Chuen-Ping Chang, Fu-Wei Huang & Jeng-Yan Tsai (2026). From Carbon Compliance to Sustainable Value Creation: A Conceptual Framework for Carbon Handprints under Carbon Pricing. *Academos Journal, Vol. 2, No. 3*, 2026, 89-103

Original scientific paper

UDC: 502.13/.14:551.588.7

Received: 12. 08.2026.
Revised: 21.08.2026.
Accepted: 25.08.2026.

DOI: https://doi.org/10.65921/8hvdkj30

From Carbon Compliance to Sustainable Value Creation: A Conceptual Framework for Carbon Handprints under Carbon Pricing

Chuen-Ping Chang[1], Fu-Wei Huang[2], Jeng-Yan Tsai[3]
[1]Department of Public Finance and Taxation, National Kaohsiung University of Science and Technology, Kaohsiung City, Taiwan; E-mail: cpchang@nkust.edu.tw ; ORCID iD: 0000-0002-7130-5413
[2]Department of Banking and Finance, CTBC Business School, Tainan, Taiwan; E-mail: kwala.wei@ctbc.edu.tw ; ORCID iD: 0000-0001-6514-6594
[3]Department of International Business, Tamkang University, New Taipei City, Taiwan; E-mail: tsaijy@mail.tku.edu.tw ; ORCID iD: 0000-0002-6011-219X

Abstract: Environmental regulation is increasingly expected not only to reduce carbon emissions but also to promote sustainable value creation through positive environmental incentives. However, existing studies generally examine carbon pricing, carbon handprints, and sustainable value creation separately, leaving the economic mechanism linking these research streams insufficiently explained. This conceptual paper develops a unified theoretical framework that integrates carbon pricing, recognized carbon handprints, and institutional recognition into firms' production decisions. Using an optimization-based analytical approach, the framework examines how carbon-pricing costs and the recognized economic value of avoided emissions jointly affect firms' optimal production decisions. The analysis shows that institutional recognition transforms avoided emissions into measurable economic value and identifies the threshold at which environmental regulation shifts from a compliance-oriented mechanism toward sustainable value creation. The findings suggest that carbon pricing and carbon handprint recognition can operate as complementary policy instruments. Policymakers may therefore strengthen climate-policy effectiveness by combining carbon-cost internalization with institutional mechanisms that reward positive environmental performance. As a conceptual study, the analysis does not rely on empirical datasets.
Keywords: Carbon pricing; Carbon handprints; Institutional recognition; Sustainable value creation; Climate policy.

Introduction

Environmental regulation is increasingly expected not only to reduce carbon emissions through regulatory compliance but also to encourage positive environmental contributions. Carbon pricing has become a cornerstone of contemporary climate policy by assigning an explicit economic cost to greenhouse-gas emissions and encouraging firms to adopt cleaner production technologies (Porter & van der Linde, 1995; Nordhaus, 2019). Although carbon pricing promotes environmental efficiency by internalizing emission-related costs, growing attention is being directed toward policy mechanisms that also recognize and reward environmentally beneficial activities. This development reflects a broader shift in climate policy from a predominantly compliance-oriented approach toward sustainable value creation, creating a need for conceptual frameworks that explain how positive environmental contributions influence firms' economic decisions.

Carbon pricing is widely recognized as one of the most effective market-based instruments for mitigating greenhouse-gas emissions because it encourages firms to internalize environmental costs while maintaining flexibility in production and investment decisions (Porter & van der Linde, 1995; Aldy & Stavins, 2012; Nordhaus, 2019). Consequently, the existing literature has primarily examined firms' responses to climate policy through environmental compliance, emission reduction, and the internalization of carbon-related costs. This perspective has

substantially advanced our understanding of the economic effects of environmental regulation. However, focusing exclusively on cost internalization provides only a partial explanation of firms' environmental decision-making. In practice, firms increasingly pursue environmental strategies not only to reduce compliance costs but also to create long-term economic value through cleaner production and sustainable innovation. This development suggests that an effective climate-policy framework should incorporate mechanisms capable of recognizing and rewarding positive environmental contributions in addition to pricing carbon emissions.

This changing policy perspective has led to increasing attention to carbon handprints, which emphasize positive environmental contributions generated through cleaner technologies and sustainable production (Grönman et al., 2019; Tuppura et al., 2024; Eberhardt et al., 2024). Unlike conventional carbon-footprint measures that primarily quantify environmental burdens, carbon handprints highlight the environmental benefits created by reducing or avoiding emissions. As a result, they provide a broader perspective for evaluating firms' environmental performance. Despite this growing interest, the economic role of carbon handprints remains insufficiently understood. Existing studies have primarily focused on environmental measurement and sustainability assessment, while relatively little attention has been devoted to explaining how positive environmental contributions influence firms' production decisions or create measurable economic incentives. Consequently, an important conceptual question remains unresolved: How can positive environmental contributions become measurable economic incentives that influence firms' production decisions under carbon pricing?

Although carbon pricing, carbon handprints, and sustainable value creation have each attracted increasing academic attention, they have largely developed as separate lines of research. Consequently, existing studies do not explain how positive environmental contributions can be systematically incorporated into firms' production decisions or transformed into measurable economic value within a unified optimization framework. This missing analytical linkage limits our theoretical understanding of how environmental regulation influences firms beyond conventional cost internalization. To address this issue, this conceptual paper introduces institutional recognition as the economic mechanism that connects recognized carbon handprints with firms' production decisions. By explicitly incorporating institutional recognition into a unified optimization model, the proposed framework explains how positive environmental contributions become measurable economic incentives and identifies the conditions under which environmental regulation evolves from compliance to sustainable value creation.

This conceptual paper develops a unified theoretical framework that integrates carbon pricing, recognized carbon handprints, and institutional recognition within firms' production decisions. The framework offers a theoretical perspective on how environmental regulation may evolve from compliance toward sustainable value creation.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature and identifies the research gap. Section 3 presents the theoretical framework and analytical methodology. Section 4 reports the main analytical results, Section 5 discusses their theoretical and policy implications, and Section 6 concludes the paper.

