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What drives embodied carbon policy? A global perspective on adoption

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Abstract
Embodied carbon refers to the greenhouse gas emission associated with the lifecycle of buildings. Embodied carbon policies are critical for addressing the environmental impact of construction materials and advancing climate goals. Despite their importance, the adoption of embodied carbon policies has been limited globally, influenced by economic, environmental, institutional, and trade factors. This study employs structural equation modeling to analyze 37 countries, testing ten hypotheses across four categorical factors. The base model reveals the significant influence of environmental vulnerability and institutional frameworks on policy adoption, while robustness models confirm the critical role of trade dependencies and economic competitiveness in shaping national embodied carbon strategies. Findings underscore that countries with high climate vulnerability and strong institutional support are more likely to adopt embodied carbon policies. Conversely, trade-reliant nations face challenges balancing competitiveness and sustainability. Policy implications suggest the need for international collaboration to align trade policies with carbon reduction goals, targeted support for vulnerable nations, and the integration of embodied carbon considerations into existing climate frameworks. These results offer a roadmap for policymakers to design more effective and equitable embodied carbon policies, fostering global progress toward sustainable construction and decarbonization.

Keywords Embodied carbon policy · Economic factor · Environmental factor · Institutional factor · Trading factor

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Abbreviations

G/C	Growth domestic product per capita
GCR	Growth domestic product growth rate
C	Environmental factors comprise four measures: consumption-based emission per capita
CCE	Cumulative carbon emission
VUL	Country vulnerability index
EVI	Ecosystem vitality index
IE	Import/Export
EDI	Electoral democracy index
FEI	Freedom of expression index
ED	Level of education
CS	Country size
SEM	Structural equation modeling
GOF	Goodness-of-fit
MLE	Maximum likelihood estimation
ML	Maximum likelihood
CFI	Comparative fit index
Pclose	Probability of close fit
RMSEA	Root mean square error of approximation
TLI	Tucker-Lewis index

1 Introduction

Understanding and reducing the embodied carbon in construction is essential for assessing its environmental impact activities. The significance of embodied carbon lies in its contribution to the total carbon footprint associated with buildings and infrastructure throughout their life cycle (Pomponi & Moncaster, 2016). Buildings are responsible for roughly 40% of global greenhouse gas emissions, with embodied carbon from construction material manufacturing making up at least 10% of total emissions globally (UN Environment Programme, 2024).

Addressing embodied carbon is crucial for achieving international climate targets, including those outlined in the United Nations Sustainable Development Goals (SDGs). SDG 9 (Industry, Innovation, and Infrastructure) and SDG 11 (Sustainable Cities and Communities) emphasize the need for resilient and environmentally sustainable infrastructure, while SDG 12 (Responsible Consumption and Production) calls for reducing material footprints and improving resource efficiency. Most importantly, SDG 13 (Climate Action) stresses the urgent need for mitigating carbon emissions across all sectors, including the construction industry. The decarbonization of the built environment is therefore central to achieving these global sustainability objectives.

To date, policy actions addressing embodied carbon in the building and construction sector have significantly lagged behind those targeting operational carbon. Historically, operational carbon—greenhouse gas (GHG) emissions generated during a building's operational phase from energy consumption for heating, cooling, lighting, and other activities—has been the primary focus of regulations due to its historically dominant share of total emissions (Hu, 2023). In contrast, embodied carbon, which includes emissions from material extraction, manufacturing, transportation, construction, maintenance, and eventual demolition or disposal, has been perceived as negligible (Hu, 2022; Hu & Esram, 2021). This outdated perception has contributed to a lack of regulatory attention and research. Recent studies, however, reveal that as operational carbon decreases due to stringent energy performance regulations, the share of embodied carbon is poised to rise. It could increase from the current 20%–25% of total life cycle emissions to 45%–50% in highly energy-efficient buildings, potentially surpassing 90% in extreme cases like net-zero energy buildings (Röck et al., 2018; Pomponi and Monscaster 2016). Despite this growing importance, studies on embodied carbon policies remain limited.

One emerging research area closely linked to embodied carbon policy adoption is the role of energy research, development, and deployment (RD&D) investments in promoting sustainable construction practices. According to Caglar et al., (2024a, 2024b), energy RD&D expenditures in leading economies play a crucial role in enhancing low-carbon innovation and climate action. Their findings suggest that national energy technology investments—including those in building materials and energy-efficient technologies—are critical to achieving SDGs 7 (Affordable and Clean Energy) and 13 (Climate Action). The resilience of RD&D expenditures to policy shocks further underscores the need for consistent government funding to support long-term sustainability objectives. Given that embodied carbon regulation involves material innovations, circular economy strategies, and green infrastructure policies, integrating RD&D-driven solutions into national frameworks could accelerate policy adoption and strengthen global climate commitments.

Currently, 41 countries have implemented mandatory building codes to regulate operational energy, while 85 nations have introduced operational energy certifications, ratings, or labels (Skillington et al., 2022). Even ambitious net-zero energy building initiatives largely focus on operational emissions, leaving embodied carbon unaddressed in most regions. Only a handful of countries have developed policies targeting embodied carbon, despite its critical role in achieving carbon neutrality. To advance global sustainability goals, understanding the factors influencing embodied carbon policy adoption is essential. These factors include global trade dynamics, supply chains, economic conditions, and the environmental risks countries face (Assogbavi & Dées, 2023).

This study addresses gaps in the literature by systematically analyzing global embodied carbon policies. It seeks to explore two key inquiries: (R1) the categorical factors influencing the adoption of embodied carbon policies and (R2) whether these factors exert positive or negative impacts. Ten specific hypotheses are tested, focusing on economic, environmental, social, and trade dimensions to identify the key drivers and barriers to policy adoption. While the study does not evaluate the effectiveness or design features of current embodied carbon policies, its findings aim to provide actionable insights for developing tailored strategies to encourage policy adoption across diverse national contexts.

This study offers several key contributions. First, it represents one of the most recent and comprehensive analyses of embodied carbon policy, utilizing the most up-to-date and widely available data. By systematically identifying and categorizing economic, environmental, institutional, and trade-related factors, the study provides a nuanced understanding of the drivers and barriers to policy adoption across different countries, addressing a critical gap in the existing literature. Second, the study employs advanced nonlinear models, notably Structural Equation Modeling (SEM), to enhance the methodological rigor of embodied carbon policy research. The SEM framework validates the proposed factor categories and quantifies their relative impacts, delivering robust, data-driven insights into the dynamics of policy implementation. Finally, the study translates its findings into actionable policy recommendations. It underscores the importance of international collaboration, targeted interventions in vulnerable regions, and balancing economic growth with environmental sustainability. These insights contribute meaningfully to the global discourse on achieving carbon neutrality, offering specific pathways for policymakers and stakeholders to advance embodied carbon policy adoption while supporting SDG targets.

