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Product Carbon Footprint Analysis Report

Polyamide Resin

Protocol Data (Accounting Standard): GHG Protocol

Senior Sustainability Consultant: Arno de Groot

Disclaimer: This report is generated based on available data and industry standards. While every effort has been made to ensure accuracy and adherence to the specified methodologies, the actual Product Carbon Footprint may vary based on specific operational data, supplier-specific emission factors, and dynamic market conditions.

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Executive Summary

This report presents a high-detail Product Carbon Footprint (PCF) analysis for 1.0 kg of Polyamide resin, conducted from a "cradle-to-gate" perspective in accordance with the GHG Protocol. The analysis focuses on final production in India with a supply chain emphasis on Europe. Key findings highlight the significant contribution of raw material production, particularly caprolactam, and energy consumption during manufacturing to the overall PCF. The report applies the 2026 Land Sector and Removals (LSR) Standard where relevant and ensures comprehensive Scope 3 coverage to meet evolving reporting requirements.

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1. Define Scope

1.1 Functional Unit

The functional unit for this Product Carbon Footprint (PCF) analysis is defined as **1.0 kilogram (kg) of Polyamide resin**. This unit serves as the reference flow to which all input and output data are normalized, ensuring comparability and transparency in the assessment.

1.2 System Boundary

The system boundary for this analysis is "**Cradle-to-Gate (factory_gate)**". This includes all processes from the extraction of raw materials, their transportation, processing into intermediate products, manufacturing of the Polyamide resin, up to the point where the finished resin exits the factory gate in India. The following stages are explicitly included:

- Raw material acquisition (e.g., crude oil/natural gas extraction and processing for petrochemical feedstocks).

- Production of monomers (e.g., Caprolactam).
- Transportation of raw materials and intermediates to the Polyamide manufacturing facility.
- Polymerization and compounding processes at the manufacturing facility.
- Energy generation and consumption associated with all included stages.
- Waste generation and its immediate treatment during manufacturing.

The use phase and end-of-life treatment of the Polyamide resin are excluded from this "cradle-to-gate" assessment.

1.3 Geographic Scope

The geographic scope specifies the **Final Production Country as India**, with a **Supply Chain Focus on Europe** for upstream activities. This necessitates the use of country-specific or regional average emission factors for electricity grids and transportation networks relevant to each stage of the value chain. For instance, emission factors for caprolactam production will reflect European conditions, while on-site electricity consumption will reflect the Indian grid mix.

1.4 Accounting Standard

This PCF analysis strictly adheres to the principles and requirements of the **GHG Protocol**. This includes the categorization of emissions into Scope 1, Scope 2, and Scope 3, as well as considerations for the 2026 Land Sector and Removals (LSR) Standard and stringent Scope 3 coverage requirements.

1.5 Allocation

Where co-production or multi-output processes occur, allocation of environmental burdens is performed based on mass allocation. For instance, if the production of caprolactam yields co-products, emissions are distributed proportionally to the mass of each product.

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2. Map Lifecycle (LCI Inventory Stages)

The lifecycle of Polyamide resin (specifically Polyamide 6, or PA6, derived from caprolactam) is mapped out in distinct stages, considering the defined "cradle-to-gate" system boundary.

2.1 Raw Material Extraction and Pre-processing

- **Petrochemical Feedstock Production:** Crude oil and natural gas extraction, refining, and cracking processes to produce base chemicals like benzene.
- **Intermediate Chemical Production:** Conversion of base chemicals (e.g., benzene) into precursors such as cyclohexane, which is then oxidized to cyclohexanone.

2.2 Monomer Production (Caprolactam)

Caprolactam is the primary monomer for Polyamide 6. Its production is an energy-intensive process involving several chemical transformations. A significant aspect of caprolactam production is the potential for nitrous oxide (N_2O) emissions, a potent greenhouse gas. European producers have significantly reduced these emissions through abatement technologies.

- Conversion of cyclohexanone to cyclohexanone oxime.
- Beckmann rearrangement of cyclohexanone oxime to caprolactam, often co-generating ammonium sulfate.
- Purification and crystallization of caprolactam.

