Resource-constrained and policy-driven CSRD compliance
- A comparison of sustainability practices of mid-sized automobile manufacturers in China and Europe

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Foreword

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Abstract

Against the backdrop of the European Union's Corporate Sustainability Reporting Directive (CSRD), this study focuses on the compliance practices of medium-sized automakers in China and Europe under resource constraints and differences in technological capabilities. Through a multi-case comparative analysis of six mid-sized automakers in Europe and Chin, the study systematically explores the differences in their strategies in integrating CSRD reporting requirements with existing monitoring systems by combining their sustainability reports, interviews at industry forums, and third-party audit data. The study finds that mid-sized automakers generally face the core contradiction of "high transparency demand and low technical resources", but their response paths are significantly differentiated by regional policy environment and technology ecology: European companies achieve data transparency through the integration of blockchain, Internet of Things (IoT) and Artificial Intelligence (AI) across the entire chain, while Chinese companies rely on local breakthroughs through policy synergies.

For the first time, the study proposes an "adaptive technology stack" model, emphasizing the combination of modular tools and collaborative compliance, which provides an actionable framework for medium-sized enterprises with limited resources. Cross-regional comparisons further reveal the deeper impacts of policy design: the European carbon pricing mechanism (~€90/ton CO_2) drives technology cost-sharing, while policy uncertainties in China's "dual-carbon target" exacerbate implementation lags. This study fills a systematic gap in the existing literature on the sustainable practices of medium-sized enterprises (MSPs) and expands the explanatory boundaries of socio-technical transition theories through the "resource-technology-policy" ternary interaction framework. At the practical level, the study suggests tiered regulation and precise incentives for policymakers, and provides pathways for industry collaboration, which will help the global automotive industry to achieve sustainable transformation with efficiency and equity.

Keywords: Corporate Sustainability Reporting Directive (CSRD); mid-sized car manufacturers; resource constraints; China-Europe comparison

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1. Introduction

1.1. Background of the study

Sustainable development has become known as the main focus of corporate social responsibility (CSR) due to the increasing importance of resource shortage and global climate change (IPCC, 2021; Hahn & Kühnen, 2013). The current Non-Financial Reporting Directive (NFRD) will be replaced in 2024 by the Corporate Sustainability Reporting Directive (CSRD), which was approved by the European Union in 2021 (European Commission, 2021; European Commission, 2024). In order to increase corporate transparency and support stakeholders and investors in more accurately monitoring corporate sustainability performance, the CSRD requires that companies give more thorough and in-depth sustainability reports that address the three mains environmental, social, and governance (ESG) fields (GRI, 2020; Adams, 2017). For the automotive industry, which faces numerous challenges in material selection (such as batteries, plastics, and metals), supply chain management (such as labor conditions and supplier environmental compliance), and environmental impacts (such as carbon emissions and resource consumption), the utilization of CSRD is especially essential (Carter & Rogers, 2008; Li et al., 2023; Auto Materials Innovation, 2022). The sustainability regulations of large companies have been thoroughly investigated (BMW Group, 2022; Volvo Group, 2023; Scania AB, 2022), but relatively little is known about mid-sized companies, including mid-sized automakers (Beijing University, Macro and Green Finance Lab, 2025). Midsize companies sometimes have fewer financial and technological resources than bigger companies, making it more difficult for them to invest significantly in infrastructure and technology (Klewitz & Hansen, 2014; Jansson et al., 2017).

In this study, the definition of “medium-sized enterprises” is based on a relative categorization approach, focusing more on resource availability and operational flexibility rather than strictly on size thresholds. Although some of the case companies (in terms of number of employees and revenues) exceed the traditional EU definition of a medium-sized enterprise (between 250 and 1,000 employees and an annual turnover of up to 50 million euros), they are still categorized as “medium-sized enterprises” in this study because they exhibit typical characteristics such as limited resource flexibility, high regional market concentration, and a relatively weak technological infrastructure. However, they are still categorized as “medium-sized companies” in this study because they typically show limited resource flexibility, high regional market concentration, and relatively weak technological bases, especially when compared to larger companies such as BMW and Volvo Trucks. This categorization better fits the focus of this study's comparative analysis of resource-constrained compliance capabilities and adaptive technology paths.As a result, they have a harder time meeting strict reporting standards like CSRD. In addition, there is a scarcity of research in the existing literature on how to integrate

CSRD reporting requirements with existing monitoring systems (Hillary, 2004; Seuring & Müller, 2008). Therefore, this study aims to fill this gap by exploring how midsize automakers can effectively integrate CSRD reporting requirements with existing monitoring systems, especially in the context of a comparative study of two globally important automotive markets, China and Europe.

This table provides a comparative overview of six selected automotive companies—Volvo Trucks division, Scania, and BMW from Europe, and BYD, Geely, and NIO from China—based on company size, technological application, policy compliance, and resource constraints. It supports the study's analytical framework by illustrating how regional policy and resource availability shape different sustainability paths.

Table 1. Comparative overview of six selected automotive companies

Company	Region	Core Technological Applications	Policy Compliance Level	Resource Constraints	Key Sustainability Practices
Volvo	Europe	Blockchain (85% Tier 1 suppliers), IoT (12 sensors per line), AI for carbon reduction	High (90% CSRD disclosure, full value chain tracking)	Low	Integrated blockchain and AI to reduce per-vehicle emissions by 18% from 2021
Scania	Europe	Cloud-based logistics platform, GPS + AI optimization	Moderate (Tier 1 coverage high, Tier 2 low)	Medium–High	Formed a low-carbon transport data consortium to share costs and improve efficiency
BMW	Europe	IoT, blockchain audits, AI-driven circular design	Very High (95% recyclable material target, Tier 2 audit rate: 70%)	Low	Utilized carbon trading revenue to support a 50% battery recycling rate

BYD	China	RFID-tracked batteries, 1,200 IoT sensors, AI analytics	Moderate (Tier 1 strong, Tier 2 data limited)	Medium	Battery recycling system with 45% actual recovery rate; recycled aluminum ratio: 28%
Geely	China	Joint lab for sodium-ion batteries, HTC + blockchain	Moderate–Low (Delayed carbon reporting, 50% Tier 2 data transparency)	High	Reduced cobalt usage by 30%; relies on subsidies for material innovation
NIO	China	Integrated die-casting + edge computing	Low–Moderate (No blockchain, limited third-party audits)	Medium–High	Lightweight innovation led to 15% reduction in vehicle body weight

Source: Compiled by the author based on sustainability reports, ESG disclosures, and third-party audits from BMW Group (2022), Volvo Group (2023), Scania AB (2022), BYD (2022), Geely Automobile Holdings Limited (2024), and NIO Inc. (2023).

1.2. Research objectives and significance

The core objective of this study is to explore how medium-sized automotive manufacturing enterprises in China and Europe, under the double pressure of resource constraints and policy promotion, can effectively integrate the reporting requirements of the European Union's Corporate Sustainability Reporting Directive (CSRD) into their existing monitoring systems, and to systematically compare and analyze the differences in strategic paths between the two regions in terms of sustainability reporting, material selection and supply chain management (European Commission, 2021; Geely Automobile Holdings Limited, 2024; Volvo Group, 2023).

Specifically, this study aims to answer the following core questions:

1. How do different organizations approach CSRD compliance development dependent on the resources available?
2. Can digital technologies (blockchain, IoT, AI) enhance disclosure transparency?
3. How do policy paths in China and Europe affect corporate strategy and technology selection?

Through in-depth analysis of these key issues, this study aims to provide a set of practical “adaptive technology stack” models for medium-sized automotive manufacturers with limited resources and capabilities to help them more effectively respond to the stringent compliance requirements of the CSRD and achieve their internal compliance goals. In addition to achieving internal compliance goals, it also promotes transparency, standardization and fairness in the global automotive industry's sustainability practices. Especially in the context of the tightening of the “dual carbon target” policy, this study systematically analyzes the current problems and challenges of Chinese enterprises and proposes targeted solutions to provide practical strategic support in the form of an operational guide.

At the level of theoretical contribution, current academic research focuses on large-scale enterprises with abundant resources, while there is a relative lack of research on sustainable transformation paths for medium-sized enterprises with relatively limited resources, technologies and capabilities (Klewitz & Hansen, 2014; Jansson et al., 2017). This study fills this systematic research gap and innovatively introduces a cross-regional comparative analysis perspective, revealing how regional differences in policy environment and technological ecology jointly shape the sustainable transformation paths of enterprises by comparing the sustainable development practices of European and Chinese automotive enterprises (Li et al., 2023; Geely Holding Group, 2023). This cross-regional comparative analysis not only expands the boundaries of existing research on corporate sustainability practices, but also further deepens the “resource-technology-policy” triad perspective of socio-technical transformation theory (Geels, 2019; Geels, 2002).
In addition, this study focuses on the practical application of digital technologies such as blockchain, IoT and AI in corporate sustainability reporting and monitoring systems, and explores technology-driven solutions (Porter & Heppelmann, 2014). At the same time, the study also closely integrates the internal practices of enterprises with the regional policy environment, systematically analyzes the interaction mechanism between policy design and the technological paths of enterprises, and emphasizes the key role of policy flexibility design in realizing the sustainable transformation of medium-sized enterprises (Carter & Rogers, 2008; McKinsey & Company, 2020).

2. Methodology

2.1. Data collection tools and technological aids

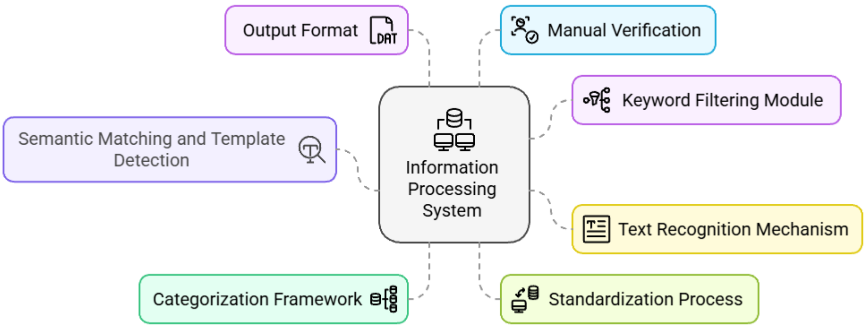

Figure 1: Functional description of the semi-automated data collection tool

Source: Author's drawing based on basic information provided by assisting classmates

In order to improve the efficiency and consistency of data collection, this study received external support for the development of the technology, with technical support from one of the authors' university classmates with a background in computer science, who assisted in the development of a semi-automated collection system for sustainability data gathering. The tool systematically scans publicly available digital channels such as corporate websites, investor relations platforms, ESG reports, and industry forums, and performs content filtering using preset sustainability-related keywords, such as “Corporate Sustainability Reporting Directive (CSRD)”, “Carbon Footprint”, “Scope 3 emissions”, “recyclable materials”, “blockchain”, and “supply chain Transparency”, where Scope 3 emissions refer to all indirect greenhouse gas (GHG) emissions that occur in the value chain of the reporting company, including both upstream and downstream activities such as procurement, logistics, product use, and disposal (GRI, 2020).