The article is organized as follows: Sect. 2 reviews recent literature, Sect. 3 outlines the research framework, data, and methodology, Sect. 4 presents findings and discusses their implications, and Sect. 5 concludes the study.

2 Literature review

2.1 Existing literature

Recent literature on the adoption of embodied carbon policies underscores a growing recognition of the need to address carbon emissions associated with building materials and construction processes. While research directly related to embodied carbon policy often emphasizes international trade, a broader body of literature provides valuable indirect insights, particularly studies on energy production and emissions. These studies contextualize how energy system transitions influence carbon strategies. For instance, Kartal et al. (2022) examines the impact of energy consumption on CO_2 emissions and policies related to energy sources, while Kartal et al. (2022) advocate transitioning from fossil fuels to renewable energy to enhance environmental quality. This aligns with the goals of embodied carbon policies, which aim to reduce the carbon intensity of construction materials and energy inputs. Similarly, Caglar et al., (2024a, 2024b) explore the interplay between economic growth and environmental policies, offering insights into how embodied carbon policies can be integrated without undermining industrial competitiveness.

Among studies directly addressing embodied carbon policy, one prominent focus is the implications of international trade. Peters and Hertwich (2008b) demonstrate how trade-related emissions significantly influence global climate policies like the Kyoto Protocol, highlighting the need to incorporate trade considerations into climate mitigation strategies. Feng et al. (2013) examine China's challenges in balancing carbon intensity reduction with economic growth, emphasizing the importance of consumption-based emissions accounting to develop equitable and effective climate policies. These findings highlight the need to address regional disparities and include embodied emissions in trade to achieve broader climate goals. Additionally, Wood et al. (2020) investigate the historical effects of globalization on international emission transfers, revealing that embodied emissions may stabilize or gradually decline due to the interplay between globalization and climate policies. Similarly, Tang et al. (2022) analyze embodied carbon flow networks across China's provinces, emphasizing the importance of incentivizing innovation in carbon reduction technologies to minimize embodied carbon at both national and international levels.

Another focus area is integrating embodied carbon considerations into existing building regulations and policy frameworks. Hu and Esram (2021) systematically examine the status of embodied carbon in U.S. building practices, highlighting a gap in mandatory policy frameworks. While operational carbon is being aggressively reduced through energy codes and net-zero energy targets, there is an urgent need for policies addressing embodied carbon in construction materials. The lack of such policies is often attributed to economic barriers, including industry resistance driven by concerns over increased costs, complexity, and potential impacts on competitiveness. Furthermore, research on the economic implications of adopting embodied carbon policies remains limited. Qi and Xia (2022) highlight the lack of comprehensive data on indirect emissions within construction supply chains, which may deter stakeholders from prioritizing embodied carbon reduction despite its long-term cost-saving potential.

Institutional and environmental factors also play a significant role in shaping embodied carbon policies. Recent studies suggest that countries with poorer environmental quality may prioritize embodied carbon emissions to mitigate broader environmental degradation. The Environmental Kuznets Curve hypothesis offers an explanatory framework, positing that as economies develop, environmental degradation initially worsens but eventually improves as income rises and societies become more environmentally conscious. Kilinc-Ata and Likhachev (2022) explore this concept in the Russian Federation, demonstrating that countries with lower environmental quality may adopt carbon emission policies as part of their development strategy to address environmental challenges.

Together, these findings highlight the necessity of advancing embodied carbon policies that integrate trade considerations, institutional factors, economic development, and environmental conditions. This multidimensional approach is used in the study.

2.2 Existing policies

These studies highlight the importance of embodied carbon in international trade and its effects on climate policy. Nonetheless, there is a scarcity of studies concentrated on embodied carbon policies within the built environment. The Carbon Leadership Forum's Embodied Carbon Policy Toolkit states that, as of 2023, there are 186 programs related to embodied carbon spanning 19 countries, as shown in Table 1. Notably, 14 countries implement a carbon tax, many of which also have related carbon policies and programs. These initiatives highlight a significant global intention to address carbon emissions embedded in goods and services throughout their life cycles beyond just direct emissions.

Table 1 lists those policies in five categories: regulation, planned action plan/executive order (EO), incentive, government-funded tool, and public pilot/study. Regulation is the largest category, with 81 total. Regulation has a variety of formats; some prescribe how the new construction should be built, and others give a limit of the total carbon embodied by the whole building. As of January 1, 2023, an addendum to the Danish Building Regulations requires a life cycle assessment for all new buildings to evaluate their environmental effects. Additionally, buildings exceeding 1,000 square meters must document a maximum global warming potential (GWP) threshold of 12 kg CO_2 equivalent per square meter annually m^2. (Mandatory New Requirements for Sustainable Construction, 2023). Starting in 2022, all new public buildings in France must be constructed using at least 50% timber or other natural materials to minimize embodied emissions. Besides wood, this requirement can also be met with bio-based materials sourced from living organisms like hemp and straw (Fabris, 2022).

The second largest category is the planned action plan/executive order with 58 programs. These plans exist at different levels. For instance, the Greening Government Strategy: A Government of Canada Directive mandates that by 2022, the Canadian government must report the embodied carbon levels in the structural materials used for significant construction projects, determined by either material carbon intensity or a life-cycle assessment analysis. The government must reduce the embodied carbon of the structural materials of major construction projects by 30%, starting in 2025, using recycled and lower-carbon materials and performance-based design standards. By 2025, the government mandates that significant buildings and infrastructure projects conduct life cycle assessments (Greening

Table 1 Embodied Carbon Policy and Program by Country

	Country	Government funded tool	Incentive	Planned action plan/EO	Public pilot/ study	Regulatory
1	Austria	2	1	0	0	0
2	Belgium	2	0	0	0	1
3	Canada	1	4	5	1	6
4	Denmark	0	1	0	0	3
5	Finland	1	0	1	0	1
6	France	2	0	2	1	2
7	Germany	1	0	0	0	0
8	Hungary	0	0	1	0	0
9	India	0	0	1	0	1
10	Ireland	0	0	1	0	0
11	Mexico	0	0	1	0	0
12	Netherlands	4	0	1	1	1
13	New Zealand	0	1	0	1	0
14	Norway	0	0	2	0	0
15	Singapore	0	0	0	0	1
16	Sweden	1	1	0	0	1
17	Switzerland	1	1	0	0	1
18	USA	1	13	41	4	59
19	UK	0	1	2	0	4
Subtotal		16	23	58	8	81
Total						186

Government Strategy: A Government of Canada Directive, n.d.). Another action plan example is at the city level. Helsinki's Action Plan for a Circular and Sharing Economy aims for a carbon–neutral circular economy by 2050. It emphasizes sustainable construction, which includes the preservation and repurposing of existing buildings, the adoption of low-carbon practices from pre-construction through project completion, and the investigation of alternatives to concrete, like low-emission concrete or substitutes, to reduce carbon impact (City of Helsinki, n.d.).

