OPEN ACCESS
Scientific journal of the
European Ecocycles Society

ECOCYCLES
ISSN 2416-2140

Ecocycles, Vol. 12, No. 1, pp. 14-25 (2026)
DOI: 10.19040/ecocycles.v12i1.633

RESEARCH ARTICLE

Assessment of Selected Slovak Car Manufacturers Using Environmental Performance Indicators

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Abstract – The Slovak automotive sector is a major contributor to the national economy and hosts several Original Equipment Manufacturers (OEMs) with diverse production profiles. Increasing environmental and sustainability commitments have reshaped production strategies and accelerated the adoption of cleaner technologies. Environmental Performance Indicators (EPIs) provide a quantitative basis for assessing plant-level environmental efficiency and benchmarking against Best Available Techniques (BAT) defined in the BAT Reference Document for Surface Treatment using Solvents (BAT STS BREF).

This study presents a quantitative, observational comparison of plant- and paint-shop-level EPIs for three OEMs operating in Slovakia in 2024. The analysis covers energy consumption, carbon dioxide equivalent (CO_2e) emissions, volatile organic compound (VOC) emissions, water consumption, wastewater generation, and waste generation, normalised per complete vehicle and, where relevant, per painted vehicle body and per square metre of coated surface. Substantial inter-factory variability was observed, with paint-shop operations identified as the primary driver of performance differences. OEM 2 demonstrated the strongest overall environmental performance, recording the lowest CO_2e emissions (0.08 t $CO_2e \cdot veh^{-1}$), lowest VOC emissions (8.66 g $VOC \cdot m^{-2}$), and relatively low water use and wastewater generation, while meeting most BAT benchmarks for energy (0.46 $MWh \cdot veh^{-1}$), water per coated body, and VOC emissions. However, OEM 2 also generated the highest plant-level waste (186 $kg \cdot veh^{-1}$). In contrast, OEM 3 exhibited the weakest performance, with the highest energy consumption (1.35 $MWh \cdot veh^{-1}$), plant-level water use (3.10 $m^3 \cdot veh^{-1}$), and wastewater discharges (plant-level: 2.81 $m^3 \cdot veh^{-1}$; paint shop: 1.55 $m^3 \cdot veh^{-1}$), and failed to meet BAT benchmarks for paint-shop waste generation (26.05 $kg \cdot veh^{-1}$) and water use (1.9 $m^3 \cdot veh^{-1}$). Although energy use per painted body and VOC emissions remained within BAT-associated levels, none of the OEMs complied with indicative BAT benchmarks for waste generation. This study provides the first cross-OEM, plant-level EPI benchmarking of the Slovak automotive sector and highlights the need for harmonised, industry-wide EPI reporting to support transparency and continuous improvement.

Keywords – Automotive industry, BAT STS BREF, Benchmarking, Environmental Performance Indicator (EPI), OEM, Slovakia

Received: November 25, 2025 Accepted: January 31, 2026

1. INTRODUCTION

Automotive Original Equipment Manufacturers (OEMs) face increasing pressure from a wide range of stakeholders, including consumers, investors, regulators, and civil society organisations, to enhance their sustainability performance (Elmer, 2024; Benedek, 2023; Bäckstrand, 2022; Karner, 2021). Meeting these expectations has become a strategic imperative rather than an option. Beyond regulatory compliance, the integration of sustainable practices such as ISO 14001-certified Environmental Management Systems (EMS), the Eco-Management and Audit Scheme (EMAS), and responsible material sourcing can strengthen operational performance and generate cost savings (Martín-Peña et al., 2014; Mondal and Goswami, 2024). Environmental Performance Indicators (EPIs) play a central role in this process by providing quantifiable metrics for assessing efficiency in resource use, energy consumption, emissions, and waste management (Azzone et al., 1996; DEFRA, 2006; Jamous and Müller, 2013; Epstein and Buhovac, 2014; EUKI, 2020; Sherif et al., 2022; Block et al., 2024; Lešková, 2025). They serve as essential tools for evaluating, monitoring, and managing the environmental impact of vehicle production. Numerous environmental reporting frameworks are applied globally, many of which incorporate EPIs. Table 1 presents an overview of these frameworks and their relevance to the automotive industry.

The automotive industry has a long-standing presence in Slovakia and has evolve into the country's most important industrial sector. (Martišková, 2022). Over the past three decades, it has attracted significant FDI (foreign direct investment) and become a key locus of manufacturing innovation in Central Europe. The sector employs around 170,000 people directly across four OEMs operating in Slovakia (Volkswagen, Stellantis, Kia, and Jaguar Land Rover) and their first-tier suppliers, with a total of about 250,000 people employed directly and indirectly in the sector. It generates 46.5% of total industrial production revenues and contributes 10.4% to national GDP (SARIO, 2025). In 2024, Slovakia produced 993,000 cars, ranking first worldwide in per capita output with 182 vehicles per 1,000 inhabitants (Liptáková, 2025). This dense concentration of automotive OEMs places Slovakia among Europe's most significant production hubs and provides a distinctive setting for analysing environmental performance at the plant level. Yet, despite its global relevance, academic research offering cross-OEM, plant-level comparisons of EPIs within Slovakia remains limited, with most data appearing in OEM sustainability or Corporate Social Responsibility (CSR) disclosures. To address this gap, the present study conducts a cross-OEM analysis of three manufacturers, focusing on their plant-level environmental performance.