2.3 Transportation of Raw Materials and Intermediates

This stage includes the transportation of caprolactam and other minor additives from their points of origin (primarily Europe for this analysis) to the Polyamide resin manufacturing facility in India.

- Sea freight for bulk transport of caprolactam from Europe to India.
- Road freight for local distribution of caprolactam and other additives within India to the factory.

2.4 Polymerization and Compounding

At the Indian manufacturing facility, caprolactam undergoes polymerization to form Polyamide 6. This process typically involves high temperatures and pressure.

- **Polymerization:** Ring-opening polymerization of caprolactam to form long chains of Polyamide 6.
- **Compounding/Pelletization:** The molten polymer is often mixed with additives (e.g., stabilizers, processing aids, colorants) and extruded into strands, which are then cut into pellets.
- **Energy Inputs:** Significant electricity and thermal energy (e.g., steam generated from natural gas combustion) are consumed for heating, mixing, extrusion, and cooling.
- **Waste Management:** On-site waste generation (e.g., off-spec material, wastewater) and its primary treatment.

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3. Collect Data (Primary/Secondary Data Points)

Data collection for this PCF analysis integrates both primary and secondary data sources to provide a comprehensive and reliable assessment.

3.1 Primary Data (Hypothetical Indian Production Facility)

For the final production stage of Polyamide resin in India, primary data points would ideally be collected directly from the manufacturing facility. For this report, representative industry average data points are used to illustrate the calculation, as specific plant data is unavailable.

- **Energy Consumption:**
    - Electricity consumption per kg of Polyamide resin.
    - On-site fuel consumption (e.g., natural gas for thermal energy/steam generation) per kg of Polyamide resin.
- **Material Inputs:**
    - Mass of caprolactam required per kg of finished Polyamide resin.

        - Mass of minor additives (e.g., heat stabilizers, UV stabilizers, pigments) per kg of finished Polyamide resin.
    - **Waste Generation:**
        - Quantities of process waste generated and their disposal methods.

3.2 Secondary Data (Industry-Standard Emission Factors)

Secondary data, primarily in the form of industry-standard emission factors, are crucial for quantifying the environmental impact of upstream processes and generic inputs. These factors are typically sourced from reputable life cycle inventory (LCI) databases such as Ecoinvent or government databases like DEFRA.

3.2.1 Material Inputs Breakdown

- **Caprolactam:** The production of caprolactam is the most significant material input. For European-focused supply chains, emission factors reflect the technology and energy mix of European producers, including efforts to abate N_2O emissions. Average emissions for caprolactam production in Europe were around 6.5 kg CO2e/kg, which some producers have reduced to 3.3 kg CO2e/kg with abatement technologies. For this analysis, an illustrative factor of **5.0 kg CO2e/kg caprolactam** is used, reflecting a mixed technology supply chain with some abatement.
- **Additives:** For minor additives, generic emission factors for commodity chemicals or plastics additives would be used. An illustrative factor of **3.0 kg CO2e/kg additives** is assumed.

3.2.2 Energy Inputs Breakdown

- **Electricity Grid Mix (India):** The carbon intensity of electricity in India is significantly influenced by a high reliance on fossil fuels, particularly coal. For 2020, the average carbon intensity was about 0.653 kg CO2e/MWh (or 0.653 kg CO2e/kWh). Other sources provide ranges such as 0.727 kg CO2e/kWh and 0.82 kg CO2/kWh. For this report, an illustrative emission factor of **0.70 kg CO2e/kWh** for the Indian electricity grid is applied for processes occurring at the final production facility.
- **Natural Gas Combustion (Thermal Energy):** For on-site heat and steam generation, the emission factor for natural gas

combustion is used. An illustrative factor of **0.056 kg CO2e/MJ** is applied.

3.2.3 Transportation Emission Factors

Transportation modes, distances, and cargo weights are used with relevant emission factors.

- **Sea Freight (Europe to India):** For bulk cargo, an illustrative factor of **0.010 kg CO2e/tonne-km** is used.
- **Road Freight (Local/Regional):** For road transport, an illustrative factor of **0.100 kg CO2e/tonne-km** (for an average truck) is used.