The third category with the largest programs is incentives. Those incentives exist in the US, Austria, Canada, Denmark, New Zealand, Switzerland, the UK, and Sweden across different levels. As an incentive, the local jurisdiction often rewards the developer or builder for constructing low-embodied carbon buildings with allowed buildable areas or reduced project costs. For example, the Quebec Wood Charter is a policy that encourages the use of wood for all publicly funded infrastructure projects. As a result of this policy, the provincial building code was updated to increase the maximum height for wood structures from four stories to six stories and taller.

The fourth category, government-funded tools, and databases are mostly at the national level. For example, Finland and the Netherlands have a single national methodology for the whole-life cycle assessment of buildings. Other countries, Austria, Belgium, and France, have their own environmental production declaration (EPD) programs and databases for construction materials and products. However those government-funded tools and databases do not directly contribute to carbon emission reduction.

3 Methods

3.1 Conceptual framework

The functionalist approach in international relations is used as the theoretical base and framework for this study. The functionalist approach emphasizes the importance of addressing collective action problems, externalities, and inefficiencies that necessitate the establishment of international regimes. This approach highlights the common interests and needs shared by institutions as a basis for cooperation at various levels (Ahmed & Hussain, 2022). Functionalism in international relations theory focuses on coordinating actions in apolitical/technocratic domains such as environmental protection through institutions to promote international cooperation (Kobayashi, 2019). Transferring technical, economic, and welfare responsibilities from nation-states to international organizations is anticipated to boost the system's legitimacy and reinforce common beliefs in its effectiveness (Patomäki, 2012). Based on this theoretical framework, a conceptual model is proposed to answer the proposed questions. As illustrated in Fig. 1, there are four constructs, and four categorical variables: economic factors, environmental factors, institutional factors, and trading factors.

The prospects for international cooperation fundamentally depend upon the creditability of a state's commitments and economic and environmental needs (Roberts & Parks, 2007). Economic factors are measured by two indicators: growth domestic product per capita (G/C) and growth domestic product growth rate (GCR). Environmental factors comprise four measures: consumption-based emission per capita (C), cumulative carbon emission (CCE), ecosystem vitality index (EVI), and country vulnerability index (VUL). For institutional factors, three measures, the electoral democracy index (EDI), freedom of expression index (FEI), and level of education (ED) are included. And lastly, trading factors are measured by the importer/exporter index (IE) and country size (CS). A detailed explanation of each variable and the data source are included in the following section.

Ten specific hypotheses are tested, that are illustrated in Fig. 2:

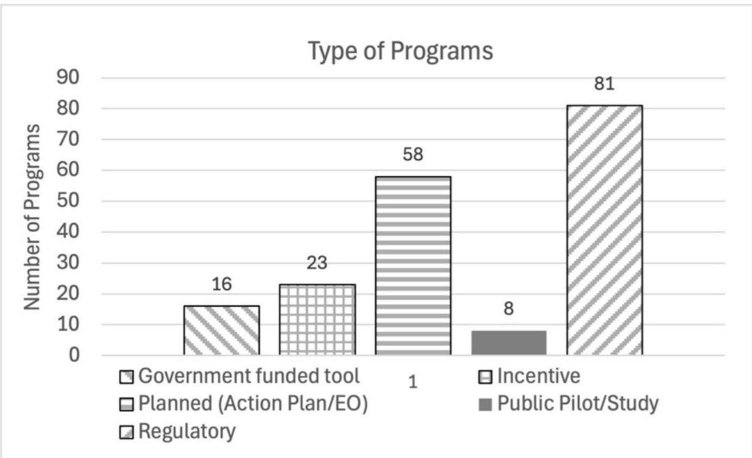

Fig. 1 Types of programs

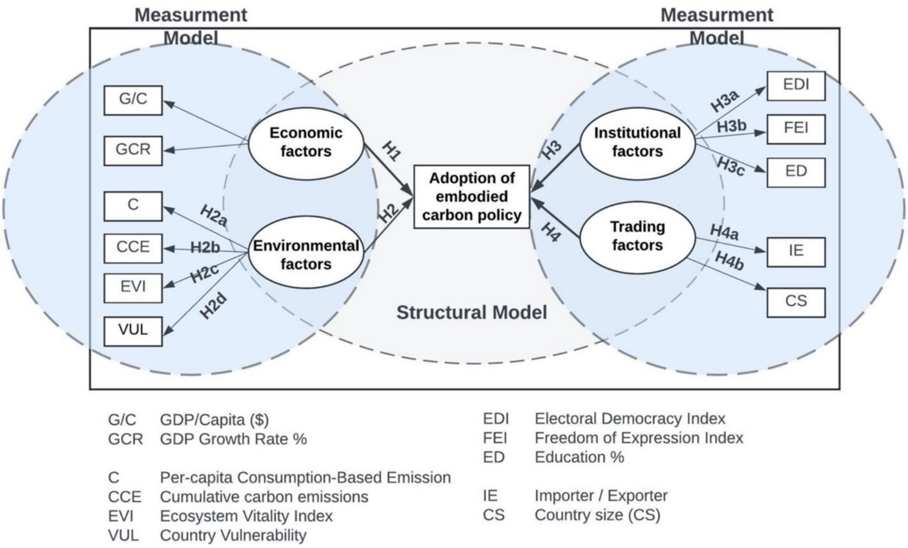

Fig. 2 Conceptual model

Hypothesis 1b (**H1**): A region with advanced economic development typically has an easier time implementing embodied carbon policies to transition to less carbon-intensive construction methods.

Hypothesis 2a (**H2a**): A country experiencing high carbon emission intensity is likely to have a strong motivation to withdraw from embodied carbon emission policies in order to maintain its current lifestyle situation.

Hypothesis 2b (**H2b**): A country with high cumulative carbon emission contribution will likely adopt programs and policies to preserve the ecosystem's well-being by limiting carbon emissions.

Hypothesis 2c (**H2c**): A country with high vulnerability to climate change will likely be motivated to adopt a policy that regulates carbon emissions to mitigate climate change risk.

Hypothesis 2d (**H2d**): A country with a low ecosystem vitality index will likely adopt programs and policies to preserve the ecosystem's well-being by limiting carbon emissions.

Hypothesis 3a (**H3a**): The more democratic society is more keen to adopt policies to reduce embodied carbon to mitigate climate change.

Hypothesis 3b (**H3b**): A country with a high educational level is more keen to adopt embodied carbon policies.

