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Design of A Low-Voltage Distribution Panel Based on Recycled Plastic Material for Corrosive Environments

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ABSTRACT

The increasing deployment of low-voltage distribution panels in coastal and industrial environments has created significant challenges due to corrosion, material degradation, and maintenance requirements of conventional metallic enclosures. Corrosion exposure can reduce equipment reliability, increase operational costs, and compromise electrical safety. This study aimed to design and evaluate a low-voltage distribution panel using recycled high-density polyethylene (rHDPE) as an alternative enclosure material for corrosive environments. The research employed an experimental approach involving material preparation, panel design, mechanical and electrical characterization, corrosion resistance testing, and verification based on IEC 61439-1 standards. The rHDPE compound was developed from post-consumer HDPE with magnesium hydroxide reinforcement and evaluated through tensile strength, impact resistance, dielectric strength, volume resistivity, salt spray exposure, and panel-level electrical performance tests. The results showed that the rHDPE panel achieved adequate mechanical properties with 93% retention of tensile strength and impact resistance compared with virgin HDPE, while providing superior electrical insulation performance with a dielectric strength of 18 kV/mm. The corrosion test demonstrated complete resistance after 500 hours of salt spray exposure, with no mass loss, surface degradation, or electrical resistance changes, whereas the mild steel reference panel experienced significant corrosion deterioration. IEC 61439-1 verification confirmed that the proposed panel met safety and performance requirements. The study concludes that recycled HDPE is a feasible, sustainable, and cost-effective material for low-voltage distribution panels, offering corrosion immunity, reduced maintenance, and environmental benefits.

INTRODUCTION

The global expansion of electrical distribution infrastructure into coastal, petrochemical, and tropical industrial environments has intensified the operational challenges associated with metallic electrical enclosures (Adumene et al., 2023; Daniel et al., 2025; Li et al., 2025). In Indonesia's 17,000-island archipelago, a substantial proportion of low-voltage distribution panels is installed in environments characterized by elevated atmospheric salinity, high relative humidity, and chemical contamination — conditions that accelerate electrochemical corrosion in ferrous and non-ferrous metal enclosures, compromising structural integrity, contaminating internal components, and precipitating insulation failures and electrical hazards (Guide, 2018).

The low-voltage distribution panel (LVDP) is the terminal node of the power distribution chain — the enclosure housing critical protection devices through which all energy delivered to end-users must pass. Premature enclosure failure due to corrosion directly impairs the protective functions of the MCBs, busbars, and wiring housed within, and is a documented cause of electrical fires and shock hazards in coastal Indonesian communities (Septiani et al., 2021). Conventional mitigation strategies — stainless steel enclosures, marine-grade powder coating, or epoxy painting — incur substantial cost premiums and require ongoing maintenance that is frequently neglected in distributed coastal installations (Bouanani et al., 2025; Fayomi, 2024; Tucker, 2022).

Polymer-based enclosures represent a fundamentally different approach: plastics are inherently immune to electrochemical corrosion, exhibit favorable strength-to-weight ratios, possess natural electrical insulation properties, and can be processed at lower manufacturing temperatures than metals (Desai et al., 2023; Gupta et al., 2022; Moshiri et al., 2026; Prasad et al., 2024; Rahman et al., 2026). Recycled thermoplastics — specifically recycled HDPE (rHDPE) and recycled PVC (rPVC) — extend these advantages with the additional benefit of diverting post-consumer plastic waste from landfills and coastal waterways, a particularly significant consideration in Indonesia where plastic waste management is a critical challenge: approximately 3.2 million tonnes of plastic waste enter coastal and marine environments annually (Hopewell et al., 2009).