Several studies have applied EPIs in the automotive and other sectors, but plant-level comparative research in Slovakia is still limited, highlighting the need for this study. Drohomeretski et al. (2015) emphasised the importance of structured performance indicators grounded in sustainability frameworks. Swarnakar et al. (2021) proposed Key Performance Indicators (KPIs) for evaluating sustainability, grounded in the Triple Bottom Line (3BL) framework. Chalak (2020) introduced SMARTL criteria for measuring performance, emphasizing the need for a unified system beyond ISO 14031 standards. Boyd (2006, 2014) developed an energy model applying the Energy Performance Indicator (EPI), expressed in MWh per vehicle, widely used in automotive and other industries to quantify energy consumption. Comoglio and Botta (2012) demonstrated that operational indicators in waste management and resource use can yield measurable economic benefits. Similarly, Beier (2022) and Nunes and Bennett (2010) highlighted the role of data-driven monitoring in optimizing energy, emissions, and water consumption. Amrina and Yusof (2011) proposed a KPI framework for sustainable manufacturing in automotive companies, addressing emissions, resource use, and waste. Neef et al. (2024) proposed the "Decarbonisation Index" (DCI), combining product-level life cycle assessment with fleet-level analysis, underlining the value of life-cycle-based decarbonization strategies. NAE & NRC (1999) investigated industrial environmental performance metrics relevant to the automotive sector, highlighting best practices in implementing indicators and the need to integrate socioeconomic criteria into sustainability assessments.

Circular economy principles are increasingly recognised as essential for sustainability in the automotive industry. Montemayor and Chanda (2023) and Prochatzki et al. (2023) stressed embedding circularity from design to end-of-life, including multi-level strategies for material recovery, reuse, and reduction of virgin materials. Both studies point to the necessity of preventative approaches and industry-wide applicability, identifying a strong demand for research and development to support scalable and effective circular solutions. These approaches are particularly relevant given the universal exceedance of BAT waste benchmarks in this study.

Therefore, this work aims to assess how effectively EPIs, benchmarked against the quantitative BAT STS BREF standard, capture and promote improvements in the environmental performance of the studied OEMs. We hypothesise that EPIs benchmarked against BAT STS BREF standards significantly enhance the environmental performance of Slovak OEMs by identifying gaps and driving targeted improvements. This study thus provides a framework to evaluate plant-level environmental management practices and to support continuous improvement across the Slovak automotive sector.

2. Materials and Methods

This study is designed as a cross-sectional quantitative analysis comparing EPIs across three OEMs operating in Slovakia. EPIs are essential tool for evaluating environmental performance, providing a structured approach to assess how effectively an organisation manages its environmental responsibilities (Jasch, 2000). They are frequently embedded within EMS and support decision-making, facilitate stakeholder communication, and drive continuous improvement. EPIs are also linked to broader sustainability frameworks, such as ESG (Environmental, Social and Governance) criteria, which are increasingly used to evaluate corporate sustainability and financial performance (Friede et al., 2015).

To contextualise the comparison, it is useful to summarise the production focus of each OEM. In 2024, Volkswagen's Bratislava plant produced 341,111 vehicles, including several high-end and electric models such as the Volkswagen Touareg, Volkswagen Passat, Audi Q7/Q8, Škoda Superb and Škoda Superb Limusine. Kia manufactured 351,270 mass-market vehicles, including the Ceed and Sportage series. Stellantis concentrated on small-segment models such as the Peugeot 208 and Citroën C3. Jaguar Land Rover (JLR) specialises in premium Sport Utility Vehicles (SUVs), notably the Land Rover Defender. Among the four OEMs in Slovakia, Volkswagen and Kia recorded the highest production volumes in 2024 (VW SK, 2024; JLR, 2025; STELLANTIS N.V., 2025; KIA, 2024).

The research design involved systematic collection, processing, and comparison of data on the environmental operational efficiency of the selectrd OEMs. Primary data for the 2024 calendar year were obtained directly from the environmental managers of the plants. As plant-level data for Stellantis were not accessible through direct contact, the manufacturer was excluded from the analysis.