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4. Calculate Emissions

The calculation of greenhouse gas emissions follows the fundamental equation: `Emissions (kg CO2e) = Activity Data × Emission Factor` All emissions are expressed in kilograms of carbon dioxide equivalents (kg CO2e).

4.1 Illustrative Activity Data for 1.0 kg of Polyamide Resin

Input/Activity	Quantity	Unit
Caprolactam (Raw Material)	1.05	kg
Additives	0.02	kg
Electricity Consumption (Indian Facility)	3.0	kWh
Thermal Energy (Natural Gas, Indian Facility)	5.0	MJ
Sea Freight (Caprolactam, 8,000 km)	1.05	tonne-km (approx.)
Road Freight (Additives, 500 km)	0.01	tonne-km (approx.)

4.2 Emission Calculation by Scope

4.2.1 Scope 1: Direct Emissions

These are direct GHG emissions from sources owned or controlled by the reporting company. For a "cradle-to-gate" analysis of Polyamide resin production in India, this primarily includes on-site combustion of fossil fuels for energy generation (e.g., natural gas for process heat/steam).

- **On-site Natural Gas Combustion:**
    - Activity: 5.0 MJ
    - Emission Factor: 0.056 kg CO2e/MJ
    - Emissions: 5.0 MJ * 0.056 kg CO2e/MJ = 0.28 kg CO2e

Total Scope 1 Emissions: 0.28 kg CO2e / kg Polyamide Resin

4.2.2 Scope 2: Energy Indirect Emissions

These are indirect GHG emissions from the generation of purchased or acquired electricity, steam, heating, or cooling consumed by the reporting company.

- **Purchased Electricity (Indian Grid):**
    - Activity: 3.0 kWh
    - Emission Factor: 0.70 kg CO2e/kWh
    - Emissions: 3.0 kWh * 0.70 kg CO2e/kWh = 2.10 kg CO2e

Total Scope 2 Emissions: 2.10 kg CO2e / kg Polyamide Resin

4.2.3 Scope 3: Other Indirect Emissions (Value Chain)

Scope 3 emissions are all other indirect emissions that occur in the value chain of the reporting company, both upstream and downstream. For a cradle-to-gate PCF, the focus is on upstream Scope 3 categories. The GHG Protocol identifies 15 categories for Scope 3 emissions.

For this Polyamide resin PCF, the primary relevant upstream Scope 3 categories include:

1. **Category 1: Purchased Goods and Services (Raw Material Production)**
    - **Caprolactam Production:**
        - Activity: 1.05 kg

    - Emission Factor: 5.0 kg CO2e/kg caprolactam (illustrative, reflecting European-focused upstream)
    - Emissions: 1.05 kg * 5.0 kg CO2e/kg = 5.25 kg CO2e
  - **Additives Production:**
    - Activity: 0.02 kg
    - Emission Factor: 3.0 kg CO2e/kg additives (illustrative)
    - Emissions: 0.02 kg * 3.0 kg CO2e/kg = 0.06 kg CO2e

2. **Category 4: Upstream Transportation and Distribution**
  - **Sea Freight (Caprolactam, Europe to India):**
    - Activity: 1.05 tonne-km (1.05 kg caprolactam * 8,000 km / 1000 kg/tonne)
    - Emission Factor: 0.010 kg CO2e/tonne-km
    - Emissions: 1.05 tonne-km * 0.010 kg CO2e/tonne-km = 0.01 kg CO2e
  - **Road Freight (Additives, local):**
    - Activity: 0.01 tonne-km (0.02 kg additives * 500 km / 1000 kg/tonne)
    - Emission Factor: 0.100 kg CO2e/tonne-km
    - Emissions: 0.01 tonne-km * 0.100 kg CO2e/tonne-km = 0.001 kg CO2e

3. **Category 3: Fuel- and energy-related activities (not included in Scope 1 or Scope 2)**

   This typically includes emissions from the extraction, production, and transportation of fuels and energy purchased and consumed by the organization that are not already covered in Scope 1 or 2 (e.g., losses in transmission and distribution of purchased electricity, upstream emissions of natural gas). For this illustrative calculation, these are embedded in the emission factors used for electricity and natural gas, but would be explicitly separated with more granular data. For simplicity here, we assume the chosen EFs for electricity and NG are "well-to-tank" or "cradle-to-gate" for the energy itself.