Hypothesis 3c (**H3c**): A country with high freedom of expression and belief is more keen to adopt embodied carbon policies.

Hypothesis 4a (**H4a**): An export-dominated country is likely to adopt the embodied carbon policies.

Hypothesis 4b (**H4b**): A large country is more motivated to adopt an embodied carbon policy due to the pressure from many trading partners.

3.2 Data collection and variables

The analysis aims to determine what influences whether a country adopts an embodied carbon policy. The key result is the binary result—yes or no—mapping all countries that introduced embodied carbon policy. This includes all policies that regulate, guide, and limit the embodied carbon associated with building materials or whole buildings. The government can do so in three formats: (i) introduce an embodied carbon reduction standard requirement, (ii) monitor embodied carbon with mandatory reporting and reduction through its own procurement process, and (iii) set up the whole life carbon intensity limit in building regulations. The embodied carbon policy and program information are mainly based on the Carbon Leadership Forum database, which includes 19 countries together (refer to Table 1). In addition, 18 countries that have some form of carbon tax are also included in the analysis because the carbon tax is a form of tax law used to regulate the embodied carbon within the country boundary (Hsu, 2017). Those 18 countries are Japan, Poland, Portugal, Australia, Estonia, Slovenia, Luxembourg, China, Brazil, Nigeria, Indonesia, Turkey, Thailand, Kazakhstan, Colombia, Chile, Argentina, and Vietnam.

The endogenous variables included in the study contribute to four exogenous variable categories as illustrated in Fig. 2. Table 2 lists the data source where the variables are extracted. Table 2

The first category, economic factors, covers a country or region's economic development condition. The hypothesis (H1) posits that nations or areas with greater economic development will, in general, find it easier to adopt less carbon-intensive construction methods. Economic conditions are evaluated using GDP per capita and GDP growth rate. Data is sourced from the World Bank website, with the latest figures available from 2022 (The World Bank, n.d.-a) (The World Bank, n.d.-b).

The second category, environmental factors, addresses the impact and risks of climate change. The ecosystem health measure was included, as the environmental impact extends beyond just carbon emissions. The hypothesis (H2a) asserts that a high level of carbon emission intensity in a country (indicated by CO_2 emissions per capita) obstructs or slows the adoption of Environmental Conservation Policies (ECPs). This is likely due to resistance from powerful national interest groups or public sentiment in wealthier nations, as the per capita carbon emissions are linked to higher living standards (Huo et al., 2023). Another way to say this is that a country with a high carbon emission intensity will likely have a strong incentive to opt out of embodied carbon emission policy to keep their current lifestyle. Similar outcomes can be anticipated for nations that derive a substantial portion of their income from the extraction and sale of crude oil and coal (Andrew et al., 2013). Conversely, the hypothesis (H2b) assumes that countries with a higher cumulative carbon emission contribution will likely adopt embodied carbon reduction policies. This is based on the logic that those countries will be facing more scrutiny and pressure to participate in the global agreement due to the damage those countries have done.

In addition to carbon emissions, other environmental impact factors are also important. In this study, the ecosystem vitality index and the country risk were chosen to index the

Table 2 Factors examined in the analysis and their data sources

Category	Variables	Measure	Data source
Economic factors	GDP per capita (G/C)	$	The World Bank (xxxx)
	GDP growth rate (GCR)	%	The World Bank (xxxx)
Environmental factors	Cumulative carbon emissions (C)	Total CO_2	Our World in Data (2024a)
	Cumulative carbon emissions intensity (CCE)	CO_2 / capita	Our World in Data (2024b)
	Ecosystem Vitality Index (EVI)	Refer to description	Yale (2020)
	Country risk of climate change (VUL)	Refer to description	Uniersity of Notre Dame (2024)
Institutional factors	Electoral Democracy Index (EDI)	Refer to description	Coppedge et al. (2024)
	Educational level (ED)	Refer to description	Our World in Data (2023)
Trade factors	Country size (CS)	Population	Our World in Data (2024c)
	Importer / Exporter (IE)	Positive/Negative	Our World in Data (2024b)

climate change index. A nation's vulnerability to climate change is a key indicator of its risk from these impacts. The Global Adaptation Initiative Index, developed by the University of Notre Dame (ND-GAIN), evaluates this vulnerability by analyzing a country's exposure and sensitivity to climate change's adverse effects across six critical aspects: food security, water resources, health care, ecosystem services, human living conditions, and infrastructure. Each area is assessed by three key factors: the chance of the sector facing climate-related hazards (exposure), the extent of the potential impact from these hazards (sensitivity), and the sector's capability to handle or adjust to these effects (adaptive capacity). Taking these factors into account, the ND-GAIN vulnerability score offers a detailed view of a nation's capacity to address the challenges of climate change. (Uniersity of Notre Dame, 2024) The hypothesis (H2d) posits that countries highly vulnerable to climate change are more likely to implement policies that regulate carbon emissions, which can help reduce the risks associated with climate change.

The Ecosystem Vitality Index, a component of the Environmental Performance Index, created through a partnership between the Yale Center for Environmental Law and Policy, Yale University, and the Columbia University Center for International Earth Science Information Network, represents the health of ecosystems. This index assesses 180 nations using 40 performance indicators distributed across 11 categories: air quality, sanitation and drinking water, heavy metals, waste management, biodiversity and habitat, ecosystem services, fisheries, acid rain, agriculture, water resources, and climate change mitigation. These categories track performance and advancement in three essential policy objectives: environmental health, ecosystem vitality, and climate change. This study centers on the Ecosystem Vitality Index (EVI), integrating metrics concerning biodiversity and habitat, ecosystem services, fisheries, acid rain, agriculture, and water resources. The hypothesis (H2d) posits that countries with a low ecosystem vitality index are more likely to adopt initiatives and policies focused on enhancing ecosystem health by curbing carbon emissions.

The third category of variables considers the institutional characteristics of a country; mainly, the political characteristics was the focus. Furthermore, earlier studies indicate that democratic institutions are more likely to collaborate on international treaties, implement stricter environmental regulations, and reduce their carbon emissions (Bättig & Bernauer, 2009; Clulow, 2018; Li & Reuveny, 2006). The hypothesis (H3a) is that the more democratic society is more keen to adopt policies to reduce embodied carbon to mitigate climate change. This analysis utilizes the V-Dem Electoral Democracy Index from the V-Dem dataset to assess democracy levels. (Coppedge et al., 2024) The V-Dem index includes five sub-components, each an index made from various indicators, collectively representing Dahl's seven institutions of polyarchy: freedom of association, suffrage, fair elections, an elected executive, and freedom of expression alongside alternative information sources (Pemstein et al., 2018).

