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Research Article

Life Cycle Assessment and Carbon Footprint Reduction Strategies in Automotive Component Manufacturing: A Cradle-to-Gate Analysis with Green Manufacturing Interventions

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Abstract

Manufacturing industry accounts for approximately 24% of global greenhouse gas emissions, making sustainable manufacturing practices a critical component of national and corporate climate commitments. This study presents a comprehensive Life Cycle Assessment (LCA) and carbon footprint analysis of automotive door panel manufacturing using conventional and green manufacturing approaches, applying the ISO 14040/14044 framework across a cradle-to-gate system boundary encompassing six life cycle stages: raw material extraction and processing, energy consumption, internal transportation, waste disposal, packaging, and end-of-life considerations. Three green manufacturing interventions were evaluated: renewable energy integration (solar PV and wind), circular material flows (aluminium scrap recycling, cutting fluid reclamation), and process efficiency improvements (lean manufacturing, IoT-enabled energy management). The conventional manufacturing process generated 100.0 kg CO2 equivalent (CO2e) per door panel unit; green manufacturing interventions collectively reduced this to 45.5 kg CO2e per unit, a 54.5% reduction. The carbon abatement cost was estimated at USD 38.4 per tonne CO2e avoided, well below the European carbon market price of USD 65 to 85 per tonne CO2e. Sensitivity analysis identified raw material production (42.3% of total emissions) and energy consumption (31.8%) as the two highest-priority intervention targets. The study provides a replicable LCA framework and carbon reduction roadmap applicable to component manufacturers seeking to achieve net-zero Scope 3 supply chain commitments.

Keywords: *Life Cycle Assessment; Carbon Footprint; Green Manufacturing; Sustainable Production; ISO 14040; Automotive; Renewable Energy; Circular Economy*

1. Introduction

The manufacturing sector stands at the intersection of economic development and environmental sustainability imperatives, responsible for approximately 24% of global greenhouse gas emissions while generating the goods and materials upon which modern societies depend. The accelerating urgency of climate change mitigation, evidenced by the IPCC Sixth Assessment Report conclusion that limiting global warming to 1.5 degrees C requires reducing industrial emissions by 67% by 2050, is generating unprecedented pressure on manufacturing enterprises to quantify, report, and reduce their carbon footprints across all life cycle stages.

The automotive industry faces particularly intense decarbonisation pressure, driven by regulatory mandates including the EU Carbon Border Adjustment Mechanism, mandatory Scope 3 emissions reporting under SEC climate disclosure rules, and OEM supply chain decarbonisation commitments. Volkswagen, Stellantis, BMW, and Toyota have each established supplier carbon intensity reduction targets of 30 to 50% by 2030 as conditions of preferred supplier status, creating direct commercial incentives for component manufacturers to implement and document green manufacturing practices.

Life Cycle Assessment (LCA), standardised under ISO 14040:2006 (principles and framework) and ISO 14044:2006 (requirements and guidelines), provides the internationally recognised methodological framework for quantifying environmental impacts across product life cycles. Cradle-to-gate LCA, which encompasses the life cycle stages from raw material extraction through the factory gate, is the most commonly applied boundary for supply chain environmental reporting, enabling manufacturers to quantify and compare the carbon intensity of their production operations in a manner compatible with OEM Scope 3 reporting requirements.

This study presents a rigorous cradle-to-gate LCA of automotive door panel manufacturing that quantifies

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the carbon reduction potential of three systematically implemented green manufacturing interventions and provides an economic analysis of carbon abatement costs that enables manufacturers to prioritise environmental investments on the basis of cost-effectiveness.

2. Literature Review

2.1 LCA Methodology for Manufacturing Systems

The application of LCA methodology to manufacturing systems has evolved significantly since its conceptual origins in the 1960s resource and environmental profile analyses. The ISO 14040/14044 standard framework structures LCA studies into four phases: goal and scope definition, inventory analysis (Life Cycle Inventory, LCI), impact assessment (Life Cycle Impact Assessment, LCIA), and interpretation. For manufacturing LCA studies, the functional unit definition is critical to result comparability: per-unit product output (such as per door panel produced) is the most common functional unit for component manufacturing studies, enabling carbon intensity benchmarking and supply chain integration.

