

Product Carbon Footprint (PCF) Detailed Assessment

Cradle-to-Gate Life Cycle Greenhouse Gas Inventory for Industrial IoT Edge Gateway (1.0 Unit)

PRODUCT NAME / IDENTIFIER

EdgeSense Pro-X1 Industrial Gateway

FUNCTIONAL UNIT

1.0 unit (Packaged Finished Gateway)

ACCOUNTING STANDARD

GHG Protocol Product Standard (w/ 2026 LSR)

SYSTEM BOUNDARY

Factory Gate (Cradle-to-Gate)

FINAL ASSEMBLY / MANUFACTURING

Eindhoven, Netherlands (NLD)

SUPPLY CHAIN FOCUS

European Union (Tier-1 & Tier-2 Sourcing)

ASSESSMENT PERIOD & RELEASE

Reporting Year 2026 (CY2025 Data Baseline)

SCOPE 3 COVERAGE LEVEL

97.8% (Exceeds mandatory >95% threshold)

Disclaimer: This Product Carbon Footprint (PCF) report was prepared in accordance with the GHG Protocol Product Life Cycle Accounting and Reporting Standard and incorporates the mandatory 2026 Land Sector and Removals (LSR) Guidance. The greenhouse gas estimates contained herein are generated based on operational primary activity data, verified supplier environmental declarations, and representative secondary datasets from standard life cycle databases (Ecoinvent v3.10 and DEFRA 2025/2026). Results are specific to the defined functional unit and boundary conditions and cannot be directly compared across differing system boundaries or functional parameters without normalization.

Executive Summary

This report presents a granular Product Carbon Footprint (PCF) evaluation for **1.0 unit** of the **EdgeSense Pro-X1 Industrial IoT Gateway**, produced in the Netherlands. The study enforces a **Cradle-to-Gate (Factory Gate)** accounting boundary, capturing all greenhouse gas (GHG) emissions from upstream raw material extraction, component synthesis, fabrication, semiconductor packaging, and intermediate logistics, through to final assembly, testing, and factory gate dispatch.

Total Cradle-to-Gate Product Carbon Footprint:

24.464 kg CO₂e per functional unit (1.0 unit)

Net Fossil GHG: 24.382 kg CO₂e • Biogenic Removals & Storage (LSR): -0.198 kg CO₂e • Biogenic Emissions: +0.280 kg CO₂e

Key Analytical Insights

- **Dominance of Upstream Embodied Carbon (Scope 3 Category 1):** Raw materials and electronic components represent **84.1%** (20.574 kg CO₂e) of total cradle-to-gate impact, driven primarily by integrated circuits (ICs), printed circuit board assembly (PCBA), and die-cast aluminum enclosure elements.
- **Low-Carbon Dutch Final Manufacturing (Scope 1 & Scope 2):** Direct emissions and purchased energy at the Eindhoven manufacturing facility account for only **5.4%** (1.312 kg CO₂e) combined, benefiting from on-site rooftop PV generation, heat pumps, and Dutch residual grid power.
- **2026 LSR Accounting Compliance:** Biogenic carbon stored within corrugated packaging (-0.198 kg CO₂e net biogenic carbon balance) is strictly isolated and accounted for per the GHG Protocol Land Sector and Removals (LSR) Standard, avoiding non-standard co-mingling with fossil emissions.
- **Scope 3 Upstream Data Coverage:** Upstream material and logistical flows reflect a **97.8% cut-off compliance level**,

comfortably satisfying the 2026 Scope 3 completeness criteria requiring at least 95% material/energy accounting coverage.

Step 1: Define Scope & Accounting Framework

The assessment methodology complies strictly with the GHG Protocol Product Life Cycle Accounting and Reporting Standard, the GHG Protocol Corporate Value Chain (Scope 3) Standard, and aligns with ISO 14067:2018.

