitatively similar results, albeit with generally smaller and less significant coefficients for *CO2_EXPECTED* and *CO2_UNEXPECTED*. This is less surprising because carbon emissions are less critical for firms in non-carbon-intensive industries. Similarly, Matsumura et al. (2014) find no significant coefficient for carbon emissions in an analysis focusing specifically on firms from non-carbon-intensive industries.

6 | CONCLUSION

We are the first to examine the firm-value effects of the two components of carbon emissions: the expected component capturing the average carbon emissions for similar firms operating in the same industry and the unexpected component capturing the management effort and ability to influence carbon emissions. We find that the capital market attaches value to both components of carbon emissions for firms from carbon-intensive industries. Lower carbon emissions are generally associated with higher firm values. Both components of carbon emissions appear to contain useful information that investors consider in their estimations of future cash flows. In addition, we find that investors attach more value to the unexpected component of carbon emissions if the information is assured. The unexpected component of carbon emissions appears to contain some "noise," which is perceived to be lower for the information contained in a firm's assured carbon emissions.

Our results have implications for both accounting research and practice. For research, we add to the literature on the firm value effects of carbon emissions (Clarkson et al., 2015; Griffin et al., 2017; Matsumura et al., 2014) by proposing a parsimonious selection of firm characteristics for the emissions estimation model, which can be used to decompose carbon emissions. The decomposition of carbon emissions allows for a more direct analysis of the effects of low carbon disclosure quality on firm value and other capital market-related measures. In practice, our results provide evidence of a firm-value effect of carbon emissions and therefore highlight the relevance and usefulness of a good carbon management system. Environmental performance alters investors' valuation of the firm's perceived future financial performance, and higher stock prices represent the actual financial benefits of low carbon emissions. In addition, we find the strongest firm-value effect for the assured unexpected component of carbon emissions. If future carbon emissions measurement and reporting systems become more accurate and reliable, investors will consider the unexpected component of carbon emissions to be more relevant to their decision-making.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from Compustat, Thomson Reuters and the CDP. Restrictions apply to the availability of these data, which were used under license for this study.

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