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TOWARD A CLEANER ROAD: ENVIRONMENTAL TRANSFORMATION IN HUNGARY'S AUTOMOTIVE SECTOR

Abstract

A transition toward sustainable logistics is crucial for Hungary's automotive industry, which remains a main contributor to environmental degradation through its reliance on carbon-based supply chains. This study aims to examine how green technology, policy regulation, and infrastructure availability influence sustainability outcomes for the industry, with a focus on reducing carbon emissions and improving operational efficiency. Partial least squares structural equation modeling with 2015–2023 empirical data was employed. The model examined direct and moderate effects of such factors on lowering carbon footprint and sustainability performance, as well as on implementation cost, firm size, and demand.

The results suggest a significant impact on carbon footprint reduction (path coefficient = 0.32) and sustainability performance (0.38) through the adoption of green technology. Availability of regulatory frameworks (0.29 for reduction of carbon footprint; 0.25 for sustainability performance) and infrastructure (0.35 and 0.40, respectively) also have a significant impact. High implementation costs (–0.22 and –0.18) and the complexity of the supply chain (–0.15 and –0.17) have a negative impact, particularly for small and medium-sized enterprises. Moderation analysis shows that firm size (0.22) and strong demand (0.26) enhance the benefits of adopting green technology.

The indications are toward enhancing regulatory enforcement, raising financial aid schemes, and upgrading logistics infrastructure as a solution for Hungary's accelerating adoption of sustainable logistics practices. Public-private partnerships are put forward as a strategic solution for bridging infrastructure and investment gaps and enabling long-term economic and environmental advantages for the automotive logistics industry.

Keywords decarbonization, infrastructure, regulations, technology, sustainability, logistics, automotive, efficiency, environment, policy

JEL Classification Q56, L62, O33, R41

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INTRODUCTION

Hungary's economy benefits from the automotive industry, which powers not just the companies that build cars here but an entire range of businesses from paint to plastics that provide parts for those vehicles. The industry, by a number of metrics, is the most competitive in the country. However, EU climate policies, including the European Green Deal, mandate decarbonization and pollution reduction.

The logistics of the future will include electric vehicles (EVs). Moreover, they will encompass not just electricity but also renewable energy. EVs are obviously a good start, but it is also essential to look at AI-driven optimization of logistics. The Mercedes-Benz Research and Development North America branch in Long Beach, California, has looked at how to apply optimization to logistics and the supply chain and, together with the company's plants in Germany and the US, has developed functionality that assigns AI capabilities to its logistics operations.

This search looks at the prime facilitators and barriers to the adoption of sustainable logistics. It delves into how low-carbon technologies shrink carbon footprints, the part played by regulations and financial aspects, and the various impacts made by certain infrastructures, including EV charging networks and renewable power grids, on logistics performance and efficiency. It also peeks at what small and medium-sized enterprises (SMEs) are up against in terms of costs, supply chain conundrums, and the apparent and not-so-apparent influences of company size and market demand on sustainability results.

The challenge undertaken is crucial to pushing sustainable logistics forward. What is needed seems straightforward: ensuring incentives are strong enough, regulations are enforced, and the logistics infrastructure is in place. All these things add up to the reasons why the use of sustainable logistics is not more widespread.

1. LITERATURE REVIEW

The integration of green logistics within Hungarian automotive industries is the first big leap toward solving different environmental, economic, and infrastructural problems facing countries. Sustainable logistics practices empower transportation systems to optimize energy use effectively and reduce carbon footprints, hence adding to operational efficiency and higher environmental responsibility (Patel et al., 2022). With the adoption of technologies like electrical vehicles, in-wheel motors, renewable energy integrations, and AI-driven logistics management systems, Hungary is trying to align with ambitious sustainability targets put forward by the European Union (Hoyk et al., 2022; Türkcan & Majune, 2022). Chen et al. (2023) indicate that the primary barriers to adopting sustainable logistics in the automotive industry in Hungary include poor infrastructure, a lack of relevant government incentives, and prohibitive costs of implementation. This literature review covers enabling factors and barriers, combining knowledge from Oravcová and Šafaříková (2024) with other academic literature that identifies critical factors affecting the transition toward sustainable logistics practices.

Kandrács (2023) notices that government-driven regulatory efforts, such as the Hungarian National Energy and Climate Plan (NECP), have charted a course for decarbonizing logistics and adopting green technologies. According to Lindberg and Wettestad (2024), such policies are in line with broader EU ambitions under the European Green Deal, focusing on the reduction of carbon emissions, increased use of mobile renewable energy sources, and enhanced efficiency in logistics. In addition, the Hungarian regulatory frameworks lack specificity and mechanisms for enforcement that could make significant changes in automotive logistics (Ogunkunbi & Meszaros, 2023). Whereas EU policies broadly guide, Hungary's logistics sector lacks adequate incentives like subsidies for EV adoption and investments in renewable energy infrastructures compared to countries like Germany and the Netherlands (Sheldon & Dua, 2024; Szabó et al., 2024).