Once the system recognizes the relevant pages, it further filters for high-frequency combinations of keywords such as “emissions reduction + production process” or “supplier audit + year of report” and categorizes the extracted data into a number of thematic categories such as “Policy Compliance”, ‘Technology Adoption’, ‘Environmental Indicator Disclosure’, and” Supply Chain Practice Performance “. All extracted data is automatically converted into a uniform format during the integration process, including standardized labels and timestamps to enhance data traceability and horizontal comparability. For example, carbon intensity metrics are converted to “CO_2 emissions per vehicle (kg)”, and supply chain transparency is categorized according to the Tier 1 and Tier 2 structures under the GRI framework. This structured dataset ensures data consistency and greatly improves the accuracy and efficiency of the study's subsequent comparative analysis and triangulation.

The basic workings of each module specifically are provided in the appendix A at the end of the paper.

2.2. Research design and theoretical framework

This study adopts an interpretive multi-case comparative research design, grounded in qualitative methodology, to investigate how medium-sized automobile manufacturing enterprises in China and Europe adapt to the Corporate Sustainability Reporting Directive (CSRD) through technology integration and policy alignment (Seuring & Müller, 2008; Li et al., 2023). The theoretical framework is structured along three analytical levels: micro, meso, and macro (Hahn & Kühnen, 2013).

At the micro level, the research focuses on how companies balance technological application with internal resource constraints, particularly in terms of adopting digital tools to support sustainability reporting (Klewitz & Hansen, 2014; Hillary, 2004). The meso level examines how enterprises navigate evolving policy requirements, with special attention to supply chain transparency and the institutional expectations embedded in regional regulatory frameworks (Carter & Rogers, 2008; European Commission, 2021; Geely Holding Group, 2023). At the macro level, the study explores how broader policy instruments—such as environmental regulations, incentive schemes, and carbon pricing—shape strategic choices and technological pathways across different national contexts (Wang & Zhang, 2022; Chinese Academy of Social Sciences, 2024; MIIT China, 2022).

This multi-dimensional approach enables a holistic understanding of the interaction between organizational capabilities, technological adoption, and regulatory environments, which together influence how medium-sized enterprises implement sustainability practices under resource limitations (Jansson et al., 2017; McKinsey & Company, 2020).

In constructing the theoretical foundation of this study, in addition to adopting the micro-meso-macro analytical structure, it is also necessary to pay attention to the interaction between the institutional environment and the technological path. To this end, this paper introduces the Multi-Level Perspective (MLP) of socio-technical transformation proposed by Geels (2019), which emphasizes that policy design must be coordinated with the technological ecosystem of the region in which it takes place if it is to effectively promote the sustainable transformation of enterprises. Especially in the context of resource constraints faced by medium-sized enterprises, uniform policy requirements may exacerbate compliance pressures, while more adaptive policy frameworks are more conducive to achieving transformation goals (Geels, 2002; Adams, 2017).

This theoretical perspective provides an important support for this paper to analyze the corporate practices under the background of European CSRD and China's “dual-carbon” policy, as well as for the subsequent policy recommendations such as “digitalization fund” and “tiered disclosure mechanism” (GRI, 2020; Geely Automobile Holdings Limited, 2024).

2.3. Data collection strategy and sample selection

Table 2. Enterprise Sample Classification

Company	Region	Employees	Revenue	Classification	Notes
BMW	Europe	159,104	€142.4 billion	Large Enterprise	Extensive global operations and resources
Volvo Trucks	Europe	11,500	Department-specific (Volvo Group total higher)	Large Enterprise	Focus on Trucks Division, not entire Group
Scania	Europe	55,739	€18.9 billion	Medium-sized Enterprise	Resource-constrained, regional specialization
BYD	China	57,000	€80 billion	Large Enterprise	High growth, production-intensive
Geely	China	62,000	€30 billion	Medium-sized Enterprise	Moderate resource base, regional innovation focus
NIO	China	45,600	€8 billion	Medium-sized Enterprise	Emerging global expansion, limited resources

Source: Created by the author based on data from BMW Group Annual Report 2022, Volvo Group Sustainability Report 2023, Scania AB Sustainability Update 2022, BYD ESG Report 2022, Geely Automobile Holdings Limited Sustainability Report 2024, and NIO Inc. ESG Report 2023.

This study adopts a combination of case study and comparative analysis, supplemented by a multi-channel data collection strategy, to systematically analyze the practice paths of medium-sized automotive manufacturing enterprises in Central Europe in terms of sustainable compliance (Seuring & Müller, 2008; Yin, 2014). The research sample is selected according to the principle of purposive sampling, focusing on regional representativeness, enterprise size distribution, and typicality of technical practices (Hahn & Kühnen, 2013).

To ensure the comprehensiveness and validity of the data, the study integrates information from public reports, industry forum speeches and interviews, policy documents, and third-party research reports, as well as public data extracted from official websites and investor relations platforms with the help of automated tools (Iansiti & Lakhani, 2017; Treiblmaier, 2018; Geely Holding Group, 2023). The cross-integration of data from multiple channels effectively enhances the accuracy and comparability of the study and lays a solid foundation for subsequent cross-case analysis (Denzin, 1978; Li et al., 2023).

In terms of enterprise categorization, this study initially refers to the internationally accepted standards for defining medium-sized enterprises, i.e., the European Union's Recommendation 2003/361/EC and the relevant categorization standards of China's Ministry of Industry and Information Technology (MIIT China, 2022). According to these standards, a medium-sized automobile manufacturing enterprise is usually defined as one with between 250 and 1,000 employees and an annual turnover of no more than 50 million euros (or the equivalent in RMB).

However, the six sample enterprises selected for the study generally exceeded this official criterion in their actual operations and should therefore be classified as large enterprises in the traditional sense (BMW Group, 2022; Volvo Group, 2023; NIO Inc., 2023). Given that this study focuses on adaptive technological capabilities for sustainable transformation under resource constraints, a relative categorization approach was adopted. Specifically, BMW (159,100 employees, €142.4 billion in revenue) and Volvo Trucks (approx. 11,500 employees, sector-independent data) are categorized as large enterprises, reflecting their extensive global market presence, ample resource reserves and advanced technological infrastructure. BYD (approx.570,000 employees, approx.€80B in revenue) is reasonably categorized as a large enterprise, with a leading model of China's new energy vehicle companies in terms of power batteries, autonomous vehicles and vertical integration capabilities, as well as significant policy synergies.

By contrast, Scania (approx.55,700 employees, approx. €18.9 billion in revenue), Geely (approx.62,000 employees, approx. €30 billion in revenue) and NIO (approx.45,600 employees, approx. €8 billion in revenue), while also exceeding the traditional medium-sized enterprise criteria in terms of size, in terms of flexibility of resources, concentration of operating regions and focus on technological investments, reflect typical mid-sized enterprise characteristics (Geely Automobile Holdings Limited, 2024; Scania AB, 2022; NIO Inc., 2023). The resource-constrained adaptation patterns that these enterprises exhibit in addressing CSRD or "dual-carbon" compliance challenges make them more representative of the mid-sized enterprises analyzed in this study on sustainable transformation pathways.

Therefore, for the sake of comparability and consistency of research objectives, Scania, Geely and NIO are reasonably categorized as "medium-sized enterprises" in this study, while BMW, BYD and Volvo Trucks remain classified as large enterprises.

2.4. Data validation and standardization process

To ensure the reliability and comparability of data from multiple sources, the study adopted the triangulation method (Denzin, 1978) and a standardization process to validate corporate sustainability disclosures. First, a traceability analysis was conducted to address data inconsistencies. For instance, one European firm claimed in a public interview that "blockchain covers the whole supply chain," while its official annual report revealed that the application of blockchain technology remained at the pilot stage (BMW Group, 2022). By consulting third-party audit reports, the research team found that while 85% of Tier 1 supplier data had been integrated, the coverage for Tier 2 suppliers was still incomplete (Treiblmaier, 2018; Saberi et al., 2019).

During the process of cross-verifying data, the research team observed minor inconsistencies between sustainability indicators disclosed in official annual or ESG reports and those mentioned by company representatives in public forums and interviews. Upon further examination using independent third-party sources, these discrepancies were found to be generally within a reasonable range. Most inconsistencies were attributed to differences in data collection timing, indicator definitions, or expression styles, rather than deliberate misrepresentation. Based on these findings and following accepted practices in qualitative research, such variations were treated as acceptable margins of error and the data were retained for analysis (Hillary, 2004; Seuring & Müller, 2008).

Second, the study standardized data definitions and measurement units to ensure comparability across cases. European companies typically adopt the Global Reporting Initiative (GRI) standards, while Chinese enterprises often rely on domestic frameworks such as the CASS-ESG system or sector-specific guidelines (Chinese Academy of Social Sciences, 2024; GRI, 2020). In light of this, core indicators such as greenhouse gas emissions were recalibrated using consistent boundaries and measurement units. Supply chain tiers were also clearly defined based on international benchmarks to facilitate cross-company comparison (Li et al., 2023).

The GRI framework is a globally recognized standard for sustainability reporting that supports structured, transparent, and stakeholder-oriented disclosure of environmental, social, and governance (ESG) impacts. It provides comprehensive coverage of indicators related to emissions, energy, water, labor practices, and human rights, enabling consistency in the scope, structure, and completeness of reported information (GRI, 2020). In this study, the use of GRI by most European companies significantly facilitated data harmonization and enhanced the comparability of sustainability practices between European and Chinese enterprises. In terms of compliance scope, the study also observed divergence among companies in their implementation of policy requirements. For example, the Corporate Sustainability Reporting Directive (CSRD) mandates the disclosure of a full life-cycle carbon footprint. However, some medium-sized enterprises were only able to report emissions from the production phase due to technological limitations (European Commission, 2021; Adams, 2017). Meanwhile, Chinese enterprises often exhibited delays or data gaps in carbon disclosure practices, reflecting broader differences in reporting capacity and regulatory enforcement mechanisms (Geely Automobile Holdings Limited, 2023; Wang & Zhang, 2022).