Table 1 Overview of Environmental Performance Frameworks – Automotive Industry Relevance
(based on EPD, 2025; ISO, 2021; OECD, 2017; OECD, n.d; UN, n.d; UNECE, n.d; EPA, 2021; WBA, 2025; Block, 2024; Gibson et al., 2015; GRI, 2025; EEA, n.d; Gaudillat, 2017; Decision (EU) 2019/62)

No.	Framework	Year Adopted	Automotive Relevance	Applications in the Automotive Sector
1	OECD Core Set of Environmental Indicators	1991	Indirect	Policy-level indicators influencing automotive environmental standards and reporting
2	The ENERGY STAR EPIs	1992	High	ENERGY STAR EPIs are directly applicable to automotive manufacturers. Designed for automobile assembly, engine, and transmission plants in the U.S. and Canada.
3	European Environment Agency (EEA) Indicators	1994	High	Sector-specific reports on transport emissions, resource use, and waste; supports EU automotive policy
4	Global Reporting Initiative (GRI)	1997	High	Widely used by automotive companies for sustainability reporting (e.g., Scope 1–3 emissions, water use, waste)
5	ISO 14031: Environmental Performance Evaluation	1999	High	Guides internal EPI development for automotive manufacturers; supports ISO 14001 EMS integration
6	Environmental Performance Index (EPI)	2002	Indirect	National-level benchmarking for air quality, emissions, and climate policy affecting automotive regulations
7	European Commission Best Environmental Management Practices (BEMPs)	2009	High	BEMPs are highly relevant to the automotive sector, particularly in areas of vehicle manufacturing, supply chain management, and energy use.
8	OECD Green Growth Indicators	2011	Relevant	Measures eco-efficiency, innovation, and links between growth and sustainability
9	EPD Indicator Framework (GPI 4 and 5)	2013	High	Quantifies environmental impacts of components (e.g., batteries, tires) using LCA
10	UNECE Environmental Indicator Guidelines	2014	Relevant	Supports national reporting of environmental impacts including transport and manufacturing
11	UN Sustainable Development Goals (SDGs) Global Indicator Framework	2015	Relevant	SDG Global Indicator Framework includes quantitative metrics that can be used to assess the automotive sector's environmental performance. (e.g., SDG 9, 12, 13)
12	WBA Automotive and Transportation Benchmark	2018	Relevant	The benchmark reveals critical insights into the automotive sector's progress and shortcomings on climate and sustainability.

A typical passenger vehicle manufacturing process includes stamping and metal forming, automotive joining, automotive painting, and final assembly (Omar, 2011). The painting of car bodies in plant paint shops has the most significant environmental impact due to emissions, solid and liquid hazardous waste, and high energy, water, and chemical consumption (Nunes and Bennett, 2010; Rivera and Reyes-Carrillo, 2011). Paint-shop processes can account for up to 75% of the plant's total energy use (Andrei, 2024) and are a major source of Volatile Organic Compound (VOC) emissions, which are tightly regulated due to air quality and health impacts (Kim, 2011). Therefore, EPIs specific to paint shops were also evaluated.

The BAT STS BREF (Best Available Techniques Reference Document for surface treatment using organic solvents) is part of the European Union's regulatory framework under the Industrial Emissions Directive (IED 2010/75/EU). It defines BAT-AELs (associated emission levels) for total and fugitive VOC emissions, emissions in waste gases, and emissions to water. It also outlines BAT-AEPLs (associated environmental performance levels) for energy use (energy efficiency) and water consumption (water efficiency). Additionally, it sets ELVs (emission limit values) for specific pollutants and ILs (indicative levels) such as waste quantities from vehicle coating processes. These benchmarks guide regulatory compliance and BAT implementation in surface treatment operations, including automotive paint shops (Chronopoulos et al., 2020). Table 2 summarises recent EU legislation establishing BAT benchmarks.

AELs are defined as the range of emission levels associated with the BATs, expressed as an average over a given period, under normal operating conditions (Chronopoulos et al., 2020). AEPLs refer to performance benchmarks related to environmental aspects beyond emissions.

Table 2 Overview of recent EU legislation for industrial emissions
(based on Directive 2010/75/EU; Decision 2020/2009; Directive 2024/1785)

Aspect	Directive 2010/75/EU (Industrial Emissions Directive, IED)	Implementing Decision (EU) 2020/2009 (BAT Conclusions for Surface Treatment)	Directive (EU) 2024/1785 (Industrial Emissions Directive 2.0, IED 2.0)
Type	Framework Directive	Commission Implementing Decision	Revised Framework Directive
Purpose	Establishes integrated pollution prevention and control across EU industries	Adopts BAT conclusions for surface treatment using organic solvents	Updates and strengthens IED 2010/75 with stricter standards and broader scope
Scope	All large industrial installations	Surface treatment sector (including automotive coating)	All large installations and new sectors (battery gigafactories, landfills, intensive agriculture)
Key content	Requires use of BAT, sets ELVs, mandates permit conditions	Defines BAT-AELs and BAT-AEPLs for VOCs and other pollutants	Enforces stricter ELVs, adopts AEPLs, expands public rights and transparency
BAT role	BAT conclusions guide permit conditions; binding within 4 years	Provides technical benchmarks for VOC emissions and performance	Legally binds AEPLs and mandates lowest achievable BAT-AELs in permits
VOC relevance	General obligation to control VOCs via BAT	Specific VOC limits for existing installations	Enforces those limits and expands obligations (e.g. EMS, public access)
Legal force	Binding on Member States; implemented via national laws (e.g. Act No. 39/2013 in Slovakia)	Binding technical reference for permitting	Fully replaces 2010/75/EU; binding across all Member States
Entry into force	6 January 2011	9 December 2020	4 August 2024

