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EDITED BY
Martin Wynn,
University of Gloucestershire, United Kingdom

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Kyushu University, Japan
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National Research University Higher School of Economics, Russia

*CORRESPONDENCE
Jeremy Ko
✉ jereko@ethz.ch

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Carbon taxes and industrial competitiveness: evidence from energy-intensive industries in the Nordic region

Mohammad Ridwan[1], Zulfiquar Ali Antor[1], Jeremy Ko[2]*, Afsana Akther[1], Chun Kai Leung[3,4] and Wai-Kit Ming[5,6]

[1]Department of Economics, Noakhali Science and Technology University, Noakhali, Bangladesh, [2]Center for Comparative and International Studies, ETH Zurich, Zurich, Switzerland, [3]Global Society and Sustainability Lab, Faculty of Social Sciences, The University of Hong Kong, Hong Kong, Hong Kong SAR, China, [4]Fairbank Center for Chinese Studies, Harvard University, Cambridge, MA, United States, [5]Department of Infectious Diseases and Public Health, City University of Hong Kong, Hong Kong, Hong Kong SAR, China, [6]Institute of Global Governance and Innovation for a Shared Future, City University of Hong Kong, Hon Kong, Hong Kong SAR, China

The key question for open economies is how to maintain ambitious climate policy while remaining competitive in the industrial sector. Carbon taxes have been accused of increasing production costs while being a driver of efficiency and innovation. The Nordic region offers a severe experiment on this argument, as it has the highest carbon prices globally and depends highly on manufacturing exports. This study examines the relationships among carbon taxation, energy consumption, and industrial competitiveness in Nordic economies from 2000-2024. We estimate the joint effect of environmental policies and structural factors on export performance via panel econometric techniques. To examine this relationship, the study used quantile regression, panel-corrected standard errors, Driscoll–Kraay standard errors, the system generalized method of moments, and panel autoregressive distributive lag model. The results indicate that carbon taxation improves manufacturing exports, implying that tougher climate policies can reinforce competitiveness via induced innovation and efficiency improvements. Exports are boosted by fossil fuel consumption and negatively affect electricity consumption, GDP per capita, and carbon intensity. Value-added manufacturing enhances competitiveness, whereby industrial upgrading and involvement in global value chains have their place. Causality tests revealed a two-way relationship between carbon taxes and exports, and robustness tests confirmed the consistency of the findings. However, the GMM establishes weaker effects of taxation and value added. This study provides evidence that climate leadership and trade competitiveness are not mutually exclusive. Nordic economies demonstrate a viable path to sustainable competitiveness in the global low-carbon transition through carbon pricing within coherent policies supporting innovation, energy efficiency, and low-carbon strategies.

KEYWORDS

carbon intensity, carbon taxation, energy consumption, export competitiveness, manufacturing value added

1 Introduction

Carbon taxes have become central to climate policy debates as one of the most urgent economic issues of the twenty-first century. Carbon taxation, which is designed to internalize environmental costs, is known as a tool to reduce emissions, although its competitiveness implications remain unresolved. An example is the United States, where carbon pricing in agriculture increases production costs and changes the market structure (Dumortier and Elobeid, 2021). These issues are reflected in European agriculture research, where coordinated structures are considered more useful than fragmented policies are (Jansson et al., 2024). The impact on manufacturing and energy-demanding industries points to trade-offs between short-term costs and long-term efficiency increases (Sheng and Wang, 2022). The study indicates that unilateral action is not always adequate, and stable combinations of pricing tools and auxiliary regulations can produce more sustainable emission reductions (Weisbach et al., 2023). The distributional impacts of carbon pricing depend on economic growth, import intensity, and environmental tax design, showing that institutional and structural settings have a strong influence (Zhong et al., 2022). The carbon tax discussion increasingly focuses on these measures' twofold purpose: the policy can initially burden export-focused industry but can influence industry to improve efficiency and become more technologically advanced (Wang et al., 2022; Zhang and Zheng, 2023). This paradox marks modern climate policy, which requires a deeper examination of the impact of taxation on industry competitiveness.

The Nordic region is a significant case for considering the overlap between carbon taxation and competitiveness. These economies have an unusual relationship between environmental ambition and world trade integration, as they both have one of the highest carbon tax levels in the world and rely heavily on manufacturing exports. An example is the carbon taxes in Sweden, which are the toughest in the world, but manufacturing still contributes to a significant proportion of exports, which demonstrates the compatibility of rigorous climate policy and competitiveness in trade. This twofold approach contrasts with the larger policy quandary of how to reconcile climate leadership and industrial performance in open economies. Empirical evidence suggests that reliance on fossil fuels puts exporters at a disadvantage related to efficiency differences and complementary changes in trade (Chen et al., 2021). Others note that restructuring fossil-based industries or applying an embargo can be expensive in terms of technology and politics in the long term and that the diversification of hydrocarbon-based economies is also a long-term problem (Fathi et al., 2021; Hancock and Ralph, 2021). The instability of the interlinkages between energy, trade, and development in resource-based economies is also evidenced by disruptions due to sanctions or market shocks in international markets (Konrad and Thum, 2023). Energy system transformation in Europe has both risks and opportunities, where hydrogen, ammonia, and methanol have become renewable fuels but are limited by transport and storage expenses (Wang et al., 2023). This dynamic renders Nordic economies an important laboratory for gaining insight into whether high carbon taxation is compatible with long-term industrial competitiveness in a globalized economy.

Available studies are informative about the effects of taxation, energy use, and structural variables on export performance, but the results are piecemeal. Research indicates that high prices of carbon can change trade patterns and reform industrial policy, with the results depending on the level of coordination in the cross-market (Roy, 2025; Bayat et al., 2025). Another aspect is energy dependence: the use of fossil fuels remains a vital component of maintaining export-based production yet increased global demands for decarbonization put such a dependence under long-term threat (Jensen, 2024). In contrast, there are mixed results of shifts toward alternative sources of energy, where the uptake of renewable energy can enhance sustainability while simultaneously introducing new infrastructure and additional burdens (Cosić et al., 2025). The creation of value added through manufacturing has been identified several times as a way of boosting competitiveness, and it was found that the resilience of export sectors was strengthened by industrial diversification, foreign direct investment, and skilled labor (Aggarwal et al., 2025; Huang et al., 2023). Moreover, opportunities and vulnerabilities can increase in both ways because of the presence of both opportunities and vulnerabilities because of the location of a country in the global value chain (Jangam and Rath, 2021). Moreover, carbon intensity is already a vital factor of export sustainability, as the greater the embodied emission is, the more susceptible one is to new regulatory frameworks, such as the carbon border adjustment mechanism by the EU (Kallummal et al., 2024; Qu et al., 2025). Combined, these threads of literature drive home the point that competitiveness is not determined by any particular aspect but through the sum of the effects of taxation, energy consumption, value-added production, and carbon efficiency.

Research on carbon taxation, energy consumption, and industry competitiveness has gaps to fill. Most research separates the impact of individual factors, including carbon taxes on trade (Bayat et al., 2025; Roy, 2025) or fossil fuels, on export performance (Jensen, 2024) without examining their interactions in a single model. The relationship between electricity consumption and competitiveness during high-carbon tax regimes remains less understood than electricity consumption in regional contexts, particularly with respect to cross-border trade and renewable integration (Cosić et al., 2025). Studies on value added and export resilience highlight the advantages of industrial upgrading (Aggarwal et al., 2025; Huang et al., 2023); however, few studies have examined how value-added dynamics in long-term competitiveness interact with taxation and energy. Embedded emissions and trade vulnerabilities are linked to carbon intensity, especially with new policies such as the carbon border adjustment mechanism (CBAM) (Kallummal et al., 2024; Qu et al., 2025). However, the relationship between carbon intensity and manufacturing exports in small, high-tax economies remains unexamined. This disintegration has led to little consensus on whether trade-offs exist in aggressive climate policies or if they can align with export competitiveness through industrial upgrading and efficiency gains. These gaps are crucial in the Nordic region, which has the highest carbon taxes globally and heavy export dependence, where empirical data and comparative studies remain limited. This gap needs to be addressed to advance academic discourse and policymaking.