Literature review

Carbon pricing and firms' production decisions

Carbon pricing has become one of the principal market-based instruments for addressing climate change by incorporating the environmental costs of greenhouse-gas emissions into firms' economic decision-making. Rather than prescribing specific abatement technologies, carbon-pricing mechanisms influence firms' production, investment, and innovation decisions by assigning an explicit economic cost to carbon emissions. Consequently, firms are encouraged to reduce emission intensity through market incentives while retaining the

flexibility to determine their own production strategies (Porter & van der Linde, 1995; Nordhaus, 2019).

A growing body of research has investigated how carbon pricing influences firms' production behavior and economic performance. Existing studies generally conclude that higher carbon prices increase production costs, alter firms' input choices, encourage technological upgrading, and accelerate investment in cleaner production technologies (Aldy & Stavins, 2012; Martin et al., 2014; Calel & Dechezleprêtre, 2016). These findings suggest that carbon pricing plays an important role in promoting technological innovation and facilitating the transition toward low-carbon production systems.

More recent studies further argue that the effectiveness of carbon pricing depends not only on the carbon price itself but also on firms' responses to environmental regulation. Well-designed environmental policies may improve both environmental and economic performance by encouraging technological innovation, resource reallocation, and productivity improvement rather than merely increasing regulatory costs (Porter & van der Linde, 1995; Calel & Dechezleprêtre, 2016). Consequently, firms increasingly regard environmental investment as part of their long-term competitive strategy instead of viewing emission reduction solely as a regulatory obligation.

Despite these important advances, existing carbon-pricing models continue to interpret environmental regulation primarily from the perspective of cost internalization. Carbon pricing typically enters firms' objective functions as an additional production cost or environmental compliance expenditure, implying that environmental improvement mainly serves to reduce regulatory burdens (Nordhaus, 2019; Aldy & Stavins, 2012). Relatively less attention has been devoted to the possibility that superior environmental performance may itself become a source of measurable economic value capable of influencing firms' production decisions.

This limitation becomes increasingly important as firms adopt climate strategies that emphasize innovation, sustainability, and long-term value creation. Recent environmental and corporate sustainability research suggests that firms may generate competitive advantages through environmental leadership rather than simply minimizing compliance costs (Hart, 1995; Eccles et al., 2014; Friede et al., 2015). However, the existing carbon-pricing literature has not yet established a formal theoretical framework explaining how positive environmental performance can be incorporated directly into firms' production decisions as a source of measurable economic value. Addressing this issue requires extending the traditional cost-internalization perspective toward a theoretical framework that explicitly recognizes the economic value of recognized avoided emissions. The following section therefore reviews the emerging literature on carbon handprints.

Carbon handprints and environmental value creation

The concept of carbon handprints has recently emerged as an important complement to conventional carbon-footprint assessment. Whereas carbon footprints quantify the environmental burdens generated by production and consumption activities, carbon handprints emphasize the positive environmental impacts created through avoided emissions, cleaner technologies, and sustainable innovation (Grönman et al., 2019). This perspective shifts environmental assessment from measuring negative environmental impacts toward recognizing positive climate contributions, thereby providing a broader framework for evaluating firms' environmental performance.

Building upon this concept, subsequent studies have further expanded the methodological foundations of carbon handprints. Existing research has primarily focused on developing standardized assessment methods, life-cycle evaluation procedures, sector-specific applications, and environmental reporting frameworks capable of quantifying avoided emissions generated by products, technologies, and production systems (Tuppura et al., 2024;

Eberhardt et al., 2024). These studies have substantially improved the consistency and transparency of carbon handprint measurement and have demonstrated its usefulness for environmental communication, sustainability assessment, and life-cycle management.

The increasing adoption of carbon handprints also reflects a broader transition in sustainability research from environmental burden reduction toward positive environmental value creation. Rather than evaluating firms solely according to the emissions they generate, carbon handprints recognize the environmental benefits that firms create by replacing more carbon-intensive technologies or production processes. Consequently, carbon handprints provide an important conceptual foundation for understanding how technological innovation contributes to climate-change mitigation while simultaneously improving firms' environmental performance (Hart, 1995; Grönman et al., 2019).

Despite these important developments, the existing carbon handprint literature remains primarily concerned with environmental measurement rather than economic decision-making. Current studies generally treat carbon handprints as indicators of environmental performance, sustainability reporting, or life-cycle assessment, while relatively little attention has been devoted to explaining how avoided emissions influence firms' production decisions, profitability, or resource allocation. Consequently, carbon handprints remain largely measures of environmental performance rather than variables that directly influence firms' economic decisions.

This limitation has become increasingly important as governments, investors, and financial institutions place greater emphasis on climate-related corporate performance. Growing evidence indicates that environmental information is becoming progressively more relevant to investment decisions, corporate valuation, and sustainable finance (Eccles et al., 2014; Friede et al., 2015; Krueger et al., 2020; Bolton & Kacperczyk, 2021). Nevertheless, the existing carbon handprint literature has not yet established a theoretical framework explaining how recognized avoided emissions influence firms' production decisions or generate measurable economic value. This limitation naturally leads to the next stream of research, which examines how environmental performance is translated into measurable economic value through sustainable value creation and institutional recognition.

Sustainable value creation and institutional recognition

Recent advances in sustainability research have increasingly shifted attention from environmental compliance toward sustainable value creation. Rather than viewing environmental protection solely as a regulatory obligation or an additional production cost, contemporary studies argue that superior environmental performance may generate long-term economic benefits by strengthening firms' competitiveness, improving stakeholder relationships, and enhancing corporate value (Hart, 1995; Eccles et al., 2014; Friede et al., 2015). Consequently, environmental performance is increasingly regarded as a strategic resource capable of contributing to firms' long-run economic success.