These levels are considered achievable when BAT is applied, although they are not always presented in numerical form (e.g. technical measures, operational practices or design features). AEPLs serve to guide operators and regulators in enhancing overall environmental performance (Chronopoulos et al., 2020). ELVs are regulatory limits that define the maximum allowable quantity of a pollutant, expressed in terms of mass, concentration, or other specific parameters, emitted over a defined period, and serve as the basis for setting conditions in environmental permits, with facilities required to demonstrate compliance unless a justified derogation is granted (Directive 2010/75/EU). Indicative levels are reference values provided in BREFs for specific environmental parameters where data availability is limited or variability is high. While not legally binding, they offer orientation and comparative value. ILs support decision-making and benchmarking, particularly in areas where BAT conclusions do not specify mandatory AELs or AEPLs (Chronopoulos et al., 2020).

All EPI values were expressed per vehicle manufactured and per square meter of painted vehicle body to enable consistent cross-plant comparison. Waste per vehicle body coated (paint shop), energy per vehicle body coated (paint shop), VOC emissions per square meter of painted vehicle body surface area (paint shop), and water consumption per vehicle body coated (paint shop) were evaluated against BAT-AEPL benchmarks set in the BAT STS BREF. To enable visual comparison (radar plots) of EPI performance among OEMs and between the paint-shop and plant levels, the data were subsequently standardised. Participating OEMs provided plant-level data subject to full anonymisation, in accordance with internal disclosure and confidentiality requirements.

Characteristics of the evaluated EPIs:

- Waste per vehicle ($kg \cdot veh^{-1}$) or per painted vehicle body ($kg \cdot veh\ body^{-1}$): Total waste generated per manufactured unit, including hazardous and non-hazardous materials (Decision (EU) 2020/2009).
- Energy per vehicle ($MWh\ veh^{-1}$) or per painted vehicle body ($MWh \cdot veh\ body^{-1}$): Total primary energy consumed, including purchased electricity, on-site renewable electricity, natural gas, and steam.
- CO_2e emissions per vehicle ($t\ CO_2e \cdot veh^{-1}$): Calculated from total primary energy consumption multiplied by the corresponding market-based emission factor.
- VOCs per square meter ($g\ VOC \cdot m^{-2}$): Total VOCs released divided by the painted surface area of vehicle bodies.
- Water consumption per vehicle ($m^3 \cdot veh^{-1}$) or per painted vehicle body ($m^3 \cdot veh\ body^{-1}$): Total water used per manufactured unit.
- Wastewater per vehicle ($m^3 \cdot veh^{-1}$) or per painted vehicle body ($m^3 \cdot veh\ body^{-1}$): Total volume of wastewater generated, normalised per unit.

The resulting EPIs were compared with BAT STS BREF benchmarks, as outlined in Table 3.

Table 3 Overview of BAT STS BREF benchmarks (based on Chronopoulos et al., 2020).

Term	Legislative origin	Definition	Current legal status	Application	Examples
BAT-AEL (BAT-Associated Emission Level)	Industrial Emissions Directive (IED) 2010/75/EU	Quantitative range of pollutant concentrations or loads that can be achieved by applying BAT.	Legally binding and enforceable, must be included in permits	Direct emissions to air, water, or soil	VOC: 8–30 g m^2 of painted vehicle body surface area
ELV (Emission Limit Value)	Industrial Emissions Directive (IED) 2010/75/EU	Maximum allowable concentration or load of a pollutant released from an installation (plant, facility)	Legally binding and enforceable, set by national authorities	Must reflect BAT-AELs under IED 2.0	VOC ELV based on BAT-AEL range: 30 $g{\cdot}m^2$ of painted vehicle body surface area
BAT-AEPL (BAT-Associated Environmental Performance Level)	Commission Implementing Decision (EU) 2020/2009 establishing the BAT conclusions, under Directive 2010/75/EU	Quantitative benchmark for environmental indicators not directly regulated as emissions	Indicative benchmarks, but formally adopted under IED 2.0	Energy, water	Energy: 0.5–1.3 $MWh{\cdot}veh^{-1}$, Water: 0.5–1.3 $m^3{\cdot}veh^{-1}$
Indicative Level	BAT Reference Documents (BREFs) under Directive 2010/75/EU	Non-binding benchmark for performance monitoring	Not enforceable	Continuous improvement, internal benchmarking	Waste: 3–9 $t{\cdot}y^{-1}$ sent off-site

3. Results and Discussion

3.1 Results

The analysis of EPIs across the three studied OEMs reveals clear differences in environmental efficiency, particularly in paint-shop operations. Table 4 presents the comparison of EPIs and their compliance with BAT STS BREF benchmarks.