On the basis of these gaps, this study investigates the role of the carbon tax, energy consumption, and industrial structure in determining export competitiveness within Nordic economies. With a specific focus on those countries where a combination of globally high carbon tax regimes is found with strong exposure to international markets, the analysis creates a perfect environment to determine whether climate leadership can be compatible with sustained competitiveness. To answer this goal, the research questions used in the study include the following: (i) Does carbon taxation improve or hamper manufacturing export performance in small open economies? (ii) What is the impact of alternative energy consumption (fossil fuel dependency vs. electricity intensity) on the competitiveness of industries with harsh climate policies? (iii) How do manufacturing value added and carbon intensity mediate the relationship between environmental taxation and trade results?

This study contributes to the climate policy and industry competitiveness literature in four ways. First, it provides new empirical evidence from Nordic economies, which are among the smallest open economies in the world, bearing the highest carbon taxes globally, and offers a severe test case of whether strict climate policy can be compatible with export-focused industrialization. Second, it constructs a combined model in which it assesses carbon taxation as well as fossil fuel dependency, electricity intensity, GDP per capita, manufacturing value added, and carbon intensity, thus incorporating the structural, energy, and environmental aspects of competitiveness that previous research has mostly treated separately. Third, it has methodological novelty: it uses panel quantile regression to show heterogeneous effects across the export distribution, which are complemented by Dumitrescu–Hurlin causes and effects tests with PCSEs, DKSE, system GMM estimators, and panel ARDL that jointly address cross-sectional dependence, slope heterogeneity, and endogeneity. Finally, this study provides policy implications, demonstrating that carbon taxation and value-added production can increase competitiveness by inducing innovation and industrial upgrading, whereas electricity intensity and carbon dependency destroy resiliency. Hence, integrative policies are necessary to balance decarbonization and export competitiveness.

The remainder of this paper is structured as follows. Section 2 provides a literature review of carbon taxation, energy consumption, industrial modernization, and carbon intensity, with special reference to their associations with export competitiveness. Section 3 outlines the data, builds constructs of these variables, and employs econometric strategies, such as unit-root, cointegration, quantile regression, causality, and robustness. Part 4 presents the empirical findings, whereby the baseline findings are first noted, followed by the distributional effects of the export quantiles. Finally, Section 5 provides instructions on how the paper comes to an end, where the main results are summarized, their theoretical and policy implications are discussed, and future research directions are suggested.

2 Literature review and hypothesis development

The interplay between carbon taxation, energy consumption, and industry competitiveness requires a systematic evidence review. Studies have identified variables such as carbon pricing, fossil fuel reliance, electric power use, value-added production, and carbon intensity, yet the results remain mixed. Some studies focus on carbon tax impacts on exporters, whereas others highlight efficiency and innovation benefits. Similarly, energy consumption and structural renovation both enhance and undermine competitiveness, depending on context. For clarity, this section synthesizes evidence and connects it with Nordic experience, where high carbon taxes parallel strong exports. On the basis of this discussion, six hypotheses are formulated to analyze the combined effects of taxation, energy, and industrial characteristics on export performance. Figure 1 shows the hypothesis development of the study.

2.1 Carbon tax and exports

Carbon taxation and export competitiveness have been the subjects of argument, and empirical evidence has provided conflicting results. According to some studies, high carbon prices cause a direct cost burden on trade-exposed sectors, which could make them less competitive. For example, Bayat et al. (2025) demonstrated that CBAM might decrease the export of iron and steel products in Türkiye by nearly 25%. Bohringer et al. (2025) indicated that border carbon adjustments can only benefit Canadian exporters when they are consistent with U.S. pricing policies. However, other researchers have concluded that carbon taxes can promote innovation and efficiency, resulting in long-term trade benefits. Using the example of Roy (2025), it is possible to show that carbon taxes increase green trade in 208 countries, but the positive impact is stagnant in the absence of complementary actions. Exbrayat et al. (2025) and Kim (2025) noted that taxation compels companies to use sophisticated technologies, although this can also cause a shift in the emission region. Practical experience with China and shipping worldwide also suggests that policy coordination leads to either a decrease in welfare losses or a safeguarding of exports as uniform carbon prices are enforced (Xu et al., 2023; Wang and Countryman, 2025). In general, the evidence in the literature suggests that the impact of carbon taxation on competitiveness depends on how the policy is designed, whether the technology has been upgraded, and whether it is internationalized. In the Nordic region, where carbon taxes are the highest in the world and export reliance is high, it is anticipated that taxation might improve instead of reduce export performance, with firms adjusting to it through efficiency and innovation.

H_1: Carbon taxation positively influences manufacturing export competitiveness in Nordic economies.

2.2 Fossil fuel consumption and exports

The use of fossil fuels is a complicated factor in determining export competitiveness. On the one hand, the availability of fossil energy is cost-effective in its production, as it aids industrial exports in industries that consume a large amount of energy. Attílio et al. (2024) demonstrated the role of fossil fuel production in the United States in enhancing emissions and simultaneously

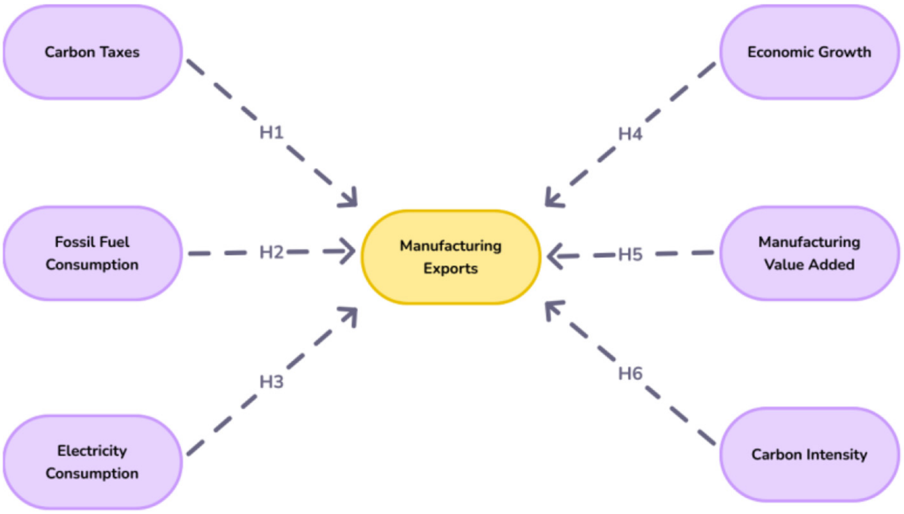

FIGURE 1
Hypothesis development of the study.

encouraging the trade of electrical goods, aiding industrial changes in partner countries. Similarly, Galimova et al. (2024) indicated that new export opportunities can be supported with fossil resources (for example, e-fuels and e-chemicals in Greenland), and competitiveness increases significantly. Conversely, according to long-term forecasts, global decarbonization may sharply reduce fossil fuel rents, which will destroy export revenues in economies that depend on resources (Jensen, 2024; Sen et al., 2025). Chinese evidence also illuminates the environmental hazards of the majority of methane emissions from fossil fuel mining being absorbed into an energy trade and being of concern about carbon leakage (Jin et al., 2025). In addition, studies indicate that tighter domestic control is likely to reduce the exports of fossil fuels and promote imports, which indicates that regulatory asymmetries may shift the flows of trade (Olasehinde-Williams and Lee, 2025). Collectively, the literature has shown that fossil fuel consumption helps encourage exports in the short term but is associated with high risks for the long-term shift to low-carbon economies. In the Nordic world, where fossil energy still forms part of manufacturing, consumption is anticipated to improve export performance, although structural changes and international climate commitments are starting to redefine long-term competitiveness.

H_2: Fossil fuel consumption positively influences export competitiveness in Nordic economies.

