

Product Carbon Footprint (PCF) Technical Report

Cradle-to-Gate Assessment for Industrial Smart Commercial Heat Pump (HP-NL-500)

Accounting Standard:	GHG Protocol Product Life Cycle Accounting and Reporting Standard
Complementary Standard:	2026 GHG Protocol Land Sector and Removals (LSR) Standard
Functional Unit:	1.0 unit (HP-NL-500, 25 kW Nominal Thermal Capacity)
System Boundary:	Factory Gate (Cradle-to-Gate: Stages A1 - A3)
Geographic Focus:	Final Assembly: Netherlands; Supply Chain: Europe-Focused
Scope 3 Coverage:	97.8% of Total Upstream Gate Boundary (>95% Threshold Compliant)
Assessment Completed:	October 2026

Notice & Disclaimer: This Product Carbon Footprint (PCF) report is generated in accordance with the GHG Protocol Product Life Cycle Accounting and Reporting Standard and the 2026 Land Sector and Removals (LSR) guidance. The findings herein are compiled based on primary activity data provided by the final manufacturing site in Tilburg, Netherlands, combined with secondary life cycle inventory (LCI) data from recognized databases (Ecoinvent 3.10 and DEFRA 2025/2026). This document is intended for formal compliance, supplier decarbonization assessments, and corporate inventory reporting.

Executive Summary

This report presents the verified cradle-to-gate Product Carbon Footprint (PCF) for one finished unit (1.0 unit) of the **HP-NL-500 Industrial Smart Commercial Heat Pump System**, assembled in the Netherlands. The assessment strictly follows the Greenhouse Gas Protocol (GHG Protocol) Product Life Cycle Accounting and Reporting Standard, integrating the 2026 Land Sector and Removals (LSR) Standard for upstream biogenic materials and direct emissions accounting.

The total cradle-to-gate carbon footprint is **1,482.42 kg CO₂e per functional unit** under the primary Market-Based electricity accounting approach (and **1,514.86 kg CO₂e per functional unit** under the Location-Based approach). Upstream Scope 3 emissions account for the vast majority of the footprint, with material extraction and component manufacturing driving the overall impact.

Key Emissions Summary (Functional Unit: 1.0 Finished Heat Pump)

- **Scope 1 (Direct Operations):** 9.42 kg CO₂e (0.64% of total)
- **Scope 2 (Indirect - Purchased Electricity & Heating, Market-Based):** 2.21 kg CO₂e (0.15% of total)
- **Scope 3 (Upstream Value Chain, Cradle-to-Gate):** 1,470.79 kg CO₂e (99.21% of total)
- **Scope 3 Boundary Coverage:** 97.8% of upstream impacts quantified, fully satisfying the 2026 ≥95% Scope 3 coverage rule.
- **2026 LSR Land Sector & Carbon Removals:** Net neutral biogenic storage of -12.40 kg CO₂e in FSC-certified timber packaging, reported distinctly in accordance with GHG Protocol 2026 LSR requirements.

1. Scope Definition and Assessment Boundary

1.1 Functional Unit

The functional unit is defined as **1.0 unit of fully assembled, tested, and packaged HP-NL-500 Commercial Heat Pump** with a rated heating capacity of 25.0 kW (R290 working fluid, total dry weight of 214.5 kg, excluding external distribution piping and secondary ducting).

1.2 System Boundary: Factory Gate (Cradle-to-Gate)

The assessment boundary extends from the extraction of raw geological and bio-based resources up to the completion and packaging of the unit at the manufacturing facility gate in Tilburg, North Brabant, Netherlands (Stages A1 through A3 according to EN 15804 / ISO 14067 modules). Downstream installation, operational lifetime refrigerant replenishment, building operational use (Use Stage B1–B7), and final decommissioning (End of Life Stage C1–C4) are excluded from this factory-gate declaration.

- **Stage A1 (Raw Material Extraction and Processing):** Mining, smelting, chemical refining, and precursor synthesis of sheet steel, copper piping, aluminum exchanger blocks, compressor castings, printed circuit boards (PCBs), and hydrocarbon refrigerants.
- **Stage A2 (Inbound Transportation):** Heavy freight, rail, and European regional container logistics transporting intermediate parts from Tier-1 and Tier-2 European suppliers to Tilburg, Netherlands.
- **Stage A3 (Manufacturing & Final Packaging):** Sheet metal cutting, automated CNC bending, copper tube expansion, robotic soldering, hermetic refrigerant charging, vacuum tightness leak testing, end-of-line electrical performance validation, and wooden/corrugated protective packaging.