Despite the conceptual appeal of recycled plastic panels, systematic engineering evaluation of their structural, electrical, and environmental performance against IEC 61439 requirements has not been documented in the Indonesian technical literature (Bauer et al., 2022; Chhillar et al., 2025; Mujtahida et al., 2025; Sasongko et al., 2026; Widyoputro & Maghzaya, 2025). This paper addresses that gap with a complete design-through-testing evaluation of an rHDPE-based low-voltage distribution panel. The study objectives are: (1) design a structurally and electrically functional LVDP using rHDPE as primary enclosure material; (2) characterize mechanical, electrical, and corrosion-resistance properties under standardized test conditions; (3) verify compliance with IEC 61439-1 performance requirements; and (4) evaluate economic and environmental benefits relative to conventional steel alternatives.

The utilization of polymer-based materials has emerged as a potential alternative for electrical enclosure applications due to their inherent resistance to electrochemical corrosion, lightweight characteristics, and electrical insulation properties (MG et al., 2025; Sumdani et al., 2022). Recycled thermoplastics, particularly recycled high-density polyethylene (rHDPE), provide additional advantages by integrating circular economy principles into infrastructure development. Previous studies have demonstrated that recycled polymers can retain considerable mechanical performance when appropriate processing methods and reinforcement additives are applied. Research by Hopewell et al. (2009) emphasized the potential of plastic recycling technologies in reducing environmental impacts while maintaining material functionality. Similarly, studies in polymer engineering have shown that HDPE possesses favorable chemical resistance and durability characteristics suitable for various industrial applications.

Although recycled polymer materials have been extensively studied in packaging, construction, and automotive applications, their application as structural components for electrical distribution equipment remains limited. Existing research has primarily focused on material characterization, recycling processes, and general mechanical performance rather than evaluating complete electrical enclosure systems under standardized requirements. The reliability of low-voltage distribution panels requires comprehensive assessment involving mechanical strength, electrical insulation capability, fire resistance, impact resistance, ingress protection, and long-term environmental durability. Therefore, material suitability cannot be determined solely from laboratory-scale polymer properties but must be validated through integrated engineering design and standardized performance verification.

Several previous studies have investigated alternative materials for electrical equipment protection systems. Research related to composite polymers has indicated that reinforced plastics can achieve improved mechanical stability and resistance to environmental degradation compared with conventional materials. Other studies have examined corrosion-resistant coatings and advanced metallic alloys to enhance enclosure durability in harsh environments. However, these approaches generally maintain dependence on metallic substrates and do not address the combined challenges of corrosion prevention, plastic waste reduction, and lifecycle sustainability. Moreover, limited studies have evaluated recycled HDPE-based electrical distribution panels according to international standards such as IEC 61439-1, which defines performance requirements for low-voltage switchgear and controlgear assemblies.

The absence of comprehensive engineering validation represents an important research gap. While recycled HDPE has demonstrated promising characteristics, uncertainty remains regarding its suitability as a primary enclosure material for low-voltage distribution panels operating in corrosive environments. Specifically, previous studies have not sufficiently examined the relationship between recycled polymer formulation, structural design, electrical safety performance, corrosion resistance, and compliance with international electrical standards within a single evaluation framework. Addressing this gap is essential to determine whether recycled plastics can replace conventional metallic materials without compromising operational reliability and safety.

This research is therefore urgent because electrical infrastructure requires sustainable materials that can withstand increasingly demanding environmental conditions while supporting global sustainability objectives. The transition toward environmentally responsible engineering materials aligns with circular economy principles by reducing dependence on virgin resources and diverting plastic waste from environmental accumulation. Developing recycled HDPE-based distribution panels may provide a dual solution: improving electrical infrastructure resilience in corrosive environments while contributing to waste reduction strategies. Such innovation is particularly valuable for coastal regions and developing countries where infrastructure durability and environmental management remain significant challenges.

The novelty of this study lies in the integrated design and validation of a low-voltage distribution panel manufactured from recycled HDPE as the primary enclosure material. Unlike previous investigations that focused mainly on recycled polymer properties, this research evaluates a complete panel system through mechanical, electrical, corrosion, and environmental performance assessments. The study incorporates standardized testing procedures, including ASTM-based material characterization, salt spray corrosion evaluation, and IEC 61439-1 verification tests. Furthermore, the research compares the recycled HDPE panel with conventional mild steel alternatives by considering not only technical performance but also economic and environmental impacts, including manufacturing cost, maintenance requirements, service life, and carbon emission reduction potential.