The reasoning for strong democratic institutions lies in the increased freedom of expression they offer. This freedom enables the media and environmental advocates to effectively highlight issues about carbon emissions and their impact on climate change. High awareness often drives citizens to insist on greater political action from their government, leading to new policies (Steinebach et al., 2021). High awareness can often be acquired through education; therefore, the education level is also included in this study. The measure is the completion rate of upper-secondary education in the country as a percentage of the population. The data source is Our World in Data that is sourced from the Barro-Lee education attainment dataset (Barro, 2015). The data counts for the percentage of the population having attained at least some formal education (Our World in Data, 2023). The hypothesis (H3b) is that the country with a high educational level is more keen to adopt embodied carbon policies. This study utilizes Freedom House's Freedom of Expression & Belief score, which aggregates four sub-components: independent media, the freedom for individuals to publicly and privately express their religious or nonbelief, academic freedom, and the ability of individuals to discuss political or other sensitive topics freely (Freedom House, 2024). The hypothesis (H3c) is that the country with high freedom of expression and belief is more keen to adopt embodied carbon policies.

The last categorical variables are trade-related and supply-chain issues. Studies on climate policies have demonstrated that governmental decisions regarding the adoption of such policies are not made in isolation. Instead, these decisions emerge from a process of trading benefits and cost among various entities (Steinebach et al., 2021). The current carbon tariff between countries penalizes the countries that export embodied carbon-intensity products. Thus, the choice to adopt the embodied policies can be reasonably concluded to depend on whether the country is predominantly import- or export-oriented. This study computes the importer-exporter distinction through the ratio of consumption-based to production-based carbon emissions, and the data are downloaded from Our World in Data, sourced from Global Carbon Budget (Our World in Data, 2024b). A country is labeled an importer if its consumption-based carbon emissions exceed production-based emissions, and the opposite holds true for exporting countries. The hypothesis (H4a) is that an export-dominated country will likely adopt the embodied policy and carbon price mechanism to keep in competitive status because the current carbon tariff is putting carbon-intensive exporters at a competitive disadvantage.

Furthermore, the larger nations are likely to experience greater pressure to cut carbon emissions. This is because the significant contributions from smaller countries—regardless of their ambition—will not suffice to combat climate change unless the larger nations also take action (Schwerhoff, 2016). The country's size is measured by its population. The hypothesis (H4b) is the large country is more motivated to adopt embodied carbon policy through pressure from many trading partners.

3.3 Empirical methodology

Structural Equation Modeling (SEM) is a statistical method used to analyze intricate relationships among several variables. It finds its roots in various disciplines such as psychometrics, econometrics, sociology, and genetics, enabling the inclusion of latent variables and the specification of systems of equations (Anderson & Gerbing, 1988). SEM is particularly valuable in indicating the strength of influence among variables, making it a powerful tool for analyzing intricate relationships in diverse fields like biology, psychology, and built environment (Gultekin et al., 2017; Hu & Skibniewski, 2022; Li et al., 2021). SEM is significant because it offers a thorough understanding of the links between observed and unobserved variables in a system (Bauldry, 2015). By incorporating both measured and latent variables, SEM offers a holistic approach to modeling complex phenomena and testing theoretical frameworks (Gultekin et al., 2017). This technique is instrumental in assessing the associations among variables, making it a valuable tool for researchers analyzing longitudinal data and investigating causal relationships.

Structural Equation Modeling (SEM) comprises measurement and structural models, as shown in Fig. 2. The measurement model incorporates exogenous (latent) and endogenous (observed) variables. The exogenous variable consists of four categories: economic, environmental, institutional, and trading characteristics. The observed variable (G/C-CS) is the variable listed in Table 2. This study examines the causal relationship between adopting embodied policy and a nation's economic, environmental, institutional, and trading characteristics. The essential structure of SEM can be represented by the following fundamental equations (Bollen, 2011):

$$\eta = \beta\eta + \Gamma\xi + \xi \tag{1}$$

Equation (1) represents a structural model, where η is the endogenous variables and ξ represents the exogenous variables. β and Γ are coefficient matrices and z denotes the hidden errors in the equation.

$$\Upsilon = \wedge\eta + \epsilon \tag{2}$$

$$\mathrm{X} = \wedge\xi + \delta \tag{3}$$

Equations (2) and (3) represent measurement models for x and y, where $\wedge$ is the coefficient between γ and η, and ε and δ are the errors in the equations.SEM is developed through a systematic three-step approach. Initially, the process focuses on identifying the structural and measurement elements. The subsequent step involves developing a conceptual test model. Next, the performance of the SEM model was evaluated. The final Structural Equation Model (SEM) is verified by assessing its goodness-of-fit (GOF) indices. After validation, the SEM model can be utilized to test hypotheses and analyze the causal connections between a country's characteristics and the adoption of embodied policy.

4 Results and discussion

4.1 Preliminary statistics

The correlation matrix, Table 3 highlights relationships with "Adoption (embodied policy)." Moderate positive correlations are observed with "IE" (0.404) and "VUL" (0.374), suggesting their stronger influence, while weaker positive correlations are seen with "EDI" (0.274), "FEI" (0.225), and "ED" (0.172). Moderate negative correlations with "C" (-0.402) and "G/C" (-0.461) indicate potential barriers to adoption. Strong inter-variable correlations, such as between "EVI" and "EDI" (0.724) and "FEI" and "EDI" (0.915), suggest environmental factors could form latent constructs, while variables like "CCE" and "CS" have weaker relationships, indicating less direct influence. Negative correlations like "VUL" and "EVI" (-0.740) highlight inverse dynamics. These findings suggest potential mediators and latent variables for structural modeling.

A factor and principal component analysis was then conducted in STATA to validate the assumed factor categories for constructing the SEM. As illustrated in Table 4, the results confirmed that "Environmental Factors" include "C," "CCE," "EVI," and "EDI"; "Economic Factors" include "GCR" and "G/C"; "Institutional Factors" include "EDI," "FEI," and "ED"; and "Trading Factors" include "IE" and "CS." The Kaiser–Meyer–Olkin (KMO) values for these factors were 0.608, 0.562, 0.724, and 0.614, respectively, all exceeding the recommended minimum threshold of 0.5, while all factor loadings were above the acceptable threshold of 0.5. A reliability test using Cronbach's alpha (α) showed that all factors had α values above 0.7, except for "Trading Factors." Despite its lower α value, "Trading Factors" was retained in the SEM due to its conceptual importance and relevance to the hypothesis.