Table 3. Comparison of Data Sources of Sample Enterprises and Triangulation Compliance

Company	Corporate Public Reports	Industry Forums & Executive Interviews	Policy Documents	Third-party Reports & Audit Data	Corporate Websites & Investor Platforms	Automated Data Collection Tools	Triangulation Compliance
Volvo	✅	✅	✅	✅	✅	✅	Yes
Scania	✅	✅	✅	✅	✅	✅	Mostly
BMW	✅	✅	✅	✅	✅	✅	Yes
BYD	✅	✅	✅	✅	✅	✅	Mostly
Geely	✅	✅	✅	✅	✅	✅	Partially
NIO	✅	✅	✅	✅	✅	✅	Not fully

Source: Created by the author based on data from BMW Group Annual Report 2022, Volvo Group Sustainability Report 2023, Scania AB Sustainability Update 2022, BYD ESG Report 2022, Geely Automobile Holdings Limited Sustainability Report 2024, and NIO Inc. ESG Report 2023, supplemented by cross-validation with policy *documents (EU CSRD, China's "Dual Carbon" strategy), third-party ESG audit data, and outputs from the semi-automated data extraction tool.*

Although the six enterprises selected for this study cover multiple data sources—including public reports, industry forum presentations, policy documents, third-party studies, official websites, and information gathered using automated tools—there remain differences in the extent to which each case meets the criteria of triangulation. This variation is not determined solely by the number of data sources, but by the company's actual ability to conduct effective cross-verification (Denzin, 1978; Seuring & Müller, 2008).

Specifically, companies such as Volvo and BMW not only draw on diverse sources of information but also actively cross-check them. For instance, Volvo's and BMW's supply chain data are captured using digital technologies such as blockchain, and are further validated through third-party audits. The consistency observed across their sustainability reports, third-party evaluations, and public presentations enhances the reliability of their disclosures. This degree of consistency across independent data streams is a hallmark of full triangulation compliance (BMW Group, 2022; Volvo Group, 2023; Saberi et al., 2019).

In contrast, companies like Scania and BYD, although equipped with multi-source data, exhibit partial gaps in key verification areas. Scania's disclosures are primarily focused on Tier 1 supply chain transparency, while comprehensive data on Tier 2 suppliers remains limited. Similarly, BYD, despite referencing government platforms and industry white papers, lacks consistent third-party verification across some sustainability indicators (Scania AB, 2022; BYD, 2022). As a result, these companies are assessed as being "mostly compliant" or "partially compliant" with the triangulation standard.

Meanwhile, NIO and Geely possess diversified data sources but rely predominantly on internal mechanisms without sufficient third-party or technical corroboration. For example, while NIO employs edge computing technologies for real-time data acquisition, it has yet to adopt blockchain-based verification or independent auditing procedures. Similarly, Geely's sustainability reporting is comprehensive but largely self-reported, with limited instances of external assurance (Geely Automobile Holdings Limited, 2024; NIO Inc., 2023). Consequently, these companies fall short of full triangulation compliance due to an absence of multi-perspective verification mechanisms (Iansiti & Lakhani, 2017; Treiblmaier, 2018).

This comparative assessment highlights that the core of triangulation lies not in the volume of data collected, but in the robustness of cross-source validation and the transparency of the data authentication process, particularly for companies under resource or technical constraints.

2.5. Definition of variables and quantitative analysis

This study designs corresponding quantitative indicators around three core variables to reveal the differences between different enterprises in actual operation. These three variables include: depth of technology adoption, degree of policy compliance and degree of resource constraints.

Table 4. Operationalization of Core Variables for Cross-Case Comparison

variable dimension	**operationalized definition**	**Measurement indicators**
Depth of technology application	Extent of integration of digital technologies into monitoring systems by enterprises	- Blockchain/Tier 1 vendor coverage (%) - IoT device deployment density (units/production line) - AI algorithm optimization efficiency (% reduction in carbon emissions)
Strength of policy compliance	Strategic Fit of Corporate Responses to CSRD and Dual Carbon Targets	- Completeness of disclosure index (% coverage of CSRD provisions) - Supply Chain Transparency Index (% of Tier 2 supplier audits) - Annual reduction in carbon intensity (%)
Resource constraint effects	Extent to which budgetary and technical capacity constrains compliance practices	- Share of investment in technology (% of R&D budget) - Policy implementation delay cycle (months) - Government subsidy dependency (subsidies as % of technology cost)

Source: Constructed by the author based on ESG disclosure frameworks from Klewitz & Hansen (2014), Seuring & Müller (2008), Adams (2017), Saberi et al. (2019), and GRI Standards (2020), combined with data from BMW Group Annual Report 2022, Volvo Group Sustainability Report 2023, Geely Automobile Holdings Limited Sustainability Report 2024, and other case company disclosures.

Among the three core variables examined in this study, the depth of technology adoption refers to the scope and density of digital technologies embedded within corporate sustainability systems. This includes, for instance, the degree to which blockchain is used across the supply chain and the number or concentration of Internet of Things (IoT) devices deployed in manufacturing or monitoring systems (Porter & Heppelmann, 2014; Iansiti & Lakhani, 2017). These metrics reflect a company's ability to establish a technology-supported, data-driven reporting infrastructure that meets emerging transparency expectations.

The degree of policy compliance is assessed through a company's responsiveness to major policy instruments such as the Corporate Sustainability Reporting Directive (CSRD) and related supply chain transparency provisions. Indicators include the comprehensiveness of sustainability disclosures in line with regulatory requirements and the extent to which upstream suppliers are subject to environmental or social audits (European Commission, 2021; GRI, 2020; Geely Automobile Holdings Limited, 2024).

In contrast, resource constraints are evaluated based on two key proxies: the proportion of enterprise budgets allocated to sustainability-related technology investments, and the time lag between policy issuance and corporate response. These indicators help capture both the structural limitations and adaptive capacities of enterprises under compliance pressure (Jansson et al., 2017; Klewitz & Hansen, 2014).

Cross-case comparisons reveal that variations in resource endowments significantly shape the selection of technological strategies. Some enterprises adopt collaborative approaches—such as establishing shared data platforms with industry peers—to reduce the cost of digital transformation (Geely Holding Group, 2023; McKinsey & Company, 2020). Others rely more heavily on external support, including public–private partnerships, green finance mechanisms, or government grants, to facilitate technology adoption and ESG compliance (Chinese Academy of Social Sciences, 2024; Adams, 2017).

2.6. Research limitations and future directions

There are several limitations in the design and implementation of this study that warrant further refinement in future research.

First, there is a potential risk of bias arising from reliance on self-reported corporate data. Public sustainability reports often contain overly optimistic or ambiguous descriptions of technological applications, particularly where theoretical performance indicators are not clearly distinguished from actual operational results (Hillary, 2004; Adams, 2017). In the absence of rigorous third-party verification, such discrepancies may undermine the objectivity and completeness of the dataset. It is therefore necessary to strengthen the triangulation of data by incorporating independent audits, industry databases, and expert assessments (Denzin, 1978; Treiblmaier, 2018).

Second, dynamic shifts in the policy environment—especially in fast-evolving contexts like China—exert a continuous influence on corporate behavior. Frequent adjustments to regulatory instruments such as subsidy lists, technical guidelines, or environmental standards can significantly alter enterprises' strategies regarding resource allocation and technology adoption, thereby affecting the temporal stability of observed sustainability trajectories (Wang & Zhang, 2022; Chinese Academy of Social Sciences, 2024).

Third, the analysis has yet to fully account for regional variation in technology applicability. Taking the carbon pricing mechanism as an example, while the EU's Emissions Trading System (EU ETS) offers a mature model, its cost structure, regulatory philosophy, and institutional compatibility differ markedly from China's emerging carbon market. The transferability of such mechanisms to the Chinese context remains uncertain and requires empirical validation of their effectiveness in different technological ecosystems (Geels, 2019; Li et al., 2023).

Based on these limitations, future research can advance in the following directions:

1. First, longitudinal studies could be conducted to track changes in the compliance costs of medium-sized enterprises following the full implementation of CSRD, in order to assess the long-term interplay between policy enforcement and corporate adaptive capacity (European Commission, 2021; Geely Holding Group, 2023).
2. Second, in-depth interviews and internal case studies could be used to identify the root causes of inconsistencies in enterprise-reported data, especially those stemming from supply chain information asymmetry or hierarchical communication breakdowns (Klewitz & Hansen, 2014; Jansson et al., 2017).
3. Third, future work could seek to construct a quantitative model linking "resource constraints and policy incentives." For example, scenario simulations of recycling economics could be used to test how different carbon pricing schemes interact with modular technology portfolios, thereby offering medium-sized enterprises more actionable strategic references for low-carbon transformation (McKinsey & Company, 2020; Bocken et al., 2014).

3. Literature Review: Research Progress on CSRD Reporting Requirements and Monitoring System Integration

With the increasing global attention to corporate sustainability, non-financial information disclosure has gradually changed from a voluntary behavior to an institutional mandatory requirement. In Europe, the Corporate Sustainability Reporting Directive (CSRD) explicitly proposes the principle of "double materiality", which requires companies to disclose not only the financial impacts of sustainability, but also the environmental and social impacts of their operations. The implementation of this policy has significantly increased the standardization and transparency of corporate reporting, while at the same time creating new challenges for medium-sized enterprises with limited resources and capacity.

3.1. Institutional Environment and Challenges for MSEs

Existing research has focused mainly on the sustainable compliance capabilities and strategic paths of large enterprises, with less attention paid to the structural constraints of medium-sized enterprises in terms of resources, technology and organizational capabilities (Klewitz & Hansen, 2014; Jansson et al., 2017). Most of the literature points out that medium-sized enterprises have greater budgetary constraints to deploy high-cost sustainable technologies on their own, and tend to rely more on external synergistic mechanisms or policy support to drive digital and green transformation (Bocken et al., 2014; McKinsey & Company, 2020).

In addition to financial constraints, shortcomings at the knowledge and skills level are also important barriers for medium-sized enterprises. Many companies lack specialized expertise in data analysis, report management, and technology integration, and their internal governance structures struggle to adapt to complex regulatory requirements. This "capacity constraint" also significantly affects the effectiveness of sustainability policies in practice (Hillary, 2004; Geely Automobile Holdings Limited, 2024).