4. **Category 5: Waste Generated in Operations (Upstream Treatment)**

Emissions from the disposal and treatment of waste generated in the organization's operations (e.g., manufacturing waste, packaging waste). For this illustrative PCF, direct operational waste emissions are considered negligible or embedded in process EFs, but would be quantified if significant.

Total Scope 3 Emissions: 5.25 + 0.06 + 0.01 + 0.001 = 5.321 kg CO2e / kg Polyamide Resin

4.3 Total Product Carbon Footprint (Cradle-to-Gate)

Total PCF = Scope 1 Emissions + Scope 2 Emissions + Scope 3 Emissions

Total PCF = 0.28 kg CO2e + 2.10 kg CO2e + 5.321 kg CO2e = **7.701 kg CO2e / kg Polyamide Resin**

This calculated PCF of 7.701 kg CO2e per kg of Polyamide resin falls within the lower to mid-range of industry benchmarks for fossil-based PA6, which can range from approximately 5.5 to 36.4 kg CO2e/kg depending on production efficiency, energy mix, and scope definition. European producers with advanced N2O abatement and renewable energy can achieve figures as low as 3.5 kg CO2e/kg for PA6.

4.4 2026 Land Sector and Removals (LSR) Standard Update

The GHG Protocol\'s Land Sector and Removals (LSR) Standard, taking effect on January 1, 2027, provides comprehensive accounting requirements for land emissions and CO_2 removals. While conventional Polyamide resin is fossil-based, the LSR Standard is relevant to this PCF in several potential ways:

- **Upstream Feedstock Production:** Although the primary feedstock for conventional polyamide is petrochemical, the extraction and processing of crude oil and natural gas can have associated land use impacts. The LSR Standard encourages companies to consider these indirect land use change emissions if they are material to their value chain.
- **Energy Mix for Upstream Processes:** If the energy used in upstream production of monomers or intermediates includes bioenergy, the LSR Standard would apply to the land use associated with the sourcing of that biomass (e.g., emissions from land use change or land management net biogenic CO_2 emissions).

- **Future Bio-Based Polyamides:** If the company were to transition to bio-based polyamide feedstocks (e.g., from castor oil or other agricultural products), the LSR Standard would directly apply to account for emissions and potential removals related to agricultural land management, land use change, and biogenic carbon within the product. This includes aspects like soil carbon sequestration and direct land use changes.
- **Technological CO_2 Removals:** The LSR Standard also covers technological CO_2 removals, such as direct air capture, which might be integrated into the value chain in the future to achieve net-zero targets.

In this report, for fossil-based polyamide, the primary relevance of LSR lies in ensuring that any land-related emissions embedded in generic emission factors for upstream materials and energy are captured and, in future, to facilitate the accounting of any bio-based content or carbon removal initiatives.

4.5 Scope 3 Compliance (95% Coverage)

As per 2026 requirements, this analysis aims for at least 95% coverage for Scope 3 reporting. The detailed breakdown of material inputs (caprolactam, additives) and their associated upstream emissions, along with comprehensive transportation emissions, ensures that the most significant contributors to Scope 3 are identified and quantified. To achieve 95% coverage, a rigorous process involves:

- **Identifying All Relevant Categories:** Systematically reviewing all 15 Scope 3 categories to determine their materiality to Polyamide resin production. For a cradle-to-gate assessment, upstream categories (Purchased Goods and Services, Capital Goods, Fuel- and energy-related activities, Upstream Transportation and Distribution, Waste Generated in Operations, Upstream Leased Assets, Business Travel, Employee Commuting) are most critical.
- **Data Collection Strategy:** Prioritizing primary data collection from tier-1 suppliers for major inputs and supplementing with high-quality secondary data for remaining categories.
- **Extrapolating and Estimating:** Using industry averages or economic input-output (EIO) models for minor categories where specific data is unavailable, with clear documentation of assumptions.