2.3 Electricity consumption and exports

Electricity consumption is a factor that facilitates industrial development and can be a limitation to competitiveness, depending on efficiency, costs, and the supply structure. In other instances, the consumption of electricity has provided export opportunities: Amiraslani and Dragovich (2024) reported that historical hydro development in Iran enabled electricity exports, and Gulagi et al. (2025) reported that the integration of renewable sources in New Zealand generated employment opportunities and new export opportunities with e-fuels. Benasla et al. (2024) noted that there is a chance that Algeria will be able to export solar-powered electricity to Europe, but these opportunities are subject to infrastructure and legislation. However, when electricity intensity is high, the cost of production is high, and exports cannot be competitive. Under carbon pricing, Cosić et al. (2025) showed that Bosnia will no longer be an exporter of electricity but will become an importer, which will completely change cross-border trade. Romano et al. (2024) also reported that exports of electricity in the EU can have an unintentional effect on the emissions of importers, and Stiewe et al. (2025) reported that interconnections change the value of renewable exports, decreasing the stability of some sources of energy. Jaxa-Rozen et al. (2025) also highlighted that despite liberalization, renewable adoption has increased, and the overall impact on competitiveness has been mixed. Generally, the literature indicates that although electricity may offer niche exporting, the ultimate result of high consumption of electricity in production is that competitiveness is compromised because of increased energy costs and carbon risks that may be faced by industries. In Nordic economies, where electricity prices are high compared with those of fossil fuels, increasing electricity intensity is assumed to undermine export results.

H_3: Increased electricity consumption negatively affects manufacturing export competitiveness in Nordic economies.

2.4 Economic growth and exports

The correlation between GDP per capita and export performance is a well-researched topic, but the results are inconsistent across regions and income levels. Exports play a positive role in the growth of developing economies, but their impact may differ depending on the sector and export mix. Hussain et al. (2025) demonstrated that the export of manufacturing and services is a substantial contributor to GDP growth in Pakistan, whereas primary exports are not productive. Similarly, Orchi and Ahmed (2025) discovered that exports and aid promote GDP growth in Bangladesh, but remittances have a demeriting effect. Conversely, in resource-dependent economies with high incomes, the causality of the relationship between GDP and exports is, in most cases, in the former way and not the other. Sojoodi and Baghbanpour (2024) show that in a sample of 60 countries, high-tech exports are hardly growth driven, but GDP levels determine the ability to export. Yusuf and Nasrulddin (2024) reported that in Saudi Arabia, exports increase GDP at the expense of sustainability, with a structural trade-off. The importance of GDP-trade linkages is also underlined by war-related disruptions that decreased global wellness due to shocks in Ukraine (Countryman et al., 2025). When combined, the literature reveals that exports can grow in emerging economies, but in advanced economies, an increase in income levels may lead to lower relative competitiveness of manufacturing exports because of structural change and specialization in services. In the Nordic region, which has the highest GDP per capita in the world, income growth is unlikely to be reflected in manufacturing exports but is indicative of structural changes in nontrade-driven competitiveness.

H_4: Economic growth negatively influences manufacturing export competitiveness in Nordic economies.

2.5 Manufacturing value added and exports

The creation of value added is well known as an important factor in industrial competitiveness because it is a measure of structural upgrading, productivity gains, and greater involvement in global value chains. Several studies suggest that increased value-added services allow economies to diversify exports and maintain sustainability at competitiveness levels. Aggarwal et al. (2025) demonstrated that when India entered world production networks due to foreign direct investment and increased value-added production, its export capacity considerably increased. Huang et al. (2023) also emphasized the role of industrial upgrading and investment in technology-intensive sectors as sources of resilience and competitiveness, especially in rapidly industrializing economies. Transition economies also indicate that policies promoting diversification in industries and value-added production are beneficial for overcoming the vulnerability caused by dependence on commodities (Jangam and Rath, 2021; Karmaker et al., 2021). Conversely, an economy with stagnant value added or reduced upgrading of industries tends to be less competitive because its exports have been stuck in low-productivity and resource-innovative sectors. In addition, research shows that value-added growth may offset the adverse effects of exogenous shocks by improving resilience to adapt and technological plasticity, thus strengthening the sustainability of the long-term performance of trade. Collectively, in the literature, there is a strong position in which the increased competitiveness of exports due to manufacturing value added is based on the fact that it has led to efficiency, diversification of industrial capacity, and strengthening of linkages in world markets. In the case of the Nordic region, where industrial upgrading and innovation are at the heart of economic strategy, it is predictable that greater value added will steadily increase manufacturing exports and create resilience under tough climate policies.

H_5: Manufacturing value added positively influences export competitiveness in Nordic economies.

2.6 Carbon intensity and exports

Carbon intensity, or the amount of emissions relative to output, is one of the factors that determines the sustainability and competitive nature of exports in the new low-carbon global economy. An increase in carbon intensity makes an organization susceptible to environmental laws and carbon trade policies. For example, Kallummal et al. (2024) show that under the carbon border adjustment mechanism (CBAM) in the EU, which levies tariffs on imports with high carbon emissions, the embodied carbon emissions of Indian exports are dangerous. Similarly, as Qu et al. (2025) noted, high carbon intensity further limits China's export performance, with foreign partners being stricter with the conditions of a climate of trade. Research also highlights that the sustainability of economies that depend on carbon-based industries is under threat in the long term because of the global demand for cleaner production and low-carbon products. On the other hand, decreasing carbon intensity through technological innovation, energy efficiency, and the adoption of renewables can strengthen export opportunities by meeting the requirements of sustainability on a global scale, as well as the preferences of consumers. However, this shift requires considerable technological and regulatory adjustments, which could be difficult for economies that are highly reliant on fossil-based industries. The literature indicates that competitiveness declines whenever carbon intensity is high, creating trade vulnerabilities and climate-related restrictions. In the Nordic region, where low-carbon policy is at the core of industrial policy, an increase in carbon intensity is anticipated to reduce the performance of manufacturing exports, whereas a decrease in intensity increases long-term trade resilience.

H_6: Carbon intensity negatively influences manufacturing export competitiveness in Nordic economies.

2.7 Literature gap

Although much research exists on environmental policies and trade relationships, several gaps remain. First, the empirical evidence is divided into policy-competitiveness paradoxes, with some arguing that carbon taxation harms trade performance, whereas others believe that it promotes innovation-based competitiveness. However, there is little systematic evidence from economies with sustained carbon taxation; thus, this question remains unanswered in mature policy settings. Second, Nordic countries have not been rigorously analyzed together despite having the most ambitious carbon tax regimes globally, combined with high export dependence. Most of the literature focuses on larger economies (China, India, or the United States) and ignores smaller open economies where climate ambition and competitiveness pressures intersect critically. Third, available empirical studies use mean-based estimators, which obscure differences in export distribution effects. Whether carbon tax and energy interactions burden low-exporting industries or drive upgrading among high performers remains poorly explored. This study fills these gaps through a systematic review of Nordic economies in a framework connecting the carbon tax, energy consumption, industrial upgrading, and carbon intensity to manufacturing exports. It illuminates heterogeneous and dynamic impacts via quantile regression, robustness checks, and causality analysis to provide empirical clarity on the trade–climate nexus.

3 Methodology

To empirically investigate the relationships among carbon taxation, energy consumption, the industrial structure, and export competitiveness in Nordic economies, this study uses a panel econometric model. The Nordic region is ideal, as these countries have the highest carbon tax rates globally while maintaining strong export-based industrial activity. The panel framework enables cross-country and time series variations, facilitating better performance estimates and consideration of common and country-specific dynamics. Higher-order econometric methods address issues related to panel data, such as cross-sectional dependence, heterogeneous slopes, non-stationarity, and possible endogeneity. The methodological strategy follows these steps: first, descriptive statistics and diagnostic tests determine data characteristics; second, panel unit root and cointegration tests establish long-run relationships; third, baseline model estimation uses quantile regression to assess heterogeneous effects within the export distribution; and last, robustness tests and causality analysis verify the findings' validity and reliability. Figure 2 shows the flow of the estimation method.

3.1 Data and variables

This study employs a balanced panel dataset covering five Nordic economies—Denmark, Finland, Iceland, Norway, and Sweden—over the period 2000–2024. The Nordic region provides an ideal context for examining the interaction between environmental policy and industrial competitiveness, as these economies were among the earliest adopters of carbon taxation globally and continue to maintain some of the highest carbon tax rates worldwide. Finland (1990), Sweden (1991), Norway (1991), and Denmark (1992) introduced carbon taxes prior to the start of the sample period, while Iceland implemented its carbon tax in 2010. The analysis begins in 2000 due to the availability and comparability of harmonized data on carbon taxation, industrial performance, and macroeconomic indicators across all five countries. To ensure consistency in the panel, carbon tax values for Iceland are recorded as zero in the pre-implementation period, allowing the study to capture both pre- and post-policy dynamics within a unified empirical framework. Across the Nordic economies, carbon taxes primarily target fossil fuel use in the energy, manufacturing, transport, and heating sectors—areas closely linked to export-oriented industrial activity. This institutional setting provides a stringent test of whether ambitious climate policies are compatible with manufacturing competitiveness in small open economies.