Waste generation per vehicle ranged from 50.0 $kg{\cdot}veh^{-1}$ (OEM 1) to 186.0 $kg{\cdot}veh^{-1}$ (OEM 2), with paint-shop-specific waste varying between 10.0 $kg{\cdot}veh^{-1}$ (OEM 2) and 26.05 $kg{\cdot}veh^{-1}$ (OEM 3). These findings indicate that paint shops remain the primary contributor to total waste generation. All three plants exceeded the BAT STS BREF indicative levels of 3–9 $kg{\cdot}veh^{-1}$, highlighting opportunities for targeted waste reduction. Energy consumption per vehicle also differed considerably, ranging from 0.70 $MWh{\cdot}veh^{-1}$ (OEM 2) to 1.35 $MWh{\cdot}veh^{-1}$ (OEM 3). When expressed per painted vehicle body, energy use varied from 0.46 MWh·veh $body^{-1}$ (OEM 2) to 0.83 MWh·veh $body^{-1}$ (OEM 3).

The paint-shop energy intensities of OEM 1 and OEM 2 were within the BAT STS BREF benchmark range (≤1.3 $MWh{\cdot}veh^{-1}$), suggesting effective implementation of energy efficiency measures, including improved oven insulation, enhanced heat recovery, and optimised air-handling systems, while OEM 2 operated slightly below the lower benchmark, indicating high productivity without downtimes.

CO_2e emissions per vehicle ranged from 0.08 t $CO_2e{\cdot}veh^{-1}$ (OEM 2) to 0.16 t $CO_2e{\cdot}veh^{-1}$ (OEM 3). The variation is consistent with differences in energy mix and consumption across plants, confirming that energy efficiency improvements in paint shops directly influence greenhouse gas emissions. VOC emissions per square meter of painted body surface area fell between 8.66 $g{\cdot}m^{-2}$ (OEM 2) and 17.70 $g{\cdot}m^{-2}$ (OEM 1). All OEMs complied with the BAT STS BREF AEL range (8–30 $g{\cdot}m^{-2}$), but OEM 1 operated closer to the upper end, indicating room for further reduction through improved solvent management or alternative coating technologies. Water consumption per vehicle ranged from 1.38 $m3{\cdot}veh^{-1}$ (OEM 2) to 3.10 $m^3{\cdot}veh^{-1}$ (OEM 3). Paint-shop water use varied between 0.57 m3·veh $body^{-1}$ (OEM 2) and 1.9 m^3·veh $body^{-1}$ (OEM 3). While OEM 2 operated within the BAT STS BREF benchmark range of 0.5–1.3 m^3·veh $body^{-1}$, OEM 3 exceeded this benchmark, indicating higher specific water consumption. Wastewater generation at the plant level ranged from 1.29 $m^3{\cdot}veh^{-1}$ (OEM 2) to 2.81 $m^3{\cdot}veh^{-1}$ (OEM 3). Paint-shop wastewater ranges from 0.50 m^3·veh $body^{-1}$ (OEM 2) to 1.55 m^3·veh $body^{-1}$ (OEM 3).

Paint-shop contributions to plant-level environmental performance vary substantially across indicators and OEMs. Energy consumption shows the highest relative impact, accounting for 50–66 % of the total plant-level energy use, with OEM 2 exhibiting the largest share. Waste generation per painted vehicle body contributes 5–31 % to total plant-level waste, with the lowest value observed for OEM 2 and the highest for OEM 3. Water consumption and wastewater generation also display considerable paint-shop contributions, ranging from 37–61 % and 31–55 %, respectively, with OEM 3 consistently at the upper end. These findings indicate that the paint shop is a critical hotspot for several environmental performance indicators, particularly energy, water, and waste, and highlight the potential for targeted interventions in this part of the production process.

Normalisation per vehicle and per square meter of painted body surface area provides a robust basis for cross-plant comparison, highlighting both best practices and inefficiencies. While energy and water use largely comply with BAT benchmarks, waste generation and VOC emissions show greater variability, pointing to areas where further technological or operational improvements are needed. OEM 2 performed best across several key indicators, including the lowest CO_2e (0.08 t $CO_2e\cdot veh^{-1}$), lowest VOCs (8.66 g $VOCs\cdot m^{-2}$), lowest paint-shop water use (0.57 $m^3\cdot veh^{-1}$), lowest paint-shop wastewater generation (0.50 $m^3\cdot veh^{-1}$), and lowest plant-level wastewater generation (1.29 $m^3\cdot veh^{-1}$). However, OEM 2 also reported the highest plant-level waste generation (186 $kg\cdot veh^{-1}$). In contrast, OEM 3 showed the weakest performance in several respects, such as the highest energy use per vehicle (1.35 $MWh\cdot veh^{-1}$), highest plant-level water consumption (3.10 $m^3\cdot veh^{-1}$), and highest wastewater discharge both at the plant level (2.81 $m^3\cdot veh^{-1}$) and in the paint shop (1.55 $m^3\cdot veh^{-1}$), indicating significant room for improvement in waste and resource management. Furthermore, OEM 3 does not comply with BAT benchmarks in the paint shop, particularly in the waste and water indicators, suggesting that its processes fall short of the best available techniques as defined in the BAT STS BREF.