Infrastructure is a decisive factor that plays a fundamental role in the viable option of sustainability for logistics. In this regard, major challenges arise when discussing Hungary as there are really underdeveloped networks of electric vehicle charging stations and generally developed renewable energy-based infrastructure (Kurz et al., 2024). According to Zrelli and Rejeb (2024), in this respect, barriers appear, especially when speaking about the position of SMEs, because those subjects often cannot invest in green technologies due to insufficient financial resources. Ponnusamy and Eswararaj (2023) further emphasize that old logistics infrastructure, such as fleets based on fossil fuel and inefficient supply chain networks, further complicates the transition toward sustainability. Targeted government grants and financial support schemes could, therefore, help bridge these infrastructural gaps and enable the participation of SMEs in green initiatives (Melander & Wallström, 2023).

There is a dire need for the latest technological developments in AI, IoT, and automation to improve logistics efficiency and sustainability. Indeed, Shobhana (2024) and Yesodha et al. (2023) find that innovations such as route optimization using AI and automation of inventory

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management result in significant fuel consumption reduction, while IoT systems, like real-time tracking, improve the overall efficiency of logistic operations. However, significant barriers exist to the adoption of these technologies in Hungary. The significant barrier, according to Gajdzik et al. (2023), is the underdeveloped infrastructure for EV charging, whereas Kurz et al. (2024) add underdeveloped renewable energy networks as another critical obstacle to the widespread adoption of electric logistics fleets.

This is particularly difficult for SMEs, which have to bear a high cost initially while adopting new technologies. Zrelli and Rejeb (2024) note that a shortage of skilled workers who can manage advanced technologies like AI and IoT further delays the transition to sustainable logistics. Other factors that Khaleel et al. (2023) and Shahzad and Cheema (2024) elaborate on are issues of finance and infrastructure, whereby SMEs become highly vulnerable to not being able to get a hold of any economies of scale and also exploit any advances in technology on account of low costs of production or at cost-competitive advantages.

Public-private partnerships (PPPs) could seriously boost sustainable logistics within Hungary's automotive industry. Such collaborations, involving the government and private sector, can surmount infrastructural and financial barriers by pooling resources together to invest in renewable energy and electric vehicle infrastructure. Wang and Shi (2024) suggest that PPPs can reduce the financial burden on any single company by enabling shared EV charging networks and renewable energy grids. Ning et al. (2023) further highlight that stronger government support in these partnerships is required since collaboration between public and private agencies has been overly critical in scaling up sustainable logistics solutions.

As their implementation is progressive, different Hungarian companies in the automotive industries have established potential models for changing the wider use of sustainable logistical operations within the sector. The example here should be Audi's rooftop solar panel installation in big numbers (Éltető & Ricz, 2024), covering its logistical operations and renewable energy usages, giving value to the model as exemplary by ensuring sustainability practices concerning the sector are warranted. Similarly, Pató et al. (2023) and Wu (2024) indicate that Mercedes-Benz Manufacturing Hungary has already integrated electric vehicles into its logistics fleet and is using AI-driven logistics systems to reduce emissions and increase efficiency. Bennani (2023) and Szabo et al. (2023) present that Suzuki Hungary is also moving in the direction of fleet electrification and increasing renewable energy investments to make its logistics activities more sustainable.

These examples, on the other hand, demonstrate how long-term planning, investment in green technologies, and collaboration between the public and private sectors are important to achieving sustainability goals. As Deberdt (2024) postulates, although this may be the case for large corporations, similar models could be adapted to smaller firms by localizing supply chains or transitioning fleets partially to electric vehicles.

Key challenges faced in the transition toward green logistics within the automotive industry in Hungary are multifaceted. Khaleel et al. (2023) and Shahzad and Cheema (2024) stress the high costs associated with the adoption of green technologies, such as electric vehicles and renewable energy systems, as some of the major drawbacks, especially for SMEs. Moreover, Neagoe et al. (2024) and Niri et al. (2024) also mentioned how a lack of countrywide EV charging infrastructure and the incomprehensive national renewable energy supply further heighten the challenge toward logistics decarbonization.

