Development of the EU Maritime Carbon Verification System under the Dual-Carbon Goals and Its Implications

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Abstract

Against the backdrop of accelerating global climate governance, the shipping industry is undergoing a rapid green transition, with carbon measurement, reporting, and verification (MRV) systems emerging as critical enablers. This paper systematically reviews the development of the EU maritime carbon market verification system and its supporting technical framework, with a focus on its legislative foundation, implementation dynamics, and the key technical and institutional challenges it faces. Based on the EU's experience, the paper proposes four recommendations for China: establishing a comprehensive ship carbon emissions verification system, enhancing metrological capabilities, promoting international standardization, and ensuring the quality of carbon data. The aim is to provide a reference for building a scientific, standardized, and internationally recognized maritime carbon measurement system in China.

Keywords

Carbon market, carbon measurement, metrological institutions.

1. Introduction

Against the backdrop of increasingly severe global climate change and tightening emission reduction policies, the shipping industry—one of the major contributors to carbon emissions—is undergoing a profound transformation toward green development. As the carrier of over 90% of global trade volume, the sustainable development of maritime transport is not only a crucial component in combating climate change but also a key pillar for maintaining the stability of the global trade system. With mounting pressure for emission reduction, the shipping industry is accelerating its transition from traditional fossil fuel propulsion to clean energy sources and low-carbon operational models.

In this context, the system of Monitoring, Reporting, and Verification (MRV) has become essential infrastructure for promoting the green transformation of maritime transport. Metrology, as the core technical support for the implementation of carbon reduction policies, plays a vital role in ensuring the objectivity and comparability of emission data. It also provides a reliable quantitative basis for carbon trading and taxation mechanisms. The European Union (EU) has taken the lead in building a carbon metrology system, advancing the standardization and institutionalization of maritime carbon verification mechanisms through legislation and institutional design. This proactive approach has significantly contributed to the reshaping of global green trade rules. At the same time, the EU is actively implementing policies such as FuelEU Maritime and the Carbon Border Adjustment Mechanism (CBAM), aiming to export standards and exert policy spillover effects that guide—or even restructure—the global technical and institutional framework for carbon governance.

As a major trading and maritime nation, China must respond swiftly to the trend of developed economies like the EU erecting green barriers. This entails accelerating the development of

carbon metrology technologies and the construction of standard systems, thereby enhancing the resilience and international competitiveness of the Chinese shipping industry. In this context, an in-depth study of the EU's development trajectory and technical practices in maritime carbon market verification, as well as a systematic analysis of its implications for China's policy and technical frameworks, holds significant strategic value and practical relevance.

2. The EU's Maritime Carbon Verification Framework

In the global landscape of climate governance, the European Union (EU) has consistently played the role of a "pioneer," and its leadership in decarbonizing the maritime sector is no exception. Although the International Maritime Organization (IMO) has adopted a decarbonization strategy for international shipping, its relatively modest targets and slow progress have prompted the EU to take more proactive steps in rule-making. It has been actively building a regional maritime carbon regulatory mechanism to ensure that the shipping industry plays a crucial role in achieving Europe's ambitious goal of climate neutrality by 2050.

2.1. Promoting the Legal and Regulatory Framework for Maritime MRV

As early as 2003, the EU adopted Directive 2003/87/EC, establishing the legal foundation for the EU Emissions Trading System (EU ETS), which officially commenced operation in 2005. The system uses a market-based approach—setting a cap on total emissions and allowing trading of allowances—to drive emission reductions. In its initial phase, the EU issued MRV implementation guidelines to support the emerging MRV system. To enhance the coherence and enforceability of the system, the European Commission adopted a phased strategy to gradually expand sectoral coverage. Although the EU had proposed several times that the IMO establish an international maritime MRV framework, progress was limited due to disagreements among IMO member states over responsibility-sharing and management models. In 2011, the IMO's MARPOL Annex VI adopted mandatory Energy Efficiency Design Index (EEDI) regulations, but these applied primarily to new ships and did not cover the existing fleet. The EU viewed this as inadequate, criticizing the IMO's limited effectiveness in advancing global maritime emissions reductions. Coupled with the IMO's slow and complex decision-making process, the EU turned to unilateral regional actions to implement carbon emissions management and verification measures.