Table 4 EPIs of Studied OEMs vs. BAT STS BREF Benchmarks

No	EPI	Unit	OEM 1	OEM 2	OEM 3	BAT STS BREF benchmark
1	Waste per vehicle (plant)	$kg\cdot veh^{-1}$	50.00	186.00	83.10	N/D*
1.1	Waste per painted vehicle body (paint shop)	$kg\cdot veh^{-1}$	12.33	10.00	26.05	3 – 9
2	Energy per vehicle (plant)	$MWh\cdot veh^{-1}$	1.30	0.70	1.35	N/D*
2.1	Energy per painted vehicle body (paint shop)	$MWh\cdot veh^{-1}$	0.65	0.46	0.83	0.5 – 1.3
3	CO_2e emissions per vehicle (plant)	t $CO_2e\cdot veh^{-1}$	0.12	0.08	0.16	N/D*
4	VOCs per square meter of painted vehicle body surface area (paint shop)	g $VOCs\cdot m^{-2}$	17.70	8.66	12.64	8 – 30
5	Water consumption per vehicle (plant)	$m^3\cdot veh^{-1}$	2.10	1.38	3.10	N/D*
5.1	Water consumption per painted vehicle body (paint shop)	$m^3\cdot veh^{-1}$	0.78	0.57	1.90	0.5 – 1.3
6	Wastewater per vehicle (plant)	$m^3\cdot veh^{-1}$	2.31	1.29	2.81	N/D*
6.1	Wastewater per painted vehicle body (paint shop)	$m^3\cdot veh^{-1}$	0.71	0.50	1.55	N/D*

*N/D: not defined by BAT STS BREF

The normalised radar plots (Fig. 1 and Fig. 2) illustrate the relative performance of each OEM across key EPIs, highlighting that OEM 2 generally performed best, showing lower energy consumption, water use, and waste generation compared to OEM 1 and OEM 3 at the plant-level. OEM 3 exhibited higher CO_2e emissions and wastewater volumes. At the paint-shop level, OEM 2 again achieved the best overall performance, with favourable values for energy use, VOC emissions, and water-related indicators. OEM 3 consistently scored worst, primarily due to high waste and water consumption in the painting process.

3.1 Discussion

The evaluation of EPIs against BAT STS BREF benchmarks reveals partial alignment across the assessed OEMs. Energy consumption per painted vehicle body largely complies with the BAT-AEPL benchmark of 0.5–1.3 $MWh\cdot veh^{-1}$. The use of Combined Heat and Power (CHP) systems in paint shops can further reduce specific energy consumption, increasing overall efficiency from 40 % to 85 %, particularly when integrated with absorption cooling in trigeneration systems (Giampieri et al., 2020).

Water consumption per painted vehicle body is compliant for OEM 1 and OEM 2 but exceeds the upper benchmark for OEM 3, indicating potential for improved water efficiency measures. Wastewater generation mirrors this pattern, with OEM 3 presenting the highest plant- and paint-shop-level values.

VOC emissions per square meter of painted surface fall within the BAT-AEL benchmark of 8 – 30 g $VOC\cdot m^2$ for all OEMs, indicating effective control of solvent-related emissions. As noted by Giampieri (2021), the reduction in VOC emissions in the automotive industry was mainly due to the development of more environmentally friendly water-based and powder-based paints. Water consumption per painted vehicle body is compliant for OEM 1 and OEM 2 but exceeds the upper benchmark for OEM 3, indicating potential for improved water efficiency measures. None of the OEMs comply with the indicative BAT level for waste generation per painted vehicle body.