Table 3 Correlation matrix

	Adoption	C	CCE	EVI	G/C	GCR	VUL	EDI	FEI	IE	CS	ED
Adoption	1.000											
C	−0.402	1.000										
CCE	−0.258	0.213	1.000									
EVI	−0.246	0.290	−0.159	1.000								
G/C	−0.461	0.669	0.049	0.477	1.000							
GCR	0.034	−0.208	−0.172	−0.444	−0.191	1.000						
VUL	0.374	−0.463	−0.026	−0.740	−0.613	0.391	1.000					
EDI	0.274	0.413	−0.131	0.724	0.647	−0.304	−0.631	1.000				
FEI	0.225	0.189	−0.196	0.754	0.531	−0.230	−0.602	0.915	1.000			
IE	0.404	−0.127	0.037	−0.429	−0.264	0.194	0.290	−0.528	−0.504	1.000		
CS	−0.166	−0.201	0.503	−0.553	−0.311	0.143	0.471	−0.522	−0.504	0.340	1.000	
ED	0.172	0.494	0.118	0.709	0.452	−0.337	−0.790	0.556	0.511	−0.311	−0.408	1.000

Table 4 Factor analysis of the variables

Principal factor	Variables	Factor loading	α
Economic factors (KMO = 0.608)	GCR	0.65	0.71
	G/C	0.54	
Environmental factors (KMO = 0.562)	C	0.56	0.82
	CCE	0.63	
	EVI	0.60	
	VUL	0.91	
Institutional factors (KMO = 0.724)	EDI	0.78	0.76
	FEI	0.86	
	ED	0.72	
Trading factors (KMO = 0.614)	CS	0.57	0.59
	IE	0.52	

4.2 SEM specification and validation

As illustrated in Fig. 3, the two measurement models include both the four exogenous categories (environmental, economic, institutional, and trading) and attributing endogenous variables. Every arrow line represents a coefficient that indicates the strength of influence in each causal relationship. These coefficients are derived from maximum likelihood estimation (MLE), calculated using the covariance matrix. The standard and commonly employed estimator in SEM is maximum likelihood (ML), which presumes multivariate normality and standardized variables. ML operates as a full information method, estimating all variables at once, which ensures that it remains unbiased, efficient, and consistent. Typically, a path coefficient is interpreted in the same way as a regression coefficient, often utilized to illustrate the degree of influence. Furthermore, Fig. 3 employs dashed lines to

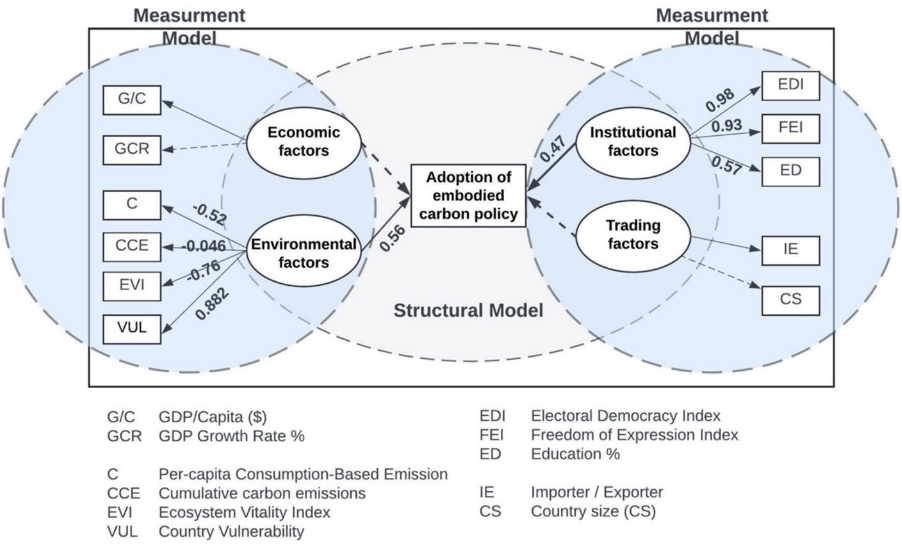

Fig. 3 SEM analysis results

Table 5 Estimation of relationship between embodied carbon policy adoption and influential factors

Standardized endogenous variables	Measurement component										
	Economic factor		Environmental factor				Institutional factor			Trading factor	
	G/C	GCR	C	CCE	EVI	VUL	EDI	FEI	ED	IE	CS
Coef	0.63	−0.10	−0.52	−0.046	−0.76	0.88	0.98	0.93	0.57	1	0.33
Std.Err	0.11	0.31	0.14	0.013	0.09	0.09	0.03	0.03	0.11	0.29	0.14
P	0.00	0.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02

Table 6 Model test and indices value

Fit Statistic	Test value	Acceptable threshold
chi-square	0.138	$p > 0.05$
RMSEA	0.04	< 0.1
pclose	0.106	$p > 0.05$
CFI	0.925	> 0.9
TLI	0.946	> 0.9

represent causal relationships that have a low confidence level, omitting the coefficient value.

Table 5 displays the statistical values for both the measurement and structural components of the SEM, including measurement errors and confidence levels, thus enhancing the information in Fig. 3. This data analysis shows that environmental and institutional factors greatly affect the adoption of embodied carbon policies, while economic and trading factors do not have a comparable effect. Specifically, carbon emissions per capita and ecosystem vitality are found to negatively affect policy adoption, suggesting that countries with lower carbon emission intensity and reduced ecosystem vitality are more inclined to adopt embodied carbon policies. This finding elucidates the proactive engagement of many smaller, economically disadvantaged countries in the Global South in global carbon reduction efforts. Contrary to the negative portrayals of these nations as lacking in cooperation, the evidence suggests a strong commitment to addressing climate change.

Once the model was estimated, five standard fit indices were utilized to assess the model's fitness. These indices include the chi-square ratio ($\chi 2$/df), root mean square error of approximation (RMSEA), probability of close fit (pclose), comparative fit index (CFI), and Tucker-Lewis Index (TLI). In this study, models were considered acceptable if at least four of the fit indices met the established criteria (Kline, 2015). Table 6 lists the test value and acceptable threshold for each statistic used. For a model to pass the chi-square test, its p-value must be greater than 0.05. A significant chi-square test indicates that the model does not fit well. In the first evaluation of model fitness, the p-value was 0.138, which is above the 0.05 threshold, demonstrating that the model is suitable. Ideally, for a close fit, the Root Mean Square Error of Approximation (RMSEA) should be below 0.05, although values up to 0.08 are usually acceptable (MacCallum, et al., 1996). In this analysis, the RMSEA was less than 0.05, and the pclose test was not significant ($p > 0.05$), indicating a close model fit. The Comparative Fit Index (CFI) and the

Tucker-Lewis Index (TLI) serve as measures of incremental fit, where values exceeding 0.95 indicate a very good fit (Schumacker & Lomax, 2004) and values above 0.90 being deemed acceptable (Pituch & Stevens, 2016). In this situation, the CFI measured 0.925 and the TLI was 0.946, both above the 0.90 threshold, which indicates an acceptable fit. Additionally, the author reviewed the coefficient values to verify there were no negative variances (as per the Haywood case), confirming that the model required no respecification.

