Do Business and Trade Facilitation Journal
Volume 5, Issue 1, 2025, Page 81-94
https://doi.org/10.6914/dbtf.050107

Do Business and Trade Facilitation Journal

Carbon Digital Twin: Artificial Intelligence, Green Protectionism, and the Reshaping of Global Trade Governance

Shuhua LIU

Business School, Qilu Institute of Technology, Jinan 250200, China

Abstract

This paper examines the emerging paradigm of the "Carbon Digital Twin" as a response to the global "measurement crisis" in climate governance. Traditional methods such as LCA and IOA are increasingly inadequate in addressing the demands of dynamic, data-intensive carbon governance. The Carbon Digital Twin integrates real-time sensing, AI-driven cognitive analysis, and blockchain-based trust mechanisms to provide granular, predictive, and verifiable carbon accounting. However, this paradigm shift raises tensions between techno-scientific legitimacy and legal-procedural legitimacy, challenging the authority of institutions like the WTO. Comparative analysis of the EU's CBAM, the US IRA, and China's state-led model reveals the fragmentation of green trade governance into competing techno-economic blocs. The paper highlights key dilemmas, including the "carbon paradox" of AI's own footprint and risks of environmental data injustice, while proposing a hybrid governance framework to balance technological efficiency with democratic accountability and global equity.

Keywords Carbon Digital Twin; Artificial Intelligence; Green Trade Governance; Techno-Scientific Legitimacy; Environmental Data Justice

1 Introduction: The Governance of Computation

1.1 The "Measurement Crisis" as a Governance Crisis

Global climate governance is facing a profound "measurement crisis", a crisis that has transcended the purely technical realm to become a fundamental governance crisis. The inherent limitations of traditional carbon footprint measurement methods, such as Life Cycle Assessment (LCA) and Input-Output Analysis (IOA), have become increasingly pronounced against the backdrop of an ever more complex and dynamic global economy. These methods are built on a foundation of static, sampled, and aggregated historical data, leading to fundamental flaws in timeliness, granularity, and accuracy. For example, the data update cycle for IOA is too long to quickly reflect the environmental impact of technological changes[2], while LCA faces significant difficulties in conducting spatially differentiated assessments due to a lack of location-specific data[3]. Consequently, the validity of using national-level average grid emission factors from several years ago to assess the carbon footprint of a high-tech product manufactured in a specific region during

©The Author(s) 2025.Article History Received: April 8, 2025; Accpted: June 12, 2025; Published: June 30, 2025. ***Do Business and Trade Facilitation Journal***, ISSN 2789-3944 (Print), ISSN 289-3952 (Online),published by Creative Publishing Co., Limited 2025.. Email: tooderdy@163.com, https://dbtf.cc, https://cpcl.hk.

a specific period is severely questionable. This crisis is not a simple technical deficiency but a failure of a governance paradigm. The existing governance framework, centered on the World Trade Organization (WTO), lacks the necessary tools to provide the credible, dynamic, and verifiable information required to achieve ambitious climate goals and enforce emerging regulatory instruments like the EU's Carbon Border Adjustment Mechanism (CBAM). This absence of information infrastructure has led to the emergence of a "legitimacy vacuum". However, as research in the politics of measurement reveals, when existing control systems face a crisis, stakeholders do not abandon measurement but instead redouble their efforts, driving innovation and expansion in measurement methods. The failure of existing institutions to provide credible carbon data creates a critical opportunity for actors who can offer "solutions" to seize legitimacy, even if these solutions are unilateral and protectionist in nature. Therefore, this measurement crisis is not merely a technical problem to be solved but a catalyst driving political and institutional change, paving the way for new governance models designed to fill the legitimacy void left by the old system.

1.2 The Emergence of the "Carbon Digital Twin": A New Paradigm

In response to this deep-seated governance crisis, a completely new techno-scientific paradigm—the "Carbon Digital Twin"—is emerging. This paradigm aims to construct a dynamic virtual replica parallel to the carbon flows of the physical world, integrating cutting-edge digital technologies to achieve comprehensive, real-time, and predictive management of carbon emissions[5]. Its architecture is built upon three interconnected layers. The first is the Sensing Layer, which achieves high-fidelity, high-frequency monitoring of carbon sources and sinks through the fusion of multi-source data streams such as Internet of Things (IoT) sensors, satellite remote sensing, and industrial control system data.

Table 1: The Paradigm Shift in Carbon Accounting

Dimension	Traditional Methods (LCA/IOA)	Carbon Digital Twin Framework	Core Transformation
Data Source	Static databases, statistical yearbooks, sample surveys	Real-time, multi-source data streams (satellites, IoT, transaction data)	From offline, sampled history to online, census-based reality
Time Granularity	Annual, quarterly	Real-time, hourly, daily	From static snapshots to dynamic video streams
Spatial Granularity	National, industry	Asset, equipment, process level	From macro-aggregation to micro-precision
Analytical Method	Linear accounting, matrix algebra	Predictive AI/ML, simulation optimization	From retrospective calculation to proactive intervention
Trust Mechanism	Periodic, manual third-party audits	Continuous dMRV, blockchain-based cryptographic verification	From centralized human trust to decentralized technological trust
Decision Support	Lagging strategic planning, compliance reporting	Real-time operational optimization, predictive risk management	From reactive response to proactive management