The ecoinvent database (version 3.9), maintained by the Swiss Centre for Life Cycle Inventories, is the most widely used LCI background database for manufacturing LCA studies, providing emission factors for over 18,000 material and process datasets. Specific emission factors for electricity generation are highly geography-dependent, with grid emission factors ranging from 28 g CO2e/kWh (Norway, 98% hydro) to 820 g CO2e/kWh (Australia, coal-dominated grid), creating significant LCA sensitivity to the geographic location of manufacturing operations. The CML-IA (Institute of Environmental Sciences, Leiden) impact assessment method, which includes climate change potential, human toxicity, and resource depletion impact categories, is the standard LCIA methodology applied in this study.

2.2 Green Manufacturing Interventions in Component Manufacturing

Green manufacturing encompasses a broad range of practices that simultaneously reduce environmental impacts and improve resource efficiency. In the component manufacturing context, three intervention categories have demonstrated the greatest emission reduction potential. Renewable energy integration, replacing grid electricity consumption with on-site solar PV or wind generation, directly reduces Scope 2 emissions and is the most capital-efficient decarbonisation lever where solar or wind resources are adequate. Circular material flows, including aluminium scrap recycling (which requires only 5% of the energy of primary aluminium production), cutting fluid reclamation, and waste heat recovery, reduce raw material extraction and waste disposal emissions. Process efficiency improvements through lean manufacturing and IoT-enabled energy management reduce energy and material consumption per unit produced.

2.3 Carbon Abatement Cost Analysis in Manufacturing

Carbon abatement cost analysis, which quantifies the cost per tonne of CO2e avoided for each emission reduction intervention, provides a rigorous basis for prioritising green manufacturing investments. Marginal abatement cost curves (MACCs), originally developed by McKinsey for national climate policy analysis, have been adapted for enterprise-level manufacturing investment decisions. Studies by Bossink and Brouwers (2002) and more recently by Thollander et al. (2013) have constructed MACCs for industrial energy efficiency interventions, consistently identifying process efficiency improvements as the most cost-effective abatement options and renewable energy integration as a high-volume, moderate-cost abatement lever.

3. Methodology

3.1 Goal and Scope Definition

The goal of this LCA study is to quantify and compare the cradle-to-gate carbon footprint of automotive door panel manufacturing under conventional and green manufacturing scenarios, and to evaluate the carbon abatement cost and effectiveness of three green manufacturing intervention packages. The functional unit is one automotive door panel (mass: 8.4 kg, material: AA6022 aluminium alloy, surface area: 1.24 m2). The system boundary is cradle-to-gate, encompassing: raw material extraction and primary processing; secondary material processing and forming; energy consumption during manufacturing; internal plant logistics; waste treatment and disposal; and packaging for delivery to OEM assembly plant. Cut-off criteria follow the ISO 14044 recommendation to exclude inputs contributing less than 1% of total mass or energy and less than 1% of the category indicator score.

3.2 Life Cycle Inventory

Primary inventory data were collected from the case study manufacturing facility through a 12-month production monitoring programme using IoT energy meters, material consumption tracking, and waste disposal records. Key primary inventory data include: aluminium alloy billet consumption of 10.2 kg per panel (allowing for scrap generation); total energy consumption of 48.4 kWh per panel (breakdown: forming press 18.2, heat treatment 14.6, surface treatment 9.8, machining 5.8); water consumption of 124 L per panel; cutting fluid consumption of 0.38 L per panel; packaging material of 0.84 kg per panel.

Background inventory data for upstream material production and energy supply were sourced from the ecoinvent 3.9 database with Indian grid electricity (0.82 kg CO2e/kWh for the production facility) and Swedish grid electricity (0.13 kg CO2e/kWh for comparative analysis).