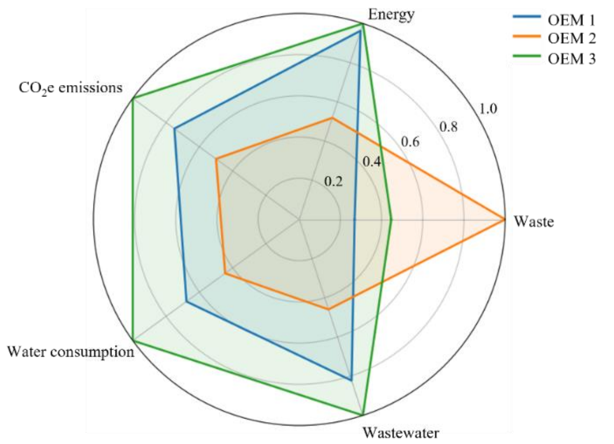

Figure 1 Comparative normalised environmental performance of the studied automotive OEMs at the plant level

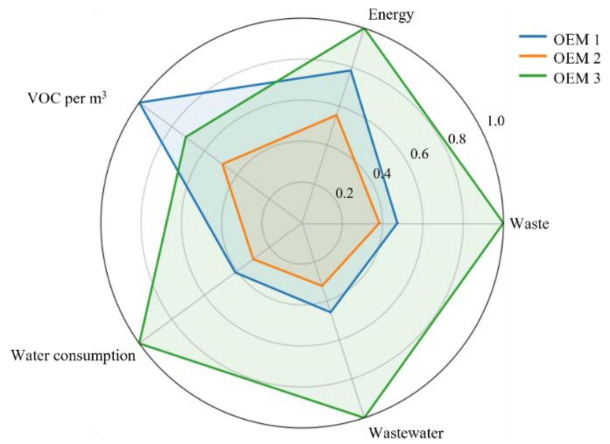

Figure 2 Comparative normalised environmental performance of the studied automotive OEMs at the paint-shop level

Waste generation per painted vehicle body exceeds the BAT indicative level of 3–9 kg·veh^{-1} for all OEMs. Notably, OEM 2, despite low energy, water, VOC, and CO_2e metrics, reports the highest plant-level waste (186 kg·veh^{-1}). This highlights a sector-wide challenge in minimizing waste and implementing circular economy practices. Introducing additional EPIs, such as the proportion of recycled content in vehicles, could provide a more complete assessment of circularity (Aguilar Esteva et al., 2021).

The literature consistently identifies paint shops as the main source of hazardous waste due to overspray, filtration, and solvent-based processes (Salihoglu and Salihoglu, 2016), with variability across plants indicating that organisational practices matter alongside technology. Research highlights limited closed-loop recycling, weak waste segregation, and inconsistent management systems as key drivers of high waste intensities, while evidence suggests that process innovations such as dry scrubbers and advanced pollutant recovery can significantly reduce hazardous sludge and enable material recovery (Khezri et al., 2012). Complementary findings show that effective paint removal is essential for high-quality recycling of automotive plastics (Zambrano et al., 2024), and that lean management tools can systematically reduce waste at source when embedded in environmental management systems (Suhardi et al., 2020). Together, these studies indicate that BAT-level waste performance is technically feasible and that continued exceedance primarily reflects implementation and managerial gaps rather than technological limits.

Although Stellantis was excluded from the core analysis due to unavailable Slovak plant-level data, its 2024 EPIs, derived from publicly available corporate environmental disclosures, provided useful contextual insight (Stellantis N.V., 2024; 2025). Stellantis reported a Scope 2 GHG intensity of 0.33 t CO_2e·veh^{-1} using the location-based method, which represented the highest value among the three OEMs analyzed (OEM 1: 0.12 t, OEM 2: 0.08 t, OEM 3: 0.16 t CO_2e·veh^{-1}). Under the market-based approach, Scope 2 emissions decreased to 0.26 t CO_2e·veh^{-1}, reflecting the impact of renewable electricity procurement strategies rather than changes in physical electricity consumption. This divergence highlights the importance of distinguishing between accounting approaches in inter-OEM comparisons and supports the use of location-based Scope 2 emissions as the more appropriate indicator for assessing relative operational performance within the same national context. In contrast, Stellantis performed more favourably with respect to material efficiency. Its waste intensity of 58.1 kg·veh^{-1} ranked as the second-best result among the OEMs examined (OEM 1: 50 kg·veh^{-1}, OEM 3: 83.1 kg·veh^{-1}, OEM 2: 186 kg·veh^{-1}), indicating relatively effective waste management practices despite its large-scale and geographically dispersed production footprint. A similar pattern emerges for water consumption intensity, where Stellantis reported 1.42 m^3 per vehicle, again representing the second-best performance within the comparison set (OEM 2: 1.38 m^3, OEM 1: 2.1 m^3, OEM 3: 3.1 m^3 per vehicle). Other Stellantis EPIs were not available in the corporate disclosures. Overall, the contextual inclusion of Stellantis suggests a heterogeneous environmental performance profile, with comparatively weaker results in Scope 2 GHG intensity but stronger outcomes in waste and water efficiency. While its inclusion would likely have increased dispersion in Scope 2 results, the broader comparative patterns identified in this study remain robust, underscoring the importance of multi-dimensional EPIs in assessing manufacturing sustainability in the automotive sector.