The growing importance of sustainable finance has further strengthened this perspective. Investors, financial institutions, and capital markets increasingly incorporate climate-related information into investment decisions, corporate valuation, and lending activities. Firms demonstrating superior environmental performance generally experience lower financing costs, improved access to capital, and stronger investor confidence because climate-related risks and sustainability performance have become increasingly relevant to corporate valuation (Krueger et al., 2020; Bolton & Kacperczyk, 2021; Flammer, 2021). These developments suggest that environmental performance may generate measurable economic value through institutional recognition rather than solely through regulatory compliance.

From an economic perspective, the recognition of environmental performance depends on institutional mechanisms capable of translating environmental improvements into economic

incentives. Institutional recognition encompasses market- and policy-based mechanisms, including carbon-credit markets, sustainability disclosure standards, green public procurement, transition-finance policies, and environmental certification systems. These mechanisms influence firms' production and investment decisions by increasing the private value associated with environmental improvement, thereby complementing conventional carbon-pricing policies that primarily operate through cost internalization (Porter & van der Linde, 1995; Krueger et al., 2020; Flammer, 2021).

Despite the rapid development of sustainable finance and corporate sustainability research, relatively little attention has been devoted to formally incorporating institutional recognition into firms' production decisions. Existing studies generally document the relationship between environmental performance and corporate value using empirical evidence, whereas the underlying economic mechanism through which recognized environmental performance influences firms' production behavior remains largely unexplored. Consequently, institutional recognition is typically treated as an empirical observation rather than an explicit mechanism within firms' economic decision-making.

This limitation is particularly important for the emerging carbon handprint literature. Although carbon handprints quantify positive environmental contributions through avoided emissions, existing studies do not explain how these environmental improvements become economically valuable once they are recognized by market and policy institutions. The present study addresses this limitation by introducing an explicit recognition mechanism through which avoided emissions are transformed into measurable economic value that directly enters firms' production decisions. This institutional-recognition perspective provides the theoretical foundation for integrating carbon pricing, carbon handprints, and sustainable value creation within a unified optimization framework.

Research gap and theoretical contribution

The preceding review highlights three important research streams concerning climate policy and sustainable production. Carbon-pricing studies have established how environmental regulation influences firms' production decisions by internalizing the costs of carbon emissions (Porter & van der Linde, 1995; Nordhaus, 2019). Carbon handprint research has advanced the measurement of avoided emissions and positive environmental contributions (Grönman et al., 2019; Tuppura et al., 2024; Eberhardt et al., 2024). Meanwhile, sustainable finance studies have demonstrated that environmental performance increasingly affects corporate valuation, financing conditions, and firms' long-term competitiveness (Eccles et al., 2014; Krueger et al., 2020; Bolton & Kacperczyk, 2021).

Despite these advances, these research streams remain only loosely connected. Existing carbon-pricing models primarily emphasize environmental cost internalization, whereas carbon handprint studies focus mainly on environmental measurement. At the same time, sustainable finance literature generally documents the economic consequences of environmental performance without explicitly incorporating those effects into firms' production decisions. Consequently, the economic role of recognized avoided emissions remains insufficiently explained within a unified theoretical framework.

To address this gap, this conceptual paper develops an optimization-based theoretical framework that integrates carbon pricing, carbon handprints, and institutional recognition into a single analytical framework. The model treats recognized carbon handprints as an explicit economic incentive rather than merely an environmental-performance indicator, allowing avoided emissions to directly influence firms' production decisions and sustainable value creation.

Accordingly, this study makes three contributions. First, it integrates carbon pricing, carbon handprints, and institutional recognition within a unified theoretical framework. Second, it

introduces an explicit recognition mechanism through which avoided emissions become measurable economic value affecting firms' optimal production decisions. Third, it identifies the institutional conditions under which environmental regulation evolves from a compliance-oriented mechanism into a value-creation mechanism.

Materials and methods: Theoretical framework

This study adopts an optimization-based analytical approach to develop a conceptual model of firms' production decisions under carbon pricing and carbon handprint recognition. Rather than relying on empirical data, the analysis specifies a representative profit-maximizing firm and derives its optimal production decision from a formal economic model. The analytical procedure consists of defining the model environment, specifying the production and environmental cost structure, deriving the firm's optimal output, and examining the resulting comparative-static effects and transition condition.

Conceptual framework

The proposed theoretical framework integrates three research streams that have largely developed independently in the existing literature: carbon pricing, carbon handprints, and sustainable value creation. Carbon pricing influences firms' production decisions by internalizing the environmental costs of carbon emissions, whereas carbon handprints represent the positive environmental contributions generated through avoided emissions. The present study further introduces institutional recognition as the mechanism through which these avoided emissions are transformed into measurable economic value.

Within this framework, firms simultaneously face two environmental incentives. Carbon pricing increases production costs through environmental compliance obligations, while recognized carbon handprints generate economic benefits by rewarding cleaner production technologies. Consequently, firms determine their production decisions by balancing conventional production costs, carbon-pricing costs, and the economic value created by recognized carbon handprints.