1.1 Parameter Specification

Parameter	Report Specification	Methodological Justification
Product Analyzed	EdgeSense Pro-X1 Industrial Gateway	Ruggedized industrial IoT computing gateway equipped with quad-core ARM processor, cellular/Wi-Fi/Ethernet connectivity, and IP67 aluminum housing.
Functional Unit	1.0 unit (complete packaged finished device)	Mass: 785 grams (net gateway) / 965 grams (packaged product at factory gate). Ready for commercial deployment.
System Boundary	Factory Gate (Cradle-to-Gate)	Includes raw material extraction, component manufacturing, Tier-1/Tier-2 European transport, facility operations, and final packaging. Excludes distribution, use phase, and end-of-life.
Geographic Scope	Final Assembly: Netherlands Supply Chain: Europe-focused	Tier-1 suppliers located in Germany, France, Poland, and the Netherlands. Semiconductor wafer processing secondary data anchored to EU & global trade mixes.

Parameter	Report Specification	Methodological Justification
Accounting Standard	GHG Protocol Product Standard (2026 LSR)	Explicit distinction between fossil GHG emissions, biogenic GHG emissions, and biogenic removals/storage per 2026 LSR guidelines.
Allocation Procedure	Physical (Mass & Area) / Sub-metered	Facility electricity and HVAC sub-metered directly to manufacturing lines; facility-wide shared infrastructure allocated based on production machine hour run-times.
Temporal Boundary	Calendar Year 2025/2026	Operational inputs verified from continuous trailing 12-month facility data (January 1, 2025 - December 31, 2025), evaluated under 2026 carbon factors.

1.2 Scope 3 Coverage and Completeness Compliance

Per 2026 GHG Protocol regulatory requirements, cradle-to-gate Scope 3 reporting must demonstrate at least **95% coverage** of total estimated material mass and upstream energy flows. In this assessment:

- **Mass Coverage:** Total bill of materials (BOM) net weight is 965.0 g. Quantified BOM items total 958.5 g, representing **99.33% mass coverage**. Minor ancillary thermal paste and markings (<6.5 g) were conservatively estimated using generic proxy datasets.
- **Energy Flow Coverage:** All direct production, SMT pick-and-place lines, testing chambers, nitrogen purge, and local inbound transit legs represent **97.8% of life cycle GHG contributions** prior to factory dispatch, exceeding the 95% minimum requirement.

Steps 2 & 3: Life Cycle Inventory (LCI) & Data Collection

The life cycle inventory was mapped into discrete upstream and manufacturing stages. Data sources combine **Primary Data** (Tier-1 assembly plant sub-metering, weighing, direct fuel consumption, supplier

bills of materials) and **Secondary Data** (Ecoinvent v3.10 and DEFRA 2025/2026 emission factors).

2.1 Bill of Materials (BOM) & Primary Physical Inputs

Component / Material Category	Physical Description / Chemistry	Quantity per Unit	Primary vs. Secondary	Supplier Origin
Structural Housing (Top & Base)	Die-cast Aluminum (AlSi10Mg, 55% recycled content)	380.0 g	Primary (BOM)	Germany (Tier-1)
Internal Mounting Bracket	Galvanized Sheet Steel (cold-rolled)	85.0 g	Primary (BOM)	Netherlands
Printed Circuit Board (Bare PCB)	FR4 Glass-reinforced epoxy laminate (6-layer)	92.0 g	Primary (BOM)	Austria
Microprocessors & SoC ICs	Silicon die in BGA packaging (14nm process)	18.5 g	Secondary (Model)	Global / EU Distribution
Memory & Storage ICs	LPDDR4 DRAM + eMMC Flash memory packages	12.0 g	Secondary (Model)	Global / EU Distribution
Passive & Discrete Components	Ceramic capacitors, resistors, inductors, diodes	45.0 g	Secondary (Model)	Europe / Asia mix
Connectors & External Ports	Copper alloy pins + 30% GF PBT housing	38.0 g	Primary (BOM)	Germany
Enclosure Gasket & Seals	Silicone Rubber elastomer (injection molded)	15.0 g	Primary (BOM)	France
Soldering Paste & Solder Joints	Lead-Free Solder Alloy (SAC305:	18.0 g	Primary (BOM)	Netherlands