The dependent variable is manufacturing exports (MNX), measured as a percentage of total merchandise exports, capturing industrial competitiveness in international markets. Carbon taxation (COT) is the key explanatory variable, reflecting policy-induced cost pressures associated with climate mitigation efforts. Fossil fuel consumption (FEC), measured as the share of fossil fuels in total energy use, reflects reliance on conventional energy sources in export-oriented production. Electricity consumption (ELC), expressed in kilowatt-hours per capita, captures energy intensity, where higher usage may indicate increased production costs and reduced competitiveness. GDP per capita (GPC), measured in constant U.S. dollars, controls for income effects and structural transformation in high-income economies. Manufacturing value added (MVA), expressed as a percentage of GDP, reflects industrial depth and upgrading, while carbon intensity (CBI), defined as CO_2 emissions per unit of GDP, captures the environmental efficiency of production under increasingly stringent global trade and climate regulations. Detailed definitions, measurements, sources, and expected signs of all variables are provided in Table 1.

3.2 Theoretical framework and model specification

The theoretical basis of this research relies on various established theories explaining how environmental policies, industry competitiveness, and trade interact. First, the Porter hypothesis (Porter and Linde, 1995), which claims that well-constructed environmental rules, such as carbon taxation, can trigger innovation and efficiency benefits, which eventually make firms more competitive. H_1 is based on this view and expects carbon taxation to be positively related to manufacturing exports in Nordic economies. Conversely, the Pollution Haven Hypothesis (Copeland and Taylor, 2004) offers an opposing view of the hypothesis that stringent environmental regulations increase expenses and even result in the offshoring of carbon-intensive industries. This argument best applies to H_6, where high carbon intensity is likely to decrease export competitiveness in the face of new trade restrictions, including border carbon adjustments. The contribution of income is informed by the Environmental Kuznets Curve (Grossman and Krueger, 1995) framework, which states that as economies develop, the nature of income vis-a-vis environmental outcomes becomes inverse. In the case of developed economies such as the Nordics, this model supports H_4, in which an increased GDP per capita correlates with less competitiveness in carbon-intensive manufacturing exports. The analysis is also informed by insights from the Heckscher-Ohlin (Ohlin, 1933; Heckscher, 1919) trade theory that the endowment of factors in fossil fuel (H_2) and electricity intensity (H_3) contribute to comparative advantages in trade. Finally, the resource-based view of competitiveness (Barney, 1991) is more focused on structural upgrading and efficiency, which is consistent with H_5, which

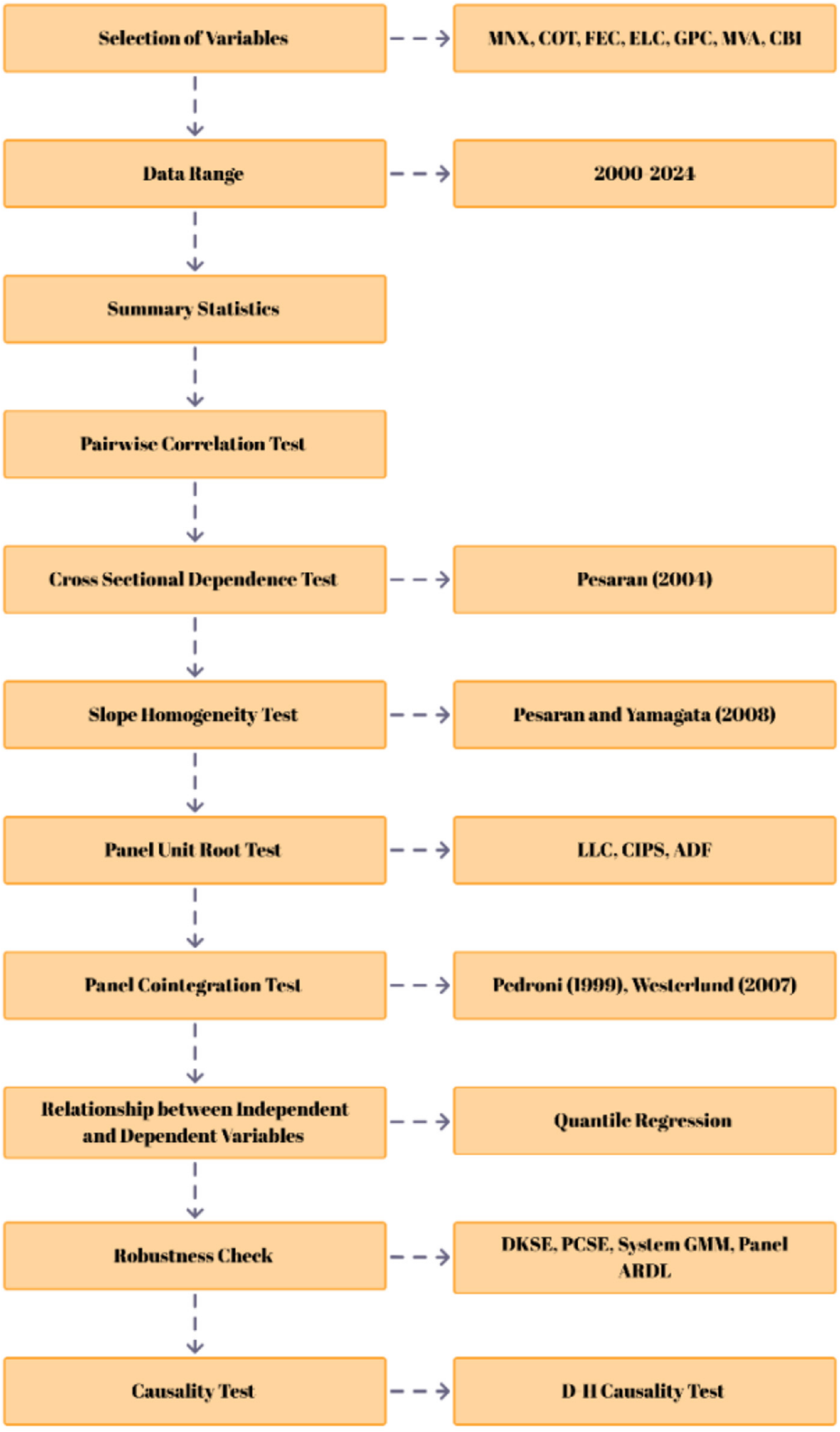

FIGURE 2
Flow of estimation methods.

assumes that manufacturing value added improves export performance. On the basis of the theoretical framework and hypotheses, an empirical model is constructed in which the connections among the carbon taxation, energy consumption, structural upgrading, and export competitiveness of the Nordic economies are defined. The initial specification can be stated

TABLE 1 Description and sources of variables.

Variable	Description	Unit of Measure	Source
LMNX	Manufactures exports	(% of merchandise exports)	WDI, 2024
LCOT	Carbon Tax	Average price on emissions covered by a carbon tax, weighted by the share of the country's CO_2 emissions	Dolphin and Merkle, 2024
LFEC	Fossil fuel energy consumption	(% of total)	WDI, 2024
LELC	Electric power consumption	(kWh per capita)	WDI, 2024
LGPC	GDP per capita	(constant 2015 US$)	WDI, 2024
LMVA	Manufacturing, value added	(% of GDP)	WDI, 2024
LCBI	Carbon intensity of GDP	(kg CO_2 emission per 2021 PPP $)	WDI, 2024

as follows:

$$MNX_{it} = f\ (COT_{it}, FEC_{it}, ELC_{it}, GPC_{it},\ MVA_{it},\ CBI_{it}) \quad (1)$$

In Equation (1), I denotes the cross-sectional dimension, and t denotes the time dimension. By using the log form, the equation for estimation can be written as Equation (2):

$$\begin{aligned} LMNX_{i,\ t} &= \alpha_0 + \beta_1 LCOT_{i,t} + \beta_2 LFEC_{i,t} + \beta_3 LELC_{i,t} \\ &\quad + \beta_4 LGPC_{i,t} + \beta_5 LMVA_{i,t} + \beta_6 LCBI_{i,t} + \ \varepsilon_{i,t} \end{aligned} \quad (2)$$

Each coefficient corresponds directly to the hypotheses formulated in Section 2. Specifically, $\beta_1 > 0$ tests H_1, $\beta_2 > 0$ tests H_2, $\beta_3 < 0$ tests H_3, $\beta_4 < 0$ tests H_4, $\beta_5 > 0$ tests H_5, and $\beta_6 < 0$ tests H_6.