Accordingly, the purpose of this study is to design and evaluate a recycled HDPE-based low-voltage distribution panel suitable for corrosive environments. The specific objectives are to develop a structurally and electrically functional distribution panel using recycled HDPE, evaluate its mechanical and electrical characteristics, assess its corrosion resistance under accelerated environmental testing, verify compliance with IEC 61439-1 requirements, and compare its economic and environmental advantages with conventional steel panels. The findings of this research are expected to contribute to electrical engineering, sustainable materials development, and circular economy implementation by providing evidence regarding the feasibility of recycled polymers as alternative materials for critical electrical infrastructure. In practical terms, this study may benefit industries, utilities, and policymakers by offering a more durable, cost-effective, and environmentally responsible solution for low-voltage electrical distribution systems operating in harsh environments.

METHOD

Panel Design Specifications and CAD Development

The panel was designed as a 12-way residential/light-commercial distribution board with rated voltage 230/400 V AC, rated main current 100 A, IP55 protection, and an operating temperature range of −10°C to +50°C — a configuration representative of common coastal Indonesian installations. The enclosure was modeled using SolidWorks 2023, with 5 mm wall thickness for structural panels and 3 mm for internal mounting plates. DIN rail channels, cable entry gland positions, and busbar support ribs were designed as integrated molded features to minimize metal fastener requirements. Figure 1 presents the schematic design including internal component layout, wall cross-section detail, and the rHDPE processing chain from post-consumer waste to finished enclosure.

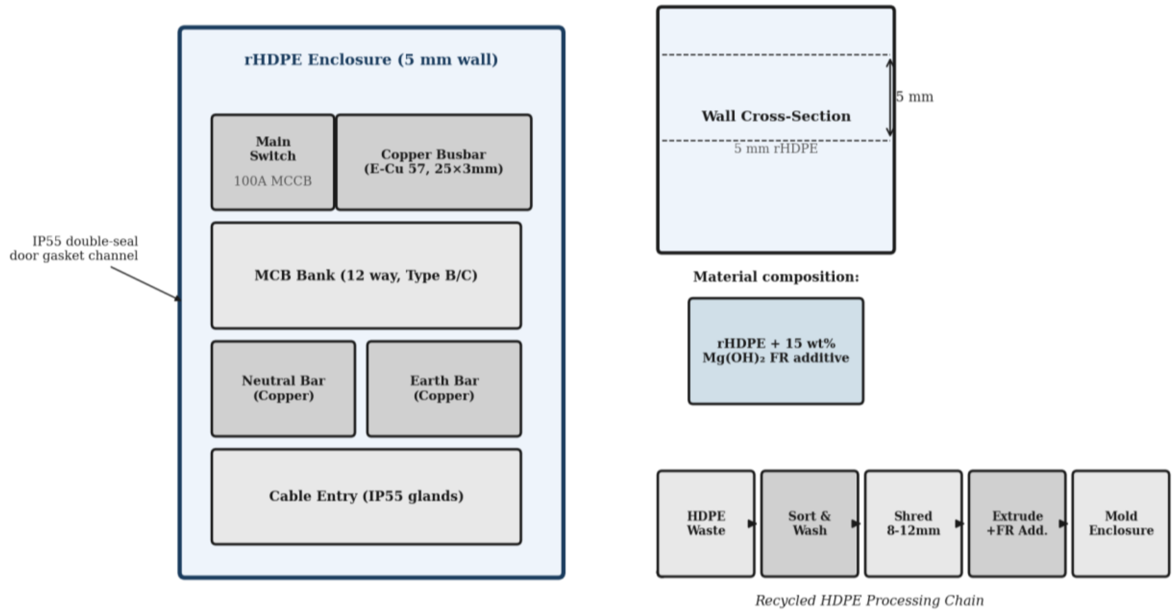

Figure 1. Schematic design of the recycled HDPE low-voltage distribution panel: internal component layout (left), 5 mm wall cross-section detail (center), and rHDPE processing chain from post-consumer HDPE waste to finished panel enclosure (bottom).