Consistent with Giampieri (2021) and SMMT (2024) report, the UK automotive sector achieved substantial reductions in manufacturing-related energy use and environmental impacts between 1999 and 2017 despite broadly stable production volumes. Over this period, energy consumption per vehicle fell from 3.9 to 1.95 MWh, water use declined from 5.3 to 2.3 $m^3 \cdot veh^{-1}$, CO_2e emissions were more than halved from 1.1 to 0.5 $t \cdot veh^{-1}$, VOC emissions intensity decreased from 55 to 34.6 $g \cdot m^{-2}$, and landfill waste per vehicle dropped sharply from 40.3 to 1.3 kg, reflecting technological upgrading, tighter environmental regulation, and gradual gains in energy and material efficiency. Evidence from the SMMT report suggests that these long-term improvements have largely been maintained, with CO_2e emissions at 0.5 $t \cdot veh^{-1}$, energy use at 2.6 $MWh \cdot veh^{-1}$, water use at 3.1 $m^3 \cdot veh^{-1}$, and VOC emissions at 25.6 $g \cdot m^{-2}$ in 2023, indicating continued progress in emissions control alongside more variable trends in resource consumption. Similarly, EC (2021) and Pendar et al. (2022) recommend closed-loop water and waste systems, operational efficiency measures, and technologies such as dry scrubbers and waste heat recovery to reduce environmental burdens. Historical data also suggest that even the relatively high resource consumption observed for OEM 3 could be significantly mitigated, consistent with findings by Babel (2020), who reported even higher water and energy consumption in other OEMs.

In the absence of harmonised and publicly available OEM-level EPI data across Central Europe, indirect comparison relies on proxy indicators. Evidence from Poland's Silesian automotive region shows that about 45 % of firms use energy performance indicators, implying more structured monitoring than in Slovakia or Czechia (Piekarski and Grübel, 2025). While all V4 countries have reduced industrial emissions intensity over time, differences in energy mix and institutional frameworks continue to produce uneven outcomes (Campos-Romero et al., 2024), pointing to persistent gaps in EPI formalisation and innovation-driven decarbonisation and underscoring the scope for policy and corporate action to improve regional convergence.

5. CONCLUSIONS

This study assessed EPIs across three Slovak automobile manufacturers in 2024, evaluating compliance with BAT STS BREF benchmarks and comparing performance among the OEMs. The analysis shows partial alignment with BAT standards. Energy consumption per painted vehicle body and VOC emissions per square meter of painted surface generally comply with BAT-AEPL and BAT-AEL benchmarks, indicating effective energy management and solvent control in most plants. Water consumption met BAT benchmarks for OEM 1 and OEM 2 but exceeded the upper limit for OEM 3, highlighting potential for improved water efficiency. In contrast, waste generation per painted vehicle body exceeds the BAT indicative range for all OEMs, revealing a persistent sector-wide challenge.

Paint-shop operations were identified as the main drivers of variability in EPI outcomes. OEM 2 showed the best overall performance in energy, water, VOC emissions, and CO_2e per vehicle, although its plant-level waste generation remained the highest. OEM 3 exhibited the weakest performance in energy use, water consumption, and wastewater generation, indicating substantial opportunities for operational and technological improvements. Variations in EPI outcomes are primarily attributable to company-level strategies rather than national infrastructure or systemic factors, and can also reflect differences in the currently manufactured vehicle portfolios.

The findings underscore the importance of benchmarking and continuous monitoring of EPIs to guide improvements and promote best practices. Future research should incorporate plant- and paint-shop-level metrics, support annual benchmarking, and integrate circular economy indicators such as the ratio of recycled waste. Coordinated digitalised EPI tracking, potentially facilitated by AIA SR (The Automotive Industry Association of the Slovak Republic), could enhance transparency, comparability, and collaboration among OEMs and with external stakeholders. Including circular economy indicators, such as the proportion of recycled waste, could further strengthen sustainability assessment.

To the author's knowledge, this study provides the first cross-OEM, plant-level assessment of environmental performance in Slovakia's automotive sector. By applying EPIs benchmarked to the BAT STS BREF standard, it fills a notable gap in the literature and offers a comparable evidence base for evaluating and improving environmental performance across manufacturers.

Several limitations should be considered when interpreting the findings. Data from OEM Stellantis were not available, which restricted the scope of the comparative analysis. The study is limited to the year 2024, preventing analysis of long-term trends. Additionally, differences in manufacturing technologies, product portfolios, process maturity, and inconsistencies arising from company-reported data affected the reliability of cross-OEM comparisons. Specifically, one OEM doesn't operate a stamping shop, thereby generating no steel or aluminium scrap, while another does, which increases its waste-per-vehicle EPI and limits the validity of direct benchmarking

DISCLAIMER

The corresponding author is directly employed by Jaguar Land Rover Slovakia s.r.o. and has worked as an environmental manager in the EPI analysis of the presented case

ACKNOWLEDGEMENTS

The authors are very grateful to the Editor in Chief (Prof. Tamas Komives) and the anonymous reviewers for their valuable contributions to improving this manuscript, and acknowledge the environmental managers of the selected Slovak automotive OEMs for providing in-plant data.

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