This layer pushes the boundary of carbon accounting from macro-statistics to micro-physical reality. The second layer is the Cognitive Layer, which utilizes Artificial Intelligence (AI) and Machine Learning (ML) models for intelligent analysis, pattern recognition, prediction, and attribution of the massive data collected by the sensing layer. This layer not only answers "how much was emitted" but also explains "why it was emitted" and "how it will be emitted in the future", providing a decision-making basis for proactive intervention[11]. The third layer is the Trust Layer, which leverages digital Measurement, Reporting, and Verification (dMRV) systems, often combined with blockchain technology, to achieve credible traceability, tamper-proofing, and transparent sharing of carbon data. This layer aims to address issues such as human error, information asymmetry, and high trust costs present in traditional audit mechanisms. The emergence of this paradigm marks a fundamental shift in the field of carbon management from "static accounting" to "dynamic intelligence". It is not merely an iterative upgrade of traditional LCA/IOA methods but a disruptive reconstruction, offering unprecedented technological possibilities for achieving real-time, granular, and predictive carbon governance[15]. The table (Table 1) systematically illustrates this paradigm transformation.

1.3 Core Argument: Techno-Scientific Legitimacy vs. Legal-Procedural Legitimacy

The core argument of this paper is that the rise of the "Carbon Digital Twin" paradigm has triggered a profound conflict between two forms of authority in global governance. The first is Legal-Procedural Legitimacy, which is the cornerstone of traditional multilateral institutions like the WTO. Its authority is built on rule negotiation, state consent, and formal dispute settlement mechanisms. However, this system is itself facing a deep "legitimacy crisis", widely criticized for being slow to respond, lacking democracy in its decision-making processes, and being unable to effectively address complex 21st-century issues like climate change and digital trade. The second is Techno-Scientific Legitimacy, a new form of authority derived from the supposed "objectivity", precision, and efficiency of complex data-driven algorithmic systems. This new legitimacy promises to solve the measurement crisis that traditional governance models cannot handle. However, its "black box" mode of operation poses a direct challenge to the principles of transparency, accountability, and appealability that are central to the traditional legal-procedural model. The failure of the existing multilateral system to resolve the measurement crisis has created the conditions for the rise of techno-scientific legitimacy, enabling major economies to package nationalist industrial policies as objective global public goods. This logical chain proceeds as follows: first, a global governance vacuum emerges from the inability of the existing system to produce reliable carbon emissions data; second, major economies such as the EU (through CBAM) and the US (through the IRA) are developing technologically complex, data-intensive climate policies that are essentially domestic industrial policies aimed at promoting their own economic interests; finally, by claiming that these algorithm-based systems solve the global measurement crisis, these countries are able to portray their unilateral and even protectionist actions as contributions to the global climate mitigation cause. Thus, a technical crisis provides a political cloak of legitimacy for unilateral actions that might otherwise be seen as purely self-serving protectionism, directly linking the technical problem of carbon accounting to the rise of green protectionism.

1.4 Research Roadmap and Contribution

To elucidate this complex dynamic, this paper will follow the subsequent research path. First, it will construct a novel theoretical framework that integrates relevant theories from global governance, technology studies, and international political economy to analyze this transformation process. Second, it will conduct a comparative analysis, supported by quantitative data, of the emerging "algorithmic green governance" mechanisms in the EU, the US, and China, revealing their different operational logics and geoeconomic impacts. Third, it will critically examine the inherent contradictions of the new paradigm, particularly through the lenses of the "carbon paradox" and "environmental data justice". Finally, it will propose policy recommendations advocating for a hybrid governance framework that can combine the efficiency of artificial intelligence with the principles of democratic accountability and social justice. The contribution of this paper lies in providing a new analytical perspective that connects technological innovation, geopolitical competition, and normative dilemmas to understand and shape the future of global trade and climate governance.

2 Theoretical Framework: Embedding the Carbon Digital Twin in Global Governance

This section aims to build the analytical engine of the paper. It moves beyond a purely technical description of the Carbon Digital Twin to theorize its profound geoeconomic and social impacts by engaging it in a dialogue with three major theoretical frameworks from international political economy and sociology, ultimately integrating these theories into a dynamic model of change.

2.1 From Global Value Chains to Algorithmic Data Chains: A Gereffian Analysis

This subsection draws on Gary Gereffi's Global Value Chains (GVC) theory to analyze the new reality of green trade. The core of traditional GVC theory is "governance" —the power of lead firms to set product standards and parameters for suppliers. This paper argues that this core of governance is undergoing a fundamental shift. The focus of governance is no longer just on product quality or production processes but on mandating that suppliers adopt specific data generation and reporting technologies. The Walmart-IBM Food Trust platform provides a powerful analogy. In this case, the retail giant Walmart required its leafy green vegetable suppliers to join the food traceability system based on IBM's blockchain technology or face the risk of being excluded from the supply chain. This demonstrates how lead firms can compel their entire supply chain to adopt a specific technology platform, thereby shifting the governance model from a traditional contractual and standards-based one to a technological and platform-based one. This shift gives rise to what this paper calls "Algorithmic Data Chains" . In Algorithmic Data Chains, control over data architecture, algorithmic standards, and digital platforms becomes the primary source of power, surpassing traditional control over production or brands. This transformation introduces a new power dynamic. In the dialogue between GVC theory and transaction cost economics, "asset specificity" is a key variable for explaining power relationships in value chains[26]. When suppliers need to make highly specialized investments for a particular buyer, they are more easily locked into an unequal "captive" or "hierarchical" relationship. This paper argues that investment in specific, often proprietary, dMRV systems creates a new and powerful form of asset specificity. For instance, a supplier in a developing country invests heavily in establishing a data reporting system compliant with EU CBAM requirements. This investment may be useless or even an obstacle to meeting the requirements of the US IRA or China's data sovereignty laws. Thus, data compliance technology itself becomes a transaction-specific asset, locking suppliers into the ecosystem of a particular regulatory body and thereby reproducing the "captive" governance model of GVCs at the data infrastructure level. This provides a new theoretical explanation for the operation of the "Brussels Effect" in the digital age.