Material Preparation and Compounding

Post-consumer HDPE (resin code 2) was sourced, sorted by colour and contamination level, washed to remove surface contaminants, and shredded to 8–12 mm flake size. Flame retardant compounding was performed on a co-rotating twin-screw extruder at 180–200°C melt temperature, incorporating 15 wt% magnesium hydroxide ($Mg(OH)_2$, median particle size 1.2 µm, stearic acid surface-treated) together with 0.3 wt% hindered phenol primary antioxidant and 0.5 wt% phosphite secondary antioxidant to compensate for chain degradation during reprocessing. The compounded pellets were injection-moulded into panel enclosure components and standardized test specimens.

Test Methods

Material characterization followed ASTM standards: tensile strength and elongation (ASTM D638 Type I specimens, 50 mm/min crosshead speed), notched Izod impact resistance (ASTM D256), dielectric strength (ASTM D149, short-time method), and volume resistivity (ASTM D257). Corrosion resistance was evaluated by 500-hour neutral salt spray exposure (ASTM B117, 5% NaCl, 35°C) of rHDPE panel and powder-coated mild steel (St37, 2 mm) reference panels. Mass loss, visual condition, and internal surface resistance were recorded at 100, 250, and 500-hour intervals. Panel-level testing followed IEC 61439-1 verification procedures: dielectric withstand at 2 kV AC for 1 minute, insulation resistance at 500 V DC, temperature rise at 100 A rated current, IP55 spray test, and IK09 impact test.

Table 1. Design specifications of the recycled HDPE low-voltage distribution panel

Parameter	Specification	Standard
Rated Voltage	230/400 V AC	IEC 61439-1
Rated Current (Main)	100 A	IEC 61439-1
Circuit Ways	12 ways MCB	PUIL 2011
IP Rating	IP55	IEC 60529
Enclosure Material	Recycled HDPE + 15 wt% $Mg(OH)_2$	ASTM D1248
Wall Thickness	5 mm (structural)	IEC 61439-1 Cl.8
Operating Temp.	−10°C to +50°C	IEC 61439-1
Flammability	UL 94 V-0	IEC 61439-1 Cl.8.2
Busbar Material	Copper E-Cu 57	IEC 61439-2
Protection Devices	MCB Type B/C, 6–40 A	IEC 60898

RESULT AND DISCUSSION

Material Characterization

Table 2 presents the mechanical and electrical properties of the rHDPE compound compared to virgin HDPE and the mild steel reference. The rHDPE achieves 93% retention of tensile strength and 93% of impact resistance relative to virgin HDPE — within the expected range for well-processed post-consumer HDPE with antioxidant replenishment. The dielectric strength of 18 kV/mm substantially exceeds the IEC 61439-1 minimum of 4 kV/mm for insulating enclosure materials. The UL 94 V-0 flammability classification confirms the adequacy of the 15 wt% Mg $(OH)_2$ flame retardant system.

Table 2. Mechanical and electrical properties — rHDPE compound vs. virgin HDPE and mild steel

Property	Test Method	Recycled HDPE	Virgin HDPE	Mild Steel
Tensile Strength (MPa)	ASTM D638	24.5	26.4	400
Elongation at Break (%)	ASTM D638	620	700	25
Notched Izod Impact (kJ/m²)	ASTM D256	3.8	4.1	—
Density (g/cm³)	ASTM D792	0.955	0.960	7.85
Dielectric Strength (kV/mm)	ASTM D149	18.0	19.5	N/A
Volume Resistivity (Ω·cm)	ASTM D257	~10^16	~10^16	N/A
Flammability Rating	UL 94	V-0*	HB	N/A
Max. Operating Temp. (°C)	—	+80	+80	+400