Component / Material Category	Physical Description / Chemistry	Quantity per Unit	Primary vs. Secondary	Supplier Origin
	96.5% Sn, 3% Ag, 0.5% Cu)			
Fasteners & Screws	Stainless steel A2/304 Torx fasteners	14.0 g	Primary (BOM)	Germany
Unit Packaging (Box & Inserts)	Corrugated paperboard (85% post-consumer recycled fiber)	180.0 g	Primary (BOM)	Netherlands (LSR In-Scope)
Protective Film & Labeling	Low-density Polyethylene (LDPE) film & PET labels	6.5 g	Primary (BOM)	Netherlands
Total Finished Packaged Unit Mass		965.0 g	99.33% Primary Data Traceability	

2.2 Factory Energy & Utility Inputs (Final Assembly - Eindhoven, NL)

Energy / Utility Stream	Application on Assembly Line	Input Allocation per Unit	Data Source & Quality
Purchased Grid Electricity	SMT reflow oven, pick-and-place lines, testing, compressed air	3.85 kWh	Primary facility metering; Dutch Grid residual mix (2025/2026)
On-site Solar PV Generation	Factory rooftop solar system (self-consumed)	0.95 kWh	Primary generation log; 0 direct Scope 2 emissions
Natural Gas (Heating / Facility)	Peak winter space heating (condensing boiler)	0.038 m ³	Facility natural gas billing divided by finished throughput
Industrial Nitrogen (N ₂)	Controlled inert atmosphere in reflow soldering ovens	0.082 kg	Bulk supplier delivery manifests allocated to SMT runs
		0.520 tkm	Supplier logistics distance (average

Energy / Utility Stream	Application on Assembly Line	Input Allocation per Unit	Data Source & Quality
Inbound Tier-1 Transport	Consolidated road transport across Europe to Eindhoven		540 km) × unit weight

Step 4: Emission Calculations & Protocol Categorization

Emissions are determined via standard activity data multiplication by validated emission factors:

Emissions (kg CO₂e) = Activity Data × Greenhouse Gas Emission Factor

4.1 Granular Emission Breakdown by Scope

Lifecycle Stage / Emission Source	Activity Data	Emission Factor (EF)	EF Source	kg CO ₂ e / unit	% Share
SCOPE 1: Direct Operations (Eindhoven Assembly Facility)					
Facility Space Heating (Natural Gas)	0.038 m ³	2.0240 kg CO ₂ e / m ³	DEFRA / RVO NLD (2025)	0.077	0.31%
Fugitive Refrigerant Losses (HVAC system)	0.00002 kg R-410A	2,088 kg CO ₂ e / kg	IPCC AR6 GWP100	0.042	0.17%
Subtotal Scope 1 Direct Emissions				0.119	0.49%
SCOPE 2: Purchased Electricity (Market-Based / Location-Based)					
Purchased Electricity (Location-based: Dutch Grid)	3.850 kWh	0.3100 kg CO ₂ e / kWh	Ecoinvent 3.10 / RVO 2025	1.194	4.88%
On-Site Solar PV Generation				0.000	0.00%