4.3 Hypothesis test results

Ten hypotheses were tested using SEM, the results are listed below.

The first category, the rejection of H1, suggests that economic development conditions alone do not guarantee a transition to less carbon-intensive construction methods. This could be due to entrenched industrial practices, economic dependencies on certain construction technologies, or lack of incentives to innovate in established economies. High economic development might also correlate with a higher demand for infrastructure, potentially sustaining traditional, carbon-intensive methods. **The data analysis results rejected the perception that wealthy Global North countries intend to have more or more stringent regulation of embodied carbon, hence the economic factors are not influential.**

In the second category, the results of the environmental factor hypothesis test demonstrate the importance and direct impact of embodied carbon policy, as the coefficient of the environmental factor is 0.56. When looking deeper, the four variables have different effects. First, confirming the assumption (H2a), it is not true that countries with high carbon emission intensity avoid adopting embodied carbon emission policies. In fact, the negative coefficient (-0.52) suggests that countries with lower carbon emission intensity are more likely to implement such policies. This trend may imply that countries in the Global North with high carbon emission intensity require additional internal and external pressures, such as international agreements and public opinion, to adopt more sustainable practices and transition away from carbon-intensive lifestyles.

The acceptance of H2b suggests that nations with significant cumulative carbon emissions tend to adopt policies aimed at reducing those emissions. This could be due to international pressure, historical accountability, and a greater capacity to invest in sustainable technologies and practices. The acceptance of H2c proves that countries with poor ecosystem health are motivated to adopt carbon-limiting policies to prevent further degradation. This acceptance suggests a direct relationship between ecosystem health and environmental policy, where deteriorating conditions drive proactive measures to mitigate further harm. On the same line, acceptance of H2d supports the notion that countries most at risk from climate change are highly motivated to adopt policies to regulate carbon emissions. This may be driven by the immediate and visible impacts of climate change, necessitating urgent action to protect their populations and economies. The results from the second category hypothesis test results paint a picture that is promising yet concerning. Global South developing countries are very engaged in adopting embodied carbon policy because they are on the frontline to bear the climate change effect; however, the unwillingness to change lifestyle to reduce carbon intensity in Global North countries will not only impede the progress of carbon neutrality, but will also shift the consumption-based carbon emission to Global South countries more and more, hence worsening the climate change inequity.

H #	Description	Results
H1	A region with advanced economic development typically has an easier time implementing embodied carbon policies to transition to less carbon-intensive construction methods method	Reject
H2a	A country experiencing high carbon emission intensity is likely to have a strong motivation to withdraw from embodied carbon emission policies in order to maintain its current situation lifestyle	Accept
H2b	A country with high cumulative carbon emission contribution will likely adopt programs and policies to preserve the ecosystem's well-being by limiting carbon emissions	Accept
H2c	A country with low ecosystem vitality index will likely adopt programs and policies to preserve the ecosystem wellbeing through limiting the carbon emission	Accept
H2d	A country with high vulnerability to climate change will likely be motivated to adopt policy that regulating the carbon emission that can mitigate the climate change risk	Accept
H3a	The more democratic society is more keen to adopt policies to reduce embodied carbon to mitigate climate change	Accept
H3b	A country with high educational is more keen to adopt embodied carbon policies	Accept
H3c	A country with high freedom of expression and belief is more keen to adopt embodied carbon policies	Accept
H4a	A export-dominated country is likely to adopt the embodied	Reject
H4b	A large country is more motivated to adopt an embodied carbon policy due to the pressure from many trading partners	Reject

The third categorical variable is the institutional factor; all those hypotheses are accepted. The overall institutional factor is the second category that has a statistically significant influence on the national's embodied carbon policy adoption, that is shown as solid line in Fig. 3. The acceptance of H3a indicates a correlation between democratic governance and the adoption of carbon reduction policies. Democracies often have higher levels of public participation and accountability, which can drive governments to implement environmentally friendly policies reflecting public concern for climate change. H3b indicates that higher educational levels correlate with greater awareness and understanding of environmental issues, leading to stronger support for sustainable practices and policies. Educated populations can exert pressure on governments to take action on climate change. H3c shows that public discourse and the ability to advocate for environmental issues likely contribute to stronger environmental policies.

The fourth and last category is the trading factor; SEM results show it does not statistically affect policy adoption. The rejection of H4a suggests that being export-dominated does not necessarily translate into adopting embodied carbon policies. Such economies might prioritize maintaining competitive advantages in the global market over implementing stringent environmental regulations that could increase production costs. The rejection of H4b indicates that the size of a country alone does not drive the adoption of embodied carbon policies. Large countries may have diverse internal priorities and face significant challenges in achieving consensus on environmental policies, diluting the pressure from trading partners.

These hypothesis testing results provide a nuanced understanding of the factors influencing adopting embodied carbon policies. While socio-economic development, democratic values, and education positively correlate with policy adoption, high carbon emission intensity and economic structure (export-dominated or large size) do not necessarily drive policy changes. These findings highlight the complexity of policy adoption and the need for multifaceted approaches to encourage sustainable practices globally.

4.4 Discussion and policy recommendation

The rejection of Hypothesis H1, which posits that economic development alone does not ensure a transition to low-carbon construction methods, underscores the presence of complex systemic barriers. These barriers likely stem from entrenched industrial norms, economic dependencies on conventional technologies, and insufficient incentives for innovation in mature economies. Even in highly developed nations, deeply ingrained construction practices and reliance on carbon-intensive materials hinder progress toward sustainability (Chi et al., 2021).

Additionally, perceived risks and skills gaps further complicate the shift to sustainable construction. Developers and contractors, often risk-averse, may view low-carbon alternatives as unproven or financially uncertain, slowing adoption. The lack of technical expertise and workforce training in novel construction techniques exacerbates these challenges. Overcoming such barriers requires a combination of targeted interventions, including carbon pricing, tax incentives, industry standards, demonstration projects, research and development (R&D), and workforce training programs. Economic growth alone is insufficient; a coordinated, multifaceted approach is necessary to catalyze a meaningful transition.

A key finding is that institutional characteristics—notably democracy, freedom of information, and education—influence embodied carbon policy adoption at levels comparable to environmental factors. This suggests that embodied carbon reduction is not merely an economic or technological issue, but also a socio-political challenge. Democratic societies, characterized by transparent governance and public participation, are more likely to enforce strict environmental policies, driven by accountability and citizen advocacy. Freedom of information further accelerates policy adoption by fostering public awareness, open discourse, and knowledge dissemination about embodied carbon's environmental impact and the benefits of sustainable practices.