2.2 The Embeddedness of Green AI: A Ruggie-Granovetterian Synthesis

This section draws on John Gerard Ruggie's concept of "embedded liberalism" and Mark Granovetter's theory of social embeddedness to understand the differentiated application of "Carbon Digital Twin" technology in different political economies. Ruggie's classic theory posits that the post-World War II international economic order was a historic compromise that "embedded" the multilateral principles of free trade within national commitments to domestic social stability and welfare, thereby providing social legitimacy for globalization[27]. This paper argues that we are witnessing the emergence of a new "embeddedness" , but one that is fragmented and competitive rather than seeking a uniform global compromise. The development and deployment of the Carbon Digital Twin are not occurring in a political vacuum but are deeply embedded in the distinct "social purposes" or national projects of major global powers. For the European Union, Carbon Digital Twin technology is embedded in its grand project of regulatory expansion and normative leadership. CBAM is the embodiment of this logic, attempting to extend the EU's internal carbon pricing and data standards as global norms, the so-called "Brussels Effect" . For the United States, the relevant technology is embedded in its techno-nationalist industrial policy and supply chain reshoring projects. The IRA, by providing huge subsidies and attaching strict domestic content requirements, uses algorithmic eligibility screening to guide global green industry chains to cluster in North America, serving its strategic goals of revitalizing domestic manufacturing and competing with China. For China, digital technology is embedded in its state-led, top-down project to achieve its "dual carbon" goals and technological self-sufficiency. China's model emphasizes state control over data infrastructure and data sovereignty, aiming to build a technological standard and governance system independent of the West. Granovetter's theory of social embeddedness further complements this analysis by reminding us that these new technological systems are not independent technical artifacts but are shaped and utilized by specific social relations, political structures, and power networks. Therefore, applying Ruggie's framework is not to seek a new, globally unified compromise, but to explain why the development and deployment of AI in the climate and trade domain are diverging so profoundly along geopolitical fault lines.

2.3 The Socio-Technical Transition of Governance: Applying Geels' Multi-Level Perspective

Finally, this subsection applies Frank Geels' Multi-Level Perspective (MLP) framework to view the entire phenomenon as a systemic socio-technical transition process. The MLP framework explains the mechanisms of major socio-technical changes by analyzing the dynamic interactions of three different levels. The first level is the Macro-landscape, which refers to the external, slowly changing macro-context. In the analysis of this paper, this includes the mounting pressure of climate change, the geopolitical competition between the US and China, and the broad wave of technological disruption led by AI. These macro-pressures collectively challenge the existing institutional arrangements. The second level is the Socio-Technical Regime, which refers to the existing, stable socio-technical system, composed of a set of interlocked rules, practices, technologies, and actor networks. In this paper, this refers to the established global trade governance system based on the WTO, whose legitimacy is rooted in legal-proceduralism, and the associated traditional carbon accounting methods (LCA/IOA). The third level is Niche Innovations, which refers to radical innovations emerging in protected spaces. The development of technologies such as the Carbon Digital Twin, AI, blockchain, and dMRV initially emerged as "niche" innovations, offering new possibilities for solving the problems of the existing regime (i.e., the measurement crisis). The MLP framework allows us to systematically see how pressures from the macro-landscape (such as the urgency of climate change) weaken the stability of the existing regime, thereby creating "windows of opportunity" for niche innovations to break through and potentially reconfigure the entire global trade governance system.

2.4 An Integrative Framework: A Dynamic Model of Change

These three theories are not simply juxtaposed for analysis but together describe a transformative process with causal and hierarchical relationships, forming a unified "analytical engine" . The process begins at the Niche Innovations level of the MLP framework, with the emergence of Carbon Digital Twin technology. This technology then gives rise to a new governance model within global value chains, transforming traditional GVCs into Algorithmic Data Chains centered on data power (Gereffi's perspective). Subsequently, this new governance capability is captured by states and, according to the theories of Ruggie and Granovetter, becomes embedded in their competing national strategies (the EU's regulatory expansion, US industrial policy, China's state integration). The ultimate outcome of this embedding process may trigger the comprehensive Regime Transition described by the MLP framework, where the old, WTO-based system is replaced or fundamentally altered. This analytical framework is further deepened by integrating the latest literature on algorithmic governance and data colonialism. Karen Yeung defines algorithmic governance as a decision-making system that regulates behavior through the "continuous generation of knowledge from data calculations". This precisely describes how CBAM's reporting requirements or the IRA's eligibility rules function as a new type of automated regulatory tool. Meanwhile, the theory of data colonialism proposed by Nick Couldry and Ulises Mejias reveals the political-economic foundation of this governance model: the appropriation and exploitation of human life itself through data extraction to generate profit or achieve control. Algorithmic governance describes how the new system operates, while data colonialism reveals its underlying motive (why). Therefore, the complex governance systems established by the EU, US, and China are all predicated on a potential, colonial-style extraction of underlying data from global supply chains and related populations, an extraction that forms the basis of the new power system.