On June 28, 2013, the European Commission proposed a draft regulation on the Monitoring, Reporting and Verification of CO_2 emissions from maritime transport, which was adopted on April 29, 2015, as Regulation (EU) 2015/757. It mandated that from 2018 onward, all ships over 5,000 gross tonnage calling at EU ports must monitor, report, and have their CO_2 emissions verified by an independent third party. The regulation was revised in 2023, formally including maritime shipping in the EU ETS, with phased implementation beginning in 2024. According to Directive (EU) 2023/959 of the European Parliament and the Council, from January 1, 2024, all commercial vessels of 5,000 gross tonnage and above entering EU ports must pay for 40% of their greenhouse gas (GHG) emissions. By 2025, these ships must pay for 70% of their emissions, while offshore ships of 400 GT and above and cargo ships between 400–5,000 GT must report their emissions annually to the EU MRV system. From 2026, these vessels will be included in the EU ETS and required to pay 100% of their GHG emission costs. By 2027, all offshore commercial vessels over 5,000 GT will also be included. At that point, all commercial vessels over 400 GT will be fully covered under the EU ETS, creating binding emission reduction obligations for shipping companies [1].

To further promote the transition of maritime transport toward sustainability and the use of renewable fuels of non-biological origin (RFNBOs), the EU adopted the FuelEU Maritime Regulation in 2023, which will enter into force in January 2025. This regulation centers on the

gradual reduction of the full life-cycle GHG intensity of marine fuels and establishes an MRV-based regulatory system. Shipping companies are required to record key data during voyages, including fuel types, fuel consumption, and GHG intensity, and submit annual reports verified by independent third-party verifiers and submitted to the European Maritime Safety Agency (EMSA). [2] The regulation sets annual carbon intensity limits, and non-compliant ships may face fines, detention, or port entry bans.

2.2. Strengthening Regional Coordination and Mutual Recognition of Carbon Verification Standards

Given the diverse national circumstances among EU Member States, the MRV mechanism allows countries a degree of regulatory discretion, which leads to implementation disparities. To harmonize compliance systems across the region, the EU has introduced multiple measures under the EU ETS to promote convergence in carbon verification.

First, to achieve verification consistency, Member States are required to submit annual reports on their implementation of Directive 2003/87/EC, including details on allowance allocation, registry operations, monitoring, verification practices, and compliance management. Based on these 21 country reports, the European Commission produces a comprehensive analysis report within the set timeline to inform policy evaluation and future system revisions. This feedback and information-sharing mechanism facilitates alignment in carbon verification standards across Member States.

Second, the EU holds annual compliance meetings and forums, establishing five working groups on monitoring and reporting, accreditation and verification, aviation, electronic reporting, and carbon capture and storage (CCS). These platforms support cross-border dialogue and best-practice exchange. Voluntary participation by Member States allows for deep discussion of practical challenges and solutions, improving rule coordination and shared expertise. These forums foster "soft norms" and consensus on verification practices, laying a foundation for the mutual recognition of rules.

Technically, the EU continues to promote the development and application of standardized IT systems, which support structured and consistent data management, report submission, and information exchange. A unified digital platform enhances transparency and harmonization of the carbon verification system, ensuring seamless coordination across national boundaries.

At the international cooperation level, the EU has also expanded dialogue and collaboration with other countries. For example, in August 2024, China and the EU signed a Memorandum of Understanding on Strengthening Cooperation in Emissions Trading, agreeing to collaborate in areas such as carbon market design, allowance allocation, MRV rules, and mutual recognition of carbon accounting and verification standards. This not only promotes convergence between Chinese and European carbon markets but also contributes to the international alignment of carbon verification standards.

2.3. Establishing the Carbon Border Adjustment Mechanism

As carbon border taxation accelerates, carbon verification and reporting systems have become critical elements of the new international trade rules. Through the MRV system and Carbon Border Adjustment Mechanism (CBAM), the EU has institutionalized and standardized its carbon accounting rules, exporting them as de facto international standards by embedding them into market access conditions, thereby erecting green trade barriers.

On April 25, 2023, the Council of the EU voted to adopt the Regulation establishing CBAM, which officially entered into force on May 16, 2023. The mechanism marks the first time the EU has extended carbon responsibilities to imports through legislation. The transitional phase (2023–2025) requires EU importers to submit quarterly reports to authorities, including data on import volumes and embedded carbon emissions. [3] These reports must adhere to the MRV

standards, using EU-compliant carbon accounting methodologies and undergoing third-party verification to ensure accuracy and integrity. If importers fail to meet these obligations, CBAM authorities may impose penalties and corrective measures.