- **Regular Review:** Periodically reviewing and updating the Scope 3 inventory to improve data quality and expand coverage as more specific supplier data becomes available.

The current illustrative calculation focuses on the most significant upstream Scope 3 emissions (raw materials and transport), which are typically the largest components for a "purchased goods and services" heavy product like Polyamide resin. Further detailed analysis would ensure all minor contributions from other upstream categories are also captured to guarantee the >95% threshold.

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5. Review & Report

5.1 Hotspot Analysis

Based on the illustrative calculation, the primary carbon hotspots for 1.0 kg of Polyamide resin (cradle-to-gate) are:

- **Monomer Production (Caprolactam):** Contributing 5.25 kg CO2e, this stage accounts for approximately 68% of the total PCF. This aligns with industry understanding that petrochemical feedstock and polymerization are major drivers of emissions. The energy intensity of chemical synthesis and potential N_2O emissions during caprolactam production are key factors.
- **Purchased Electricity (Indian Facility):** At 2.10 kg CO2e, electricity consumption at the manufacturing site accounts for about 27% of the total PCF. The high carbon intensity of the Indian electricity grid, which heavily relies on fossil fuels, significantly contributes to this figure.
- **On-site Thermal Energy:** At 0.28 kg CO2e, on-site fuel combustion contributes a smaller but notable portion (approx. 4%) of the PCF.
- **Transportation and Additives:** These categories contribute marginally to the total PCF, less than 1%.

5.2 Data Reliability and Limitations

The reliability of this report is dependent on the quality and specificity of the underlying data.

- **Primary Data:** For this report, primary data points for the Indian production facility are illustrative. Actual emissions could vary significantly based on specific plant efficiency, energy sources, and operational practices.
- **Secondary Data (Emission Factors):** Generic, industry-average emission factors from databases like Ecoinvent/DEFRA (or similar credible sources) have been used. While robust, these may not perfectly reflect the specific technologies or regional nuances of all suppliers in the value chain. Continuous efforts to collect supplier-specific data will improve accuracy.
- **System Boundary:** The "cradle-to-gate" boundary excludes downstream impacts (use phase and end-of-life), which could be significant for certain products.
- **LSR Standard:** While the LSR Standard\'s principles have been considered, detailed application would require specific data on land use for feedstock or bioenergy if applicable.

5.3 Recommendations for Emission Reduction

To significantly reduce the Polyamide resin\'s carbon footprint, the following actions are recommended, focusing on identified hotspots:

1. **Decarbonize Monomer Production (Caprolactam):**
    - Engage with caprolactam suppliers to encourage the adoption of best available technologies for N_2O abatement.
    - Explore opportunities for sourcing caprolactam produced with lower carbon intensity, potentially through renewable energy integration or bio-based feedstocks (e.g., EcoLactam BIO offers potential for footprints below 2.0 kg CO2e/kg).
    - Investigate mass balance approaches to incorporate certified renewable or recycled feedstocks in caprolactam production.
2. **Transition to Renewable Energy in Manufacturing (India):**
    - Increase the procurement of renewable electricity (e.g., solar, wind) for the Indian manufacturing facility, either

through direct investment, power purchase agreements (PPAs), or renewable energy certificates. India is increasing its low-carbon electricity generation.

   - Explore options for generating on-site renewable energy (e.g., rooftop solar).
   - Switch from natural gas to lower-carbon alternatives for thermal energy, such as bio-methane or electrification of heating processes where feasible.

3. **Optimize Process Efficiency:**
   - Implement energy efficiency measures throughout the polymerization and compounding processes to reduce overall electricity and thermal energy consumption.
   - Minimize process losses and waste generation.
4. **Improve Supply Chain Data Quality:**
   - Collaborate with all key suppliers to obtain primary, supplier-specific emission data for raw materials and services, which will further refine the accuracy of Scope 3 emissions.

By strategically addressing these hotspots, the carbon footprint of Polyamide resin can be significantly reduced, contributing to broader sustainability goals.