3 The Algorithmic Weaponization of Green Trade: A Comparative Analysis

This section constitutes the empirical core of the paper. It applies the aforementioned theoretical framework to a comparative analysis of the three major global economic blocs. Through specific policy instruments and quantitative data, it reveals how each actor is developing a unique model of "algorithmic green governance" and clarifies how these models are collectively leading to the fragmentation of the global green economy.

3.1 The European Union: Governance through Regulatory Externalization

This part focuses on the EU's Carbon Border Adjustment Mechanism (CBAM), viewing it not just as a carbon tariff but as a complex algorithmic governance system that externalizes the EU's cumbersome measurement and reporting standards globally, representing a concentrated manifestation of the "Brussels Effect" in the climate domain. The operational logic of CBAM relies on the precise calculation of "embedded emissions" in imported products, which is itself a data-intensive algorithmic process that requires non-EU producers to track and report carbon emissions from their production processes according to EU methodology. The real-world impact and coercive power of this system are embodied in its compliance costs and penalty mechanisms. According to the European Commission's official impact assessment, the total annual administrative costs for businesses to comply with CBAM regulations are estimated to be between €9.8 million and €14.3 million, while enforcement costs for authorities are projected at €15 million per year. Even more deterrent are its penalty clauses: during the transitional period from 2023 to 2025, companies that fail to submit compliant reports will face fines of up to €50 per tonne of unreported emissions. These figures clearly quantify the "teeth" of CBAM as a regulatory tool; it compels non-EU companies to adopt its data standards and technological ecosystem by creating significant compliance burdens and high costs for non-compliance. Furthermore, the intense debate over CBAM's compatibility with WTO rules shows how legal discourse serves political will. Academic research indicates that the legal community's view on CBAM compatibility shifted from initial widespread skepticism to later broad support, a change not stemming from major shifts in WTO case law but reflecting the strengthening of EU political will and the corresponding adjustment of legal arguments.

3.2 The United States: Governance through Subsidies and Techno-Nationalism

This part analyzes the Inflation Reduction Act (IRA) as a quintessential techno-nationalist industrial policy aimed at reshaping global supply chains, reshoring high-end manufacturing, and engaging in geoeconomic competition with China. Unlike CBAM's direct reporting requirements, the algorithmic governance element of the IRA is embodied in the complex, data-intensive eligibility rules that companies must meet to receive subsidies. For example, its electric vehicle subsidies explicitly require that a certain percentage of the battery's critical minerals and components must come from the United States or its free trade agreement partners, effectively acting as an algorithmic filter that excludes non-compliant supply chain participants. The power of the IRA lies in its unprecedented scale of subsidies, which constitutes a potent market-distorting force. The act provides approximately $783 billion in funding and tax credits for energy and climate-related projects. Specifically, the act includes enormous appropriations such as $37 billion for advanced manufacturing, $30 billion for nuclear power, and $12 billion for electric vehicle incentives. Key incentives include a 30% Investment Tax Credit (ITC) and a Production Tax Credit (PTC) of 2.75 cents per kWh for renewable energy projects that meet specific requirements. These massive financial incentives, channeled through algorithmic eligibility screening, guide global investment and supply chains to cluster in North America and among its allies, which is widely seen as a direct challenge to WTO non-discrimination principles like Most-Favored-Nation and National Treatment.

3.3 China: Governance through State-Led Integration and Data Sovereignty

This part focuses on China's "dual carbon" goals and their application in local pilot projects. China's model is unique, characterized by a combination of top-down state policy directives (the "1+N" policy system) and innovative pilot projects at the local level, with extensive use of digital technology and AI for monitoring and efficiency improvement. Unlike the European and American models, the core of the Chinese model is the emphasis on data sovereignty and the development of indigenous technical standards, treating carbon data as a national strategic asset and aiming to build a self-sufficient governance system with state-controlled data infrastructure and technology standards. The effectiveness of China's local pilots can be verified through statistical data from official and academic research. For example, one study on low-carbon city pilots found that, compared to non-pilot cities, the ecological efficiency of pilot cities was on average about 3.0% higher. Another study on low-carbon transport system (LCTS) pilots showed that the policy led to a significant average reduction of 17.3% in carbon emission intensity in pilot cities. These data indicate that China, through its state-led, data-driven governance model, has achieved quantifiable results in promoting substantial emission reductions at the local level. This model aims to build a technological ecosystem independent of Western standards and to promote it externally through initiatives like the Belt and Road.