Qadir et al. (2024) realize this by asking for increased financial intervention by governments in terms of subsidies that would support the development of both electric vehicle fleets and renewable energy infrastructure. Melander and Wallström (2023) underline the need for increased collaboration between industries, especially in joint ventures, by car manufacturers and logistics companies, to establish mutual infrastructures, such as a network of EV charging points. Additionally, Krishnan et al. (2024) point out that further development in innovation within logistics technologies, especially AI-based optimization tools, will be crucial with regard to a low-emission, efficient supply chain.

Although much research has recently been carried out on the issues of sustainable logistics within the automotive industry, several gaps remain open, and some particularly refer to the Hungarian context. The filling of such gaps is an essential step toward providing a framework that will balance the practice of sustainable logistics with climate goals for Hungary while ensuring scalability and inclusivity across diverse firms and supply chain structures.

In an effort to explore the major causes of, and enablers for, Hungary's automotive sector's slow take-up of green logistics, this study aim to examine infrastructural preparedness, policy support, financial resources, and technological competencies with a view to recommending interventionist strategies for the expedient development of green logistics in support of European Union targets of sustainability.

Therefore, the study elaborated on the following hypotheses:

H1: Green technology adoption, supported by regulations and infrastructure, reduces carbon footprints in Hungary's automotive logistics.

H2: Implementation cost, company size, and market demand moderate the impact of green technologies on sustainability outcomes.

H3: Supply chain complexity and industry type affect the relationship between sustainability measures and carbon reduction.

H4: Public-private partnerships address financial and infrastructural barriers to sustainable logistics adoption.

H5: Lessons from corporate sustainability case studies can guide SME adoption of green logistics.

2. METHOD

This study has used a quantitative approach by applying partial least squares structural equation modeling (PLS-SEM) with Smart PLS 4 to explore the relationships between green technology adoption, regulatory frameworks, and infrastructure availability regarding sustainability outcomes within the automotive logistics sector in Hungary. The PLS-SEM method is best suited for this study because it can handle complex models involving latent constructs and is flexible in handling non-normal data distributions. This methodological choice allows the analysis of direct and moderating effects while also controlling for variables.

PLS-SEM was preferred instead of covariance-based SEM, for example, AMOS, for a number of reasons. It is highly appropriate for exploratory research and imposes fewer restrictions on sample size and normality of data, thus fitting the objective of this study, which is to analyze the combined impacts of such variables as green technology adoption and regulatory frameworks. The research design involves multiple independent variables, moderators such as cost of implementation and company size, and control variables such as industry type and supply chain complexity, which makes PLS-SEM an optimal choice given its capability to handle complex models. Thirdly, because this paper is about predicting sustainability based on diverse influences, PLS-SEM offers great predictive capabilities. It allows for assessing relationships in formative and reflective measurement models (Cheah et al., 2023).

Measurement validation tests the reliability and validity of the constructs. Internal consistency is ensured by Cronbach's alpha and composite reliability (CR), while convergent validity is checked by average variance extracted (AVE), which ensures that the indicators capture the essence of their respective constructs. Discriminant validity is checked by the Fornell–Larcker criterion, which states that a construct is unique and different from another (Guenther et al., 2023). Path coefficients are used for hypothesis testing, and the significances of paths are tested by bootstrapping with 5,000 resamples. This would thus explain whether green technology adoption, regulatory frameworks, and availability of infrastructure are of the essence in carbon footprint reduction and sustainability performance. In addition, this study will also seek to describe precisely how a number of moderator variables – a function of the interaction terms of cost of implementation, company size, and mar-

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ket demand for sustainability – affect the strength of the relationship between the adoption of green technology and resultant sustainability outcomes. Control variables such as industry type and supply chain complexity are added to a model to take these considerations into account in evaluating primary relationships (Vaithilingam et al., 2024).

The model performance is measured by a few important metrics. R^2 (coefficient of determination) shows the amount of variance in dependent variables (carbon footprint reduction and sustainability performance) that can be explained by independent variables. A higher value of R^2 is indicative of a better explanation of outcomes by the model. The Stone-Geisser criterion of predictive relevance (Q^2) is checked to ensure the model exhibits good out-of-sample predictive power for the endogenous variables (Kamranfar et al., 2023).

f^2 is the effect size that provides an idea about the contribution of every independent variable to R^2 of dependent variables with respect to each predictor's practical significance. Lastly, the multicollinearity issues are examined through the variance inflation factor (VIF) in cases where testing for interaction effects on moderation may cause problems (Singh et al., 2023).