1.3 Geographic Scope & Supply Chain Sourcing

The manufacturing and quality verification take place exclusively in the **Netherlands**. The supply chain has an explicit **Europe-Focused** geographic footprint:

- Chassis structural steel and brackets: Germany and Belgium (average transit 350 km).

- Copper coils, piping, and brass fittings: Germany and Poland (average transit 720 km).
- Aluminum microchannel evaporators: Sweden and France (average transit 950 km).
- Inverter motor drive, semiconductors, and electronic control boards: Germany and Czech Republic (average transit 780 km).
- Refrigerant fluid (Ultra-pure R290 Propane): Netherlands domestic chemical distributor (transit 85 km).

1.4 Cut-off Criteria & Allocation Rules

In conformance with the GHG Protocol Product Standard, all mass and energy flows exceeding 0.1% of the total unit weight or primary energy use were cataloged. Cumulative exclusions (such as grease lubricants, traceability barcode labels, and minor soldering flux residues) do not exceed 0.8% of unit mass, ensuring that **>99.2% of total mass** and **>95% Scope 3 emissions** are completely accounted for.

Physical allocation based on mass and unit throughput is applied to allocate general facility electrical consumption, heating gas, and internal scrap handling at the Tilburg production facility.

2. Life Cycle Inventory (LCI) & Mapping

The LCI accounts for every material input, chemical additive, sub-assembly component, and energy stream entering the manufacturing gate.

LCI Category / Sub-Assembly	Material / Energy Constituent	Quantity per Unit	Data Source Tier	Geographic Provenance
Chassis & Structural Framework	Galvanized Structural Steel Plate (S250GD)	82.40 kg	Tier 1 Primary / Supplier EPD	Duisburg, Germany
Hydronic Circuitry & Coils	Deoxidized High Phosphorus Copper (Cu-DHP)	26.80 kg	Tier 1 Primary / Supplier EPD	Wieland, Germany
	Wrought Aluminum Alloy	31.50 kg		Rheinwerk, Germany

LCI Category / Sub-Assembly	Material / Energy Constituent	Quantity per Unit	Data Source Tier	Geographic Provenance
Heat Exchanger Arrays	(AlMn / Series 3000)		Tier 2 Secondary / Ecoinvent	
Hermetic Scroll Compressor	Cast Iron Casing, Rotor, Stator, NdFeB Magnet	42.00 kg	Tier 1 Primary Bill of Materials	France / EU
Variable Speed Inverter & Control	PCB Substrates, Silicon MOSFETs, Solder, Cu traces	6.80 kg	Tier 2 Secondary / Ecoinvent	Germany / Czech Rep.
Thermal & Acoustic Insulation	Rigid Polyurethane Foam (PUR) & EPDM Gaskets	11.20 kg	Tier 2 Secondary / Ecoinvent	Antwerp, Belgium
Working Fluid (Refrigerant)	R290 Hydrocarbon (GWP = 3.0, AR6 100-yr)	1.65 kg	Primary Chemical Receipt	Rotterdam, Netherlands
Factory Packaging	FSC Certified Kiln-Dried Pine Pallet	16.50 kg	Primary Supplier Delivery Data	Netherlands (LSR Compliant)
Packaging Protective Enclosure	Double-wall Corrugated Paperboard (70% recycled)	6.20 kg	Primary Supplier Delivery Data	Netherlands
Assembly Electricity	Grid Electricity (Offset via Dutch Wind PPA)	108.50 kWh	Primary Factory Sub-meter	Tilburg, Netherlands
Assembly Space & Test Heating	Direct Natural Gas (High-efficiency boiler)	46.20 kWh (4.52 m³)	Primary Gas Utility Invoice	Tilburg, Netherlands

3. Data Collection & Quality Assessment

Data sets are classified into primary (activity data gathered directly from facility systems and primary tier-1 bills of materials) and secondary data (peer-reviewed life cycle databases including Ecoinvent v3.10 cut-off and DEFRA 2025/2026 GHG conversion factors).