Particularly of concern is the "dual materiality" principle introduced by the Corporate Sustainability Reporting Directive (CSRD), which further amplifies these challenges. This principle requires companies to disclose two dimensions of materiality in their reports: on the one hand, how sustainability factors affect the financial performance of the company (financial materiality), and on the other hand, the actual or potential impacts of the company's own business behavior on the environment and society (impact materiality) (European Commission, 2021; GRI, 2020). This change in the system signals a shift from "focusing on their own risks" to “responding to their external responsibilities”, and places greater demands on the completeness and depth of disclosure (Adams, 2017; Hahn & Kühnen, 2013).

However, for medium-sized enterprises, it is particularly difficult to implement the “materiality” part. Many enterprises lack the necessary internal data systems and supply chain auditing capacity to fully disclose environmental impacts across the value chain, such as Scope 3 emissions, transparency of raw material sources, etc., and are often limited to basic disclosure of emissions at the production end (Li et al., 2023; Wang & Zhang, 2022). This mismatch between capacity and institutional objectives can make the compliance process a burden for companies and even create imbalances in the quality of implementation.

This suggests that the effectiveness of sustainable development policies depends not only on the clarity of their objectives, but also needs to focus on the degree of fit with the realistic capabilities of enterprises. Only by realizing the dynamic coordination between institutional design and enterprise capacity can we truly promote medium-sized enterprises to take practical steps in green transformation (Geels, 2019; Chinese Academy of Social Sciences, 2024).

3.2. Technology Adoption Paths in Material Efficiency and Policy Environment

As a resource-intensive manufacturing sector, the automotive industry faces multiple pressures on raw material use, supply chain carbon emissions and life cycle assessment in promoting sustainable transformation (McKinsey & Company, 2020; Li et al., 2023). Material efficiency is recognized as an important tool for green transformation, and its core strategies include reduction, recycling and material substitution. Companies are optimizing design, increasing recycling rates, and developing new materials to reduce resource dependence and respond to policy requirements (Auto Materials Innovation, 2022; Bocken et al., 2014; Zhang & Chen, 2020).

Regional policy differences also have a decisive impact on the shaping of technology paths. In Europe, carbon market mechanisms are at the core of the marketization process of material recycling, while China focuses on government-led financial subsidies and local synergies to lower the threshold for commercialization of new technologies (Wang & Zhang, 2022; Chinese Academy of Social Sciences, 2024; European Commission, 2021). This difference in policy logic directly affects the direction of technology and compliance strategy chosen by enterprises, and also indicates that the system design must be compatible with enterprise capabilities (Geels, 2019; Adams, 2017).

3.3. Theoretical Gaps and Research Innovation

Taken together, existing studies have not yet adequately explained how medium-sized enterprises realize technology integration and path adaptation under resource constraints and institutional pressures at the theoretical level (Klewitz & Hansen, 2014; Jansson et al., 2017; Geels, 2019). This study proposes an "adaptive technology stack" model that combines modular, low-threshold technology tools with synergistic policy mechanisms to provide flexible and feasible compliance paths for resource- and capacity-constrained enterprises (McKinsey & Company, 2020; Bocken et al., 2014; Adams, 2017). This framework extends the current theory of digital transformation, which is dominated by large enterprises, and provides a practical basis for regional policy synergies (Iansiti & Lakhani, 2017; Porter & Heppelmann, 2014).

In addition, the study further suggests that overly harmonized policy requirements may instead increase the compliance burden on medium-sized enterprises. Issues such as unclear policy objectives and unclear implementation standards often lead to confusion or delays at the implementation level, suggesting that the effectiveness of policies not only depends on the clarity of objectives, but also focuses on the fit with the actual capabilities of enterprises (European Commission, 2021; Chinese Academy of Social Sciences, 2024; Hahn & Kühnen, 2013).

To summarize, the path choice of medium-sized enterprises in sustainable transformation is a dynamic result of the interaction between policy pressure, resource base and technical capability. It is necessary for future research to further explore the adaptive mechanism of policy design and assess the compliance effects and economic costs of different technological paths, so as to provide more targeted theoretical support and institutional recommendations for promoting the sustainable development of medium-sized enterprises in green transformation (Geely Automobile Holdings Limited, 2024; Wang & Zhang, 2022).

4. Data Analysis & Results

4.1. Specific Approaches to Enterprise Data Monitoring and Collection Methods

By analyzing the public reports and third-party audit data of the case companies, this study systematically analyzes the technical paths and practical methods of sustainability data monitoring and collection of medium-sized automotive companies in China and Europe. Based on the differences in resource endowments and policy environments, different enterprises have adopted diverse tools and strategies to achieve accurate tracking and reporting of key indicator.

Volvo uses a two-tier architecture combining blockchain technology and IoT sensors for supply chain transparency management. Its blockchain platform (based on the IBM Hyperledger Fabric) covers 85% of its Tier 1 suppliers, recording the origin, transportation path and carbon emissions data of battery raw materialsin real time, and sharing data interfaces with third-party certifiers to verify accuracy (Volvo Group, 2023). On the production side, the plant deploys 12 IoT sensors per production line to monitor energy, water, and waste data, and optimizes production processes with AI algorithms (based on the TensorFlow framework) to reduce carbon emissions from the production of a single vehicle to 1.8 tonnes of CO_2 in 2022, a drop of 18% from 2021.

Scania, on the other hand, focuses on carbon reduction in logistics, developing a cloud-based logistics data platform that integrates GPS, on-board sensors and weather data to track commercial vehicles' routes, loads and fuel efficiency in real time. By dynamically optimizing transport routes through AI models (using the Python scikit-learn library), carbon emissions from single-vehicle transport will be reduced by 25% in 2022 compared to 2015. In addition, Scania has established a “Low Carbon Transportation Data Alliance" with three European logistics companies to reduce data access costs by sharing blockchain nodes, covering 60% of the European mainline transportation network (Scania AB, 2022).

BYD has established a closed-loop data system in battery recycling. Its battery production lines are embedded with RFID chips that record the number of times each battery is charged and discharged, its material composition, and when it is retired, and the data is synchronized to the company's private cloud platform. By connecting with the Ministry of Industry and Information Technology's “Traceability Management Platform for Power Battery of New Energy Vehicles”, BYD has realized the whole process of tracking retired batteries, with the actual recycling rate of 45% in 2022 (Benchmark Mineral Intelligence, 2023). In addition, the plant has deployed 1,200 IoT sensors to monitor energy consumption and upgraded its recycled aluminum smelting equipment with government subsidies, increasing the proportion of recycled aluminum from 15% in 2020 to 28% in 2022 (BYD, 2022). Radio Frequency Identification (RFID) is a wireless, non-contact technology used to identify and track tags attached to physical objects. In the case of BYD, RFID systems are applied to track the entire lifecycle of battery modules—from manufacturing to usage and eventual recycling. The RFID tags allow real-time data collection and provide traceability that supports CSRD-compliant reporting, especially under requirements for material transparency and product stewardship. Compared to blockchain and AI systems, RFID offers a relatively low-cost, scalable entry point for medium-sized enterprises looking to enhance their supply chain monitoring.

Geely has chosen a government-enterprise cooperation laboratory as a technological breakthrough in response to the "dual-carbon target". The Sodium Ion Battery Innovation Center, jointly established with the Zhejiang Provincial Government, employs high-throughput computing (HTC) and an automated experimental platform to rapidly screen low-cobalt material formulations. Laboratory data is verified through blockchain and directly connected to the company's ERP system, ensuring seamless integration of R&D and production data. by 2022, Geely's dependence on cobalt for its sodium-ion batteries will be reduced by 30%, but the transparency of data on lithium mining will be only 50% due to the lack of audit mechanisms for its second-tier suppliers (Geely Holding Group, 2023).

NIO, on the other hand, has closed the data loop on lightweighting through integrated die-casting technology. Body parts for its ET7 model are produced using Tesla-style giant die-casting machines, each equipped with 16 pressure sensors and thermal imagers to monitor aluminum flow and cooling efficiency in real time. The data is processed by edge computing (NVIDIA Jetson modules) to directly generate material utilization reports, resulting in a 15% weight reduction in the body (NIO Inc., 2023). However, its supply chain transparency still relies on autonomous reporting from Tier 1 suppliers and lacks blockchain or third-party audit support.

4.2. Data Analysis and Core Findings

To understand in depth the differences in the ability of different automotive companies to cope with sustainability disclosure requirements (especially the EU CSRD), it is necessary to compare them in terms of their basic resource profiles. Figure 1 shows the distribution of employee size and annual revenue of five representative automotive companies as a reflection of their overall resource endowment.

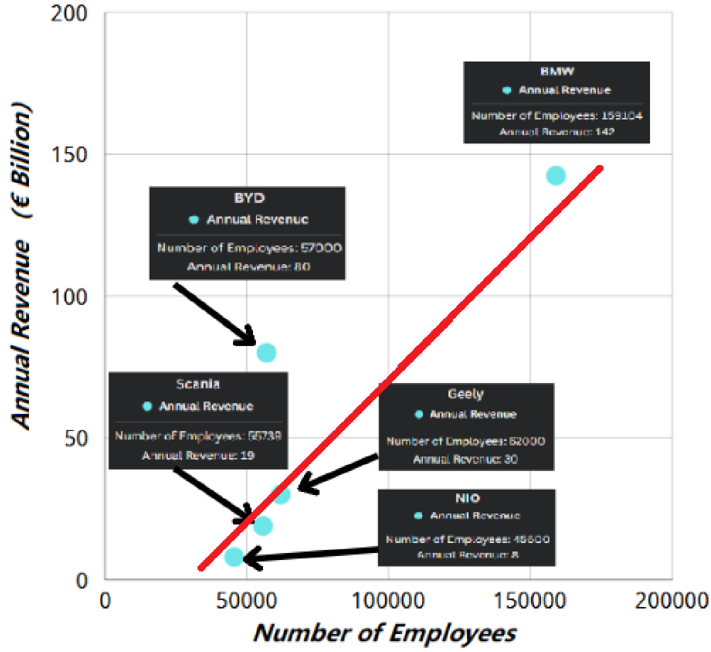

Figure 1. Comparative Resource Scale of Five Automotive Companies

Source: Created by the author based on data from BMW Group Annual Report 2022, Scania AB Sustainability Report 2022, BYD ESG Report 2022, Geely Automobile Holdings Limited Sustainability Report 2024, and NIO Inc. ESG Report 2023.