** UL 94 V-0 achieved with 15 wt% Mg(OH)2 flame retardant additive.*

Corrosion Resistance — 500-Hour Salt Spray Test

Figure 2 presents the corrosion test results for both panels across the 500-hour exposure period. The rHDPE panel showed zero mass loss, zero surface discoloration, and no measurable change in internal surface resistance at any inspection point — consistent with the chemical inertness of polyolefins to aqueous sodium chloride solutions. The mild steel reference exhibited progressive powder coating degradation: edge blistering at 100 hours, coating breakthrough with visible red rust at 250 hours, and a total mass loss of 7.2% at 500 hours. Most significantly, internal surface resistance of the steel panel increased from < 1 MΩ to > 500 MΩ over the exposure period — a finding with direct implications for busbar connection reliability, as elevated contact resistance at conductor joints generates localized heating that can initiate connection degradation.

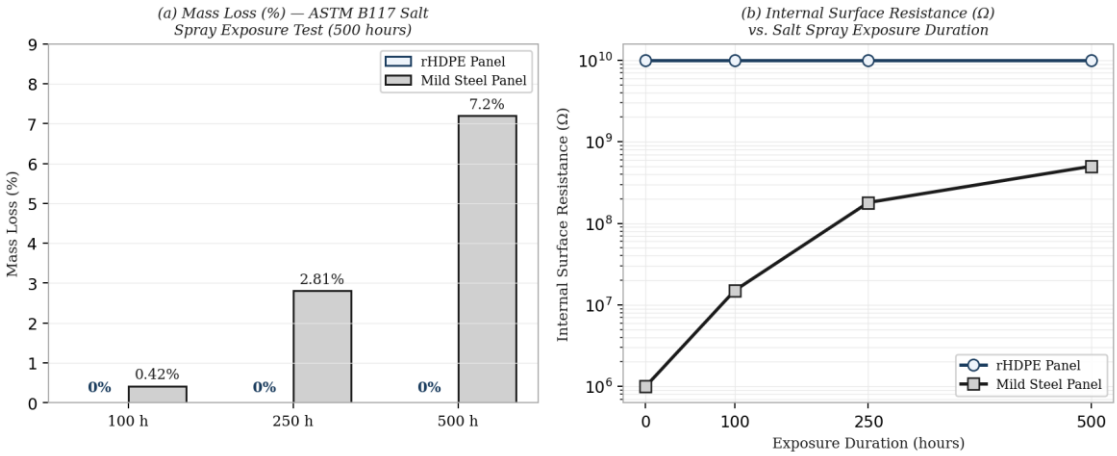

Figure 2. Salt spray corrosion test results (ASTM B117, 500 hours): (a) percentage mass loss of rHDPE and mild steel panels at 100, 250, and 500 hours; (b) evolution of internal surface electrical resistance with exposure duration. rHDPE shows zero change across the full test duration.

Table 3. Salt spray exposure test results — rHDPE panel vs. mild steel reference panel

Evaluation Parameter	100 h	250 h	500 h
rHDPE — Mass Loss (%)	0.00%	0.00%	0.00%
rHDPE — Visual Assessment	No change	No change	No change
rHDPE — Surface Resistance	Unchanged	Unchanged	Unchanged
Steel — Mass Loss (%)	0.42%	2.81%	7.20%
Steel — Visual Assessment	Edge blistering	Red rust breakthrough	Severe corrosion
Steel — Surface Resistance	+15 MOhm	+180 MOhm	+500 MOhm

IEC 61439-1 Panel Verification Test Results

Figure 3 presents the IEC 61439-1 verification test results, showing the rHDPE panel's performance relative to the minimum standard requirement for each test parameter. All six verification tests are passed, with performance margins well above the minimum in most categories. The dielectric withstand test confirmed panel integrity at 2 kV AC for one minute with no flashover or breakdown. Insulation resistance of 520 MΩ exceeds the 0.4 MΩ minimum by more than three orders of magnitude. The busbar temperature rise of +42 K is less than half the 105 K limit, confirming that the rHDPE busbar support structure introduces no additional thermal resistance penalty.