3.3 Empirical strategy

This empirical analysis starts by discussing the main diagnostic problems that are usually faced in the context of panel data. Given that the Nordic economies are well connected by their trade and energy markets, cross-sectional dependence (CSD) will likely occur. This feature should not be ignored, as it can skew the estimates and yield spurious results. Thus, the Pesaran (2004) CD test is used to test the CSD, and the slope heterogeneity test developed by Hashem Pesaran and Yamagata (2008) is used to test the hypotheses that the estimates of the parameters vary significantly across countries. Since the time series aspect of the panel is present, the second approach is to ensure that all the data are stationary. The conventional first-generation panel unit root tests are cross-sectionally independent and do not work with interconnected economies. Therefore, this analysis uses first- and second-generation tests, namely, the augmented Dickey–Fuller (ADF), Levin–Lin–Chu and cross-sectionally augmented Im-Pesaran–Shin (CIPS) testing methods, which explicitly factor in the cross-sectional correlation. After incorporating the properties of integration, the analysis then progresses to cointegration tests, which are used to test the presence of a long-run equilibrium between manufacturing exports, carbon taxation, energy use and structural variables. This study employs Pedroni (2004) and Westerlund (2007) panel cointegration tests.

To account for distributional heterogeneity in export performance, this study applies panel quantile regression. Unlike mean-based estimators, quantile regression estimates conditional relationships across different points of the export distribution, allowing the identification of asymmetric effects that may not appear at the average level (Koenker and Bassett Jr, 1978). This is particularly relevant for Nordic economies, where sectoral and policy variations may affect low- and high-performing exporters differently. Moreover, quantile regression is robust to outliers and non-normal error terms, making it well suited for macroeconomic panels (Koenker, 2004). The conditional quantile function is expressed formally as:

$$Q_{MNX_{it}}(\tau\ |X_{it})\ =\ \alpha_{i(\tau)} + X_{it}^{'}\,\beta(\tau),\ \ 0\ <\ \tau\ <\ 1 \quad (3)$$

where $Q_{MAN_{it}}(\tau\ \ |X_{it})$ denotes the τ-th conditional quantile of manufacturing exports, $\alpha_{i(\tau)}$ captures country fixed effects, and $\beta(\tau)$ represents the vector of slope parameters that vary across quantiles.

The estimation is obtained by solving the following minimization problem:

$$\hat{\beta}(\tau) =\ \arg\ min_{\beta} \sum_{i=1}^{N} \sum_{t=1}^{T} \rho_\tau \left(MNX_{it} -\ \alpha_{i(\tau)} -\ X_{it}^{'}\beta\ (\tau) \right) \quad (4)$$

where $\rho_\tau\ (\mu) = \mu(\tau - I\ \{\mu\ < 0\})$ is the quantile loss function.

To validate the reliability of the baseline estimates, the study incorporates a series of robustness checks. The panel-corrected standard errors (PCSE) estimator (Beck and Katz, 1995) and the Driscoll–Kraay (DKSE) estimator (Driscoll and Kraay, 1998) is employed to address heteroskedasticity, serial correlation, and cross-sectional dependence. In addition, the system GMM estimator (Arellano and Bover, 1995; Blundell and Bond, 1998) is used to account for potential endogeneity and dynamic effects. The study also used panel autoregressive distributive lag (ARDL) model to capture both short-run and long run relationship. Finally, causal directions are examined through the Dumitrescu–Hurlin panel causality test (Dumitrescu and Hurlin, 2012), which accommodates heterogeneity and interdependence across countries. These procedures ensure that the findings are robust, consistent, and reflective of both short-run dynamics and long-run relationships.

4 Results and discussion

4.1 Discussion of results

The summary statistics of the variables used in the analysis are presented in Table 2. The mean value of manufacturing exports is 3.67, with moderate fluctuations between 2.09 and 4.45, suggesting the stability but differentiated performance of manufacturing exports in the Nordic economies. Carbon taxation shows the broadest distribution, with a mean of 2.57 and a standard deviation of 2.26 between −8.38 and 4.32, which shows a high disparity in the intensity of national policies. The average fossil fuel usage is 3.64, with a relatively small standard deviation, compared with electricity, which is always high, with 9.74 as the average and a high value of 10.92. The GDP per capita is constant among the countries, with an average of 10.89 and a standard deviation of minimal fluctuations. The average manufacturing value added is 2.48, and the lowest and highest values are 1.59 and 3.19, respectively, which indicate the variation in industry specialization. Finally, the mean intensity of carbon is −2.07, with a range of −2.95 to −1.25, which is indicative of progress in efficiency yet still has a level of variation. These trends verify the stability of core economic conditions as well as heterogeneity in energy and policy aspects to support the appropriateness of panel econometric methods.

The Pearson pairwise correlations between the study variables are presented in Table 3. The findings show moderate relationships, and no coefficients approach unity, indicating that multicollinearity is unlikely to influence the estimations. Carbon taxation and manufacturing exports have a positive relationship, as environmental policy can increase competitiveness through efficiency gains. The theoretical expectations are met by a positive association between fossil fuel consumption and exports and a negative correlation between electricity consumption and carbon intensity. A weak negative relationship between manufacturing exports and GDP per capita shows structural changes in advanced economies. Exports have a positive relationship with manufacturing value added, indicating that industrial upgrading enhances competitiveness.

Table 4 indicates that the variables are all significantly cross-sectionally dependent, represented by the CD statistics and their *p*-values. This means that economic shocks of one Nordic economy are passed to others as a sign of their economic and policy integration. This cross-sectional dependence is an indication that second-generation panel unit root and cointegration methods should be used because they are resistant to cross-country interdependence.

TABLE 2 Summary statistics.

Variable	Obs	Mean	Std. Dev.	Min	Max
LMNX	125	3.674	0.753	2.088	4.447
LCOT	125	2.566	2.255	−8.377	4.321
LFEC	125	3.641	0.597	2.194	4.496
LELC	125	9.741	0.659	8.647	10.917
LGPC	125	10.886	0.195	10.542	11.286
LMVA	125	2.479	0.347	1.586	3.185
LCBI	125	−2.066	0.398	−2.951	−1.251

The results in Table 5 confirm slope heterogeneity, as both the delta and adjusted delta statistics are significant. This finding indicates that the effects of explanatory variables on exports differ across Nordic economies. Hence, estimation methods that account for parameter heterogeneity are needed to ensure reliable results.

The findings of the panel unit root tests (LLC, CIPS, and ADF) for all the variables are provided in Table 6. The results indicate that none of the series are stationary at levels but that all become stationary after first differencing, which implies that they are series of order one, that is, $I(1)$. Manufacturing exports, the carbon tax, and fossil fuel use all reject the null of a unit root at $I(1)$ and are consistent across various test applications. The applicability of panel cointegration methods in the analysis that follows these results can be explained by the fact that variables share the order of integration and can be in a long-run equilibrium relationship.

Table 7 shows the findings of the Westerlund and Pedroni cointegration tests. The statistic of the Westerlund variance ratio is significant in the presence of a deterministic trend (2.41, $p = 0.008$), which means that there will be evidence of cointegration under trend specification. The altered Phillips–Perron t test is more convincing and decreases the null hypothesis in both instances: no trend (2.80, $p = 0.0025$) and trend (3.30, $p = 0.0005$). The Pedroni tests are also consistent: the Phillips–Perron statistic is significantly small without a trend ($p = 0.077$) and significantly small with a trend ($p = 0.032$), whereas the augmented Dickey–Fuller statistic is nearly significant in both cases. Taken together, these findings support the hypothesis that there is a stable equilibrium in the long run among the variables in the study, hence justifying the application of long-term estimators in future empirical research.