3.4 The Emerging Trilemma and Geoeconomic Fragmentation

The divergent paths of these three major economies are not merely policy differences; they are creating three incompatible green trade "techno-economic spheres". The EU's CBAM requires foreign companies to adopt EU-centric data reporting standards; the US's IRA incentivizes companies through subsidies to locate their supply chains in North America or allied countries; and China's model promotes domestic technology standards and data localization requirements within its sphere of influence. This situation poses a severe trilemma for a multinational enterprise (MNE) seeking to operate globally: it cannot simultaneously optimize its operations and supply chains for all three systems. For example, an automobile manufacturer that relocates its battery supply chain to the US to obtain IRA subsidies might face high CBAM tariffs when exporting to the EU due to the carbon footprint of its production process (e.g., using electricity from the US grid). Meanwhile, both models could conflict with China's increasingly stringent laws on data sovereignty and cross-border data flows. This has moved beyond simple trade friction and represents the fragmentation of the global green economy into separate blocs governed by different algorithmic logics, each with its own rules, standards, and data infrastructure. Analyses from the United Nations Conference on Trade and Development (UNCTAD) and the Organisation for Economic Co-operation and Development (OECD) also confirm that these unilateral green policies are having a profound structural impact on the global trade landscape, particularly for developing countries, and are exacerbating the fragmentation of the global economy. The following table (Table 2) provides a systematic comparison of these three emerging algorithmic green governance mechanisms.

Table 2: A Comparative Analysis of Algorithmic Green Governance Mechanisms

Variable	**European Union (EU)**	**United States (US)**	**People's Republic of China (PRC)**
Main Policy Instrument	Carbon Border Adjustment Mechanism (CBAM)	Inflation Reduction Act (IRA)	"Dual Carbon" goals with "1+N" policy framework and local pilots
Core Governance Logic	Regulatory externalization ("Brussels Effect")	Subsidy-driven industrial policy and supply chain reshoring	State-led integration and technological self-sufficiency
Role of AI/Data	Mandatory reporting and verification: AI used to calculate complex "embedded emissions" based on EU methodology	Eligibility screening and compliance: AI used to optimize supply chains to meet domestic content requirements for subsidies	Monitoring and optimization: AI used for urban/industrial efficiency monitoring in pilot zones; data treated as a national strategic asset
Legal Basis/ Justification	Preventing "carbon leakage"; creating a level playing field	National security, supply chain resilience, domestic manufacturing	National strategy for sustainable development and technological leadership
Stance on WTO Rules	Defensive compliance: Publicly claims compatibility with WTO while pushing the boundaries of existing rules	Strategic neglect: Prioritizes domestic goals, largely ignoring potential WTO challenges	Strategic utilization: Uses WTO to challenge others' policies while developing its own non-transparent domestic standards
Specific Impact on MNEs	High data reporting and compliance costs; must adopt EU standards to access the market.	Supply chains must relocate to North America or allied countries to qualify for subsidies, potentially losing cost advantages.	Must comply with data localization requirements, restricting cross-border data flows; faces pressure to adopt Chinese tech standards.
Impact on Global South	High compliance burden, potentially constituting a new trade barrier	Investment diverted from developing countries to the US and its allies	Offers non-Western technology standards and development cooperation models (e.g., via the Belt and Road Initiative)

4 Discussion: Dilemmas of a Digitalized Earth

This section synthesizes the empirical findings from the third section, elevating the analysis to a higher level of theoretical and critical reflection. It moves beyond merely describing what is happening to delve into the internal contradictions and normative dilemmas of this transformation, directly addressing the core tensions and paradoxes identified in the introduction.

4.1 The Legitimacy Showdown: WTO's Rules vs. AI's Results

This subsection elaborates on the paper's core argument: the conflict between two models of legitimacy in global governance. AI-driven systems, with their efficiency, granularity, and purported objectivity, directly challenge the slow, consensus-based, and often ambiguous nature of the WTO legal system. This conflict is not arising in a vacuum but is rooted in the WTO's own long-standing "legitimacy crisis". Classic literature from scholars like Robert Keohane and Joseph Weiler has long pointed out that the WTO's legitimacy has been continuously eroded by the democratic deficit in its decision-making processes, its systematic neglect of non-trade values like environment and health, and its elite-driven "club" model. This crisis has been magnified in the digital age. The WTO's institutional deficiencies in emerging areas like digital trade and data flows—such as the lack of dedicated, binding agreements and the increasingly frequent abuse of national security exception clauses—have created a significant governance vacuum. It is precisely this vacuum that has provided fertile ground for the rise of techno-scientific governance. This is not just a competition between two tools (legal texts vs. algorithmic code) but a showdown between two epistemologies of governance. The WTO's epistemology is legal-interpretive; it seeks "truth" and solutions through debate, precedent, and negotiation. In contrast, AI's epistemology is computational-empirical; it defines "truth" and optimal solutions through the correlation and pattern recognition of massive data sets. The rise of the latter is fundamentally challenging the authority and raison d'être of the former. When an AI model can "calculate" a product's carbon footprint in seconds and claim its result is more "accurate" than a ruling from a years-long dispute settlement process, the very foundation of traditional legal-procedural legitimacy is shaken.