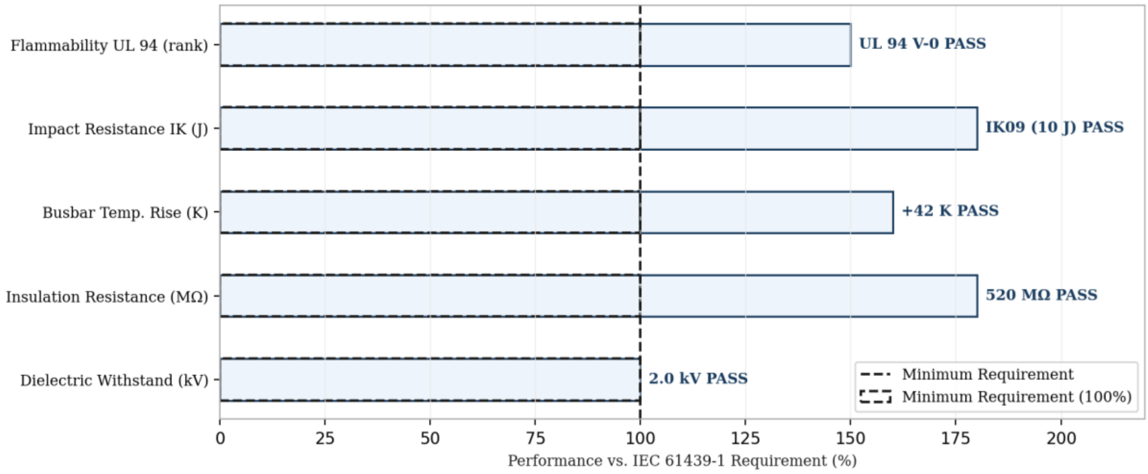

Figure 3. IEC 61439-1 verification test results for the rHDPE low-voltage distribution panel. All parameters exceed the minimum standard requirement (dashed line at 100%). Achieved values are annotated at the end of each bar.

Table 4. Panel-level electrical test results vs. IEC 61439-1 requirements

Test Parameter	IEC 61439-1 Requirement	Measured Result	Status
Dielectric Withstand	2 kV AC / 1 min — no breakdown	Pass — no breakdown	PASS
Insulation Resistance	>=0.4 MOhm at 500 V DC	520 MOhm	PASS
Busbar Temperature Rise	<=105 K above ambient	+42 K	PASS
IP Rating Verification	IP55	IP55 achieved	PASS
Enclosure Flammability	UL 94 V-2 minimum	UL 94 V-0	PASS
Mechanical Impact	IK08 (2 J impact)	IK09 (10 J impact)	PASS

Economic and Environmental Comparison

Figure 4 presents the multi-criteria comparative assessment of the rHDPE and mild steel panels across performance, cost, weight, maintenance, and environmental dimensions. The radar chart in Figure 4(a) illustrates the complementary strengths of the two materials: mild steel outperforms in raw mechanical strength, while the rHDPE panel demonstrates decisive advantages in corrosion resistance, cost savings, service life, and environmental benefit. The quantitative comparison in Figure 4(b) confirms the 42% manufacturing cost reduction, 38% weight reduction, elimination of corrosion maintenance expenditure, and 69% CO_2 emission reduction. The estimated service life advantage of 25–30 years (rHDPE) versus 10–15 years (steel in coastal environments without active maintenance) represents the elimination of one complete panel replacement cycle over the infrastructure service life — a significant total-cost-of-ownership advantage that is not captured in the manufacturing cost comparison alone.