This study availed itself of authenticated and publicly available data to carry out an analysis of the trends in the adoption of green technologies, regulatory frameworks, infrastructure availability, and sustainability outcomes in automotive logistics in Hungary. The dataset covers a period from 2015 to 2023, a timeframe selected to represent the critical development in sustainability policies and green technology adoption in tandem with global and EU climate initiatives. These are drawn from sustainability reports of key automakers such as Audi, Mercedes-Benz, and Suzuki regarding the reduction in carbon footprint and/or the adoption of green technology. Such reports give details on emissions, integrations of electric vehicles, and the use of renewable energy in logistics. Their sustainability performance is sourced from the Carbon Disclosure Project database, which provides standardized metrics on environmental initiatives, including emissions reductions and green logistics practices (Cormier et al., 2024).

The regulatory framework is assessed through the National Energy and Climate Plan (NECP) of Hungary, which defines national objectives for the reduction of emissions and the enhancement of renewable energy use in logistics. Infrastructure availability data, especially on EV charging stations, are obtained from energy providers like E.ON and MOL, which publish detailed reports on the expansion and development of charging networks.

Euromonitor International market research reports are helpful in finding the demand of the market concerning sustainability practices in the automotive sector. This report traces the consumer trends in environmentally friendly vehicle and logistics solutions. The financial implications of green technologies adoption for electric vehicle fleets and renewable energy systems in logistics are sourced from PricewaterhouseCoopers and Deloitte reports, among others. Financial reports from automakers yield company size, revenue, and logistics budgets to show how such factors affect sustainability. The complexity of supply chains is gauged from reports by the Hungarian Automotive Association and corporate disclosures, which describe logistics network configurations and supplier relationships (Szalavetz & Sass, 2023).

The period chosen, 2015–2024, includes the most significant sustainability developments, namely the Paris Climate Agreement in 2015, the European Green Deal in 2019, and Hungary's updates of the NECP. This captures the aftereffects of the above policies and initiatives in the Hungarian automotive logistics sector.

The dependent variables in this study are carbon footprint reduction and sustainability performance in logistics. Carbon footprint reduction is an outcome of the mitigation of greenhouse gas emissions, explicitly CO_2, from the use of logistics sustainability practices. It is measured by two key indicators, namely CO_2 emissions per ton-kilometer and the total percent reduction in CO_2 emissions achieved by the adoption of green logistics initiatives (Osorio-Reyes et al., 2023). Sustainability performance shows the extent to which the introduction of sustainable practices is realized in logistics operations. This refers to performance through indicators such as the percent-

age of electric vehicles integrated within the logistics fleets or the percentage of renewable energy usage in the warehousing and transportation operations. These can thus reflect the ways in which the logistics system is aligning itself with environmental sustainability.

Current data identified three underlying independent variables that drive the aspects of sustainability performance. These are the adoption of green technologies, regulatory framework, and availability of infrastructure. The adoption of green technologies means that the adoption of eco-friendly solutions concerning electrical or hybrid motor transport, renewable systems, or AI-enabled complex routing plans takes center stage in logistics. This variable refers to the adoption of green technology expressed through the percentage use of electric and hybrid vehicles that are engaged within the operations concerning logistics and renewal level applied across its warehouses and/or transport systems (Arévalo et al., 2024).

The regulatory framework discusses the role that government policies and financial incentives can play in encouraging environmentally friendly logistics. This variable was considered in relation to the number of supportive policies and financial mechanisms, such as subsidies, available to encourage green technology adoption (Morshed, 2024a).

Finally, infrastructure availability means the facilities and systems available to support sustainable logistics operations. It includes factors such as the availability of electric vehicle charging stations along logistics routes and geographic coverage of renewable energy grids. Such elements guarantee smooth and efficient implementation of logistics sustainability.

Cost of implementation, company size, and market demand for sustainability are moderating variables. Here, the cost of implementation stands for the amount invested financially into adopting green technologies in logistics. This variable is measured by examining the total cost associated with transitioning to electric vehicles and renewable energy sources, as well as the investment in AI or IoT-based logistics optimization systems. Company size reflects the scale of a firm's operations, which can influence its ability to adopt sustainable logistics practices. This is measured using two indicators: total revenue and the budget allocated specifically for logistics operations. Market demand for sustainability refers to the pressure from consumers for companies to adopt eco-friendly logistics practices. This is measured by assessing consumer preference scores for sustainable logistics solutions and the percentage of customers specifically demanding eco-friendly products or services (Shoaib et al., 2023).

The control variables include industry type and supply chain complexity. Industry type accounts for variations in logistics practices based on the specific sub-sector within the automotive industry. This is measured by identifying the type of logistics operation (e.g., manufacturing vs. retail distribution) and the industry classification based on the intensity of logistics activities (Sun & Xu, 2023). Complexity in supply chains has to do with how intricate a company's logistics network is, which in turn affects the number of suppliers it has and the geographic scope of its operations. Not surprisingly, this variable is crucial and anchoring as it does the supply chain itself – for the development of future digital twins (Ramadan et al., 2024).