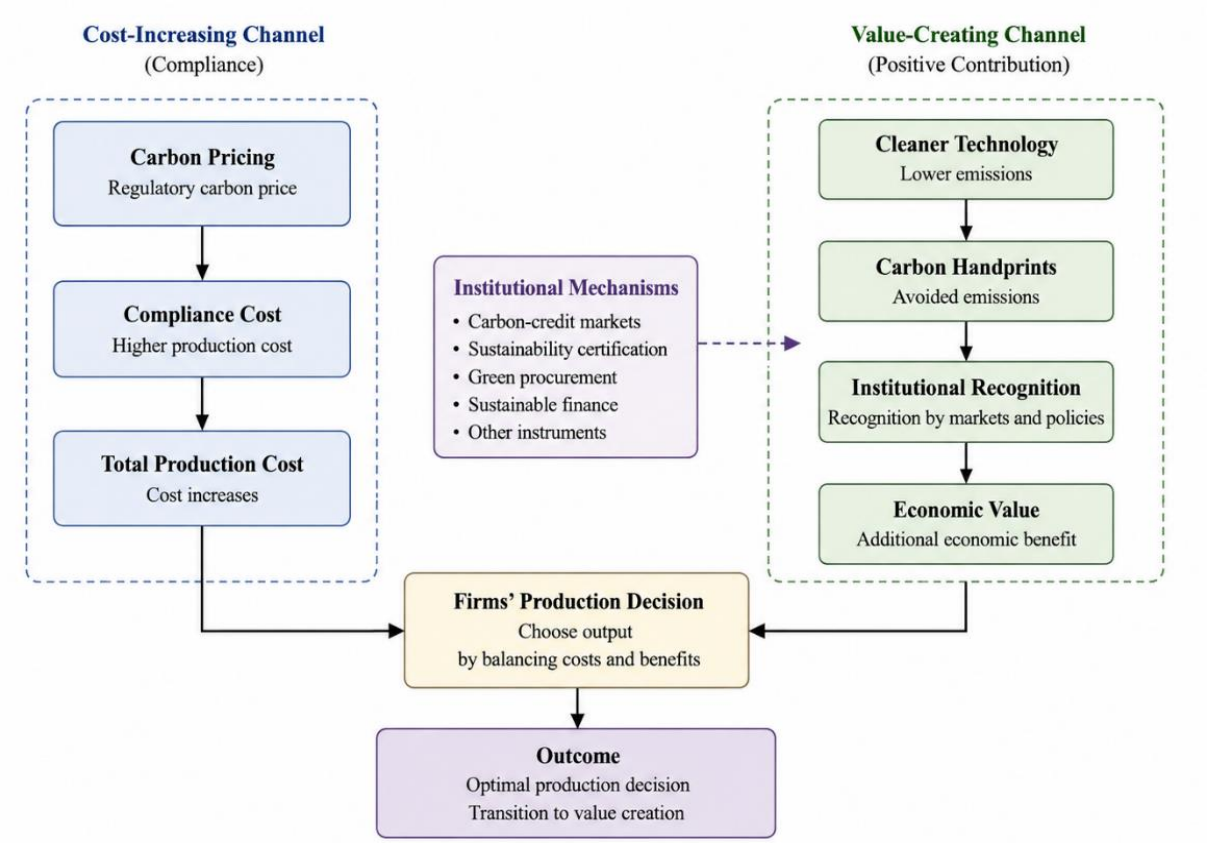

Figure 1: Conceptual Framework for the Interactions among Carbon Pricing, Carbon Handprints, and Institutional Recognition

Note. The framework illustrates the cost-increasing channel through carbon pricing and the value-creating channel through recognized carbon handprints. Source: Authors' own elaboration.

Figure 1 summarizes the conceptual structure of the proposed framework. Environmental regulation and institutional recognition jointly influence firms' production decisions through two complementary economic channels: carbon pricing discourages carbon-intensive production by increasing environmental costs, whereas recognized carbon handprints encourage cleaner production by creating additional economic value. The interaction between these two mechanisms determines firms' optimal production decisions and establishes the conditions under which environmental regulation evolves from a compliance-oriented system toward sustainable value creation.

Based on this conceptual framework, the following sections formally develop the theoretical model. Section 3.2 defines the model environment, while Sections 3.3 and 3.4 specify the firm's production-cost structure and derive its optimal production decision. Section 4 presents the analytical results, and Section 5 discusses their theoretical and policy implications.

Model environment

We consider a representative profit-maximizing firm operating under a carbon-pricing regime. The firm produces a homogeneous product using a technology characterized by its carbon-emission intensity and determines its production decisions by jointly considering conventional production costs, carbon-pricing obligations, and the economic value generated by avoided emissions. Consistent with the environmental economics literature, carbon pricing internalizes the social cost of greenhouse-gas emissions by assigning an explicit price to carbon emissions, thereby encouraging firms to adopt cleaner production technologies (Porter & van der Linde, 1995; Nordhaus, 2019). At the same time, recent developments in carbon handprint research emphasize that firms may create positive environmental value through avoided emissions

relative to a benchmark technology rather than merely reducing their own emissions (Grönman et al., 2019; Eberhardt et al., 2024). Accordingly, firms simultaneously face two complementary environmental incentives: the regulatory cost imposed on emissions and the economic opportunity created by superior environmental performance.

Let $Q \geq 0$ denote the firm's production level. The firm's production technology is characterized by its carbon-emission intensity $E_T > 0$, measured as carbon emissions per unit of output. Total emissions generated by the firm are therefore expressed as

$$\varepsilon(Q) = E_T Q \tag{1}$$

To evaluate environmental performance, production emissions are compared with those generated by a benchmark technology. Let $E_B > 0$ denote the benchmark emission intensity, which may represent an industry-standard production process, a conventional technology, or an appropriate baseline adopted for environmental assessment (Grönman et al., 2019; Tuppura et al., 2024). Throughout the analysis, the benchmark technology is assumed to be exogenously given and observable to regulators, investors, customers, and other market participants.

Following the carbon handprint framework proposed by Grönman et al. (2019), the firm's carbon handprint is defined as the avoided emissions generated per unit of output relative to the benchmark technology,

$$C_H = E_B - E_T \tag{2}$$

Accordingly, the firm's total avoided emissions are

$$H(Q) = C_H Q = (E_B - E_T) Q \tag{3}$$

A positive value of C_H indicates that the firm's production technology emits less carbon than the benchmark technology and therefore generates positive environmental benefits through avoided emissions. When $C_H = 0$, the firm's environmental performance is identical to that of the benchmark technology. Conversely, $C_H < 0$ implies that the firm's technology is more emission-intensive than the benchmark and therefore does not generate a positive carbon handprint. Because this study focuses on the transformation of environmental performance into economic value, the subsequent analysis considers firms satisfying $C_H > 0$.