Data Parameter	Assessment Criteria	Quality Rating	Mitigation & Methodological Notes
Temporal Representativeness	Data collected over calendar year 2025/2026	Very High	All meter readings and shipping manifests represent recent 12-month production.
Geographical Specificity	Netherlands final gate & West-European supply nodes	High	Country-specific grid factors and specific European freight distance models applied.
Technological Alignment	State-of-the-art heat pump manufacturing lines	High	Direct measurement of energy sub-meters for sheet pressing, soldering, and vacuum pumps.
Completeness & Uncertainty	Comprehensive mass balance verification	Very High	Mass balance discrepancy is under $\pm 0.8\%$. Monte Carlo standard deviation: $\pm 3.4\%$.

4. Emissions Calculation & Results Matrix

Emissions calculations follow the foundational formula:
Emissions (kg CO₂e) = Activity Data × Emission Factor (EF)

4.1 Consolidated Emissions Breakdown (By Scope and Activity)

GHG Scope & Life Cycle Stage	Activity Description	Activity Volume	Emission Factor Used	EF Source	Emissions (kg CO ₂ e)	Share (%)
Scope 1 (Direct)	Natural gas combustion (factory heating & drying)	46.20 kWh	0.2023 kg CO ₂ e/kWh	DEFRA 2025	9.35	0.63%
Scope 1 (Direct)	Fugitive test loss during vacuum & gas charge (R290)	0.024 kg	3.00 kg CO ₂ e/kg	IPCC AR6	0.07	<0.01%
Scope 2 (Market-Based)	Assembly plant electricity (Dutch Wind PPA w/ GoO)	108.50 kWh	0.0204 kg CO ₂ e/kWh	AIB EECS 2025	2.21	0.15%
Scope 3 (Cat 1: Materials)	Galvanized Sheet Steel (Chassis/ Frame)	82.40 kg	2.28 kg CO ₂ e/kg	WorldSteel / Ecoinvent	187.87	12.67%
Scope 3 (Cat 1: Materials)	High-Purity Copper Tubing & Wire	26.80 kg	5.14 kg CO ₂ e/kg	ICA / Ecoinvent 3.10	137.75	9.29%
Scope 3 (Cat 1: Materials)	Aluminum Microchannel Exchanger Fins	31.50 kg	8.25 kg CO ₂ e/kg	European Aluminium	259.88	17.53%
Scope 3 (Cat 1: Materials)	Hermetic Scroll Compressor Assembly	42.00 kg	6.85 kg CO ₂ e/kg	Supplier EPD / Ecoinvent	287.70	19.41%
Scope 3 (Cat 1: Materials)	Power Inverter, Silicon & Control PCB Module	6.80 kg	64.20 kg CO ₂ e/kg	Ecoinvent 3.10 (Electronics)	436.56	29.45%

GHG Scope & Life Cycle Stage	Activity Description	Activity Volume	Emission Factor Used	EF Source	Emissions (kg CO ₂ e)	Share (%)
Scope 3 (Cat 1: Materials)	Rigid Polyurethane Insulation (PUR) & EPDM	11.20 kg	3.72 kg CO ₂ e/kg	PlasticsEurope	41.66	2.81%
Scope 3 (Cat 1: Materials)	Refrigerant R290 Chemical Synthesis	1.65 kg	3.45 kg CO ₂ e/kg	Ecoinvent 3.10	5.69	0.38%
Scope 3 (Cat 1: Packaging)	Corrugated Cardboard Enclosure (70% recycled)	6.20 kg	0.88 kg CO ₂ e/kg	FEFCO / DEFRA	5.46	0.37%
Scope 3 (Cat 1: Packaging)	Kiln-Dried Pine Pallet (Fossil GHG fraction)	16.50 kg	0.28 kg CO ₂ e/kg	Ecoinvent 3.10	4.62	0.31%
Scope 3 (Cat 3: WTT & T&D)	Well-to-Tank Fuels & Electricity T&D Losses	154.7 kWh eq	0.046 kg CO ₂ e/kWh	DEFRA 2025 WTT	7.12	0.48%
Scope 3 (Cat 4: Transport)	Inbound Road Freight (Euro 6 Diesel Truck >32t)	412.0 tkm	0.218 kg CO ₂ e/tkm	EcoTransIT / DEFRA	89.82	6.06%
Scope 3 (Cat 4: Transport)	Inbound Electric Freight Rail (Components)	185.0 tkm	0.028 kg CO ₂ e/tkm	EcoTransIT World	5.18	0.35%
Scope 3 (Cat 5: Waste)	Factory Scrap Metal & Polymer Recycling routes	4.80 kg	0.31 kg CO ₂ e/kg	DEFRA Waste 2025	1.49	0.10%
Total Cradle-to-Gate Footprint (Market-Based Scope 2)					1,482.42	100.00%
Alternative: Location-Based Scope 2 (Dutch Grid @ 0.320 kg CO₂e/kWh = 34.72 kg)					1,514.86	-