Table 1 summarizes the main sustainability variables in logistics. It includes the reduction of carbon footprint and the adoption of green technology. A logistics company could have a good plan on how to invest in renewables and switch the fleet to electrification. But if society do not provide the right incentives, it will be extremely hard to go down that path. It also includes infrastructure development. If a logistics company does not have the infrastructure to fuel vehicles (be they EVs or hydrogen), this attempt will fail.

This PLS-SEM model appraises the direct and moderating relationships among green technology adoption, regulatory framework, and infrastructure availability. It also estimates their effect on carbon footprint reduction and sustainability performance. The degree of effect is controlled for the cost of implementation, company size, and market demand. Some variables are controlled (e.g., industry type), while others run wild on the unfettered supply chain.

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Table 1. Statistical descriptive analysis

Variable	Measurement	Mean	S. D	Min	Max
Carbon Footprint Reduction	CO_2 emissions per ton-kilometer	14.2	4.0	8.0	22.0
	% reduction in overall CO_2 emissions	16.8%	3.0%	10.0%	25.0%
Sustainability Performance	% of EVs in logistics fleet	65%	15%	35%	80%
	% renewable energy usage in logistics operations	72%	12%	50%	90%
Adoption of Green Technologies	% of electric or hybrid vehicles in logistics	55%	18%	30%	85%
	Extent of renewable energy use in logistics	65%	14%	40%	85%
Regulatory Framework	Number of policies supporting sustainable logistics	6.8	2.0	3.0	10.0
	Financial incentives for green logistics (in million €)	12.0 M€	3.5 M€	6.0 M€	18.0 M€
Infrastructure Availability	Number of EV charging stations	170	45	90	250
	Geographic coverage of renewable energy grids	78%	18%	50%	100%
Cost of Implementation	Total cost of transitioning to EVs (in M €)	14.5 M€	4.5 M€	8.0 M€	22.0 M€
	Investment in AI/IoT-based logistics systems (in million €)	9.8 M€	2.8 M€	5.5 M€	15.0 M€
Company Size	Total revenue (in billion €)	7.0 B€	2.2 B€	4.0 B€	10.0 B€
	Budget allocated to logistics (in million €)	15.0 M€	5.0 M€	8.0 M€	22.0 M€
Market Demand for Sustainability	Consumer preference score for sustainable logistics	70%	15%	40%	90%
	% of customers demanding eco-friendly logistics solutions	65%	13%	40%	85%
Industry Type	Type of logistics operation (manufacturing vs retail)	4.2	1.6	2.0	6.0
	Intensity of logistics activities	4.0	1.5	2.0	7.0
Supply Chain Complexity	Number of suppliers in the supply chain	9.0	2.2	6.0	12.0
	Geographic scope of logistics network	8.5	2.0	5.0	12.0

Direct effect are measured using the following equations.

Carbon footprint reduction equation:

$$CFR = \beta 1 \cdot GT + \beta 2 \cdot RF + \beta 3 \cdot INF + \beta 10 \cdot IT + \beta 11 \cdot SCC + \varepsilon 1. \quad (1)$$

Sustainability performance equation:

$$SP = \beta 4 \cdot GT + \beta 5 \cdot RF + \beta 6 \cdot INF + \beta 12 \cdot IT + \beta 13 \cdot SCC + \varepsilon 2, \quad (2)$$

where GT (Green Technology Adoption): EV adoption, renewable energy integration, AI-driven optimization. RF (Regulatory Framework): Policies, subsidies, incentives supporting sustainable logistics. INF (Infrastructure Availability): EV charging stations, renewable energy grids. IT (Industry Type): Logistics intensity (manufacturing vs retail). SCC (Supply Chain Complexity): Number of suppliers, geographic logistics network scope.

Moderating effects are measured using the following equations.

Equation where cost of implementation moderates the relationship between green technology adoption and carbon footprint reduction:

$$CFR = \beta 1 \cdot GT + \beta 2 \cdot RF + \beta 3 \cdot INF + \beta 7 \cdot (GT \cdot CI) + \varepsilon 3. \quad (3)$$

Equation where company size moderates the relationship between green technology adoption and sustainability performance:

$$SP = \beta 4 \cdot GT + \beta 5 \cdot RF + \beta 6 \cdot INF + \beta 8 \cdot (GT \cdot CS) + \varepsilon 4. \quad (4)$$

Equation where market demand moderates the relationship between green technology adoption and sustainability performance:

$$SP = \beta 4 \cdot GT + \beta 5 \cdot RF + \beta 6 \cdot INF + \beta 9 \cdot (GT \cdot MD) + \varepsilon 5, \quad (5)$$

where CI (Cost of Implementation): Total financial investment in EVs, AI/IoT systems. CS (Company Size): Total revenue, logistics budget. MD (Market Demand): Customer preference for sustainable logistics solutions.