Although carbon handprints measure avoided emissions, avoided emissions alone do not automatically create economic value. Their economic significance depends on whether positive environmental performance is recognized and rewarded through institutional arrangements such as carbon-credit systems, green procurement programs, sustainability certification, environmental subsidies, climate-related financial markets, or investors' valuation of low-carbon production (Krueger et al., 2020; Bolton & Kacperczyk, 2021; Eberhardt et al., 2024). To capture this institutional mechanism, let $\theta \geq 0$ denote the recognition coefficient assigned to each unit of avoided emissions. The parameter θ summarizes the extent to which environmental performance can be converted into measurable economic value through market and policy institutions. The recognized economic value generated by carbon handprint per unit of output is therefore defined as

$$h = \theta C_H = \theta(E_B - E_T) \tag{4}$$

and the firm's total recognized handprint value is

$$H(Q) = hQ = \theta(E_B - E_T) Q \tag{5}$$

When $\theta = 0$, avoided emissions receive no economic recognition, and the carbon handprint remains solely an environmental-performance indicator. As θ increases, avoided emissions generate progressively greater economic value, strengthening firms' incentives to adopt cleaner production technologies and improve environmental performance. Consequently, the parameter θ reflects not only environmental policy but also the maturity of sustainable finance,

carbon markets, and institutional mechanisms that reward positive climate contributions (Eccles et al., 2014; Friede et al., 2015).

This formulation establishes an important distinction between physical environmental performance and economic value creation. The carbon handprint C_H is determined by technological differences between the firm's production process and the benchmark technology, whereas the recognized handprint value $H(Q)$ depends on institutional recognition through the parameter θ. Consequently, environmental performance alone is insufficient to generate economic benefits unless supported by effective policy and market institutions. This distinction enables the carbon handprint to be interpreted as an environmental asset whose measurable economic value depends on technological performance and institutional recognition, thereby providing the analytical foundation for the production-cost and profit-maximization framework developed in the following sections (Hart, 1995; Porter & van der Linde, 1995).

Production and cost structure

Production activities simultaneously generate market output and carbon emissions. Under carbon-pricing regulation, firms therefore face a broader production problem than that considered in conventional production theory. Besides conventional operating expenditures, firms must bear the environmental costs associated with carbon emissions while simultaneously considering the potential economic benefits arising from avoided emissions. Consequently, production costs are jointly determined by technological efficiency, environmental regulation, and the institutional recognition of positive environmental performance (Porter & van der Linde, 1995; Nordhaus, 2019; Grönman et al., 2019).

The firm's conventional production cost is assumed to consist of a constant marginal production cost together with increasing marginal operating costs associated with capacity utilization, production adjustment, and organizational coordination. This cost structure is represented by

$$C_P(Q) = cQ + kQ^2 \tag{6}$$

where $c > 0$ denotes the constant marginal production cost and $k > 0$ measures the degree of increasing marginal operating costs. The quadratic specification provides a tractable convex-cost structure in which marginal production costs increase with output (Dixit, 1979).

Environmental regulation further modifies the firm's production cost through two distinct but complementary mechanisms. First, carbon pricing imposes an environmental compliance cost proportional to emissions. Second, recognized carbon handprints generate an economic benefit by rewarding avoided emissions relative to the benchmark technology. Combining these two effects, the firm's total production cost is specified as

$$C(Q) = cQ + kQ^2 + \tau E_T Q - \theta(E_B - E_T)Q \tag{7}$$

where the third term represents the carbon-pricing obligation, while the fourth term represents the recognized economic value generated by carbon handprints. The parameter τ measures the regulatory price assigned to carbon emissions, whereas θ captures the degree to which avoided emissions are recognized and rewarded by environmental policies, carbon markets, sustainable finance, and other institutional mechanisms (Krueger et al., 2020; Bolton & Kacperczyk, 2021).

Eq. (7) constitutes the central cost function of the proposed framework. Unlike conventional environmental-economic models, in which carbon regulation only increases firms' production costs, the present formulation explicitly incorporates both the cost-increasing effect of carbon pricing and the cost-reducing effect of recognized carbon handprints. Consequently, firms are encouraged not only to reduce emissions in order to avoid regulatory costs but also to create positive environmental value that can be transformed into measurable economic returns. This dual-incentive mechanism distinguishes the proposed framework from traditional carbon-pricing models and establishes the theoretical foundation for the firm's optimal production

decisions developed in the following section (Hart, 1995; Eccles et al., 2014; Eberhardt et al., 2024).

Optimal production decisions

Having established the firm's production-cost structure, we now examine how carbon pricing and carbon handprint recognition jointly influence production decisions. Unlike conventional environmental-economic models, in which firms respond only to the compliance costs generated by carbon regulation, the proposed framework recognizes that cleaner production technologies may simultaneously create measurable economic value through recognized carbon handprints. Consequently, firms determine their production decisions by balancing market demand, production costs, environmental compliance costs, and the economic benefits associated with avoided emissions (Porter & van der Linde, 1995; Hart, 1995; Nordhaus, 2019).

Assume that market demand is represented by the inverse demand function:

$$P(Q) = a - bQ \tag{8}$$

where $a > 0$ is the intercept of market demand, and $b > 0$ measures the responsiveness of market price to output. Accordingly, the firm's total revenue is given by $R(Q) = P(Q)Q$, and together with the production-cost function in Eq. (7), profit can be expressed as

$$\Pi(Q) = (a - bQ)Q - [cQ + kQ^2 + \tau E_T Q - \theta(E_B - E_T)Q] \tag{9}$$

Eq. (9) indicates that carbon pricing and carbon handprint recognition influence firms' production decisions through distinct but complementary channels. Carbon pricing reduces profitability by increasing environmental compliance costs, whereas recognized carbon handprints improve profitability by transforming avoided emissions into measurable economic returns. Consequently, firms have incentives not only to reduce emission intensity but also to create environmental value that can be recognized by policy and market institutions (Krueger et al., 2020; Bolton & Kacperczyk, 2021; Eccles et al., 2014).