TABLE 4 Cross-sectional dependence test.

Variable	CD statistics	*p*-value
LMNX	2.98	0.003***
LCOT	6.138	0.000***
LFEC	12.71	0.000***
LELC	2.331	0.020**
LGPC	14.167	0.000***
LMVA	4.709	0.000***
LCBI	14.959	0.000***

$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

TABLE 5 Slope homogeneity test.

Test statistic	Delta	*p*-value
	2.200**	0.028
Adj.	2.668***	0.008

$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

Carbon taxation positively and statistically significantly affects manufacturing exports in all quantiles. The coefficients also vary between 0.079 at the 5th quantile and 0.087 at the median and are significant at the 1% level. The effects are still positive even in higher quantiles [0.046 at Q (0.75); 0.065 at Q (0.90)], although the strength is slightly smaller. The positive relationship indicates that an increase in carbon taxes leads firms to participate in increased efficiency, cleaner technology, and modernization of production processes, thus creating competitiveness. This moderation effect at higher quantiles would mean that, as much as carbon taxes can be of great benefit to low- to mid-exporting industries, the marginal effect would decrease for already-performing exporters. In the Nordic picture, the outcome comes as no surprise: robust policy frameworks and commitments to green innovation have enabled carbon taxation to play not a cost role but an upgrading competition and sustainability force. The findings reveal that Nordic industries have, to a large extent, internalized the cost of carbon and used it to strengthen the potential of exports on a long-term basis. These results are not new; similar results were reported by Roy (2025), who stated that carbon taxes can spur green trade among nations, and by Exbrayat et al. (2025), who reported that taxation induces firms to use cleaner technologies. However, they contrast with Bayat et al. (2025), who discovered the negative impact of CBAM on Turkish steel exports and indicated that institutional capacity and policy formulation are decisive factors. These findings validate $H1$, which states that carbon taxation positively impacts the competitiveness of manufacturing exports in Nordic economies.

The quantile regression findings from Table 8 show that the effect of fossil fuel consumption on manufacturing exports is significant across all quantiles. The estimates range from 0.398 at Q (0.25) to 0.411 at $Q(0.50)$, confirming a constant role in export competitiveness. The effect remains positive at lower ($Q(0.05) = 0.408$) and higher quantiles ($Q(0.90) = 0.213$) but decreases at higher quantiles. This indicates stronger fossil fuel dependence in low- and median-exporting industries, whereas best exporters show weaker dependence. Economically, this shows that fossil fuels remain vital for cost-effective production and energy security in Indonesia's export industries. Fossil energy provides stable input prices and reliability, which are essential for small- and mid-level exporters in international markets. However, the decreasing effect at higher quantiles suggests that major exporters can shift to renewables, use less energy, or benefit from economies of scale, reducing fossil fuel dependence.

These findings align with Nordic historical evidence. Norway's petroleum industry has sustained industrial exports and fossil fuel-based electricity, stabilizing production in Finland and Denmark (Attílio et al., 2024). In Sweden and Iceland, high-performing exporters are incorporating more renewables, following European energy transition pathways (Galimova et al., 2024). Lower-quantile exporters' fossil fuel dependence vs. higher-quantile exporters' diversification shows the structural heterogeneity of Nordic industries. This finding matches Attílio et al. (2024), who showed that fossil fuel consumption supports energy-intensive trade, and Galimova et al. (2024), who identified fossil resources as facilitating e-fuel and chemical exports. Jensen (2024) warned

TABLE 3 Pearson pairwise correlation coefficients.

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1)LMNX	1.000***						
(2) LCOT	0.376***	1.000***					
(3) LFEC	0.446***	0.206**	1.000***				
(4) LELC	−0.775***	−0.238***	−0.731***	1.000***			
(5) LGPC	−0.577***	0.239***	0.144*	0.179**	1.000***		
(6) LMVA	0.789***	0.058*	0.079*	−0.397***	−0.857***	1.000***	
(7) LCBI	−0.146*	−0.520***	−0.027	0.312***	−0.488***	0.255***	1.000***

$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

TABLE 6 Panel unit root test.

Variable	LLC		CIPS		ADF		Order
	$I(0)$	$I(1)$	$I(0)$	$I(1)$	$I(0)$	$I(1)$	
LMNX	−2.8383*	−9.3807***	−1.689	−5.701***	11.5608	69.8671***	$I(1)$
LCOT	−3.8462*	−5.7225***	−2.028	−3.829***	16.5514*	26.6178***	$I(1)$
LFEC	1.5685	−8.9383***	−1.489	−4.244***	1.0279	62.7336***	$I(1)$
LELC	−2.0218	−8.9201***	−3.279***	−5.015***	12.9003	85.1322***	$I(1)$
LGPC	−3.0553*	−8.5309***	−1.227	−4.171***	8.9921	52.3452***	$I(1)$
LMVA	−3.4382*	−9.2405***	−1.551	−4.255***	7.6890	89.3568***	$I(1)$
LCBI	1.2968	−9.5592***	−1.640	−5.233***	0.1590	75.7731***	$I(1)$

$^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

TABLE 7 Cointegration test.

Test statistic		Without trend		With trend	
		Statistics	*p*-value	Statistics	*p*-value
Westerlund	Variance Ratio	0.5871	0.2786	2.4102	0.0080
Pedroni	Modified Phillips-Perron *t*	2.8048	0.0025	3.3013	0.0005
	Phillips-Perron *t*	1.4231	0.0774	1.8473	0.0324
	Augmented Dickey-Fuller *t*	0.9692	0.1662	1.6139	0.0533

TABLE 8 Quantile regression.

Variable	*Q*(0.05)	*Q*(0.25)	*Q*(0.50)	*Q*(0.75)	*Q*(0.90)
LCOT	0.079471^{***} (0.0104231)	0.0830566^{***} (0.0101208)	0.0869556^{***} (0.0114321)	0.04566^{***} (0.0129808)	0.0651256^{***} (0.0148004)
LFEC	0.4077609^{***} (0.0747734)	0.3970315^{***} (0.0726044)	0.4109297^{***} (0.0820117)	0.3859866^{***} (0.093122)	0.2126886^{**} (0.106175)
LELC	-0.2506381^{***} (0.0744543)	-0.23189^{***} (0.0722946)	-0.2202822^{***}(0.0816617)	-0.1593184^{*} (0.0927246)	-0.2676193^{***} (0.1057219)
LGPC	-1.96038^{***} (0.2785673)	-2.10733^{***} (0.2704869)	-2.113919^{***}(0.3055336)	-1.750127^{***} (0.3469249)	-1.323373^{***} (0.3955539)
LMVA	0.8594731^{***} (0.1253012)	0.6927976^{***} (0.1216666)	0.6526074^{***} (0.1374308)	0.7455064^{***} (0.1560489)	0.7748939^{***} (0.1779225)
LCBI	-0.5868095^{***} (0.0977802)	-0.6344113^{***}(0.0949439)	-0.6109019^{***} (0.1072456)	-0.5591914^{***} (0.1217744)	-0.3748145^{***} (0.1388437)
_Cons	22.20569^{***}(2.855693)	24.09778^{***}(2.772857)	24.2056^{***} (3.132133)	19.86483^{***} (3.55645)	17.24458^{***} (4.054963)

Standard errors in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

that global carbonization makes fossil fuel dependence a long-term competitive risk, potentially reducing Nordic advantages, as decarbonization lags behind emission reduction commitments. The data support H_2, showing that fossil fuels still contribute to Nordic export competitiveness. The findings indicate a temporary dynamic: fossil fuels remain important for high-performing exporters but are gradually being replaced by low-carbon strategies. Although fossil fuel consumption shows a positive effect on export performance, this outcome should be interpreted cautiously. The result likely reflects short-term cost and energy-security advantages rather than a durable source of competitiveness. Increasing global carbon regulation and mechanisms such as EU-CBAM mean that fossil-based production may become less competitive over time, exposing exporters to tariff penalties, compliance costs, and potential lock-in to carbon-intensive systems. Therefore, fossil fuel-driven competitiveness is a transitional advantage and must gradually be replaced by low-carbon energy integration to avoid future trade vulnerability.