3. RESULTS AND DISCUSSION

The results demonstrate the strong reliability and validity of the constructs used to analyze sustainability outcomes in Hungary's automotive logistics sector. The findings highlight that adopting green technologies, regulatory frameworks, and infrastructure availability positively impact both carbon footprint reduction and sustainability performance. However, higher costs of implementation can hinder these positive effects. Moderation

analyses show that larger companies and strong market demand enhance the benefits of green technologies, while complexities in the supply chain pose challenges. Overall, the model effectively explains the key drivers of sustainability in this sector.

Table 2. Cronbach's alpha and composite reliability

Construct	Cronbach's Alpha	Composite Reliability
Carbon Footprint Reduction	0.81	0.85
Sustainability Performance	0.78	0.82
Adoption of Green Technologies	0.80	0.84
Regulatory Framework	0.75	0.79
Infrastructure Availability	0.83	0.86
Cost of Implementation	0.77	0.81
Company Size	0.82	0.87
Market Demand for Sustainability	0.79	0.83
Industry Type	0.74	0.78
Supply Chain Complexity	0.76	0.80

Table 2 shows that all constructs in the study exhibit strong internal consistency and reliability. Cronbach's alpha values range from 0.74 to 0.83, indicating acceptable to good consistency among the items within each construct. Composite reliability values, ranging from 0.78 to 0.87, confirm strong reliability across constructs. Constructs like infrastructure availability and company size show particularly high reliability, reflecting well-structured and cohesive measurement models. Overall, the results indicate that the constructs are reliable and suitable for further analysis (Morshed, 2024b).

Table 3. Average variance extracted (AVE)

Construct	AVE
Carbon Footprint Reduction	0.62
Sustainability Performance	0.58
Adoption of Green Technologies	0.60
Regulatory Framework	0.52
Infrastructure Availability	0.66
Cost of Implementation	0.55
Company Size	0.68
Market Demand for Sustainability	0.59
Industry Type	0.54
Supply Chain Complexity	0.57

Table 3 values of AVE were between 0.52 and 0.68, all positive and above the threshold level of 0.50, hence indicating good convergent validity. This indicates that each construct explains a suitable portion of the variation in its items. Construct validity is good for items that are high in value, such as 0.66 for infrastructure availability and 0.68 for company size. Overall, these results confirm the proper definition of the constructs (Cheung et al., 2024).

Table 4 gives validity to the Fornell–Larcker criterion test as evidence that all constructs in this model meet the requirements for discriminant validities. Its AVE square root for each construct is bigger than its relation to other constructs. Each construct also shares more variances with its own items as opposed to any other constructs; thus, by induction, that means that a construct is distinguishable from any other, and it can also be well-defined in the model (Dirgiatmo, 2023).

Table 5 informs about the relationships among the key variables of interest in this study since it explains how green technology adoption, regulatory frameworks, and infrastructural availability contribute to sustainability outcomes in Hungary's automotive logistics industry. Specifically, strong positive coefficients are noted between green technology adoption and both carbon footprint reduction at 0.32 and sustainability performance at 0.38, underlining the pivotal role of technology as the driver of environmental improvement. Accordingly, the infrastructure availability demonstrates a robust positive impact of 0.35 on both

Table 4. Fornell–Larcker criterion

Construct	Carbon Footprint Reduction	Sustainability Performance	Adoption of Green Technologies	Regulatory Framework	Infrastructure Availability
Carbon Footprint Reduction	0.79	0.45	0.30	0.35	0.40
Sustainability Performance	0.45	0.76	0.55	0.42	0.47
Adoption of Green Technologies	0.30	0.55	0.77	0.44	0.50
Regulatory Framework	0.35	0.42	0.44	0.72	0.53
Infrastructure Availability	0.40	0.47	0.50	0.53	0.81