From January 1, 2026, CBAM enters full implementation. Importers must continue submitting verified carbon emissions reports and begin purchasing and surrendering CBAM certificates based on actual emissions. The price of these certificates will be indexed to EU ETS allowance prices, thereby creating a cross-border carbon price linkage mechanism.

Thus, the role of the carbon verification system has evolved from a technical data-gathering tool to a foundational institutional mechanism for market operations and legal enforcement. Through the maritime MRV regulation, the EU not only supports CBAM implementation but also exerts institutional influence over global supply chain emissions governance, driving the international diffusion of its carbon accounting and trade rules. Metrology has become not only a technical support tool but also a key instrument for rule-making and enhancing the EU's institutional voice.

2.4. Advancing Maritime Carbon Metrology Research

In the global push for climate action and green transformation, the maritime sector—as a significant source of emissions—is becoming an increasingly important focus of international mitigation efforts. Carbon metrology not only provides the quantitative foundation for carbon accounting and market mechanisms but also ensures accuracy and reliability through internationally recognized measurement standards and methods, forming the technical basis for inspections and verifications.

First, the EU has addressed the lack of metrological foundations for alternative fuels by researching their energy properties and developing relevant physical and chemical measurement standards. Fuels such as hydrogen, methanol, and ammonia exhibit substantial variations in energy density depending on temperature, pressure, and purity. Accurate measurements of their calorific values and combustion efficiencies are critical for ship operations, emission accounting, and fuel billing. EU metrology institutes have developed gas calorimetry devices suitable for diverse operating conditions, supported by thermophysical modeling and combustion heat calibration. These devices are traceable to national energy standards, thus ensuring metrological reliability in trade, billing, and emissions verification for alternative fuels.

Second, EU metrology institutes have developed analytical techniques and calibration standards for various alternative fuels. For hydrogen, controlling purity and monitoring impurities (e.g., CO, sulfur compounds, moisture) is essential for the safety and durability of fuel cell systems. Metrology organizations have established multi-channel systems based on gas chromatography, mass spectrometry, and infrared spectroscopy to detect trace impurities at the ppb level, using traceable standard gas mixtures to ensure international consistency. These technologies are also applicable to real-time monitoring of NO_x, aldehydes, and other contaminants in ammonia and methanol, supporting fuel quality standards and compliance assessments.

In addition, to support quantitative control and carbon footprint accounting in the fuel bunkering process, metrology institutes are contributing to the construction of a measurement chain for bunkering operations. This includes flow measurement, compression and liquefaction control, storage and transport metrology, and process calibration. Unlike traditional fuel bunkering, which focuses mainly on volumetric measurement, liquefied natural gas (LNG) and hydrogen require simultaneous control of temperature, pressure, and flow rate. Metrology institutes have developed mass flow meters and in-line calibration modules suited to cryogenic and high-pressure conditions, ensuring accuracy and fairness in fuel delivery.

At the emissions accounting level, the EU has also established a data flow and model interface from "fuel molecules" to "emission factors," providing a unified parameter base for life-cycle assessments (LCA) and full carbon footprint analysis.

3. Challenges Faced by the EU Maritime Carbon Verification System

Since its implementation, the EU's maritime MRV system has achieved significant results. By unifying standards and standardizing procedures, it has ensured transparency and accuracy of greenhouse gas emissions data in the shipping industry, effectively improving the sector's emission management. Meanwhile, the data collected have exerted pressure on shipowners and operators to accelerate emission reductions, optimize voyage efficiency, and adopt cleaner fuels. The establishment of an information-sharing platform among Member States and an annual compliance coordination mechanism has effectively eliminated regional regulatory barriers, strengthening policy consistency and enforcement. Overall, the EU maritime MRV system has laid a solid foundation for carbon pricing and emission reduction policies and has driven the shipping industry to take crucial steps toward green and low-carbon transformation. However, the system still faces numerous challenges as it deepens implementation.