4.2 Application of 2026 GHG Protocol Land Sector and Removals (LSR) Standard

In accordance with the **2026 Land Sector and Removals (LSR) Guidance**, land-use change (dLUC/sLUC), biogenic emissions, and carbon removals cannot be bundled into an unweighted fossil net figure without transparent itemization. The wood packaging utilized for the transport framework was audited as follows:

LSR Accounting Category	Physical Stream	Primary Parameter	LSR Carbon Value	Standard Compliance Status
Direct Land Use Change (dLUC)	Sustainably Managed Pine (FSC Certified)	Zero Deforestation post-Dec 2020	0.00 kg CO ₂ e	Fully Compliant with EUDR & LSR
Biogenic Carbon Inflow (Removals)	16.50 kg Softwood Timber (50% Carbon)	Photosynthetic atmospheric uptake	-24.75 kg CO ₂ e	Reported separately (Non-fossil credit)
Biogenic Carbon Processing Emissions	Kiln drying and timber offcut handling	Kiln boiler bio-combustion	+12.35 kg CO ₂ e	Reported under LSR Biogenic Flux
Net Land Sector Biogenic Storage at Factory Gate			-12.40 kg CO ₂	Stored in unit until end-of-life disposal

5. Hotspot Analysis, Data Quality & Reduction Recommendations

5.1 Hotspot Identification

The cradle-to-gate inventory indicates three critical emissions hotspots:

- **Inverter Power Electronics & PCBs (29.45% of total):** Despite comprising only 3.2% of the unit mass (6.80 kg), high-temperature silicon fabrication, gold/copper substrate plating, and cleanroom vacuum etching make the electronic control module the single highest emissions contributor (436.56 kg CO₂e).

- **Hermetic Compressor Sub-Assembly (19.41% of total):** Driven by energy-intensive nodular cast-iron machining, stator winding copper, and neodymium permanent magnet refinement (287.70 kg CO₂e).
- **Aluminum Microchannel Heat Exchanger (17.53% of total):** Smelting primary aluminum requires substantial thermal and electrochemical energy (259.88 kg CO₂e).
- **Transport & Inbound Logistics (6.41% of total):** Road transport from central and southern Europe contributes 95.00 kg CO₂e.

5.2 Compliance Verification: 2026 Scope 3 Coverage (≥95%)

Under the 2026 GHG Protocol guidance, cradle-to-gate product footprint declarations must guarantee at least 95% coverage of all relevant upstream Scope 3 emissions. As calculated:

- Total Scope 3 Cradle-to-Gate emissions quantified: **1,470.79 kg CO₂e**.
- Identified negligible cut-offs (adhesives, small rubber grommets, zinc coatings <0.5 kg): Estimated at **32.8 kg CO₂e**.
- **Coverage Ratio:** $1,470.79 / (1,470.79 + 32.80) = 97.82\%$, which strictly satisfies the ≥95.0% compliance threshold.

5.3 Decarbonization Roadmap

1. **Low-Carbon Aluminum Procurement:** Transitioning the heat exchanger coil suppliers to certified post-consumer recycled aluminum or European smelters powered by low-carbon hydroelectric power (<4.0 kg CO₂e/kg Al) will eliminate up to 133.8 kg CO₂e per unit (-9.0% total PCF).
2. **Direct Supplier Inverter Electronics Engagement:** Mandate tier-1 power electronics suppliers to purchase renewable electricity for cleanroom fabrication, targeting a 25% reduction in inverter carbon intensity by 2028 (-109.1 kg CO₂e).
3. **Shift Inbound Transport to Intermodal Rail:** Transitioning cross-border freight from Germany and France from Euro-6 road trucks to the electrified Trans-European Rail freight corridor will reduce Category 4 logistics emissions by over 62% (-58.9 kg CO₂e).
4. **Factory Electrification (Scope 1 Elimination):** Replace the natural gas boiler used for factory space heating and chamber testing with a

unit from the Tilburg site's own heat pump line, reducing direct Scope 1 operational emissions to near-zero (<0.1 kg CO₂e).