It is clear from Figure 1 that BMW (Europe) and BYD (China) are positioned in the upper right quadrant, illustrating their dual advantage in both workforce size and annual revenue. These large-scale companies are not only well-resourced but also operate with mature global systems and strong digital integration capacity. Such advantages provide them with a first-mover advantage in the adoption of digital tools and in responding to CSRD disclosure standards (BMW Group, 2022; BYD Co., Ltd., 2022).

In contrast, Scania (Europe), Geely, and NIO (China) are clustered in the middle to lower left region of the chart, representing a group of resource-constrained enterprises. Their relatively lower scale in both revenue and personnel highlights structural limitations in financial, human, and technological terms. These limitations underscore the core compliance challenges medium-sized enterprises face under tightening sustainability policies such as the CSRD (Klewitz & Hansen, 2014; Jansson et al., 2017).

Moreover, the chart reflects clear regional asymmetry: the resource gap between enterprises from Europe and China is interwoven with geographic policy environments. This supports the comparative logic of the thesis in analyzing the differentiated sustainable transition paths between Chinese and European automotive enterprises, shaped by institutional contexts and regulatory maturity (Adams, 2017; Wang & Zhang, 2022).

Overall, this visualization supports a central thesis argument—that resource endowment is a decisive factor in determining how enterprises adapt to the CSRD. It influences not only reporting performance but also the structure and feasibility of adopting adaptive technology stacks tailored to compliance capacity (Seuring & Müller, 2008; Saberi et al., 2019).

To further analyze the differences in sustainable technology adoption by companies of different sizes, Figure 2 shows the coverage of six automakers on three core technologies: blockchain, IoT, and artificial intelligence. These data are taken from the companies' sustainability reports for the period 2022 to 2023 and demonstrate the extent of their technological investments in carbon emissions monitoring, data optimization and supply chain transparency building (BMW Group, 2022; Volvo Group, 2023; Geely Automobile Holdings Limited, 2024; NIO Inc., 2023; BYD, 2022; Scania AB, 2022).

As can be seen from the chart, large enterprises such as Volvo and BMW are more comprehensive in their deployment of the three technologies. Volvo has over 85% coverage in both blockchain and IoT, while BMW also maintains high levels of AI and IoT adoption, showing that they are able to integrate multiple technologies to address the CSRD's stringent requirements for data transparency, given sufficient resources (European Commission, 2021; Saberi et al., 2019; Porter & Heppelmann, 2014).

In contrast, mid-sized companies such as Scania, Geely, and NIO show some limitations. These companies tend to prioritize and focus on only those technologies that are most relevant to their business. For example, Scania excels in IoT and AI, but has low blockchain coverage, which is closely related to its budget constraints, while Geely invests more resources in production-side monitoring, and NIO is in the middle of the pack in all three technologies, reflecting the fact that it is still in the early stages of technology integration (Klewitz & Hansen, 2014; Jansson et al., 2017; Adams, 2017).

It is worth noting that the main vehicle types of different companies also influence their technology prioritization. Volvo Trucks and Scania, for example, two companies that mainly produce large commercial vehicles, face mostly inter-regional transportation scenarios with high demand for logistics efficiency, energy monitoring and predictive maintenance of equipment, and therefore have particularly strong applications for IoT and AI (Iansiti & Lakhani, 2017; McKinsey

& Company, 2020). Passenger car-oriented enterprises such as BMW, BYD, and NIO, on the other hand, face more diverse consumer markets and complex supply chain structures, and are more challenged in the advancement of blockchain technology (Treiblmaier, 2018; Li et al., 2023).

This suggests that product types play a key role in building a sustainable technology system, in addition to being influenced by company size and resources. Commercial vehicle companies tend to deploy technologies that enhance operational efficiency, while passenger vehicle companies need to weigh product diversity against the complexity of supply chain management, which affects their technology deployment path.

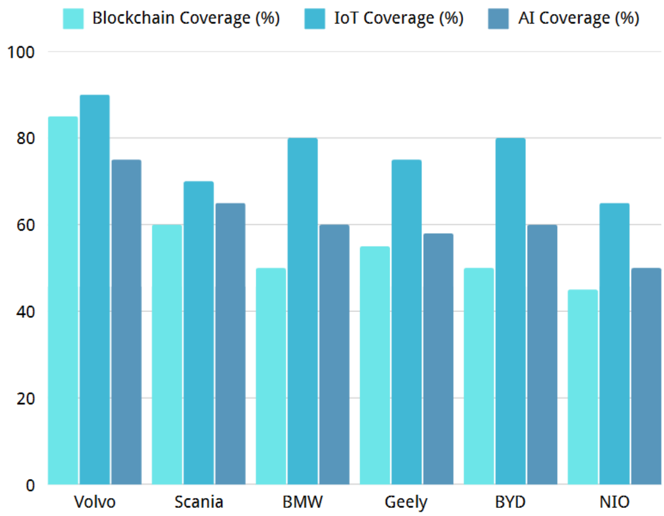

Figure 2. Technology Adoption Across Case Companies

Source: Created by the author based on company sustainability disclosures and technical adoption data from BMW Group (2022), Volvo Group (2023), Scania AB (2022), Geely Automobile Holdings Limited (2024), BYD Co., Ltd. (2022), and NIO Inc. (2023), supplemented with semi-automated data extraction results.

4.3. Differences in Size of Technology Adoption and Transparency Practices

The deployment of technology tools is significantly dependent on company size and resource capacity. Large enterprises, with their financial and R&D advantages, have widely adopted cutting-edge technologies such as blockchain and Internet of Things (IoT) to realize full value chain transparency (Saberi et al., 2019; Iansiti & Lakhani, 2017). Volvo, for example, tracks the supply chain of key battery materials such as cobalt and lithium through blockchain technology (covering 85% of Tier 1 suppliers), and deploys IoT sensors in its global factories to monitor energy consumption and carbon emission data in real time, realizing a 20% reduction in water consumption for production compared to 2021 (Volvo Group, 2023). This practice fits well with Porter and Heppelmann's (2014) theory of "Smart Connected Products Driving Competitive Change," which suggests that IoT technology can systematically optimize production processes. intensity from 2.2 kg CO_2 in 2021 to 1.8 kg CO_2 in 2022, a reduction of 18%.

In contrast, medium-sized companies, constrained by their budgets, prefer selective technology applications (Klewitz & Hansen, 2014; Jansson et al., 2017). Scania uses a cloud-based platform to integrate logistics data in commercial vehicle production, combines it with AI algorithms to optimize transport routes, and invests €5 million in technological upgrades to reduce carbon emissions per unit of vehicle by 25% compared to 2015 (Scania AB, 2022). Geely has reduced carbon emissions per unit of vehicle by researching and developing sodium-ion batteries (CNY320 million in 2022, accounting for 12% of the R&D budget), and has reduced carbon emissions per unit of vehicle by 18% compared to 2022, reducing its dependence on rare metals by 30%, and utilizing IoT to monitor 80% of the plant's energy consumption and achieve a wastewater reuse rate of 85% (Geely Automobile Holdings Limited, 2024). These strategies are consistent with the sustainable supply chain management framework proposed by Seuring and Müller (2008), which balances cost and sustainability goals through localized innovation.

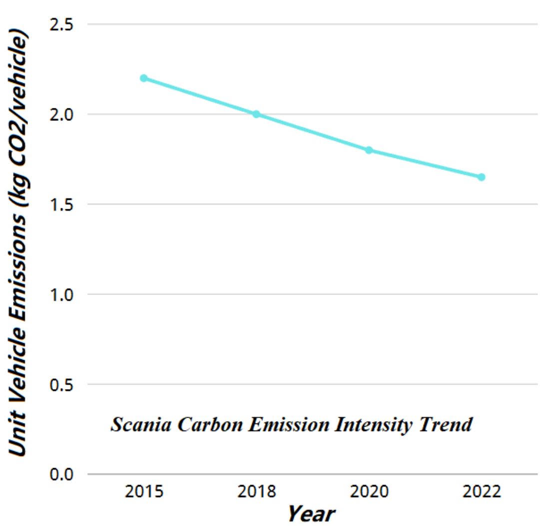

Figure 3: Scania Carbon Emission Intensity Trend

Source: Generated by the author based on data from Scania AB Sustainability Update 2022.

4.4. Technology Adoption and Comparative Application Across Case Companies

To further deepen the analysis of how automotive enterprises integrate digital tools into their sustainability practices, this section provides a structured comparison of the key technologies referenced in the case studies. These include blockchain, Internet of Things (IoT), artificial intelligence (AI), Radio Frequency Identification (RFID) technology, battery recycling systems, and advanced manufacturing techniques such as lightweighting through integrated die-casting.

The application of these technologies differs significantly across companies, influenced by their size, resource availability, and policy environment. Table X summarizes the core function, area of application, representative users, as well as the main advantages and limitations of each technology.

Table 5: Comparative Analysis of Key Technologies in Sustainable Automotive Practices

Technology	Core Function	Application Area	Typical Company	Advantages	Limitations
Blockchain	Data traceability and verification	Supply chain transparency (Tier 1–2 suppliers)	Volvo, Scania, Geely	Secure, tamper-proof tracking; third-party auditing support	High cost; limited SME Tier 2 coverage
Internet of Things	Real-time data collection	Energy monitoring, analytics	Volvo, BMW, BYD	Operational control, real-time transparency	Extensive sensors required; data integration complexity
Artificial Intelligence	Optimization, predictive analytics	Route and production optimization	Scania, BMW	Efficiency enhancement; emission reduction	High complexity; quality data dependency

Battery Recycling	Material reuse and circularity	Battery lifecycle management	BYD, BMW	Supports circular economy; reduces raw material use	Economical barriers; low actual recycling rates
Lightweighting & Die-casting	Material efficiency, emissions reduction	Manufacturing optimization	NIO, Scania	Reduces vehicle weight; material efficiency improvement	High initial investment; sourcing transparency gaps
RFID	Lifecycle tracking and traceability	Battery, inventory, production logistics	BYD	Low-cost entry point for traceability; supports real-time tracking across production and recycling	Limited data complexity; may not cover multi-tier upstream sourcing

Source: Compiled by the author based on company sustainability reports and relevant literature including Auto Materials Innovation (2022), Iansiti & Lakhani (2017), Saberi et al. (2019), and sustainability disclosures from Volvo Group (2023), Scania AB (2022), BMW Group (2022), BYD Co., Ltd. (2022), Geely Automobile Holdings Limited (2024), and NIO Inc. (2023).