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Table 5. Path coefficients

Path	Path Coefficient	*t*-value	*p*-value	Significance
Adoption of Green Technologies → CFR	0.32	2.7	0.008	Significant ($p < 0.05$)
Adoption of Green Technologies → SP	0.38	3.0	0.004	Highly Significant ($p < 0.01$)
Regulatory Framework → CFR	0.29	2.4	0.015	Significant ($p < 0.05$)
Regulatory Framework → SP	0.25	2.2	0.030	Significant ($p < 0.05$)
Infrastructure Availability → CFR	0.35	2.8	0.007	Significant ($p < 0.01$)
Infrastructure Availability → SP	0.40	3.2	0.002	Highly Significant ($p < 0.01$)
Cost of Implementation → CFR	–0.22	2.1	0.040	Significant ($p < 0.05$)
Cost of Implementation → SP	–0.18	2.0	0.048	Marginally Significant ($p \approx 0.05$)
Company Size → SP	0.20	2.4	0.018	Significant ($p < 0.05$)
Market Demand → SP	0.28	2.7	0.007	Significant ($p < 0.01$)
Industry Type → CFR	0.15	2.1	0.035	Significant ($p < 0.05$)
Industry Type → SP	0.12	2.0	0.045	Marginally Significant ($p \approx 0.05$)
Supply Chain Complexity → CFR	–0.15	2.3	0.022	Significant ($p < 0.05$)
Supply Chain Complexity → SP	–0.17	2.4	0.021	Significant ($p < 0.05$)
Moderation: GT x CI → CFR	–0.18	2.2	0.030	Significant ($p < 0.05$)
Moderation: GT x CS → SP	0.22	2.7	0.007	Significant ($p < 0.01$)
Moderation: GT x MD → SP	0.26	2.9	0.004	Highly Significant ($p < 0.01$)

Note: GT = green technology adoption; CFR = carbon footprint reduction; SP = sustainability performance; CI = cost of implementation; CS = company size.

carbon footprint reduction and 0.40 on sustainability performance reinforcing the idea of how vital infrastructure, like a network of EV charging stations, will make the business viable and sustainable.

The regulatory framework also positively impacts carbon footprint reduction (0.29) and sustainability performance (0.25), indicating that policies and incentives are crucial for promoting sustainable logistics. However, the negative coefficients for the cost of implementation on both carbon footprint reduction (–0.22) and sustainability performance (–0.18) suggest that higher costs can hinder the adoption of green practices, particularly for smaller firms. The significant moderation effects of company size and market demand indicate that larger firms and strong consumer demand enhance the positive impact of green technologies on sustainability.

Control variables like industry type and supply chain complexity have smaller but significant impacts, suggesting that sector-specific factors and the complexity of logistics networks can influence sustainability outcomes.

The evaluation of moderation in Table 6 makes clear that the cost of implementation weakens the seemingly straightforward relationship between green technology adoption and carbon footprint reduction.

In the pool of control variables, the type of industry has a positive effect on outcomes. This means that some industries are better at achieving certain sustainability types than others. On the other hand, supply chain complexity makes sustainability much harder to achieve, and this effect is magnified in parallel with the complexity of the logistics network in a given supply chain (Xiu et al., 2024).

Table 6. Moderation and control analysis

Path	Path Coefficient	*t*-value	*p*-value
GT x CI → CFR	–0.18	2.1	0.036
GT x CS → SP	0.20	2.5	0.014
GT x MD → SP	0.24	2.8	0.005
Industry Type → CFR	0.12	2.0	0.048
Industry Type → SP	0.11	2.1	0.038
Supply Chain Complexity → CFR	–0.14	2.3	0.021
Supply Chain Complexity → SP	–0.15	2.4	0.018

Note: GT = green technology adoption; CFR = carbon footprint reduction; SP = sustainability performance; CI = cost of implementation; CS = company size; MD = market demand.

Table 7. R^2, Q^2, f^2, and VIF tests

Metric	Value
R^2 (CFR)	0.55
R^2 (SP)	0.63
Q^2 (CFR)	0.34
Q^2 (SP)	0.41
Adoption of Green Technologies → CFR (f^2)	0.21
Regulatory Framework → CFR (f^2)	0.13
Infrastructure Availability → CFR (f^2)	0.19
Adoption of Green Technologies → SP (f^2)	0.26
Regulatory Framework → SP (f^2)	0.11
Infrastructure Availability → SP (f^2)	0.31
Cost of Implementation → CFR (f^2)	0.09
Cost of Implementation → SP (f^2)	0.08
Adoption of Green Technologies (VIF)	2.6
Regulatory Framework (VIF)	2.2
Infrastructure Availability (VIF)	2.4
Cost of Implementation (VIF)	2.0
Company Size (VIF)	2.3
Market Demand (VIF)	2.1
Industry Type (VIF)	1.8
Supply Chain Complexity (VIF)	2.5

Note: CFR = carbon footprint reduction; SP = sustainability performance.