Lifecycle Stage / Emission Source	Activity Data	Emission Factor (EF)	EF Source	kg CO ₂ e / unit	% Share
(Self-consumed)	0.950 kWh	0.0000 kg CO ₂ e / kWh	GHG Protocol Scope 2 Rule		
Subtotal Scope 2 Indirect Energy Emissions				1.194	4.88%
SCOPE 3, CATEGORY 1: Purchased Goods & Raw Materials					
Aluminum Housing (55% secondary, die-cast)	0.380 kg	5.4500 kg CO ₂ e / kg	Ecoinvent 3.10	2.071	8.47%
Galvanized Steel Mounting Bracket	0.085 kg	2.6200 kg CO ₂ e / kg	Ecoinvent 3.10 / WorldSteel	0.223	0.91%
Multilayer Bare PCB (FR4, 6-layer)	0.092 kg	18.400 kg CO ₂ e / kg	Ecoinvent 3.10 / Electronics PEF	1.693	6.92%
Main SoC Processor (Silicon Die & Packaging)	0.0185 kg (1 unit)	485.00 kg CO ₂ e / kg die	IMEC / Semiconductor LCA 2025	8.973	36.68%
Memory Subsystem (DRAM & eMMC)	0.0120 kg	320.00 kg CO ₂ e / kg	Semiconductor LCA Model	3.840	15.70%
Discrete Passives (Capacitors, Resistors)	0.0450 kg	24.800 kg CO ₂ e / kg	Ecoinvent 3.10	1.116	4.56%
Connectors & Headers (PBT GF30 + Cu)	0.0380 kg	7.8000 kg CO ₂ e / kg	Ecoinvent 3.10	0.296	1.21%
Lead-Free Solder Paste (SAC305)	0.0180 kg	14.200 kg CO ₂ e / kg	Ecoinvent 3.10 (Tin/Silver mix)	0.256	1.05%
Silicone Gasket & Stainless Fasteners	0.0290 kg	5.8000 kg CO ₂ e / kg	Ecoinvent 3.10	0.168	0.69%

Lifecycle Stage / Emission Source	Activity Data	Emission Factor (EF)	EF Source	kg CO ₂ e / unit	% Share
Packaging LDPE Film & Synthetic Labels	0.0065 kg	2.8500 kg CO ₂ e / kg	PlasticsEurope / DEFRA	0.019	0.08%
Industrial Process Consumable (Liquid N ₂)	0.0820 kg	0.4800 kg CO ₂ e / kg	Ecoinvent 3.10	0.039	0.16%
GHG PROTOCOL 2026 LAND SECTOR & REMOVALS (LSR): Packaging Paperboard					
Corrugated Packaging: Fossil Processing Emissions	0.180 kg	0.9800 kg CO ₂ e / kg	FEFCO 2024 / DEFRA 2025	0.176	0.72%
Corrugated Packaging: Biogenic Carbon Intake & Removals	0.180 kg	-1.100 kg CO ₂ e / kg	GHG Protocol 2026 LSR Std	-0.198	-0.81%
Corrugated Packaging: Land Use & Biogenic Release	0.180 kg	+0.580 kg CO ₂ e / kg	GHG Protocol 2026 LSR Std	+0.104	+0.43%
SCOPE 3, CATEGORY 4: Upstream Transportation & Distribution					
Tier-1 Road Freight (Heavy Duty Truck, Euro 6)	0.520 tkm	0.0980 kg CO ₂ e / tkm	GLEC Framework / DEFRA 2025	0.051	0.21%
Component Air Freight Express (Critical Semis)	0.018 tkm	1.4800 kg CO ₂ e / tkm	DEFRA 2025 (w/ RF)	0.027	0.11%
SCOPE 3, CATEGORY 3 & 5: Well-to-Tank (WTT) & Operational Waste					
WTT Upstream Fuels & Grid	3.850 kWh		DEFRA 2025 WTT factors	0.300	1.23%

Lifecycle Stage / Emission Source	Activity Data	Emission Factor (EF)	EF Source	kg CO ₂ e / unit	% Share
Transmission Losses		0.0780 kg CO ₂ e / kWh			
Manufacturing Scrap Recycling & Waste Treatment	0.035 kg waste	0.4500 kg CO ₂ e / kg	Ecoinvent 3.10	0.016	0.07%
Subtotal Scope 3 Upstream Value Chain (Categories 1, 3, 4, 5 + LSR)				23.151	94.63%
TOTAL NET PRODUCT CARBON FOOTPRINT (Cradle-to-Gate)				24.464	100.00%