Maximizing Eq. (9) with respect to production yields the firm's optimal production decision:

$$Q^* = \frac{a - c - \tau E_T + \theta(E_B - E_T)}{2(b + k)} \tag{10}$$

Since both the slope of market demand (b) and the marginal operating-cost parameter (k) are assumed to be positive, the profit function is strictly concave with respect to output. Accordingly, the second-order condition is satisfied, ensuring that Eq. (10) represents a unique interior optimum.

Eq. (10) constitutes the central behavioral result of the proposed framework. Unlike conventional carbon-pricing models, the firm's optimal production depends not only on production costs and environmental compliance obligations but also on the economic value generated by recognized carbon handprints. A higher carbon price lowers the firm's optimal production by increasing compliance costs, whereas stronger institutional recognition of carbon handprints increases optimal production by improving the profitability of cleaner technologies. The carbon handprint therefore functions not merely as an environmental-performance indicator but as an explicit economic incentive that directly influences firms' production decisions. This mechanism provides the theoretical foundation for the comparative-static analysis presented in Section 4.1 (Porter & van der Linde, 1995; Friede et al., 2015; Eberhardt et al., 2024).

Results

Comparative statics and theoretical implications

The analytical solution in Eq. (10) provides the basis for evaluating how environmental regulation and carbon handprint recognition affect firms' optimal production decisions. Comparative-static analysis demonstrates the individual effects of policy variables on optimal

production while providing theoretical insights into the interaction between carbon pricing and positive environmental incentives.

Differentiating Eq. (10) with respect to the carbon-pricing parameter yields

$$\frac{\partial Q^*}{\partial \tau} = -\frac{E_T}{2(b+k)} < 0 \tag{11}$$

Eq. (11) indicates that a higher carbon price unambiguously reduced the firm's optimal production level. As environmental compliance costs increased, production became more expensive, thereby reducing firms' incentives to expand output. This result is consistent with the primary objective of carbon-pricing policies, namely to internalize environmental externalities by discouraging carbon-intensive production (Nordhaus, 2019; World Bank, 2024).

By contrast, differentiating Eq. (10) with respect to the recognition coefficient gives

$$\frac{\partial Q^*}{\partial \theta} = \frac{E_B - E_T}{2(b+k)} > 0 \tag{12}$$

provided that the firm generates a positive carbon handprint ($E_B > E_T$). Eq. (12) demonstrates that stronger institutional recognition of avoided emissions increased firms' optimal production by improving the private returns to cleaner production technologies. Unlike carbon pricing, which operated through a cost-increasing mechanism, carbon handprint recognition created incentives through value creation. Consequently, environmental regulation may simultaneously discourage carbon-intensive production while encouraging environmentally superior production.

Taken together, Eqs. (11) and (12) reveal that carbon pricing and carbon handprint recognition represented two complementary policy instruments rather than competing regulatory approaches. Carbon pricing penalized undesirable environmental outcomes, whereas carbon handprint recognition rewarded positive environmental contributions. The interaction between these two mechanisms enabled environmental policy to influence firms through cost-increasing and value-creating incentives, thereby establishing a more balanced framework for sustainable production (Porter & van der Linde, 1995; Hart, 1995; Eccles et al., 2014).

The above results lead directly to the following theoretical propositions.

Proposition 1. An increase in carbon pricing reduces the firm's optimal production by increasing environmental compliance costs.

Proposition 2. For firms generating a positive carbon handprint, an increase in carbon handprint recognition raises the firm's optimal production by increasing the economic value generated by avoided emissions.

Proposition 3. Carbon pricing and carbon handprint recognition constitute complementary policy instruments, simultaneously penalizing carbon emissions and rewarding positive environmental performance.

Unlike conventional environmental-economic models that emphasize only the cost of carbon emissions, the present framework demonstrates that sustainable production depends on the joint operation of regulatory pressure and positive environmental incentives. The carbon handprint therefore functions as an explicit economic mechanism through which recognized avoided emissions influence firms' production decisions and sustainable value creation. This theoretical result provides the conceptual basis for the transition conditions discussed in Section 4.2 (Friede et al., 2015; Eberhardt et al., 2024).

Transition from compliance to value creation

The preceding analysis demonstrates that carbon pricing and recognized carbon handprints influence firms through two distinct economic channels. Carbon pricing increases production costs by assigning an explicit economic cost to greenhouse-gas emissions, whereas recognized

carbon handprints create economic value by rewarding avoided emissions generated through cleaner production technologies. Recent developments in climate policy increasingly emphasize that effective environmental regulation should combine both mechanisms by discouraging environmentally harmful activities while simultaneously encouraging environmentally beneficial innovation (Porter & van der Linde, 1995; Nordhaus, 2019; Stern et al., 2021). Consequently, firms' production decisions depend not only on the level of carbon pricing but also on whether environmental institutions recognize and reward positive climate contributions.

Within the proposed framework, the transition occurs when the economic value generated by recognized carbon handprints exactly offsets the environmental compliance cost associated with carbon pricing:

$$\theta(E_B > E_T) = \tau E_T \tag{13}$$

Eq. (13) defined the threshold separating two fundamentally different regulatory environments. The left-hand side represented the economic value created through recognized avoided emissions, whereas the right-hand side represented the environmental compliance cost imposed on production. Their relative magnitudes determined whether environmental regulation functioned primarily as a compliance obligation or as a source of economic value creation.