4.2 The Carbon Paradox: The Environmental Cost of Climate AI

This part critically examines the environmental footprint of the "Carbon Digital Twin" solution itself, revealing a profound "Carbon Paradox": the computational technology used to solve the carbon problem has a massive carbon footprint of its own. This paradox is not alarmist speculation but is supported by concrete quantitative data. Research shows that data centers currently consume about 2% of the world's electricity, and with the explosive growth in AI demand, their carbon emissions could account for 14% of the global total by 2040. The carbon emissions generated from training a single large language model (like a predecessor to GPT-3) can be as high as 300,000 kilograms of CO_2 equivalent, which is comparable to the emissions of 125 round-trip flights between New York and Beijing. Even more alarmingly, an academic paper published in 2023 that used a deep learning model may have generated 42 times more carbon emissions during its research process than a paper from 2013 using traditional computational models. These staggering figures warn us that if we do not rigorously scrutinize and optimize the energy efficiency of computational processes, the very technology we use to combat climate change could become a new, uncontrollable environmental burden. The discovery of this paradox has spurred urgent calls for a transition to "Sustainable AI" or "Green AI". This new paradigm advocates that the energy efficiency and life-cycle carbon cost of algorithms must be placed alongside traditional metrics like accuracy and speed as core criteria for their success and design principles. This is not just a matter of technical optimization but a governance issue: who will set and oversee the energy efficiency standards for AI? How can we ensure on a global scale that the development of AI does not come at the expense of the environment? This presents new, more complex challenges for the governance of climate AI and opens up new battlegrounds for geopolitical competition. The country or company that can develop the most energy-efficient and effective AI models will not only lead technologically but will also occupy the moral and legitimate high ground, as their "solutions" will not exacerbate the problem they are trying to solve.

4.3 Environmental Data Justice: AI as a Driver of Inequality

This subsection provides the core normative critique of this paper, drawing on the concept of Environmental Data Justice (EDJ) to reveal how policies like CBAM, despite being packaged as universal and objective climate solutions, may systematically exacerbate global inequality. The EDJ framework requires us to examine how the entire lifecycle of data collection, analysis, and application affects different communities and to challenge power structures that may intensify social inequalities through data practices. This paper operationalizes this framework into a three-tiered analysis. The first is data ownership, which addresses who owns and controls the massive datasets generated from global carbon monitoring. Under the current system, there is a risk of "data colonialism," where technology platforms and regulatory bodies in the Global North (like the EU) set data standards and infrastructure, forcing suppliers in the Global South to adopt these systems to access markets. This effectively means that producers in Southern countries are compelled to cede control over their own production data for the sake of trade, and this data is then used to train and optimize the AI models of the North, further consolidating their technological and regulatory advantages. The second is algorithmic bias. AI models trained primarily on industrial data and production processes from the Global North may exhibit systemic biases when applied to developing countries. These models may fail to accurately reflect the unique production processes, energy structures (e.g., off-grid or unstable grids), climatic conditions, or informal economic activities in developing nations, leading to unfair assessments of their carbon emissions and potentially penalizing producers who adopt different technological paths or cannot provide data in the "standard format". The third is the capacity gap. The traditional "digital divide" is evolving into a "carbon data divide". Implementing advanced dMRV systems requires enormous financial, technical, and human capital investment, which constitutes an insurmountable barrier for many developing countries, especially small and medium-sized enterprises (SMEs). This structural gap in capacity makes the high cost of compliance itself a new, technical non-tariff trade barrier. A case in point is the plight of the African continent under CBAM, which serves as a stark illustration of environmental data injustice. Quantitative analyses by institutions like UNCTAD and the South African Institute of International Affairs (SAIIA) show that CBAM will have a disproportionately negative impact on African economies. It is estimated that the mechanism could reduce the continent's GDP by 0.91% (equivalent to a $16 billion loss at 2021 levels) and decrease its exports to the EU by as much as 13.9% in the aluminum sector and 8.2% in the steel sector. Countries like Mozambique are particularly vulnerable, with 62.2% of their exports to the EU falling into CBAM-regulated product categories. This vulnerability stems from deep structural factors: a relatively high carbon intensity of production processes, a lack of capital and technology for transitioning to low-carbon technologies, and a significant capacity gap in data collection, verification, and reporting. This clearly demonstrates that a system pursuing technically "perfect" data, without considering its social justice consequences, can lead to politically and environmentally suboptimal or even disastrous outcomes. A seemingly objective and neutral technical solution may conceal profound political choices, resulting in a system that is technically precise but politically explosive, and even environmentally counterproductive. The blind pursuit of a "technically optimal solution" may ultimately lead to a "politically worst-case scenario".

5 Conclusion: Towards a Just and Intelligent Green Transition

5.1 Summary of Research Findings

Through an in-depth analysis of the emerging techno-scientific paradigm of the "Carbon Digital Twin," this paper has revealed the profound transformations and inherent contradictions it has triggered in the realm of global trade and climate governance. The core research findings can be summarized in the following three points. First, the "measurement crisis" in global climate governance is not a purely technical problem but a governance crisis. This crisis has created the conditions for a new "algorithmic green governance" paradigm, which has the "Carbon Digital Twin" as its technological core and challenges the traditional "legal-procedural legitimacy" represented by the WTO with its claimed "techno-scientific legitimacy". Second, this new paradigm has not led to a unified global solution but is instead causing the global economy to fragment into three competing techno-economic blocs dominated by different algorithmic governance logics: the EU's regulatory externalization, the US's techno-nationalist industrial policy, and China's state-led integration. This trend towards fragmentation poses a new "trilemma" for the global operations of multinational enterprises and is reshaping the geoeconomic landscape. Third, although this new paradigm holds great promise for enhancing the efficiency of carbon management, it also brings profound internal dilemmas. These include its own massive environmental footprint (the "Carbon Paradox") and the risk of exacerbating global inequality through mechanisms such as data sovereignty, algorithmic bias, and the capacity gap (the "Environmental Data Justice" issue).