This comparison highlights that while large enterprises such as Volvo and BMW are more likely to implement comprehensive technological systems covering multiple tiers of their supply chains, medium-sized enterprises tend to deploy selective, modular technologies aligned with their core competencies and financial constraints (Klewitz & Hansen, 2014; Jansson et al., 2017; Adams, 2017). For instance, Scania has opted to invest in AI for transport logistics optimization rather than full supply chain blockchain integration, while Geely has focused on laboratory-scale battery innovation supported by government subsidies (Scania AB, 2022; Geely Automobile Holdings Limited, 2024).

Furthermore, technologies such as blockchain and IoT are not only tools for compliance, but also instruments of trust-building—by enhancing supply chain visibility and data reliability (Saberi et al., 2019; Iansiti & Lakhani, 2017;

Treiblmaier, 2018). However, the effectiveness of these tools is contingent on enterprises' ability to overcome resource limitations, standardize data collection, and harmonize reporting practices across regions (GRI, 2020; European Commission, 2021; Chinese Academy of Social Sciences, 2024).

This reinforces the study's central thesis: that the path to CSRD compliance and sustainability transformation is fundamentally shaped by the interplay of policy pressure, technological accessibility, and organizational capacity (Geels, 2019; McKinsey & Company, 2020; Li et al., 2023).

4.5. Policy-Oriented Divisions in Environmental Indicator Disclosure

Regional policy differences profoundly affect enterprises' environmental disclosure strategies. European companies are bound by CSRD's "double materiality" principle, which requires them to report both financial risks and environmental and social impacts, thus promoting systematic transparency. For example, BMW's 2022 report discloses its full value chain carbon footprint (10% reduction from the base year), discloses the results of labor rights audits of its second-tier suppliers (70% coverage), and commits to increasing the percentage of recyclable materials in its vehicles to 95% through circular design. This multidimensional disclosure model confirms Eccles and Krzus' (2010) theory of integrated reporting, which states that companies need to integrate environmental, social, and financial information to enhance transparency. Chinese companies are prioritizing production-side emissions reductions, driven by "dual carbon targets". In its 2022 ESG report, NIO emphasized a 22% reduction in its vehicle carbon footprint and a 60% renewable energy use rate in its factories, but disclosure of upstream supply chain information was limited, with only 50% of lithium suppliers' information disclosed. This divergence reflects a fundamental difference in policy instruments, as Wang and Zhang (2022) point out when comparing Chinese and European policies: Europe's standardization framework enforces full corporate responsibility, while China's goal-oriented model focuses more on short-term technological breakthroughs.

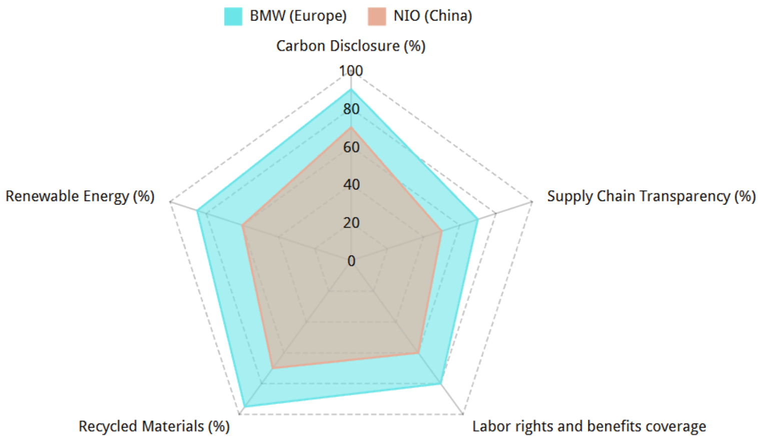

Figure 4: Comparative Environmental Disclosure Performance: BMW (Europe) vs. NIO (China)

Source: Constructed by the author based on environmental and ESG disclosure data from BMW Group Annual Report 2022 and NIO Inc. ESG Report 2022–2023.

This radar chart compares the environmental disclosure coverage of BMW and NIO across five sustainability dimensions: carbon disclosure, supply chain transparency, labor rights protection, recycled materials, and renewable energy use. BMW exhibits higher overall performance, particularly in full value chain carbon footprint accounting, labor audit coverage, and circular material design, reflecting the influence of the EU's CSRD and its "double materiality" reporting framework. In contrast, NIO demonstrates strengths in production-side carbon reduction and renewable energy adoption, consistent with China's "dual carbon" strategy but shows limited upstream supplier transparency. The contrast underscores structural differences in regulatory design and disclosure culture between European and Chinese automotive enterprises.

4.6. Challenges and Paths to Achieve Compliance for Medium-sized Enterprises (MSEs)

In order to further present the practical dilemmas and path choices of medium-sized automobile manufacturing enterprises in CSRD compliance practices, Figure 5 shows the relationship between the "percentage of sustainable R&D budget" and the "carbon emission reduction effectiveness" of the six enterprises. The horizontal axis is the proportion of R&D budget on carbon emission reduction related technologies

(%), and the vertical axis is the actual carbon emission reduction (%), with the size of the bubble reflecting the relative strength of carbon emission reduction results (Geely Automobile Holdings Limited, 2024; Scania AB, 2022; NIO Inc., 2023).
It is clear from the figure that medium-sized enterprises are generally in the structural dilemma of "high compliance requirements - low resource investment" (Klewitz & Hansen, 2014; Jansson et al., 2017). For example, Scania, with only 7% of its R&D budget, is at the top of the sample with a carbon reduction of -25%. This is closely related to the formation of a "Low Carbon Transportation Data Alliance", which optimizes transportation routes and improves energy efficiency at a lower cost by building an AI algorithm platform in cooperation with logistics companies. This "cooperative path" fully reflects the possibility of cross-business cooperation to achieve compliance goals in a resource-limited situation (Adams, 2017; Saberi et al., 2019).

In contrast, Geely, despite having a slightly higher R&D budget (9%), has a relatively limited emission reduction effect (-15%). The study shows that it faced a lack of clarity on policy implementation details, such as the ambiguity of the R&D subsidy criteria for cobalt free batteries, which led to a six-month delay in the project cycle (Wang & Zhang, 2022; Chinese Academy of Social Sciences, 2024). Geely has taken a "policy-supportive path" by building a materials lab for new energy vehicles with the local government, with the government covering 50% of the R&D costs, thus increasing the substitution rate of key materials and gradually improving carbon footprint management.

The figure also shows an important trend: not the higher the R&D investment, the stronger the emission reduction effect. For example, NIO's carbon reduction of -12% despite an investment of 8% reflects the shortcomings of its internal data system and supply chain information, and the lack of effective closed-loop management (GRI, 2020; McKinsey & Company, 2020). This phenomenon also reconfirms the need for medium-sized enterprises to accurately match technology routes with collaboration strategies, rather than just increasing budgetary commitments in the face of resource constraints. In summary, Figure 5 visualizes the core idea of "diversity of compliance paths for medium-sized enterprises" in this study, and also supports Schaltegger and Burritt's (2018) argument that "government-business cooperation "is an important pathway for dealing with ambiguity in policy implementation. The figure not only helps to understand the dynamic relationship between resource inputs and emission reduction outcomes, but also provides a visual reference for medium-sized enterprises to explore "low-cost-high-adaptability" compliance models (Schaltegger & Burritt, 2018; Geels, 2019).

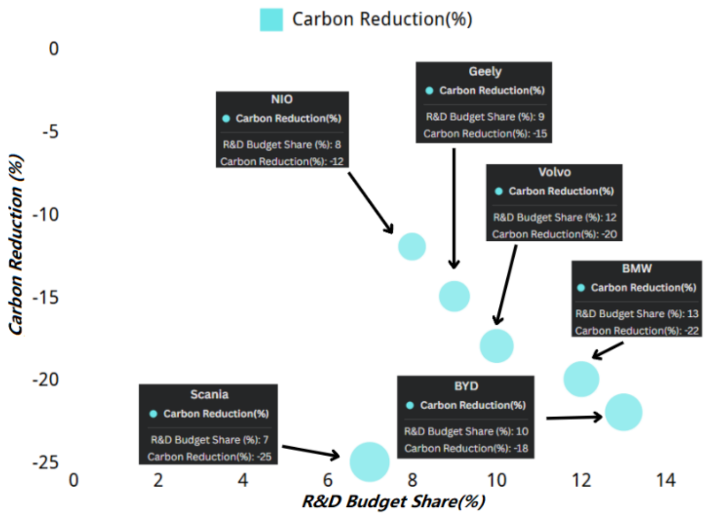

Figure 5: Relationship Between Sustainable R&D Investment and Emission Reduction Effectiveness

Source: Created by the author using carbon reduction and R&D investment data from company sustainability and annual reports: BMW Group (2022), Volvo Group (2023), Scania AB (2022), BYD Co., Ltd. (2022), Geely Automobile Holdings Limited (2024), and NIO Inc. (2023).

4.7. Technical Practicability and Market Barriers to a Circular Economy

Despite companies' general commitment to promote battery recycling, actual progress is constrained by economics and market mechanisms. BYD, for example, has a closed-loop recycling system that can theoretically cover 90% of decommissioned batteries, but the actual recycling rate in 2022 will be only 45%. The fundamental reason is that the cost of lithium recycling is as high as $6,500 per ton, far exceeding the cost of mining ($4,000.) Zhang and Chen (2020) show that the economics of lithium recycling requires policy intervention, otherwise it is difficult to break through the cost bottleneck. European companies are partially offsetting recycling costs through carbon pricing mechanisms (~€90/ton), such as BMW is using carbon trading revenues to support its battery regeneration program with a 50% recycling rate by 2022. The Chinese market lacks a similar mechanism, with companies such as Geely relying on government subsidies to drive technology development, but the volatility of policy support has led to unstable commercial viability. the IPCC (2021) report emphasizes that carbon pricing is a core tool for promoting the circular economy, and European practice has validated its effectiveness.

4.8. Relevance of Material Efficiency to Corporate Sustainability Practices

Material efficiency is a key dimension for automotive manufacturers to achieve sustainability goals, covering raw material use optimization, recycling rate improvement and lightweight technology application (Bocken et al., 2014; McKinsey & Company, 2020). This study combines corporate annual reports and industry data to show the differences in material efficiency strategies of Chinese and European automakers and their impact on CSRD compliance (European Commission, 2021; Li et al., 2023).