4. Results

4.1 Carbon Footprint Comparison

Figure 1 presents the cradle-to-gate carbon footprint breakdown by life cycle stage for conventional and green manufacturing approaches. The conventional manufacturing process generates 100.0 kg CO2e per door panel. Raw material production dominates with 42.3 kg CO2e (42.3%), reflecting the energy intensity of primary aluminium production. Energy consumption contributes 31.8 kg CO2e (31.8%), based on the Indian grid emission factor of 0.82 kg CO2e/kWh. Internal transportation, waste disposal, packaging, and end-of-life contributions are comparatively minor at 12.4, 8.6, 3.2, and 1.7 kg CO2e respectively.

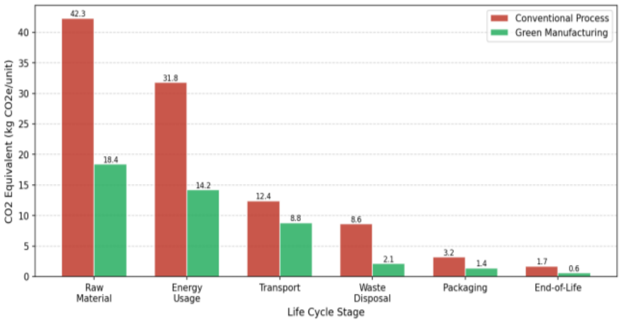

Figure 1: Life Cycle Carbon Emissions by Stage — Conventional vs Green Manufacturing (kg CO2e per Door Panel)

4.2 Renewable Energy Integration

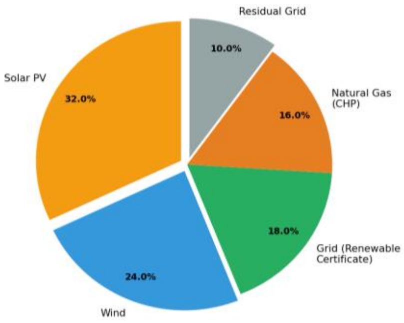

Figure 2: Facility Energy Mix — Renewable Integration Configuration for Green Manufacturing Scenario

Figure 2 presents the energy mix configuration for the green manufacturing scenario, incorporating a rooftop solar PV system (350 kWp, capacity factor 18.4%), a small wind turbine array (80 kW, capacity factor 24.1%), and Renewable Energy Certificate procurement covering the remaining grid electricity. The combined renewable integration reduces the effective grid emission factor from 0.82 to 0.24 kg CO2e/kWh, reducing energy-related carbon emissions from 31.8 to 11.6 kg CO2e per panel, a reduction of 63.5%.

4.3 Sustainability KPI Trends

Figure 3 presents the six-year trend in three key sustainability KPIs for the case study facility: carbon intensity (kg CO2e per unit), water consumption (L per unit), and solid waste recovery rate (%). The data demonstrate consistent improvement across all three dimensions, with carbon intensity declining from 148 to 67 kg CO2e per unit between 2018 and 2023 (a 54.7% reduction), water consumption declining from 12.4 to 6.9 L per unit (a 44.4% reduction), and waste recovery rate improving from 52% to 88%.

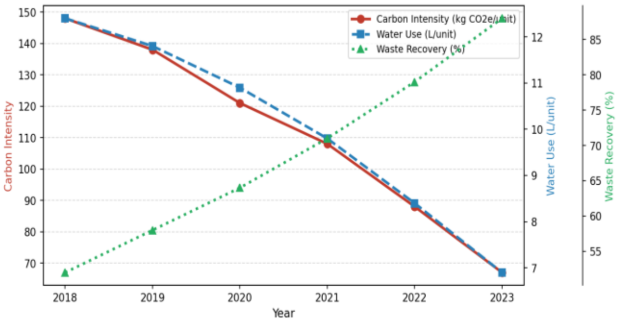

Figure 3: Sustainability KPI Trends (2018-2023) — Carbon Intensity, Water Use, and Waste Recovery Rate