Moreover, higher education levels correlate with greater policy adoption, reinforcing the role of informed populations in driving climate action. Citizens with greater climate literacy are more likely to demand progressive policies, pressuring governments to prioritize low-carbon regulations. This underscores the need for strengthening democratic institutions, expanding access to environmental education, and ensuring information transparency as pivotal strategies for advancing global sustainability goals.

Despite growing awareness, economic, institutional, and trade-related challenges continue to hinder the widespread adoption of embodied carbon policies. However, international evidence suggests that well-structured policies can drive emissions reductions while sustaining economic growth. A common barrier is the perceived financial burden on industries, yet experiences from Sweden and Canada illustrate that carbon pricing and targeted incentives can enable decarbonization without economic decline. Sweden's carbon tax (\$137 per ton of CO_2) has led to a 38% reduction in emissions (from 52.1 Mt CO_2 in 1990 to 32.5 Mt CO_2 in 2022), while its GDP expanded by 122% in the same period (Sterner, 2020) (International Energy Agency, 2023) (World Bank Group, 2024). This highlights the potential of financial mechanisms, such as tax credits and subsidies, to facilitate a smooth transition to low-carbon construction materials and technologies while preserving economic competitiveness.

Institutional strength also plays a decisive role in embodied carbon policy adoption. Countries with robust regulatory frameworks, such as Germany and Denmark, have successfully embedded life-cycle carbon assessments into building policies. Denmark, for instance, mandates carbon impact assessments for all buildings over 1,000 m^2, demonstrating how strong governance enables policy enforcement (World Bank, 2023). In contrast, nations with weaker institutions often struggle to implement and enforce carbon regulations. Addressing institutional gaps through capacity-building initiatives and regulatory reforms is therefore crucial to expanding embodied carbon policies globally.

Additionally, trade dynamics significantly influence policy adoption. While export-driven economies are expected to enforce stricter environmental regulations, our findings indicate that trade openness does not always lead to stronger policies. High trade volumes, combined with weak carbon regulations, often result in carbon leakage, where emissions are outsourced to less-regulated markets—a trend seen in China and India (The World Bank, 2022).The European Union's Carbon Border Adjustment Mechanism (CBAM) offers a potential solution by incorporating embodied carbon considerations into trade policies. Expanding similar mechanisms—such as bilateral trade agreements favoring low-carbon supply chains or import tariffs on carbon-intensive materials—could mitigate outsourcing of emissions and incentivize cleaner global production.

A sectoral focus is also essential for maximizing impact. The construction sector alone accounts for 37% of global CO_2 emissions (United Nations Environment Programme, 2023), yet fewer than 25% of countries have embodied carbon regulations (Moncaster et al., 2019). Given that materials like cement, steel, and aluminum contribute over 20% of industrial CO_2 emissions, targeted interventions in these industries could yield significant reductions ((International Energy Agency, 2018).Canada's Clean Fuel Standard, which provides incentives for low-carbon alternatives, offers a potential model for construction material policies (Hoyle et al., 2024). Implementing similar sector-specific regulations could enhance policy effectiveness while balancing economic and environmental priorities.

By addressing economic, institutional, and trade-related challenges, policymakers can design comprehensive strategies to facilitate the adoption of embodied carbon policies. These measures, informed by empirical evidence and international best practices, can help bridge existing policy gaps and accelerate global decarbonization efforts.

5 Conclusion

Overall, this study provides one of the very few comprehensive analyses of embodied carbon policy adoption, offering a holistic understanding of the factors influencing its implementation. By systematically examining economic, environmental, institutional, and trade-related variables, this research moves beyond the narrower focus of prior studies, such as trade missions or operational carbon policies, to deliver a broader perspective. Using a global sample of 37 countries, both adopters and non-adopters of embodied policies, the study tests ten hypotheses and uncovers critical insights. The findings reveal that economic development alone does not drive the transition to low-carbon construction methods, as the sector remains constrained by entrenched practices and insufficient financial incentives for innovation. Environmental factors emerge as key motivators, with countries exhibiting high cumulative carbon emissions and poor ecosystem health being more likely to adopt carbon-limiting policies. This highlights the influence of historical accountability and immediate ecological risks. Moreover, democratic governance, freedom of expression, and higher educational levels are shown to positively impact policy adoption, underscoring the role of public participation and awareness in driving sustainable practices.

In contrast, the findings challenge the assumption that being export-dominated or large in size inherently translates to stronger embodied carbon policies. This complexity underscores the need for multifaceted approaches that extend beyond economic growth to encompass robust policy frameworks, public engagement, and educational initiatives. Governments facing significant climate change risks with limited ecosystem support are more likely to implement embodied policies, reflecting the urgency of addressing these vulnerabilities. Additionally, the study's recommendations for integrating embodied carbon into international trade agreements and balancing economic growth with carbon reduction provide actionable strategies that distinguish this research from previous studies. Furthermore, aligning embodied carbon policies with national climate action plans and providing financial incentives and support for sustainable materials and construction can accelerate the decarbonization progress. By addressing the interplay of institutional characteristics, environmental conditions, and economic priorities, the findings contribute to the broader discourse on sustainable construction practices and global decarbonization efforts.

This research also advances understanding of how embodied carbon policies align with the United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (affordable and clean energy) and SDG 13 (climate action). The study emphasizes the importance of incorporating embodied carbon considerations into building regulations and planning processes, identifying education and awareness as critical drivers of policy adoption. Recognizing that advanced economic development does not guarantee easier policy implementation, the findings call for continued efforts to promote embodied carbon policies, especially in developed nations with large economies. By addressing these diverse factors and leveraging targeted strategies, this study provides a roadmap for fostering a global transition toward sustainable and equitable construction practices.

Despite its contributions, the study acknowledges certain limitations. First, it is constrained by the inherent limitations of the SEM method. As SEM is a collection of statistical techniques, there is no universal consensus on defining the quality of SEM results, despite its widespread use in social science and policy research (Hu & Skibniewski, 2022; Vinodh & Joy, 2012). Second, the study is limited by the number of variables and categorical factors included. Incorporating additional variables could alter the results, and the quality of the analysis is dependent on the accuracy of the primary data sources, which vary by methodology. Third, the study's scope is restricted to 37 countries, representing less than 20% of the global total, which limits the generalizability of the findings. These limitations highlight opportunities for future research: (a) expanding data collection to include more countries, particularly from the Global South; (b) incorporating additional categorical factors to enhance analytical depth; and (c) exploring alternative methods, such as multivariate adaptive regression splines or factor-augmented autoregressive distributed lag models, to improve robustness and reliability.

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Data availability The data that support the findings of this study are available on request from the corresponding author.

Declarations

Conflict of interest No potential conflict of interest was reported by the author(s).

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