As an example of a European automaker, Volvo Car Corporation noted in its 2023 Sustainability Report that 92% of waste from its operations is recycled and reused, demonstrating significant progress in resource recycling. In addition, Volvo has established a closed-loop aluminum recycling system with its partners to achieve non-degradation recycling of 6XXX series aluminum alloy materials, further promoting the sustainable use of materials (Volvo Group, 2023).

In contrast, Chinese automaker BYD disclosed in its 2022 CSR report that it has reduced cobalt use in its lithium iron phosphate batteries by 60% compared to 2018, demonstrating efforts to reduce the use of key materials. However, industry analysis points out that lithium recycling rates remain low, at around 45%, reflecting the tension between technical feasibility and economics (BYD, 2022; Benchmark Mineral Intelligence, 2023).

In terms of lightweight technological innovation, third-party analysis shows that Scania has optimized its body design with high-strength steel and carbon fiber composites, significantly reducing vehicle weight and carbon emissions (Scania AB, 2022). Chinese automaker Azalea, on the other hand, significantly reduced the body weight of its ET7 model by reducing the number of aluminum alloy parts through integrated die-casting technology, but the lack of specific quantitative data reflects the higher demand for transparency from European automakers under the CSRD framework (GRI, 2020; Adams, 2017).

Policy-driven differences in material efficiency are equally significant. The EU has promoted the adoption of low-carbon materials by requiring disclosure of material carbon footprints through CSRD's Full Life Cycle Assessment, while China's Industrial Energy Efficiency Improvement Action Plan focuses on emissions reductions at the production end, requiring automotive companies to reduce material consumption per unit of product by 10 percent by 2025 (European Commission, 2021; MIIT China, 2022). This difference has led European automakers to prioritize

investments in recycled material technologies, while Chinese companies are reducing unit consumption through process optimization (Wang & Zhang, 2022).
In the long term, automakers should promote a “reduce-recycle-substitute” strategy, drawing on BMW's circular design concept to increase the proportion of recyclable materials to 95 percent, while considering regional policy characteristics to develop differentiated paths (BMW Group, 2022). For example, Europe can rely on a carbon pricing mechanism (around 90€/tCO_2) to partially pass on the cost of recycling to the carbon market, while China needs to rely on government subsidies and local cooperative laboratories to lower the threshold for technology commercialization (Chinese Academy of Social Sciences, 2024; Geels, 2019).

4.9. The role of material efficiency in mitigating resource constraints and optimization paths

Under the reality of limited resources, medium-sized automobile manufacturers need to enhance the efficiency of material use and promote the realization of sustainable goals through innovative cooperation mechanisms and technology modularization strategies (Klewitz & Hansen, 2014; McKinsey & Company, 2020).

For example, Geely and the Zhejiang Provincial Government have established the “New Energy Vehicle Materials Innovation Center” to share the R&D costs of sodium-ion batteries through government-enterprise collaboration, reflecting a cooperative and innovative path in the field of key material substitution (Geely Holding Group, 2023; Geely Automobile Holdings Limited, 2024). This model not only reduces the pressure of a single enterprise in terms of finance and technology, but also provides a model for medium-sized enterprises to explore the synergistic innovation mechanism of “policy+industry” (Schaltegger & Burritt, 2018).

Through long-term strategic cooperation with Nordic battery manufacturer Northvolt, Scania has developed a battery cell designed specifically for heavy-duty transportation applications, which is capable of supporting vehicles for more than 1.5 million kilometers, significantly improving battery performance and service life. The project is based on a modular design concept and localized production in a newly built battery assembly plant in Sweden. While there is no publicly available data to quantify the reduction in the use of materials such as copper, the modular design itself has been widely recognized as contributing to improved assembly efficiency and material utilization (Scania AB, 2022; Porter & Heppelmann, 2014).

Policy support is also a key driver of material efficiency. According to China's Ministry of Finance Announcement No. 40 of 2021, recycled aluminum companies are entitled to an immediate 70% VAT refund. BYD disclosed in its 2022 CSR report that the policy has prompted an increase in its use of recycled aluminum from 15% in 2020 to 28% in 2022, demonstrating the direct effect of policy levers in driving resource recovery and material substitution (BYD, 2022; Ministry of Finance, China, 2021).

In terms of technology synergies, mid-sized companies can reduce deployment costs through modular tools and drive standardization in data collection and monitoring (Adams, 2017; Treiblmaier, 2018). For example, in its 2023 sustainability report, Volvo notes that its blockchain pilot project has covered 85% of its tier 1 suppliers, but has not yet included integration of tier 2 supplier data due to budgetary constraints. This phenomenon highlights the tension between resource constraints and compliance needs (Volvo Group, 2023; Saberi et al., 2019).

Therefore, future policy design should be more inclusive and targeted. For example, the EU could consider setting up a "Digitalization Fund for Medium-sized Enterprises" to support the development and deployment of low-cost data monitoring tools, while China could further optimize its "dual-carbon" subsidy policy by linking it to specific technical indicators to avoid inefficient use of funds or deviation from targets (European Commission, 2021; Chinese Academy of Social Sciences, 2024). Through the triple path of policy tools, industrial synergy and technology modularization, material efficiency is expected to become a key pivot point for medium-sized enterprises to break through the resource bottleneck and achieve green transformation (Geels, 2019; Bocken et al., 2014).

4.10. Policy Collaboration and Future Optimization Directions

The one-size-fits-all requirements of the current CSRD framework exacerbate the compliance burden on medium-sized enterprises. For example, the CSRD mandates disclosure of the full lifecycle carbon footprint, but medium-sized enterprises are only able to cover the production process due to technological constraints, resulting in incomplete reporting. Future policies need to be more inclusive: the EU could establish a tiered disclosure system, allowing MSEs to hold back some indicators, and establish a "Digital Fund for MSEs" to support the development of low-cost monitoring tools. This proposal echoes Geels' (2019) theory that policy design needs to be integrated with the regional technology ecology. China needs to link "dual-carbon" subsidies to specific technical parameters to avoid policy drift, and McKinsey & Company (2020) suggests quantifying policy effects through technical parameters, which provides direction in this regard. In addition, cross-regional experience is crucial - Europe can learn from China's government-enterprise cooperation model, and China can learn from Europe's data standardization practices, to jointly build a sustainable development framework that balances efficiency and fairness.

5. Discussion and Implications

5.1. Compliance challenges under resource constraints

The core findings of this study expose differentiated strategic paths that medium-sized European automotive manufacturing firms have taken in response to the Corporate Sustainability Reporting Directive (CSRD). These paths not only confirm the consensus in the established literature that 'resource constraints limit technology adoption' (Adams, 2017; Seuring & Müller, 2008), but also complement the gap in current theory that pays insufficient attention to the capability barriers of mid-sized companies.

In addition to the commonly observed financial constraints, the study further found that mid-sized companies also commonly face shortcomings in technological capabilities and knowledge base. For example, in key areas such as data monitoring, systems integration, and supply chain carbon accounting, many enterprises lack in-house specialized staff and the necessary technological base. ***This dual constraint of "resources + capacity" makes them react slowly and react conservatively when dealing with complex regulation.***

5.2. Case support: The practical value of collaborative pathways and modularization tools

The study further validates the above points through comparative analysis. Take Scania for example, the company shared the cost of building a blockchain platform with its logistics partner to realize the application of the technology under a limited budget, while BYD significantly increased the use of recycled aluminum by getting subsidies from the local government. These cases demonstrate the practical application of the "cost-transparency trade-off" theory (Eccles & Krzus, 2010) in resource-constrained contexts. They also show that it is easier for medium-sized enterprises to deploy and implement technology tools when they are modular and low-threshold.

Unlike the previous "smart connected product" strategy (Porter & Heppelmann, 2014), which focused on large enterprises, this study systematically proposes an "adaptive technology stack" framework for the first time based on a comparison between China and Europe, emphasizing the combination of open-source tools and policy support mechanisms. It emphasizes the combination of open-source tools and policy support mechanisms to provide a practical and compliant transformation path for medium-sized enterprises with resource and capacity constraints.

5.3. Institutional differences affect path choice

This study finds that the variability of regional regimes has a significant impact on the choice of sustainable strategic paths by enterprises. In Europe, enterprises can partially transfer compliance costs through carbon pricing mechanisms, such as using the proceeds obtained from carbon exchanges to feedback related technology investments, thus creating a stronger motivation effect under the market-based mechanism; whereas in China, the policy relies mainly on financial subsidies and local support to promote the research and development and implementation of new technologies, and the government plays a more dominant role in the allocation of resources. This difference in institutional logic directly affects enterprises' choices in terms of technology paths, funding arrangements and organizational collaboration.

5.4. Dynamic response mechanisms in medium-sized enterprises

Relying on the socio-technical transformation theory proposed by Geels (2019), this study further points out that the compliance behavior of medium-sized enterprises is not a simple response to policies, but rather the result of a dynamic adjustment between their resource, technological capabilities, and external institutions. This adjustment not only determines the enterprise's choice of technology path, but also influences the evolutionary direction of its management structure, cooperation model and data management approach.

At the level of management practices, medium-sized enterprises prefer to adopt modular, low-cost digital tools to gradually build their data transparency capabilities while lowering the deployment threshold. This “adaptive technology stack” path provides a theoretical supplement and practical demonstration for solving the key challenge of “low resources - high transparency requirements”.

5.5. Policy recommendations: Enterprise-specific approaches, strengthening institutional adaptability and collaborative mechanisms

This study finds that the CSRD's current implementation poses high compliance pressure on medium-sized enterprises, especially in the context of both resource and capacity constraints. On the one hand, the CSRD's “integrated disclosure” requirement fails to fully take into account the differences in technology deployment, data processing and personnel capacity of enterprises, resulting in some enterprises only being able to complete the disclosure of data at the production end, which makes it difficult to meet the requirements of a complete life cycle. On the other hand, although Chinese “dual-carbon target” has an incentive effect in terms of direction, there are still uncertainties in terms of subsidy setting and implementation norms. In this regard, policymakers should pay more attention to the match between institutional design and enterprises' real-world capabilities.

Specifically, more inclusive support mechanisms need to be introduced at the institutional level. For example, Europe could set up a digitization support fund for resource-constrained enterprises to help reduce the initial investment pressure on enterprises by financing the development and deployment of low-threshold monitoring tools. At the same time, the alignment between policy objectives and the technological capabilities of enterprises should be promoted, such as linking technology subsidies to the actual carbon emission reduction parameters achieved. In the two regions of China and Europe, the encouragement of supply chain data standard coordination and inter-regional experience sharing mechanism will also help promote cooperation and joint construction among enterprises, and achieve reasonable sharing of compliance costs and industrial synergy optimization.