The quantile regression analysis reveals that electricity consumption negatively and significantly affects manufacturing exports. The coefficients are negative across all quantiles, i.e., −0.251 [*Q*(0.05)] and −0.220 [*Q*(0.50)], with 1% significance, and remain negative at the upper quantiles [−0.159 at *Q*(0.75)] and [−0.268 at *Q*(0.90)]. Although the scale decreases at the middle quantile, the trend shows that increasing electricity consumption decreases export competitiveness across the distribution. This is related to production costs, which are electricity intensive in developed economies. Unlike globally traded fossil fuels, Nordic electricity depends on domestic supply, infrastructure, and renewable energy intermittency. Higher electricity consumption per person means greater reliance on power-intensive processes, increasing costs and reducing global price competitiveness. The negative impacts across quantiles show that both smaller exporters and leading firms face electricity intensity strain, although to varying degrees. These findings align with empirical data on electricity reliance risk in Nordic competitiveness. Cosić et al. (2025) revealed that in CO_2 pricing systems, some electricity exporters may become net importers, showing electricity-dependent competitiveness vulnerability. Romano et al. (2024) reported that EU electricity exports can transfer emissions liabilities to importing countries, reducing their environmental and economic effectiveness. For Nordic exporters, where electricity consumption ranks highest globally, dependence on electricity-intensive processes may reduce cost efficiency, even with renewable integration. This shows tension between industrial price competitiveness and low-carbon electrification progress. These findings match those of Stiewe et al. (2025), who reported that renewable interconnection reduces the stability of electricity export competitiveness, and those of Jaxa-Rozen et al. (2025), who highlighted the inconsistent competitiveness outcomes of liberalization with renewables. However, they contrast with Benasla et al. (2024), who outlined potential renewable electricity export benefits in Algeria, noting that the results depend on institutional capacity, cost structure, and market schemes. These findings confirm *H*3: increased electricity consumption negatively impacts Nordic manufacturing export competitiveness. The analysis reveals that renewable electricity aids in decarbonization, but its high per capita cost impacts industry price competitiveness in the short and medium terms.

The quantile regression results reveal a negative significant effect on manufacturing exports via electricity consumption. The coefficients range from −0.251 at *Q*(0.05) to −0.220 at *Q*(0.50), with a significant value of 1%, and remain negative at other quantiles [−0.159 at *Q*(0.75) and −0.268 at *Q*(0.90)]. While the magnitude decreases slightly at the middle quantiles, increased electricity consumption leads to reduced exportability.

The adverse effect stems from production costs in developed economies. Unlike fossil fuels sold globally, Nordic electricity prices depend on local supply, infrastructure limitations, and renewable resource integration. Higher per capita electricity consumption indicates increased industrial reliance on power-intensive processes, increasing production costs and reducing global price competitiveness. The persistent negative effects across quantiles show that both small exporters and major exporters face cost pressures from electricity intensity. These findings align with findings on competitiveness risk in Nordic countries. Cosić et al. (2025) show that electricity exporters might become net importers under CO_2 pricing, demonstrating unpredictable competitiveness. Romano et al. (2024) reported that EU electricity exports could shift emissions to importing nations, creating environmental and economic inefficiencies. For Nordic exporters with high electricity consumption, dependence on electricity-intensive processes may reduce cost efficiency despite renewable integration. This indicates a trade-off between competitive industrial prices and low-carbon electrification. These findings align with those of Stiewe et al. (2025), who show that renewable interconnection destabilizes export competitiveness, and those of Jaxa-Rozen et al. (2025), who note that liberalization has inconsistent competitiveness effects with renewables. They contradict Benasla et al. (2024), who highlight the potential benefits of renewable electricity exports in Algeria, noting that the results depend on institutional capacity and the market structure. These findings confirm *H*3 that increased electricity consumption negatively impacts Nordic manufacturing exports. While renewable electricity drives decarbonization, its costs reduce industrial competitiveness in the short to medium term.

The quantile regression shows a strong and significant influence of manufacturing value added on export performance across all quantiles. At $Q(0.50)$, the coefficients are 0.65–0.86 at $Q(0.05)$, which are significant at the 1 percent level. The positive effect remains constant throughout the distribution, although the magnitude fluctuates slightly, indicating that increased manufacturing value added enhances export competitiveness irrespective of export intensity. Manufacturing value added encompasses industrial upgrading, diversification, and technological innovation. Increased value-added production indicates improved efficiency, productivity, and integration into global value chains, contributing to competitiveness. Value added helps low-quantile exporters enter global markets through product differentiation and high-quantile exporters through technological advantages and innovation-based competitiveness. This shows how developed industrial policies maintain export performance in the Nordic setting. Nordic economies remain competitive amid high energy prices and environmental regulations through investments in R&D, skilled labor, and green technologies. These findings align with those of Aggarwal et al. (2025), who emphasize the role of industrial upgrading in increasing exports, and with those of Huang et al. (2023), who show that value-added innovation increases firm resilience and competitiveness. Similarly, Jangam and Rath (2021) indicate that economies in global production networks benefit from diversification through value-added activities. These findings correlate with global evidence that manufacturing upgrading drives competitiveness in export-oriented economies. These results contrast with those for resource-dependent economies, where a lack of value-added capacity compromises long-term competitiveness. The results confirm *H*5: manufacturing value positively affects export competitiveness in Nordic economies. The quantile-wide uniformity shows that structural upgrading serves as both a short-term and long-term resilience facilitator against climate and trade stress.

The quantile regression results reveal a negative and significant impact of carbon intensity on manufacturing exports in each quantile. The coefficients range from -0.635 at $Q(0.25)$ to -0.375 at $Q(0.90)$, all of which are significant at the 1% level. While its negative impact is strongest at the lower and median quantiles, it moderates among top exporters but remains significant. More carbon-intensive manufacturing exports have become less competitive due to climate-related trade barriers, reputational risk, and compliance expenses. Barriers to carbon-intensive industries have increased globally, notably the carbon border adjustment mechanism (CBAM) in the EU, which penalizes exporters with high embodied emissions. This penalty particularly affects lower-quantile exporters, although high-performing exporters can offset the impact through efficiency measures or low-carbon production. In the Nordic context, these results highlight the importance of low-carbon innovation for competitiveness. Nordic exporters operate in highly regulated markets where customers require low-emission supply chains. Kallummal et al. (2024) indicate India's potential trade partnership under CBAM due to embodied carbon emissions, whereas Qu et al. (2025) note China's export constraints from high carbon intensity. These findings support carbon efficiency as a key trade performance factor. The results align with those of other studies linking carbon efficiency to competitiveness globally but contrast with the pollution haven hypothesis, which suggests that carbon-intensive production could compete in less regulated markets. Nordic evidence demonstrates that high carbon intensity is detrimental in developed economies with strict environmental regimes. These findings support *H*6, validating that carbon intensity is adverse for Nordic export competitiveness. The results show that decarbonization is both an environmental necessity and a competitive requirement in international markets.

Although the aggregate outcomes provide a single image of the relationship between carbon tax, energy consumption, and structural variables and the competitive aspect of exports, it is worthy to note that not all Nordic region has a similar energy content and industrial base. Norway continues to be significantly motored by petroleum-related operations wherein inexpensive fossil energy continues to support export capacity in metals, chemicals, and the energy-consuming manufacturing. Sweden and Iceland, in turn, are provided mostly by hydro and nuclear power, which are less carbon-intensive but more vulnerable to electricity costs and grid instability. Denmark has a fast penetration of wind-energy which provides it with a robust foundation in green manufacturing at the expense of introducing intermittency and storage issues. Finland is placed between these two extremes, being mixed fossil-renewable dependent and with developing electrification. These non-uniform energy forms indicate that potential estimates of coefficients can indicate differentiated underlying processes: fossil-based competitiveness can be higher in Norway, and long-term resilience to exports in Sweden or Iceland can be based on low-carbon production. Such a weakening effect of

TABLE 9 PCSEs, DKSE, and system GMM.