The model's power of explanation and prediction is demonstrated in Table 7 with R^2 values of 0.55 for carbon footprint reduction and 0.63 for sustainability performance. Thus, the variance explained in these two sums by the independent variables is far from marginal. Moreover, to say that the model has predictive power is to say something quite different than if one were to describe it as having explanatory power. The former is a stronger claim that the model is not just a good fit for the data it was built on but is also useful for interpreting future data.

Among the key drivers, green technology adoption and infrastructure availability have the strongest effects on both outcomes, while regulatory framework has a moderate impact. Cost of implementation exerts a smaller negative effect. Additionally, all VIF values remain below 5, confirming no multicollinearity issues and ensuring reliable variable contributions to the model's predictions (Khedraoui et al., 2024).

This study focused on finding drivers for sustainable logistics for Hungary's automotive sector with a view on how adoption of green technology, regulatory frameworks, and availability of infrastructure drive reduction of carbon footprint and sustainability performance. The evidence supports those all three drivers – most importantly, green technology and infrastructure – contribute positively and strongly. However, these drivers' advantages are not realized across the industry, primarily due to high implementation costs and a lack of sufficient instruments for small and medium-sized enterprises (SMEs).

The findings are also as per Chen et al. (2023) and Shahzad and Cheema (2024), where cost has also been identified as a main obstacle to the logistics adoption of green technology. The role played by infrastructure and regulation is also as per Lindberg and Wettestad (2024), where integrated public policy and strong institutions are crucial for achieving environmental goals. Hungary, as compared with economies such as Germany and the Netherlands, is still behind with severe lags in building the necessary infrastructure and enforcing environmental policy, a finding also ascertained by Kurz et al. (2024) and Zrelli and Rejeb (2024) for transition economies.

Green technology as a driver is strengthened at large companies, with a foundation provided by firm size and demand for the market. Companies as large as Audi, Mercedes-Benz, and Suzuki have already demonstrated how organizations with a lot of resources can transition into sustainable logistics through investment in electric fleets and AI-driven logistics optimization. SMEs, on the other hand, are behind due to financial constraints, high initial investment, and talent shortages. These discrepancies explain the asymmetric development of the industry toward sustainable practices.

While the regulatory system – evinced through the National Energy and Climate Plan (NECP) – provides a blueprint for decarbonization, it is lacking in implementation. It is weak on enforcement, and financial incentives are not focused. Suggestions here must be purely formalistic in scope. That includes making legal obligations clear, strengthening policy coherence, and having measures for ensuring that the NECP and related regulations are not aspirational but actionable and measurable.

In the coming years, Hungary will have three priority areas for increasing automotive logistics sustainability:

- strengthen regulatory supervision and codify sector-specific incentives, especially for SMEs;

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- increase financial support, such as grants, subsidies, and green financial instruments, to make sustainable technology adoption affordable;

- invest in employee development, particularly in AI, IoT, and green logistics management, to fill the capability gap.

Long-term impacts should be targeted through future policy research, with disaggregation of results according to firm size and value chain complexity. SMEs and their specific issues should receive special consideration, with a view to ensuring inclusiveness in the transition. Greater cooperation with EU partners can help transfer knowledge, speed up infrastructure development, and bring with it successful market-based measures such as carbon pricing, as well as performance-based subsidies. These efforts will fill policy and practice implementation gaps, ensuring Hungary's logistics sector sustainability goals are not just on paper – but truly feasible.

CONCLUSION

The purpose of this study was to analyze the impact of green technology adoption, regulatory frameworks, and infrastructure availability on sustainability outcomes in Hungary's automotive logistics sector. Using a quantitative approach with partial least squares structural equation modeling (PLS-SEM), the study evaluated the relationships between these factors and key performance indicators such as carbon footprint reduction and sustainability performance.

The results indicated that the diffusion of green technology, supportive regulatory policies, and strong infrastructure contribute positively to carbon emission reduction and operational efficiency in logistics. Financial barriers, prohibitive implementation costs, and gaps in infrastructure remain major challenges, especially for small and medium-sized enterprises. Company size and strong market demand strengthen the positive impact of sustainability measures, whereas the complexity of the supply chain decreases the efficiency of such measures.

Hungary needs targeted financial incentives, improved infrastructure, and stronger regulatory enforcement to obtain sustainable logistics in the automotive industry. Public-private partnerships can help bridge the existing infrastructure gaps. Training the workforce in preparatory logistics, with an emphasis on advanced technologies, will help realize the sustainable vision. These measures help eliminate the existing barriers. They will accelerate the wider adoption of environmentally friendly logistics practices and support the long-term environmental and economic sustainability of this sector.

AUTHOR CONTRIBUTIONS

Conceptualization: Maha Alsheikh.
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