From the perspective of policy adaptation, this study emphasizes the importance of constructing hierarchical, adjustable, and implementable regulatory tools from the capability boundaries of medium-sized enterprises. This not only enhances the effectiveness and fairness of policy implementation, but also provides institutional safeguards for the future green transformation of the group of medium-sized enterprises.

5.6. Theoretical contributions and future research directions

The “Adaptive Technology Stack” model proposed in this study theoretically responds to the lack of attention in the existing literature to the technology transformation mechanisms of resource-constrained enterprises. Unlike traditional studies that emphasize high-integration and high-cost paths, this study systematically explains how modular, low-threshold, and synergistic technology application models can support enterprises to achieve sustainable disclosure goals under resource constraints through comparative analyses of six automotive manufacturing enterprises in China and Europe. This model not only explains how enterprises can achieve CSRD or “dual-carbon” compliance under capacity constraints, but also provides operational theoretical support for the sustainable governance strategies of medium-sized enterprises.

Based on this foundation, future research can further explore the actual impacts of the “adaptive technology stack” pathway on compliance costs and performance of enterprises under different policy environments. For example, a dynamic assessment model can be constructed to systematically quantify the intensity of policy support, the maturity of technology deployment, and the final carbon performance results, so as to fill the empirical gaps in the existing studies. In addition, considering the dynamic differences between China and the EU in terms of institutional evolution, regulatory pace, and industrial policies, a longitudinal tracking approach can be used to analyze how enterprises gradually adjust their compliance paths and capability structures during the policy cycle, especially how they fill the internal capability gaps through organizational synergies and external support mechanisms.

It should be noted that although this study has made initial progress in terms of theoretical framework and cross-regional comparison, it is still subject to the objective limitations of data availability, frequency of policy adjustments, and completeness of enterprise information disclosure. With the full implementation of the CSRD and the continuous improvement of the "dual-carbon policy" system, subsequent studies are expected to deepen the understanding and theoretical extension of the sustainable transformation path of medium-sized manufacturing enterprises on the basis of more detailed empirical evidence.

6. Conclusions and Outlook

To enhance the overall clarity, the following section revisits the core research questions posed in Chapter 1 and summarizes the key findings for each.

6.1. Research Conclusions and Academic Contributions

This study focuses on the Corporate Sustainability Reporting Directive (CSRD), and systematically compares the compliance strategies of medium-sized automotive manufacturing enterprises in China and Europe in the context of resource constraints, revealing the contradiction between limited technical resources and increased transparency requirements. ***Regarding the first research question—how medium-sized automotive manufacturers in China and Europe approach CSRD compliance under resource constraints—this study finds the following that these enterprises generally face a "high demand-low capacity" situation in the process of CSRD implementation, but their response paths are significantly influenced by the regional policy environment and technological environment.***

In response to the second research question concerning the role of digital technologies and the influence of regional policy differences, the study presents these insights: in Europe, enterprises have realized high transparency from raw material traceability to production data monitoring by integrating digital technologies such as blockchain, Internet of Things (IoT), and Artificial Intelligence (AI), while Chinese enterprises rely more on policy collaboration to achieve breakthroughs in key areas such as battery recycling and material substitution. For example, BYD has promoted the use of recycled aluminum through government subsidies, while Geely has promoted the development of sodium-ion batteries through government joint laboratories.

In this context, the study proposes the "Adaptive Technology Stack" model, which emphasizes the use of modular, low-cost tools and collaboration mechanisms to provide resource-constrained enterprises with a workable path to compliance. The model extends the boundaries of socio-technical transition theory, emphasizing that the interaction between technology and policy should not be unidirectional, but rather dynamically adapted in the regional context.

At the academic level, the study fills a gap in sustainable transformation paths for medium-sized enterprises, while also pointing out that policies that are too vague or lacking in detail may weaken the willingness and efficiency of enterprises to implement them, challenging the traditional assumption that "the clearer the policy, the easier it is to implement".

6.2. Multidimensional Impacts of Practice, Industry, and Society

For the third research question—how key materials such as batteries, aluminum, and plastics shape sustainability strategies and vary between China and Europe—the findings reveal the following: the findings are of reference value to enterprise managers, policy makers and industry organizations. For medium-sized automotive enterprises, they should prioritize the adoption of low-threshold and compatible technology modules, such as utilizing open-source blockchain to track key raw materials, rather than pursuing full supply chain coverage from the start. Meanwhile, collaboration among enterprises can effectively share the cost of technology deployment.

At the policy level, Europe can support the development of simple and practical monitoring tools by setting up a digitization fund for medium-sized enterprises and allowing staged disclosure of some non-core indicators, while China needs to link subsidies to technical parameters achievable by enterprises, such as the battery recycling rate, in order to improve the targeting and implementation of policies.

Industry associations can promote the harmonization of cross-regional data standards, such as the establishment of a unified carbon accounting method or supply chain tier definitions, to lower the threshold of collaboration between enterprises.

Meanwhile, drawing on BMW's practice of supporting recycling projects with carbon trading proceeds, cross-border carbon market mechanisms can be explored in the future to realize cost sharing and compliance incentives.

From a social perspective, improved supply chain transparency will enhance consumer trust in sustainable products, and the government-enterprise cooperation model provides a replicable practice sample for low-carbon transformation of the manufacturing industry, which will help to promote the overall transition of society to a green economy.

6.3. Limitations and Room for Improvement

This study builds a research path based on the “three-stage data collection model” (enterprise report analysis-policy text matching-case comparison and validation) proposed in Chapter 2, aiming to maximize the systematic analysis and the accuracy of the cross-validation under limited data resources. However, despite the clear structure and feasibility of the methodology, there are still several limitations in the following aspects.

First, in terms of sample dimension, this study focuses on six representative medium-sized automobile manufacturing enterprises in China and Europe with publicly disclosed data, most of which are medium-sized and large enterprises. This choice helps to present the typical practices of enterprises in the context of CSRD, but it also limits to some extent the understanding of the particular challenges faced by small manufacturing enterprises or enterprises in emerging markets.

Second, although the study has enhanced the reliability of the data through dual cross-checking of reports and policies, some of the data may suffer from positive selection or strategic disclosure due to the primary reliance on enterprises' public ESG reports and third-party audit documents. The "case comparison verification" step in the three-stage model reduces this bias to a certain extent, but the lack of supplemental information from within the enterprise is still a major limitation of the current study.
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Finally, the dynamic nature of policy poses a challenge to the applicability of the study. For example, China's new round of battery recycling subsidy policy in 2023 and the EU's phased implementation plan for CSRD may affect enterprises' medium- and long-term strategic adjustments. Therefore, the applicability of the conclusions of this study needs to be continuously observed and revised in light of future policy advancement.

In the future, the study can be further deepened based on the three-stage model proposed in this study, especially by introducing field interviews or internal data collection from enterprises in the section of "Stage 3: Case Study Verification", so as to further enhance the validity and convincing power of the study. Meanwhile, the scope of the study can be expanded to markets with significant differences in policy environments, such as Southeast Asia and North America, in order to compare the response strategies of enterprises under different institutional backgrounds.

6.4. Future Research Directions

Based on the findings and analytical framework of this study, future research could be further expanded and deepened in the following three areas. First, it is necessary to establish a quantitative analysis model of the relationship between technology modules and compliance costs, and systematically measure the correlation between, for example, blockchain coverage, IoT deployment density, and enterprise budgets, so as to provide medium-sized enterprises with a more targeted basis for decision-making on digital transformation.

Second, future research could further focus on the issue of flexibility in policy implementation. Taking the European Union's CSRD as an example, it has adopted a phased approach to indicator disclosure, and following research could explore in depth how this approach can help medium-sized enterprises reduce initial pressure and gradually adapt to compliance requirements.

Third, the study should also focus on how to lower the technological threshold for medium-sized enterprises in the compliance process. Currently, a large number of digital tools such as carbon management platforms or tracking systems are costly and complicated to use, which are not conducive to their promotion by SMEs. In the future, we can encourage the development of simpler and easier-to-use, open-source or low-cost compliance tools, such as standardized carbon footprint calculation templates and monitoring plug-ins that can be integrated into the existing systems of enterprises, so as to help enterprises complete basic compliance tasks with fewer resources and gradually build up digital capacity

In addition, the construction of cross-regional synergistic mechanisms is also an important direction for future research. As global carbon disclosure tends to converge, it is necessary to explore how to build more effective connecting mechanisms between different institutional systems. For example, it is necessary to explore the complementary relationship between the EU carbon trading system and China's financial incentives, and to construct a cost-sharing mechanism based on carbon performance, so as to provide medium-sized enterprises with institutional support for cross-regional cooperation in emission reduction. This will not only help to reduce the pressure caused by the system mismatch between regions, but also provide more feasible low-carbon transformation paths for resource-constrained enterprises in the global industrial chain.

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Appendix A

Table 6. Functional Overview of the Semi-Automated Data Collection Tool

Module	Description
Keyword Filtering Module	Predefined keyword list includes (but is not limited to): 'CSRD', 'carbon footprint', 'Scope 3 emissions', 'recyclable materials', 'supply chain transparency', 'blockchain', 'AI optimization', 'IoT monitoring'. These terms are derived from CSRD texts, GRI indicators, and common ESG terminology.
Text Recognition Mechanism	The crawler extracts webpage body text and annotates structural layers such as headings and paragraphs to improve semantic recognition accuracy.
Semantic Matching and Template Detection	Identifies data-relevant sentences using co-occurrence frequency and logical structures. For example, 'recycling rate reached 50% in 2023' is extracted and categorized under 'Material Recycling'.
Categorization Framework	All data are organized into four categories: (1) Policy Compliance, (2) Technological Application, (3) Environmental Indicators, (4) Supply Chain Information. Subcategories include blockchain coverage rate, Tier 1/2 audit coverage, recycled material ratios, etc.
Standardization Process	Data are converted to standard units, date formats (YYYY-MM-DD), and labeled with metadata such as company name, region, and year before being imported into analysis tools.
Output Format	Final output is in structured CSV/Excel formats, compatible with NVivo, Excel, or Python for further analysis or visualization.
Manual Verification Points	Items with uncertain semantic matching are flagged with a '⚠' for manual review by researchers to avoid misinterpretation or technical errors.