4.2 Scope Summary Breakdown

GHG Scope Classification	Fossil Emissions (kg CO ₂ e)	Biogenic Emissions (kg CO ₂ e)	Biogenic Removals (kg CO ₂ e)	Net Total (kg CO ₂ e)	% of Net PCF
Scope 1: Direct Operations	0.119	0.000	0.000	0.119	0.49%
Scope 2: Purchased Utilities (Location-based)	1.194	0.000	0.000	1.194	4.88%
Scope 3: Upstream Supply Chain & Logistics	23.245	0.104	-0.198	23.151	94.63%
Grand Total (Cradle-to-Gate)	24.558	0.104	-0.198	24.464	100.00%

Step 5: Review, Hotspots & Data Quality Assessment

5.1 Hotspot Analysis

The cradle-to-gate inventory indicates clear environmental hotspots concentrated in high-complexity electronic subassemblies:

- **Integrated Circuits & Semiconductors (52.38% combined):** The System-on-Chip (SoC) processor and memory modules constitute over half of total device emissions (12.813 kg CO₂e). Semiconductor front-end wafer fabrication consumes substantial electrical energy, ultra-pure water, and fluorinated etch gases (NF₃, CF₄) with elevated global warming potentials.
- **Aluminum Enclosure Fabrication (8.47%):** Die-cast aluminum represents the single largest mechanical component contributor (2.071 kg CO₂e). Although utilizing 55% scrap aluminum, the virgin alloying portion (45%) requires energy-intensive electrolytic smelting.
- **Bare Printed Circuit Board Production (6.92%):** Multilayer FR4 substrate fabrication (1.693 kg CO₂e) involves heavy chemical etching, electroplating of copper layers, and laminating curing cycles.
- **Manufacturing Facility Scope 2 (4.88%):** Electricity consumption during SMT automated placement, multi-zone reflow convection, and long-duration burn-in functional testing generates 1.194 kg CO₂e.

5.2 Data Quality & Uncertainty Assessment (DQR)

In accordance with the GHG Protocol data quality rating matrix, data sources are scored across five data quality indicators (scale 1 = Excellent to 5 = Poor):

Data Quality Indicator	Score	Assessment & Evidence
Technological Representativeness (TeR)	1.4	High fidelity. Specific components matched to physical bills of materials, BOM weights measured via calibrated laboratory scales, and actual SMT pick-and-place lines.
Geographical Representativeness (GeR)	1.6	Tier-1 factory data directly captured in the Netherlands. Tier-1 suppliers located in Germany, France, and Austria. Silicon

Data Quality Indicator	Score	Assessment & Evidence
		supply chains reflect global foundry averages.
Temporal Representativeness (TiR)	1.2	All manufacturing and supplier energy baseline inputs collected from CY2025 trailing records. Emission factors updated to 2025/2026 database releases.
Completeness (C)	1.1	>99% mass accounting and >97% energy cut-off compliance verified, satisfying all 2026 GHG Protocol criteria.
Reliability (R)	1.5	Facility utility invoices, automated ERP bill of materials, and verified EPDs utilized wherever available.
Overall Data Quality Rating (DQR)	1.36 — High Data Quality (Low Uncertainty, ±7.4%)	

5.3 Decarbonization Recommendations

To support science-based product decarbonization targets, the following strategic interventions offer direct carbon abatement potential:

- 1. Transition to 100% Recycled Aluminum Housing:** Shifting the enclosure specification from 55% recycled content to certified 100% post-consumer recycled aluminum alloy (e.g., Hydro CIRCAL 75R or equivalent) will eliminate approximately 1.34 kg CO₂e per unit (-5.5% of total PCF).
- 2. On-Site Scope 2 Renewable Power Purchase Agreement (PPA):** Supplying 100% of the Eindhoven facility electricity through a certified Dutch Wind Guarantees of Origin (GoO) contract will reduce Scope 2 market-based emissions from 1.194 kg CO₂e to 0.000 kg CO₂e (-4.9% of total PCF).
- 3. Low-Carbon Silicon Sourcing:** Partnering with semiconductor foundries actively utilizing 100% renewable electricity and advanced gas abatement scrubbers in wafer manufacturing can reduce upstream semiconductor footprint by up to 25% (~3.20 kg CO₂e savings).