Variable	PCSEs	DKSE	GMM
LCOT	0.0756061***(0.0126632)	0.0756061***(0.0160772)	0.0153919(0.0100715)
LFEC	0.3653818***(0.0840517)	0.3653818***(0.1065382)	0.1161095***(0.0452677)
LELC	−0.2403055***(0.0647708)	−0.2403055**(0.0960931)	−0.0693956**(0.0330054)
LGPC	−2.02005***(0.2078088)	−2.02005***(0.1850762)	−0.6223463***(0.203847)
LMVA	0.6374849***(0.0901289)	0.6374849***(0.0972301)	0.202466(0.2048732)
LCBI	−0.5377016***(0.092781)	−0.5377016***(0.1327348)	−0.1946338***(0.0658574)
Cons	23.78858***(2.014898)	23.78858***(1.647132)	7.200874***(2.40239)

Standard errors in parentheses. $^{***}p < 0.01$, $^{**}p < 0.05$.

TABLE 10 Panel ARDL results.

Test statistic	Variable	Coef.	Std. Err.	*z*-value	*p*-value
Long-Run	LCOT	−0.1341506	0.0677196	−1.98	0.048
	LFEC	−1.631219	0.6379417	−2.56	0.011
	LELC	−4.122696	0.8503164	−4.85	0.000
	LGPC	2.652102	0.6177754	4.29	0.000
	LMVA	0.4656272	0.0839305	5.55	0.000
	LCBI	1.641565	0.4777826	3.44	0.001
ECT		−0.1729256	0.1172211	−1.48	0.140
Short-Run	D.LCOT	−0.0414472	0.031766	−1.30	0.192
	D.LFEC	0.1394581	0.1508892	0.92	0.355
	D.LELC	0.4635166	0.3536681	1.31	0.190
	D.LGPC	−1.040388	0.9605658	−1.08	0.279
	D.LMVA	0.2837028	0.5465013	0.52	0.604
	D.LCBI	−0.4121317	0.2060755	−2.00	0.046
Cons		3.770592	2.442175	1.54	0.123

the intensity of electricity could be more intense in those countries where the electrification experienced a more rapid development than the decrease of costs. The consideration of these variations provides some complexity to the interpretation and suggests that outcomes of climate-competitiveness are not merely functions of tax policy, but also reflect the energy portfolio and transition pathway of each country.

Table 9 reports the robustness estimations using panel-corrected standard errors (PCSEs), Driscoll–Kraay standard errors (DKSE), and system GMM. The PCSE and DKSE estimators yield results that are highly consistent with the quantile regression outcomes: carbon taxation, fossil fuel consumption, GDP per capita, manufacturing value added, and carbon intensity retain their expected signs and remain statistically significant, while electricity consumption continues to exert a negative effect on manufacturing exports. Under the system GMM specification, fossil fuel consumption, electricity consumption, GDP per capita, and carbon intensity remain robustly significant, although the coefficients of carbon taxation and manufacturing value added lose statistical significance, which may reflect the correction for endogeneity and dynamic adjustments.

Given the mixed order of integration identified in the unit root tests, a panel ARDL model is further employed as an additional robustness check, with the results reported in Table 10. The long-run estimates indicate that carbon taxation exerts a negative and statistically significant effect on manufacturing exports, suggesting that higher environmental tax burdens may dampen export competitiveness in carbon-intensive production. Fossil fuel consumption and electricity consumption also exhibit significant negative long-run effects, reflecting the cost-intensive nature of conventional energy dependence in export-oriented manufacturing. On the other hand, manufacturing exports are positively and significantly impacted by GDP per capita and manufacturing value added, underscoring the importance of income growth and industrial upgrading in maintaining global competitiveness. Carbon intensity shows a positive long-run association, implying that economies with higher export shares may remain relatively carbon-intensive despite environmental regulations. The error-correction term is negative, confirming the presence of a long-run equilibrium relationship, although its statistical insignificance suggests a relatively slow adjustment toward equilibrium. In the short run, most coefficients are

TABLE 11 Causality test.

Test statistic	*w*-stat	*z*-bar	*p*-value
LMNX→ LCOT	1.5438	0.8598	0.3899
LMNX→ LFEC	1.4049	0.6403	0.5220
LMNX→LELC	1.4814	0.7612	0.4465
LMNX→LGPC	1.6810	1.0768	0.2816
LMNX→LMVA	4.1411	4.9665	0.0000***
LMNX→LCBI	1.3812	0.6028	0.5466
LCOT→LMNX	5.7786	7.5556	0.0000***
LFEC→LMNX	3.5417	4.0187	0.0001***
LELC→LMNX	8.5173	11.8860	0.0000***
LGPC→LMNX	0.6737	−0.5158	0.6060
LMVA→LMNX	2.7802	2.8148	0.0049***
LCBI→LMNX	2.3143	2.0781	0.0377**

***$p < 0.01$.

insignificant, except for carbon intensity, which exerts a negative effect, indicating that short-term increases in emissions intensity may temporarily weaken export performance. Overall, the ARDL results reinforce the robustness of the baseline findings by jointly confirming the long-run relationships and short-run dynamics under mixed integration properties.

Table 11 reveals that carbon taxation, fossil fuel consumption, electricity consumption, manufacturing value added, and carbon intensity all have regressive effects on manufacturing exports; thus, $H1$, H_2, $H3$, $H5$, and $H6$ are correct. There is bidirectional causality between manufacturing value added and unidirectional causality between carbon taxation, fossil fuel use, electricity use, and carbon intensity to exports. The short-term causality of GDP per capita is nonexistent, implying that its effect is long-term. Overall, the causality findings validate the directions projected in the hypotheses and are in line with the regression results.

4.2 Limitations and future research opportunities

This study has several limitations that need to be recognized. First, panel data at the national level limit the possibility of measuring firm- or industry-specific reactions to carbon taxation and energy intensity and may miss critical heterogeneities within industries. Second, the Nordic focus, although useful as a worldwide model of high-carbon tax systems, constrains the applicability of the findings to emerging and resource-intensive economies with a lower institutional position. Third, measurement limitations, especially with respect to energy and taxation data, can impact the accuracy of the estimated effects regardless of the use of sound econometric methods. This analysis can be developed in three ways in the future: Firm- or sector-level data would also bring about microlevel processes of innovation, productivity and technological upgrading. A comparison of regional blocs such as the EU, BRICS, and ASEAN would indicate the roles played by institutional contexts in defining the policy–competitiveness nexus. Finally, nonlinearities, dynamic feedback effects, and global value chain connections would be advantageous for investigating long-term trade adaptation in regimes with carbon constraints.

Conclusion

This study examined how carbon taxation, energy consumption, industrial modernization, and carbon intensity influence manufacturing export competitiveness in Nordic economies during 2000–2024. Using a panel quantile regression supported by robustness and causality analyses, the findings indicate that carbon taxation enhances efficiency, drives innovation, and strengthens export resilience in economies with advanced institutional and technological capacities. Fossil fuel use continues to support short-term competitiveness, but its importance is gradually declining as economies move toward cleaner energy systems. Electricity consumption exerts a negative impact on export performance, reflecting the high production costs associated with power-intensive processes. In contrast, manufacturing value added increases competitiveness by fostering technological upgrading and industrial diversification, while higher carbon intensity reduces export performance and heightens vulnerability to emerging carbon trade regulations.

Overall, the results demonstrate that ambitious climate policies and industrial competitiveness can coexist when supported by coherent carbon pricing, industrial upgrading, and energy efficiency strategies. Policymakers should channel carbon tax revenues into green innovation, renewable energy expansion, and cleaner production technologies to enhance long-term competitiveness. For industry leaders, aligning sustainable manufacturing practices with export strategies will be critical to maintaining market advantage in low-carbon global trade. Future research should extend this framework using firm- or sector-level data and cross-regional comparisons to deepen understanding of how carbon taxation and energy transitions shape competitiveness in diverse economic contexts.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

Author contributions

MR: Writing – original draft, Writing – review & editing. ZA: Writing – original draft, Writing – review & editing. JK: Writing – original draft, Writing – review & editing. AA: Writing – original draft, Writing – review & editing. CL: Writing – original draft, Writing – review & editing. W-kM: Writing – original draft, Writing – review & editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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