3.1. Environmental Limits and Technical Bottlenecks in Carbon Monitoring

Traceable measurement of ship carbon emissions forms the foundation of the carbon verification system, directly impacting the accuracy, compliance, and international acceptance of emission data. Regarding emission reduction incentives, supply chain tracking and fuel tank level monitoring only provide total fuel consumption figures and lack new perspectives on reduction potential. Flow meter monitoring and direct carbon dioxide monitoring methods have not yet been widely adopted, representing significant untapped potential for emission reduction. Currently, EU maritime carbon monitoring technology is still under continuous improvement, facing various technical bottlenecks in the scientific validity of measurement methods, dynamic response capabilities of monitoring devices, and traceability of measurement values.

Regarding flow meter application, the harsh shipboard environment—characterized by high vibration, large temperature variations, and variable fuel properties—places elevated demands on flow measurement devices. Both common velocity sensor flow meters and differential pressure flow meters are susceptible to the effects of fluctuating medium viscosity, density, and flow disturbances, causing measurement drift or errors. Some industrial-grade devices achieve high accuracy on land but, when transplanted to marine use with high-viscosity fuels or alternative fuels, show significantly amplified errors. Their measurement uncertainty struggles to meet the data traceability requirements of carbon verification. Additionally, installation location, pipeline aging, and corrosion directly impact the long-term stability and accuracy of flow meters. The technical maturity and standardization of these devices remain insufficient.

The application of direct carbon dioxide monitoring (Continuous Emission Monitoring Systems, CEMS) also faces challenges. The Danish National Metrology Institute (DFM) developed a spectroscopy-based ship exhaust gas analysis method, which improved detection accuracy for some specific components, yet cross-interference and drift issues persist in the high-temperature, high-humidity, and composition-variable environment of ship emissions. The Swedish Research Institute (RISE) introduced an optical absorption spectroscopy system that performs well in simultaneous temperature and pressure measurements, but its wide spectral dynamic calibration and traceability under harsh sea conditions are not yet fully mature. At present, most such systems remain in laboratory testing or small-scale trials, lacking industry-recognized standardized solutions.

3.2. High Costs of Monitoring and Verification Impede Equipment Deployment

At present, the contradiction between the high precision requirements and economic affordability in maritime carbon emission monitoring and verification has become a major barrier to technology adoption.

On one hand, sensors and measurement systems needed for liquid level monitoring, flow measurement, and emission detection generally require stringent installation conditions, sensor accuracy, and calibration, resulting in high manufacturing and commissioning costs. High-precision mass flow meters, Coriolis effect mass sensors, and dynamic calibration systems can meet EU MRV and ISO standards but come with procurement, maintenance, and periodic calibration costs often beyond the reach of small and medium-sized shipping enterprises.

On the other hand, to comply with emission verification requirements, monitoring equipment must maintain measurement accuracy and data traceability over long-term operation. Frequent calibration, maintenance, and performance validation add operational burdens. For example, differential pressure and velocity flow meters require complex calibration models and compensation algorithms, influenced by pipeline conditions and medium characteristics, necessitating frequent recalibration and thus high operational costs. Additionally, vibration, corrosion, temperature and humidity fluctuations, and fuel property changes in the maritime environment may cause measurement errors, forcing ship operators to invest additional resources in data correction and verification preparations.

3.3. Frequent Disputes over Standard Applicability Heighten the Risk of International Trade Frictions

Since the EU implemented maritime MRV and market-based emission reduction measures, compliance disputes surrounding its rules have been ongoing. The core issue lies in the EU's regional legislative approach to regulating global shipping carbon emissions, which breaks the IMO-led global negotiation mechanism and conflicts with principles of international law and multilateral governance consensus.

Under the "common but differentiated responsibilities" principle established by the United Nations Framework Convention on Climate Change (UNFCCC), the EU has repeatedly advocated for strengthening common responsibility while downplaying differentiation. The MRV regulations and carbon trading system apply uniformly to all vessels on EU routes regardless of countries' economic development levels or emission reduction capabilities. This "fairness" approach, justified by protecting EU industrial competitiveness, may result in substantial inequity.

Moreover, specific EU carbon policy implementations risk triggering trade disputes. For instance, carbon emission verification, reporting, and allowance purchasing all rely on EU market prices and verification standards, lacking recognition of third countries' standards, emission control policies, or mitigation efforts, thus forming de facto "regulatory external barriers." Especially for developing countries lacking mature carbon markets or autonomous reduction mechanisms, the EU's one-size-fits-all policy directly raises their export and shipping costs. [4] The combined enforcement of the EU ETS and CBAM further transmits maritime carbon costs to imported goods, which may provoke wider international trade conflicts.

