

Product Carbon Footprint (PCF) Analysis

Detailed Life Cycle Greenhouse Gas Assessment: Industrial Fuel-Grade Bioethanol (1.0 kg)

Accounting Standard:	GHG Protocol (Product Life Cycle Standard & 2026 Land Sector and Removals Standard)
Subject Product:	Fuel-Grade Anhydrous Bioethanol (99.5% purity)
Functional Unit:	1.0 kg bioethanol at factory gate
System Boundary:	Cradle-to-Factory Gate
Final Production Country:	Germany
Supply Chain Focus:	Europe-Focused (Central/Northern European Agricultural Feedstock)
Feedstock Transport Mode:	Rail Freight (Dedicated 500 km Route)
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Assessor / Practice:	Senior Sustainability Practice & Corporate Decarbonization Advisory

Disclaimer: This Product Carbon Footprint (PCF) report is generated based on available engineering process data, validated regional secondary datasets (Ecoinvent v3.10, DEFRA 2026, Agri-footprint v6.3), and established industry accounting principles. All accounting

Executive Summary

This technical report presents a rigorous cradle-to-factory-gate Product Carbon Footprint (PCF) for **1.0 kg of anhydrous bioethanol (99.5% purity)** manufactured at an industrial wet-milling biorefinery in **Germany**. The supply chain model integrates regional European feedstock production (feed wheat), specialized bulk logistics comprising a **500 km rail transit route**, and an on-site cogeneration bio-processing facility.

The accounting methodology strictly complies with the **GHG Protocol Product Life Cycle Accounting and Reporting Standard**, full **Scope 3 completeness requirements (>95% data coverage)**, and the integrated **2026 GHG Protocol Land Sector and Removals (LSR) Standard**.

- **Total Net Cradle-to-Gate Fossil & Land GHG Footprint: 1.249 kg CO₂e per 1.0 kg bioethanol** (energy-allocated; equivalent to 46.6 g CO₂e/MJ based on an LHV of 26.8 MJ/kg).
- **Embodied Biogenic Carbon Removal (LSR Memo Item): -1.913 kg CO₂/kg** sequestered photosynthetically during crop growth and temporarily stored in the ethanol molecule.
- **Scope Distribution:** Scope 1 accounts for 21.6% (0.270 kg CO₂e), Scope 2 accounts for 8.9% (0.111 kg CO₂e), and Scope 3 accounts for 69.5% (0.868 kg CO₂e) of allocated lifecycle impacts.
- **Logistics Efficiency:** Implementing 500 km electric-predominant rail freight for bulk feedstock yields an ultra-low transport impact of **0.022 kg CO₂e/kg** bioethanol (1.8% of total footprint), achieving a 74% emissions reduction compared to equivalent diesel road haulage.

Step 1: Scope & Boundary Definition

Establishing unambiguous system boundaries and allocation principles is foundational under the GHG Protocol Product Standard.

1.1 Functional Unit & Reference Flow

The functional unit is defined as **1.0 kg of denatured anhydrous bioethanol** (ethanol content $\geq 99.5\%$ by weight, moisture content $\leq 0.3\%$, lower heating value LHV = 26.8 MJ/kg), packaged in bulk at the biorefinery loading terminal in Germany.

1.2 System Boundary: Cradle-to-Factory Gate

The study incorporates all upstream material extraction, agricultural operations, logistics, direct biorefinery conversion, and co-product handling up to the factory gate:

- **Agricultural Production (Upstream):** Cultivation of milling-grade feed wheat in Central Europe, synthetic nitrogen/phosphorus/potassium fertilizer manufacturing, machinery diesel use, and direct/indirect soil dinitrogen monoxide (N_2O) emissions.
- **Inbound Logistics:** Rail transport spanning **500 km** from regional aggregation elevators (Poland/East Germany) to the processing hub in Germany.
- **Biorefinery Processing (Gate):** Grain milling, enzymatic liquefaction, saccharification, yeast propagation, fermentation, multi-stage distillation, molecular sieve dehydration, and wastewater treatment.
- **Co-Product Generation:** Co-production of high-protein **Distillers Dried Grains with Solubles (DDGS)** for animal feed.
- **Excluded Downstream Phases:** Factory-gate boundary excludes finished fuel distribution, blending with fossil gasoline, pump dispensing, and vehicle tailpipe combustion.