When $\theta(E_B > E_T) < \tau E_T$, carbon-pricing obligations exceed the economic value generated by recognized carbon handprints. Under this condition, firms primarily respond by reducing emissions to minimize environmental compliance costs. Environmental regulation therefore operates predominantly through cost internalization, which remains the principal objective of contemporary carbon-pricing policies (Nordhaus, 2019; World Bank, 2024). When $\theta(E_B > E_T) = \tau E_T$, the economic value created by recognized carbon handprints exactly compensates for environmental compliance costs. At this threshold, firms become economically indifferent between treating environmental regulation as a compliance obligation and viewing environmental improvement as a source of competitive advantage. The production system therefore reaches a transition point between cost internalization and value creation. Finally, when $\theta(E_B > E_T) > \tau E_T$, recognized carbon handprints generate economic value exceeding environmental compliance costs. Environmental performance consequently becomes a source of profitability rather than merely a means of reducing regulatory burdens. Firms therefore have incentives to invest continuously in cleaner technologies, thereby expanding recognized carbon handprints and reinforcing sustainable value creation. This outcome is consistent with the Porter Hypothesis that appropriately designed environmental regulation stimulates innovation and competitiveness (Porter & van der Linde, 1995), while also reflecting growing evidence that financial markets increasingly reward firms exhibiting superior climate performance and sustainability outcomes (Krueger et al., 2020; Bolton & Kacperczyk, 2021; Flammer, 2021).

Unlike existing carbon-pricing models, which primarily emphasize environmental compliance, the proposed framework identifies the institutional conditions under which environmental regulation evolves into a value-creation mechanism. Recognized carbon handprints therefore constitute a measurable source of economic value whose magnitude depends jointly on technological performance and institutional recognition. This theoretical perspective extends the existing carbon handprint literature (Grönman et al., 2019; Tuppura et al., 2024; Eberhardt et al., 2024) by integrating recognized carbon handprints directly into firms' production decisions and establishing a formal transition from compliance-driven regulation to sustainable value creation.

The above analysis led to the principal theoretical proposition of this study.

Proposition 4. Environmental regulation evolves from a compliance mechanism to a value-

creation mechanism when the economic value generated by recognized carbon handprints exceeds the environmental compliance cost imposed by carbon pricing.

This proposition represented the central theoretical contribution of this study by identifying the condition under which carbon pricing and recognized carbon handprints operated as complementary institutional mechanisms. This result provides a theoretical explanation for the transition from compliance-oriented regulation toward sustainable value creation.

Discussion

The proposed theoretical framework offers several policy implications for the design of carbon-pricing systems and sustainable industrial policies. Unlike conventional environmental-economic models, which primarily rely on carbon pricing to discourage carbon-intensive production, the present framework suggests that effective environmental regulation should combine carbon-pricing mechanisms with institutional arrangements that recognize and reward positive environmental performance. Sustainable production therefore depends not only on increasing the cost of carbon emissions but also on strengthening the economic incentives associated with recognized carbon handprints (Porter & van der Linde, 1995; Nordhaus, 2019).

The findings extend the existing literature in several ways. Consistent with Porter and van der Linde (1995), the model suggests that environmental regulation may influence firm behavior through channels beyond simple compliance-cost increases. However, the present framework further shows that this effect depends on whether positive environmental performance is institutionally recognized and converted into measurable economic value. This result also complements the carbon handprint literature, which has primarily focused on environmental measurement (Grönman et al., 2019; Tuppura et al., 2024; Eberhardt et al., 2024), by demonstrating how recognized avoided emissions can directly affect firms' production decisions. In this sense, the proposed framework provides a theoretical bridge between carbon pricing, positive environmental performance, and sustainable value creation.

First, the analytical results indicate that carbon pricing alone may be insufficient to support sustained technological transformation. Although higher carbon prices increase firms' incentives to reduce emissions, they also increase production costs and may discourage productive investment when environmental compliance costs become excessive. Consequently, environmental policies should be designed to complement carbon pricing with mechanisms that recognize avoided emissions and reward firms that continuously improve environmental performance. Such complementary policies may strengthen incentives for environmental innovation while limiting an exclusive reliance on compliance-cost mechanisms (Porter & van der Linde, 1995; Stern et al., 2021).

Second, Eq. (13) demonstrates that institutional recognition plays a decisive role in determining whether environmental regulation functions primarily as a compliance mechanism or as a value-creation mechanism. Governments can strengthen the recognition coefficient, θ, through the development of credible carbon-credit markets, environmental certification systems, green public procurement, sustainability disclosure standards, and transition-finance policies. By increasing the economic value associated with recognized avoided emissions, these institutional arrangements may strengthen firms' incentives to invest in cleaner technologies and expand positive environmental contributions (Krueger et al., 2020; Bolton & Kacperczyk, 2021; Flammer, 2021).

Third, the proposed framework suggests that environmental innovation should be evaluated not only according to its ability to reduce emissions but also according to its capacity to generate recognized environmental value. Firms that improve production technologies increase the difference between benchmark emissions and actual emissions, thereby expanding recognized carbon handprints and potentially improving their economic performance. Consequently, technological innovation, environmental improvement, and firm

competitiveness may become mutually reinforcing objectives rather than necessarily conflicting policy goals. This conclusion is consistent with the growing emphasis on sustainable value creation in both environmental economics and sustainable finance (Hart, 1995; Eccles et al., 2014; Friede et al., 2015).

Finally, the proposed framework provides implications for sustainable finance. Financial institutions increasingly incorporate climate-related information into investment decisions, lending policies, and corporate valuation. The present model suggests that recognized carbon handprints may serve as an economically meaningful indicator of positive climate performance, complementing conventional carbon-emission measures that primarily capture environmental costs. Integrating recognized carbon handprints into sustainable-finance frameworks could strengthen the alignment between environmental performance and financial incentives, thereby supporting the transition toward a low-carbon economy (Krueger et al., 2020; Bolton & Kacperczyk, 2021; Flammer, 2021).

Overall, the discussion highlights that the effectiveness of climate policy depends not only on carbon-cost internalization but also on the institutional capacity to recognize positive environmental performance. This perspective broadens the policy interpretation of carbon handprints by emphasizing their potential role in linking environmental improvement with economic incentives. More specifically, institutional recognition converts verified avoided emissions into measurable economic value through mechanisms such as carbon credits, green procurement, sustainability certification, and sustainable finance. In this way, carbon handprints complement carbon pricing by transforming positive environmental performance from a measurement indicator into an economic incentive for sustainable value creation.