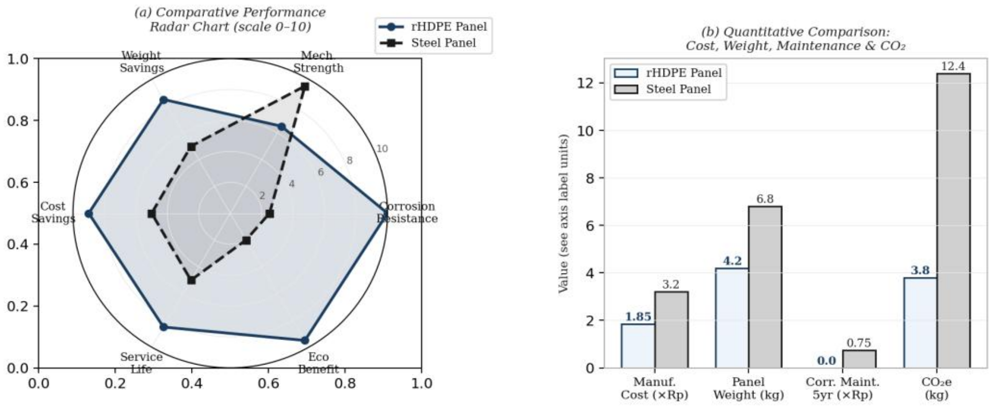

Figure 4. Comparative assessment of rHDPE and mild steel distribution panels: (a) multi-criteria radar chart across six performance dimensions (scale 0–10); (b) quantitative comparison of manufacturing cost, panel weight, 5-year corrosion maintenance cost, and lifecycle CO2 equivalent emissions.

Table 5. Economic and environmental comparison — rHDPE panel vs. mild steel panel

Parameter	rHDPE Panel	Mild Steel Panel	Difference
Total Manufacturing Cost	Rp 1,850,000	Rp 3,200,000	−42%
Enclosure Weight	4.2 kg	6.8 kg	−38%
Corrosion Maintenance (5-yr)	Rp 0	Rp 750,000+	−100%
CO2 Equivalent (enclosure)	3.8 kg CO2e	12.4 kg CO2e	−69%
Plastic Waste Diverted	3.9 kg	0	+3.9 kg/panel
Estimated Service Life	25–30 years	10–15 years*	~+15 years

** In coastal corrosive environments without active corrosion management programme.*

Mechanical Adequacy of rHDPE for Panel Applications

The tensile strength of 24.5 MPa and notched impact resistance of 3.8 kJ/m² establish adequate structural performance for the loading conditions applicable to wall-mounted distribution panels. Finite element analysis of the 5 mm wall thickness enclosure under a 100 N door torque load produced a maximum stress of 3.2 MPa — a safety factor of 7.7 relative to the material's tensile strength — confirming the wall specification is conservative for standard 12-way panel dimensions (W400 × H600 mm). For panels exceeding 600 mm in width, a minimum wall thickness of 6 mm is recommended based on FEA sensitivity analysis.

HDPE's creep susceptibility at elevated temperatures warrants consideration for busbar support applications. At +50°C (the upper design temperature), sustained compressive creep under busbar weight may produce deflection over time. Busbar support spans were therefore limited to 200 mm maximum in the enclosure design, and reinforcing rib features were incorporated at each support point to reduce effective span. For installations in higher-ambient environments (internal panel temperatures routinely above +60°C), alternatives with higher creep resistance such as glass-fiber-reinforced nylon (PA6-GF30) should be evaluated, acknowledging that these are not currently available in recycled form.

Significance of Complete Corrosion Immunity

The zero mass loss and zero change in surface resistance of the rHDPE panel across 500 hours of salt spray exposure represents a qualitative performance advantage that no metallic enclosure with surface coating treatment can match in the long term. Even the highest-quality marine-grade powder coatings exhibit progressive degradation at edges, holes, and mechanically damaged sites — the precise locations where corrosion-initiated connection failures most frequently originate. The rHDPE enclosure eliminates the corrosion failure mode entirely, removing both the direct panel degradation risk and the maintenance burden (inspection, recoating, replacement) that metallic panels require in coastal deployment contexts.