1.3 Allocation Methodology

The bioethanol conversion process yields two economic outputs: fuel ethanol and DDGS. Following GHG Protocol hierarchy and EU Renewable Energy Directive (RED II/III) alignment, process inputs and emissions are partitioned using **Energy Allocation (Lower Heating Value - LHV)**:

- Bioethanol LHV: $26.8 \text{ MJ/kg} \times 1.00 \text{ kg yield} = 26.80 \text{ MJ}$ (**64.89% allocation factor**).

- DDGS LHV: 16.5 MJ/kg × 0.88 kg yield = 14.52 MJ (**35.11% allocation factor**).
- Combined Energy Base: 41.32 MJ per reference run.

1.4 2026 Land Sector and Removals (LSR) Protocol Adherence

Under the 2026 GHG Protocol LSR guidance:

- Biogenic removals and fossil emissions are reported strictly as distinct line items; biogenic carbon is not netted out against fossil emissions to obscure structural footprint intensity.
- Land management emissions (agricultural soil N₂O and CH₄) are isolated from industrial fossil emissions.
- Direct Land Use Change (dLUC) is evaluated based on a 20-year historical land-use assessment across European agricultural statistical databases (Eurostat/CORINE Land Cover).

Step 2 & 3: Lifecycle Mapping & Inventory Data Collection

The process lifecycle maps mass flows, chemical auxiliaries, utility streams, and logistics legs required to manufacture 1.0 kg of bioethanol. Primary biorefinery operational data is coupled with regional secondary datasets (Ecoinvent 3.10 and DEFRA 2026).

2.1 Life Cycle Inventory (LCI) Inputs & Outputs

The table below details all raw materials, process aids, fuels, and energy carriers entering the system boundary per 1.0 kg bioethanol reference flow (pre-allocation gross values, alongside allocation factors applied).

Lifecycle Stage & Parameter	Gross Input / FU	Allocated Input (64.89%)	Data Category	Data Source & Quality Notes
Agricultural Feedstock Feed Wheat (13.5% moisture)	2.80 kg	1.817 kg	Secondary / Agri-footprint	Central European average wheat cultivation; Ecoinvent 3.10 / Agri-footprint 6.3. High temporal quality (2024-2026).

Lifecycle Stage & Parameter	Gross Input / FU	Allocated Input (64.89%)	Data Category	Data Source & Quality Notes
Feedstock Rail Transport Bulk freight (electric/ diesel traction)	1.400 t·km (2.80 kg × 500 km)	0.908 t·km	Logistics Specified	500 km direct rail freight in Europe. European average rail mix (78% electric, 22% diesel traction; DEFRA 2026).
Enzymes: Alpha-Amylase Liquefaction biochemical catalyst	2.50 g	1.62 g	Secondary	Fermentation-derived enzyme concentrate; Novozymes / Ecoinvent proxy.
Enzymes: Glucoamylase Saccharification biochemical catalyst	3.50 g	2.27 g	Secondary	Industrial fungal enzyme broth; production via aerobic submerged fermentation.
Fermentation Yeast Saccharomyces cerevisiae active dry	2.00 g	1.30 g	Secondary	European active dry yeast manufacturing process; molasses substrate.
Process Water & Conditioning Demineralized & treated well water	4.80 kg	3.11 kg	Primary facility data	On-site closed-loop cooling and condensate recovery system; municipal/well source.
Industrial Chemicals Sulfuric acid (98%) & NaOH (50%)	12.0 g	7.79 g	Secondary	pH adjustment during mash and Clean-In-Place (CIP) sanitation protocols.
Thermal Energy (Natural Gas) Steam generation / evaporation	7.20 MJ	4.67 MJ	Primary facility data	High-efficiency natural gas condensing boiler / on-site CHP unit in Germany.
Electricity (Grid Mix) Biorefinery parasitic load	0.450 kWh	0.292 kWh	Primary / Secondary	German residual electrical grid mix (BDEW / Federal Environment Agency UBA).
Co-Product Generated DDGS (10% moisture)	0.880 kg	—	Primary co-product	High-protein animal feed co-product; energy-allocated out of boundary.

Scope 3 Completeness Verification (>95% Target): In accordance with the 2026 GHG Protocol Scope 3 provisions, this inventory captures 98.4% of total cradle-to-gate mass and energy inputs. Minor infrastructure capital goods (plant construction steel and concrete) were screened via economic input-output (EEIO) modeling and determined to contribute <1.6% of total lifecycle CO₂e, falling within the permitted de minimis exclusion threshold.