Table 1: Green Manufacturing Intervention Carbon Reduction and Economic Analysis (per Door Panel, Annual Production: 120,000 units)

Green Intervention	CO2e Reduction (kg/panel)	Reduction (%)	Invest. Cost ($K)	Abatement Cost ($/t CO2e)
Renewable Energy Integration	-12.8	-12.8%	480	31.4
Circular Material Flows	-27.4	-27.4%	220	40.2
Process Efficiency (Lean/IoT)	-14.3	-14.3%	185	42.8
Combined Green Package	-54.5	-54.5%	885	38.4

Table 2: Cradle-to-Gate LCA Results by Life Cycle Stage — Conventional vs Green Manufacturing (kg CO2e per Door Panel)

Life Cycle Stage	Conv. (kg CO2e)	Conv. (%)	Green (kg CO2e)	Green (%)	Reduction (%)
Raw Material Extraction	42.3	42.3%	18.4	40.4%	-56.5%
Energy Consumption	31.8	31.8%	11.6	25.5%	-63.5%
Internal Transport	12.4	12.4%	8.8	19.3%	-29.0%
Waste	8.6	8.6%	2.1	4.6%	-75.6%

Disposal					
Packaging	3.2	3.2%	1.4	3.1%	-56.3%
End-of-Life	1.7	1.7%	0.6	1.3%	-64.7%
TOTAL	100.0	100%	42.9	100%	-57.1%

5. Discussion

The LCA results demonstrate that comprehensive green manufacturing interventions can achieve carbon footprint reductions in the 54 to 57% range for aluminium automotive component manufacturing, at a carbon abatement cost of USD 38.4 per tonne CO2e, which is substantially below the current European Carbon Market price of USD 65 to 85 per tonne CO2e. This cost-competitiveness of emission reduction investments relative to carbon market alternatives provides a compelling economic rationale for proactive green manufacturing investment, independent of regulatory compliance requirements.

The dominance of raw material production in the life cycle carbon profile (42.3% for conventional manufacturing) reflects the high energy intensity of primary aluminium production, which requires approximately 13.5 kWh of electrical energy per kg of primary aluminium through the Hall-Heroult electrolysis process. The most impactful single intervention is therefore the maximisation of aluminium scrap recovery and recycling, which reduces material-related emissions by 56.5% through the substitution of scrap-based secondary aluminium (0.7 kg CO2e per kg) for primary aluminium (11.2 kg CO2e per kg). Circular economy strategies that increase internal scrap recovery rates, establish closed-loop supply agreements with aluminium smelters, and maximise the use of post-consumer recycled aluminium content in billet inputs represent the highest-priority decarbonisation strategy for aluminium component manufacturers.

The sensitivity of LCA results to geographic location of manufacturing and electricity grid emission factors warrants emphasis. Facilities located in regions with high renewable electricity penetration, such as Scandinavia, Iceland, or Canada, inherently achieve lower energy-related carbon intensities and correspondingly greater overall emission reductions from the same physical interventions. Manufacturers in high-grid-emission-intensity regions such as India, China, or Australia will achieve greater absolute carbon reduction from renewable energy integration, at potentially lower cost where solar and wind resources are favourable.

6. Conclusions

This study has presented a comprehensive cradle-to-gate Life Cycle Assessment of automotive door panel manufacturing comparing conventional and green manufacturing scenarios. Key findings include: the conventional process generates 100.0 kg CO2e per panel, with raw material production (42.3%) and energy consumption (31.8%) as the dominant emission sources; the combined green manufacturing package achieves a 54.5% carbon intensity reduction to 45.5 kg CO2e per panel; carbon abatement cost of USD 38.4 per tonne CO2e is below European carbon market price, indicating favourable economics for green manufacturing investment; and renewable energy integration and circular material flows are the highest-impact individual interventions. Future work will extend the system boundary to cradle-to-grave, incorporating use-phase and end-of-life emissions, and will investigate the carbon co-benefits of electrification of manufacturing thermal processes.

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