5.2 Policy Recommendations: Building a Hybrid Governance Framework

In the face of the rise of algorithmic green governance, we can neither fall into naive technological optimism, blindly believing that technology can solve all problems, nor adopt a regressive Luddism, refusing to leverage the potential of new technologies. The goal must be to construct a Hybrid Governance Framework that can harness the powerful capabilities of AI in data processing and optimization while firmly embedding it within principles of justice, transparency, and democratic accountability. To this end, this paper proposes the following specific policy recommendations. For the WTO and multilateral institutions, it is recommended to accelerate digital trade negotiations. WTO members should expedite negotiations on the Joint Statement Initiative (JSI) on E-commerce to clearly address core issues such as AI governance, cross-border data flows, data localization, and source code protection, thereby establishing a predictable rule framework for trade in the digital age. Additionally, "security exception" clauses like GATT Article XXI should be reformed and modernized by introducing stricter evidentiary standards and procedural reviews to prevent their abuse by member states for de facto green protectionist policies. A "Global Carbon Data Trust" or an "Algorithmic Climate Governance Fund" should be established. This would be a neutral multilateral platform tasked with hosting core, non-commercially sensitive carbon data; developing open-source carbon accounting models to counter proprietary "black box" algorithms and enhance transparency; and providing developing countries with support for independent auditing, technical assistance, and capacity building to cope with complex policies like CBAM. This body could be modeled on the Financial Stability Board to monitor and assess national algorithmic trade measures. For national governments, the principle of "Sustainable AI" should be integrated into national strategies. When formulating climate and digital strategies, countries should explicitly require AI systems and data centers to meet specific energy efficiency and life-cycle carbon emission standards, and incentivize investment in the research and development of energy-saving algorithms. Governments should also adopt UNCTAD's recommendation for revenue recycling, explicitly using the revenue generated from carbon pricing mechanisms (like CBAM) to fund green technology transfer, infrastructure upgrades, and data capacity building in developing countries to offset negative impacts and reflect the principle of common but differentiated responsibilities. For the private sector, developers of carbon accounting platforms and dMRV systems should adopt Environmental Data Justice (EDJ) principles in platform design. Tech companies should incorporate EDJ principles from the outset of product design to ensure system transparency, algorithmic explainability, data interoperability, and accessibility for data providers. Furthermore, innovative mechanisms should be explored to share the emission reduction benefits achieved through data optimization with the communities that are the source of the data, especially suppliers in the Global South.

5.3 Future Research Agenda

Finally, this study also highlights key areas that require future research to further deepen our understanding of this complex phenomenon. Future research must break down disciplinary silos, closely integrating Computer Science (to develop more efficient, energy-saving, and interpretable AI models), International Political Economy (to analyze the geoeconomic impacts and power dynamics of algorithmic governance), and International Law (to design new governance frameworks and dispute resolution mechanisms adapted to technological change). There is a need for multi-scale model coupling. This involves developing comprehensive computational models that can link micro-level agent behavior (e.g., using Agent-Based Models), meso-level supply chain dynamics (GVC analysis), and macro-level trade mechanisms (WTO rules). Such models would help to more systematically simulate and assess the cross-scale, cross-domain spillover effects of new policies like CBAM and the IRA. Lastly, the governance of Sustainable AI needs to be addressed. This includes developing internationally accepted norms, standards, and best practices for measuring and mitigating the environmental footprint of AI itself. Future research should aim to elevate the energy efficiency and carbon footprint of algorithms from a secondary technical consideration to one of their core performance evaluation metrics and explore the establishment of corresponding international certification and regulatory mechanisms.

Author Biography LIU Shuhua, female, born in March 1976 in Liangshan, Shandong Province. She is an Associate Professor at the Business School of Qilu Institute of Technology. Her research focuses on digital transformation and SME growth, as well as regional economy. Correspondence address: No. 3028 Jingshi East Road, Jinan, Shandong Province, 250200, P.R. China. Email: 280261734@qq.com , https://orcid.org/0009-0001-8587-3286.

References

[1] World Trade Organization. (2025). *World Trade Organization (WTO) trade policy reviews and green technology adoption: Global evidence*. Retrieved from https://www.researchgate.net/publication/385404332_World_Trade_Organization_WTO_trade_policy_reviews_and_green_technology_adoption_Global_evidence

[2] Geels, F. W., Sovacool, B. K., Schwanen, T., & Sorrell, S. (2016). *The enactment of socio-technical transition pathways*. Institut für Sozialwissenschaften. Retrieved from https://www.sowi.uni-stuttgart.de/abteilungen/oi/publikationen/Geels.et.al_2016_Enactment.of.sociotechnical.transitions.pathways.pdf

[3] RIFS. (2025). *Understanding the Complexity of Governing Energy Transitions*. Retrieved from https://publications.rifs-potsdam.de/rest/items/item_6004128_1/component/file_6004129/content

[4] Galileo AI. (2025). *AI Accuracy Metrics: Evaluating Model Performance*. Retrieved from https://galileo.ai/blog/accuracy-metrics-ai-evaluation

[5] Kellton. (2025). *AI Data Quality: Ensuring robust Data Hygiene layer for better AI accuracy*. Retrieved from https://www.kellton.com/kellton-tech-blog/ai-data-quality-data-hygiene-for-better-ai-accuracy

[6] World Bank. (2025). *What You Need to Know About the Measurement, Reporting, and Verification (MRV) of Carbon Credits*. Retrieved from https://www.worldbank.org/en/news/feature/2022/07/27/what-you-need-to-know-about-the-measurement-reporting-and-verification-mrv-of-carbon-credits