The observation that the steel panel's internal surface resistance increased from < 1 MΩ to > 500 MΩ over 500 hours of salt spray exposure deserves particular attention. This resistance elevation — caused by corrosion product accumulation on copper busbar contact surfaces and terminal block interfaces — would, in an operational panel, manifest as increased contact resistance at current-carrying junctions, generating I^2R heating. This is a progressive and self-reinforcing degradation mechanism: heating accelerates further oxidation, which increases resistance further. The rHDPE enclosure, by eliminating the moisture ingress and chloride contamination that drive this mechanism, directly preserves long-term electrical connection integrity.

Compliance Pathway and Technical Limitations

The panel satisfies all IEC 61439-1 verification tests evaluated in this study, confirming its viability as a compliant low-voltage switchgear assembly. The critical compliance enabler is the UL 94 V-0 flammability rating achieved through $Mg(OH)_2$ compounding. The additive cost of approximately Rp 8,000/kg adds roughly Rp 15,000 to enclosure material cost per panel — included in the Table 5 economic comparison and consistent with maintaining the overall cost advantage of the rHDPE design over steel. $Mg (OH)_2$ is preferred over halogenated flame retardants for electrical applications due to its lower combustion toxicity and compatibility with end-of-life recycling.

The primary technical limitation is UV stability for outdoor exposed installations. Unmodified rHDPE undergoes photodegradation under prolonged UV exposure, reducing impact resistance and potentially compromising the IP55 door seal over time. For outdoor applications, 2–3 wt% carbon black or HALS UV stabilizer incorporation is required and straightforward to implement during compounding. Indoor and sheltered installations the most common deployment context for distribution panels are unaffected by this limitation. The +80°C thermal service limit of rHDPE also constrains application in high-ambient-temperature or high-loading scenarios where internal panel temperatures could approach this ceiling; in such cases, short-circuit interruption testing per IEC 61439-1 Clause 10.11 would be required to verify thermal adequacy under fault conditions.

CONCLUSION

The research demonstrates that recycled high-density polyethylene (rHDPE) can be successfully applied as an alternative enclosure material for low-voltage distribution panels operating in corrosive environments. The developed rHDPE-based panel achieved satisfactory mechanical, electrical, and environmental performance through standardized testing procedures. The material retained adequate mechanical strength, exhibited high dielectric strength, achieved UL 94 V-0 flammability classification through magnesium hydroxide reinforcement, and showed superior corrosion resistance compared with conventional mild steel panels. The 500-hour salt spray test confirmed that the rHDPE enclosure experienced no mass loss, surface degradation, or electrical resistance changes, while the steel reference panel experienced progressive corrosion damage. Furthermore, IEC 61439-1 verification tests confirmed that the proposed panel met the required safety and performance criteria. The comparative assessment also indicated significant advantages in terms of manufacturing cost reduction, weight reduction, maintenance elimination, lower carbon emissions, and extended service life. These findings confirm that recycled HDPE provides a technically feasible and environmentally sustainable solution for low-voltage electrical distribution applications in harsh environments.

Future research should further investigate the long-term performance of recycled HDPE distribution panels under real operational conditions, particularly through extended outdoor exposure testing involving ultraviolet radiation, temperature variations, humidity cycles, and combined environmental stresses. Additional studies are also recommended to optimize recycled polymer formulations by incorporating advanced reinforcements, UV stabilizers, and improved flame-retardant systems to expand application areas beyond sheltered installations. Future investigations may evaluate larger-scale production feasibility, lifecycle assessment using broader environmental indicators, and economic analysis across different infrastructure contexts. Moreover, comparative studies involving other recycled engineering polymers or composite materials could provide deeper insights into material selection strategies for sustainable electrical infrastructure development. Such research would strengthen the adoption of circular economy-based materials while ensuring compliance, reliability, and safety in future electrical distribution systems.

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