Step 4: Emission Calculations & Impact Assessment

Emissions are calculated applying the standard formula: Emissions (kg CO₂e) = Activity Data × Emission Factor. Global Warming Potentials (GWPs) are sourced from the IPCC 6th Assessment Report (AR6) with a 100-year time horizon (GWP₁₀₀: CO₂ = 1, CH₄ = 27.9, N₂O = 273.0).

4.1 Comprehensive Life Cycle Emissions Inventory

Activity / Source Item	Allocated Activity	Emission Factor (EF)	Factor Source	Scope	kg CO ₂ e / FU
Wheat: Fossil Cultivation Machinery fuel, seed, agrochemicals	1.817 kg grain	0.2200 kg CO ₂ e / kg	Ecoinvent 3.10 / Agri-footprint	Scope 3 (Cat 1)	0.400
Wheat: Land Management Biogenic soil N ₂ O & urea hydrolysis	1.817 kg grain	0.1800 kg CO ₂ e / kg	IPCC Tier 2 / LSR 2026	Scope 3 (Cat 1)	0.327
Feedstock Transport (Rail) Electric/diesel rail, 500 km route	0.908 t·km	0.0245 kg CO ₂ e / t·km	DEFRA 2026 / EcoTransIT	Scope 3 (Cat 4)	0.022
Enzymes & Active Yeast Submerged aerobic fermentation	0.0052 kg	8.3200 kg CO ₂ e / kg	Ecoinvent 3.10 bio-catalysts	Scope 3 (Cat 1)	0.043
Process Chemicals	0.0078 kg	0.3205 kg CO ₂ e / kg	Ecoinvent 3.10 chemical database	Scope 3 (Cat 1)	0.003

Activity / Source Item	Allocated Activity	Emission Factor (EF)	Factor Source	Scope	kg CO ₂ e / FU
H ₂ SO ₄ (98%) & NaOH (50%)					
Stationary Combustion (Gas) On-site steam generation boiler	4.672 MJ th	0.0561 kg CO ₂ e / MJ	GHG Protocol / German UBA	Scope 1	0.262
Fugitive & Effluent CH₄/N₂O On-site wastewater anaerobic plant	0.6489 unit	0.0120 kg CO ₂ e / FU	Biorefinery internal telemetry	Scope 1	0.008
Purchased Electricity Location-based German grid mix	0.2920 kWh	0.3800 kg CO ₂ e / kWh	German UBA 2025/2026 mix	Scope 2	0.111
Upstream Fuel & Energy (WTT) Well-to-tank losses for gas & power	4.67 MJ / 0.29 kWh	Composite WTT factors	DEFRA 2026 (Cat 3 WTT)	Scope 3 (Cat 3)	0.073
Total Net Cradle-to-Gate Product Carbon Footprint (Fossil + Land)					1.249

4.2 GHG Protocol Standard Scope Classification

Disaggregating emissions across Scope 1, Scope 2, and Scope 3 provides complete accounting transparency for external reporting and CSRD/ESRS E1 alignment:

GHG Protocol Emission Scope	Included Life Cycle Activities	Emissions (kg CO ₂ e)	Percentage Contribution
Scope 1: Direct Operations	On-site natural gas boiler combustion (0.262) and anaerobic wastewater process emissions (0.008).	0.270	21.62%
Scope 2: Purchased Electricity	Indirect emissions from biorefinery grid electricity consumption (German grid mix).	0.111	8.89%
Scope 3: Upstream Value Chain	Agricultural wheat cultivation (0.727), rail logistics 500 km (0.022), chemical inputs (0.046),	0.868	69.49%

GHG Protocol Emission Scope	Included Life Cycle Activities	Emissions (kg CO ₂ e)	Percentage Contribution
	and upstream WTT fuels/power (0.073).		
Total Cradle-to-Gate GHG Footprint	Combined Scopes 1, 2, and 3	1.249	100.00%

4.3 2026 Land Sector and Removals (LSR) Protocol Multi-Disciplinary Balance

In accordance with the 2026 LSR Standard, emissions are categorized into fossil emissions, land management fluxes, land use change, and biogenic removals:

LSR Accounting Classification	Physical Mechanism & Boundary Details	Impact (kg CO ₂ e / kg)
1. Industrial & Agricultural Fossil GHG	Fossil CO ₂ from fuel combustion, grid power, fertilizer manufacturing, and rail transport.	+0.922
2. Land Management Biogenic GHG	Direct and indirect soil dinitrogen monoxide (N ₂ O) resulting from synthetic and organic N fertilizer application.	+0.327
3. Direct Land Use Change (dLUC)	Zero dLUC attributed: feed wheat cultivated on historical European cropland (>20 years continuous arable status).	0.000
Total Net Reporting Emissions (Fossil + Land Sector)	Standard gate-to-gate inventory sum required for compliance disclosures	+1.249
4. Biogenic Atmospheric Removal (LSR Memo)	Gross photosynthetic CO ₂ sequestered during wheat growth, stored in ethanol molecule (MW C ₂ H ₅ OH = 46.07; 52.14% C content).	-1.913

Step 5: Review, Hotspot Analysis & Data Reliability

5.1 Emission Hotspot Analysis

Evaluation of the life cycle reveals that emissions are concentrated in three key operational nodes:

- **Agricultural Production (58.2% of Total Footprint):** Raw wheat cultivation (0.727 kg CO₂e) is the single largest contributor. Synthetic nitrogen fertilization drives both high upstream manufacturing footprints (Haber-Bosch process) and biological soil emissions (N₂O nitrification/denitrification pathways).
- **Biorefinery Thermal Generation (21.0% of Total Footprint):** Evaporation, distillation column reboilers, and DDGS ring-dryers consume substantial thermal energy (0.262 kg CO₂e Scope 1 from natural gas).
- **Grid Electricity Consumption (8.9% of Total Footprint):** Reliance on the German national grid mix generates 0.111 kg CO₂e Scope 2 emissions due to residual coal and fossil gas power plants in the German generation portfolio.
- **Logistics Advantage (1.8% of Total Footprint):** The 500 km rail supply chain generates only 0.022 kg CO₂e/kg product. Rail freight efficiency in Germany and Central Europe leverages electrified rail lines, avoiding approximately 0.063 kg CO₂e per functional unit compared to equivalent Euro-6 road transport.

5.2 Data Quality and Pedigree Uncertainty Matrix

Data Parameter	Data Type	Temporal	Geographical	Technological	Overall Quality Score
Thermal Energy & Utilities	Primary plant telemetry	2025/2026	Germany (Direct)	Direct plant meters	Very High (1.1)
Rail Transport Logistics	Specified primary route	2025/2026	Central Europe	Standard electric/diesel rail	High (1.3)
Wheat Cultivation	Secondary average	2022-2025	Germany / Poland	Standard mechanization	Good (1.6)
		2021-2024			

Data Parameter	Data Type	Temporal	Geographical	Technological	Overall Quality Score
Enzyme Manufacturing	Secondary proxy		Global / Europe	Industrial fermentation proxy	Moderate (2.1)

5.3 Sensitivity Analysis: Allocation Methodologies

Allocation choices significantly influence the resulting footprint. A sensitivity comparison between Energy Allocation (baseline), Economic Allocation, and Mass Allocation demonstrates variability:

- **Energy Allocation (Baseline):** Factor = 64.89% → **1.249 kg CO₂e / kg**.
Conforms to RED II/III methodology and calorific displacement.
- **Economic Allocation:** Assuming 5-year average commodity pricing (€850/t bioethanol vs. €260/t DDGS; revenue share = 78.78% ethanol) → **1.516 kg CO₂e / kg** (+21.4% increase).
- **Mass Allocation:** Ethanol (1.00 kg) vs. DDGS (0.88 kg); mass share = 53.19% → **1.024 kg CO₂e / kg** (-18.0% reduction).

5.4 Strategic Decarbonization Roadmap

1. **Biorefinery Biomethane / Biomass Transition:** Replacing fossil natural gas with on-site biomethane or lignin-rich biomass for distillation reboilers would eliminate 0.262 kg CO₂e Scope 1 emissions, reducing the gate footprint by 21.0%.
2. **Renewable Electricity Power Purchase Agreement (PPA):**
Transitioning from the German grid average to an off-site solar/wind PPA would reduce Scope 2 footprint from 0.111 to <0.005 kg CO₂e/kg.
3. **Regenerative Agriculture Interventions:** Partnering with grain cooperatives along the 500 km rail corridor to introduce nitrification inhibitors, cover cropping, and optimized precision nitrogen placement can lower upstream agricultural N₂O emissions by 25% to 35% (saving ~0.18 kg CO₂e/kg).
4. **Fermentation CO₂ Capture & Utilization (CCUS):** Direct capturing of high-purity biogenic CO₂ emitted during fermentation (approx. 0.95 kg biogenic CO₂/kg ethanol) for industrial beverage carbonation or e-fuel synthesis creates an additional carbon mitigation asset.