[7] 1t.org US. (2025). *Technology and MRV in Forest Carbon Finance*. Retrieved from https://us.1t.org/wp-content/uploads/2022/05/1t.org-US-Technology-and-MRV-in-Forest-Carbon-Finance.pdf

[8] Transatlantic Policy Network. (2025). *SME adoption of digital technologies: a Transatlantic view*. Retrieved from https://www.transatlantic.org/wp-content/uploads/2022/01/11-03-2021-SME-digitalization_SdE-GM-final.pdf

[9] ResearchGate. (2025). *Adoption of Digital Technologies Among U.S. SMEs*. Retrieved from https://www.researchgate.net/figure/Adoption-of-Digital-Technologies-Among-US-SMEs_fig1_387722419

[10] KPMG International. (2025). *EU Carbon Border Adjustment Mechanism (CBAM)*. Retrieved from https://kpmg.com/xx/en/our-insights/esg/carbon-border-adjustment-mechanism-cbam.html

[11] DEHSt. (2025). *CBAM reports*. Retrieved from https://www.dehst.de/EN/Topics/CBAM/Transition-phase/CBAM-reports/cbam-reports_node.html

[12] BDO. (2025). *European Union - Importers struggling with embedded emissions data under CBAM*. Retrieved from https://www.bdo.global/en-gb/insights/tax/indirect-tax/european-union-importers-struggling-with-embedded-emissions-data-under-cbam

[13] Energy Transition Partnership. (2025). *CARBON BORDER ADJUSTMENT MECHANISM IMPACT ...*. Retrieved from https://www.energytransitionpartnership.org/wp-content/uploads/2024/06/20240318_Final-CBAM-Assessment-Report-final.pdf

[14] European Commission. (2025). *Update: Technical issues related to the CBAM Transitional Registry ...*. Retrieved from https://taxation-customs.ec.europa.eu/news/update-technical-issues-related-cbam-transitional-registry-and-import-control-system-2-ics2-2024-01-29_en

[15] MDPI. (2025). *Blockchain Traceability for Sustainability Communication in Food ...*. Retrieved from https://www.mdpi.com/2071-1050/15/18/13486

[16] ResearchGate. (2025). *Blockchain-Driven Green Traceability: Greener or More Profitable?*. Retrieved from https://www.researchgate.net/publication/388909632_Blockchain-Driven_Green_Traceability_Greener_or_More_Profitable

[17] SmythOS. (2025). *Agent-Based Modeling in Climate Change*. Retrieved from https://smythos.com/managers/ops/agent-based-modeling-in-climate-change/

[18] ResearchGate. (2025). *Sensitivity analysis of environmental models: A systematic review with practical workflow*. Retrieved from https://www.researchgate.net/publication/294889912_Sensitivity_analysis_of_environmental_models_A_systematic_review_with_practical_workflow

[19] ResearchGate. (2025). *(PDF) Sensitivity analysis of agent-based models: a new protocol*. Retrieved from https://www.researchgate.net/publication/357767243_Sensitivity_analysis_of_agent-based_models_a_new_protocol

[20] GOV.UK. (2025). *Auditing algorithms: the existing landscape, role of ...*. Retrieved from https://assets.publishing.service.gov.uk/media/626910658fa8f523c1bc666c/DRCF_Algorithmic_audit.pdf

[21] ISACA. (2025). *2022 Volume 4 Focal Points for Auditable and Explainable AI*. Retrieved from https://www.isaca.org/resources/isaca-journal/issues/2022/volume-4/focal-points-for-auditable-and-explainable-ai

[22] Blavatnik School of Government - University of Oxford. (2025). *Policy brief - AI governance and the future of digital trade policy*. Retrieved from https://www.bsg.ox.ac.uk/sites/default/files/2024-10/Policy%20brief%20-%20AI%20governance%20and%20the%20future%20of%20digital%20trade%20policy.pdf

[23] ResearchGate. (2025). *(PDF) Explainable AI in Algorithmic Trading: Mitigating Bias and Improving Regulatory Compliance in Finance*. Retrieved from https://www.researchgate.net/publication/390170221_Explainable_AI_in_Algorithmic_Trading_Mitigating_Bias_and_Improving_Regulatory_Compliance_in_Finance

[24] Global FinTech Series. (2025). *Building Explainable Behavioral-Aware Trading Algorithms for Institutional Compliance*. Retrieved from https://globalfintechseries.com/featured/building-explainable-behavioral-aware-trading-algorithms-for-institutional-compliance/

[25] PMC. (2025). *Digital health and capability maturity models—a critical thematic ...*. Retrieved from https://pmc.ncbi.nlm.nih.gov/articles/PMC9846694/

[26] PMC. (2025). *Climate Shocks and Migration: An Agent-Based Modeling Approach ....* Retrieved from https://pmc.ncbi.nlm.nih.gov/articles/PMC5004973/

[27] JASSS. (2025). *Agent-Based Modeling as a Tool for Trade and Development Theory*. Retrieved from https://www.jasss.org/16/2/1.html

To Cite This Article Shuhua LIU(2025). Carbon Digital Twin: Artificial Intelligence, Green Protectionism, and the Reshaping of Global Trade Governance. *Do Business and Trade Facilitation Journal*, *5*(1), 81–94. https://doi.org/10.6914/dbtf.050107

(Editor: Xin HUANG tooderdy@163.com)