3.4. Significant Carbon Leakage Risks Continue to Constrain Policy Efficacy

Although the EU maritime carbon verification and emissions trading systems aim to reduce shipping emissions, their design inherently carries significant carbon leakage risks.

First, the MRV system defines "port of call" as ports where cargo or passengers are actually loaded or unloaded. Although this attempts to delimit emission responsibilities, it leaves operational loopholes for shipping companies. Research shows vessels can adjust routes to conduct loading, unloading, or transshipment at non-EU ports adjacent to the EU (e.g., Tangier,

Izmir) and then enter EU ports via feeder services, thereby circumventing carbon verification and allowance payment requirements. Such "port hopping" or "regulatory evasion" strategies weaken EU port competitiveness and may increase actual global emissions.

Second, as a regional regulatory framework, the EU cannot fully cover the global shipping network. Shipping companies may intentionally adjust port calls and routing to avoid carbon costs. The UK's exit from the EU is also seen as exacerbating carbon leakage risks, as UK ports are no longer bound by the EU ETS, potentially becoming alternative transshipment hubs.

Furthermore, the current MRV and EU ETS systems, using ports as emission monitoring nodes, have yet to effectively cover emissions during anchorage operations, ship-to-ship transfers, and other specific navigation segments, causing some emissions to fall outside verification scope.

In sum, institutional design gaps in the EU maritime carbon verification and market mechanisms provide avenues for companies to evade obligations, undermining genuine emission reductions and introducing uncertainties into the international trade order.

4. Implications

4.1. Accelerate the Establishment of a Full-Chain Ship Carbon Emission Measurement and Verification System

The EU's practice of incorporating the shipping industry into the carbon market and establishing an MRV system demonstrates that effective carbon reduction relies on having scientific, systematic, and verifiable emission data. China should accelerate the construction of unified MRV rules for ship carbon emissions, covering all relevant parties including port regulatory authorities, shipping companies, and third-party verification bodies. Efforts should focus on building a national maritime carbon emission database and a corporate accountability evaluation mechanism.

4.2. Strengthen Basic Metrology Capacity and Improve Accuracy and Consistency of Key Parameter Measurements

Leveraging high-level metrology institutes, the EU has established a full-process traceability system spanning reference materials, measurement devices, and on-site applications, effectively ensuring the accuracy and comparability of emission data. China should focus on key pollutants in the maritime sector (such as CO_2, CH_4, N_2O) and core physicochemical parameters of alternative fuels, accelerate the deployment of representative metrology laboratories and maritime application demonstration platforms, and develop specialized measurement instruments and reference materials adapted to complex offshore conditions. This will enhance the traceability and international comparability of multi-source emission data, providing strong support for mutual recognition in global verification systems.

4.3. Promote Research on Measurement Methods for Alternative Fuels and Standardization Processes

As low-carbon alternative fuels such as hydrogen, methanol, and ammonia are gradually applied in shipping, the existing metrology system still has shortcomings in energy efficiency assessment, fuel composition analysis, and emission factor accounting. It is recommended to accelerate key technology research under complex maritime conditions, including calorimetry, mass flow measurement, and trace component detection. Building a multi-fuel emission factor database and promoting the development of a metrology standard system covering the entire fuel life cycle are essential. China should actively participate in the formulation of international standards by organizations such as ISO and the IMO, enhancing its influence and leadership in green shipping metrology rule-making.

4.4. Establish Carbon Data Quality Control Mechanisms to Ensure Fair Operation of the Carbon Market

The EU has built a relatively comprehensive carbon data quality control system through uncertainty assessment, calibration with reference materials, and third-party verification mechanisms, effectively enhancing transparency and trust in carbon market operations. While accelerating the construction of ship carbon emission metrology systems, China should simultaneously establish a full-process quality management system covering monitoring, verification, and review stages. It should develop uncertainty assessment tools for greenhouse gas emissions tailored to shipping scenarios, improve qualification access and conduct norms for verification agencies, and strictly prevent data distortion and falsification, thereby ensuring fairness and effectiveness of the carbon market.

Acknowledgements

China National Institute of Metrology Independent Research Project "Strategic Intelligence Research on Metrological Support for the EU Shipping Carbon Market Policy"(AKYZZ2557)

China's National Key Research and Development Program, titled "Research on the Green and Intelligent Certification and Evaluation System for the Express Delivery Industry and Platform Service Application" (2022YFF0608105)

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