Conclusions

This study developed a unified theoretical framework integrating carbon pricing, carbon handprints, and institutional recognition into firms' production decisions. The results showed that environmental regulation influenced firms through both cost-increasing and value-creating channels and identified the condition under which recognized carbon handprints could offset carbon-pricing compliance costs.

The proposed framework makes three principal theoretical contributions. First, it establishes an integrated optimization model linking carbon pricing, carbon handprints, and institutional recognition within a unified analytical framework. Second, it introduces institutional recognition as an explicit economic mechanism through which avoided emissions directly influence firms' production decisions rather than serving solely as environmental-performance indicators. Third, it identifies the transition condition under which environmental regulation evolves from a compliance-oriented mechanism toward sustainable value creation, providing a new theoretical explanation for the interaction between environmental regulation and firms' economic incentives.

From a policy perspective, the findings suggest that carbon pricing is likely to be more effective when complemented by institutional mechanisms that recognize and reward positive environmental performance. Such complementary arrangements may strengthen the alignment between climate-policy objectives and firms' economic incentives.

This study has several limitations that provide directions for future research. The present study develops a deterministic theoretical framework and therefore abstracts from uncertainty, dynamic technological change, and heterogeneous firm behavior. Future studies may extend the model by incorporating dynamic optimization, stochastic production environments, supply-chain interactions, general-equilibrium analysis, or empirical validation using firm-level data. Such extensions would further enhance our understanding of how recognized carbon handprints influence firms' production decisions and sustainable economic development under evolving climate-policy environments.

Acknowledgements
The authors would like to thank the editor and anonymous reviewers for their helpful comments and suggestions. The usual disclaimer applies.

Conflict of interests
The authors declare no conflict of interest.

Funding
This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data Availability Statement
No datasets were generated or analyzed in this conceptual study.

References

Aldy, J. E., & Stavins, R. N. (2012). The promise and problems of pricing carbon: Theory and experience. *The Journal of Environment & Development, 21*(2), 152–180. https://doi.org/10.1177/1070496512442508

Bolton, P., & Kacperczyk, M. (2021). Do investors care about carbon risk? *Journal of Financial Economics, 142*(2), 517–549. https://doi.org/10.1016/j.jfineco.2021.05.008

Calel, R., & Dechezleprêtre, A. (2016). Environmental policy and directed technological change: Evidence from the European carbon market. *The Review of Economics and Statistics, 98*(1), 173–191. https://doi.org/10.1162/REST_a_00470

Dixit, A. K. (1979). A model of duopoly suggesting a theory of entry barriers. *The Bell Journal of Economics, 10*(1), 20–32. https://doi.org/10.2307/3003317

Eberhardt, M. L. C., Kuittinen, M., Häkkinen, T., Moinel, C., Nibel, S., & Birgisdottir, H. (2024). Carbon handprint – A review of potential climate benefits of buildings. *Building Research & Information, 52*(6), 708–723. https://doi.org/10.1080/09613218.2023.2266020

Eccles, R. G., Ioannou, I., & Serafeim, G. (2014). The impact of corporate sustainability on organizational processes and performance. *Management Science, 60*(11), 2835–2857. https://doi.org/10.1287/mnsc.2014.1984

Flammer, C. (2021). Corporate green bonds. *Journal of Financial Economics, 142*(2), 499–516. https://doi.org/10.1016/j.jfineco.2021.01.010

Friede, G., Busch, T., & Bassen, A. (2015). ESG and financial performance: Aggregated evidence from more than 2000 empirical studies. *Journal of Sustainable Finance & Investment, 5*(4), 210–233. https://doi.org/10.1080/20430795.2015.1118917

Grönman, K., Pajula, T., Sillman, J., Leino, M., Vatanen, S., Kasurinen, H., Soininen, A., & Soukka, R. (2019). Carbon handprint – An approach to assess the positive climate impacts of products demonstrated via renewable diesel case. *Journal of Cleaner Production, 206*, 1059–1072. https://doi.org/10.1016/j.jclepro.2018.09.233

Hart, S. L. (1995). A natural-resource-based view of the firm. *Academy of Management Review, 20*(4), 986–1014. https://doi.org/10.2307/258963

Krueger, P., Sautner, Z., & Starks, L. T. (2020). The importance of climate risks for institutional investors. *The Review of Financial Studies, 33*(3), 1067–1111. https://doi.org/10.1093/rfs/hhz137

Martin, R., Muûls, M., de Preux, L. B., & Wagner, U. J. (2014). Industry compensation under relocation risk: A firm-level analysis of the EU emissions trading scheme. *American Economic Review, 104*(8), 2482–2508. https://doi.org/10.1257/aer.104.8.2482

Nordhaus, W. (2019). Climate change: The ultimate challenge for economics. *American Economic Review, 109*(6), 1991–2014. https://doi.org/10.1257/aer.109.6.1991

Porter, M. E., & van der Linde, C. (1995). Toward a new conception of the environment-competitiveness relationship. *Journal of Economic Perspectives, 9*(4), 97–118. https://doi.org/10.1257/jep.9.4.97

Stern, N., Stiglitz, J. E., & Taylor, C. (2021). The economics of immense risk, urgent action and radical change: Towards new approaches to the economics of climate change (NBER Working Paper No. 28472). National Bureau of Economic Research. https://doi.org/10.3386/w28472

Tuppura, A., Palomäki, K., Grönman, K., Lakanen, L., Pätäri, S., Vatanen, S., & Soukka, R. (2024). Communicating positive environmental impacts – User experiences of the carbon handprint approach. *Journal of Cleaner Production, 434*, 140292. https://doi.org/10.1016/j.jclepro.2023.140292

World Bank. (2024). *State and trends of carbon pricing 2024*. https://doi.org/10.1596/978-1-4648-2127-1