THE LIFE CYCLE ASSESSMENT OF PET PLASTIC BOTTLE

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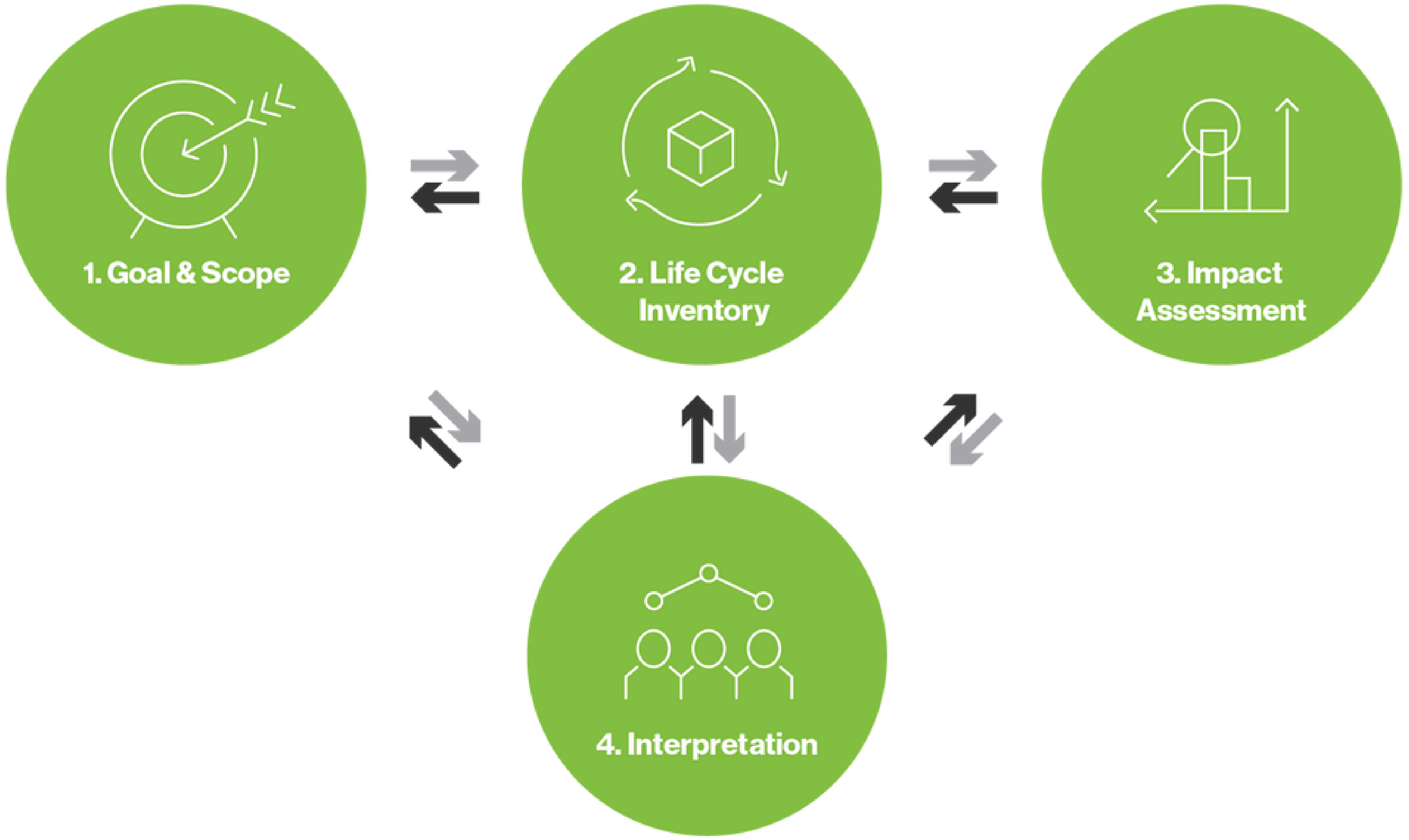
LESSON OUTLINE

- Understand the LCA framework and its application to plastic bottles.
- Assess environmental impacts throughout the life cycle of plasticbottles.
- Explore sustainable solutions for managing plastic bottle waste.
- Focus on polyethylene terephthalate (PET) bottles due to their prevalence.
- Highlight the relevance of LCA in addressing solid waste management challenges

IMPORTANCE OF PLASTIC BOTTLES IN WASTE MANAGEMENT

- Plastic bottles are widely used due to their lightweight, durability, and recyclability
- However, improper disposal leads to significant environmental issues like pollution and resource depletion
- Globally, only 9% of plastic bottles are recycled, with countries like Norway (97%) and Germany (98%) leading in recycling rates.

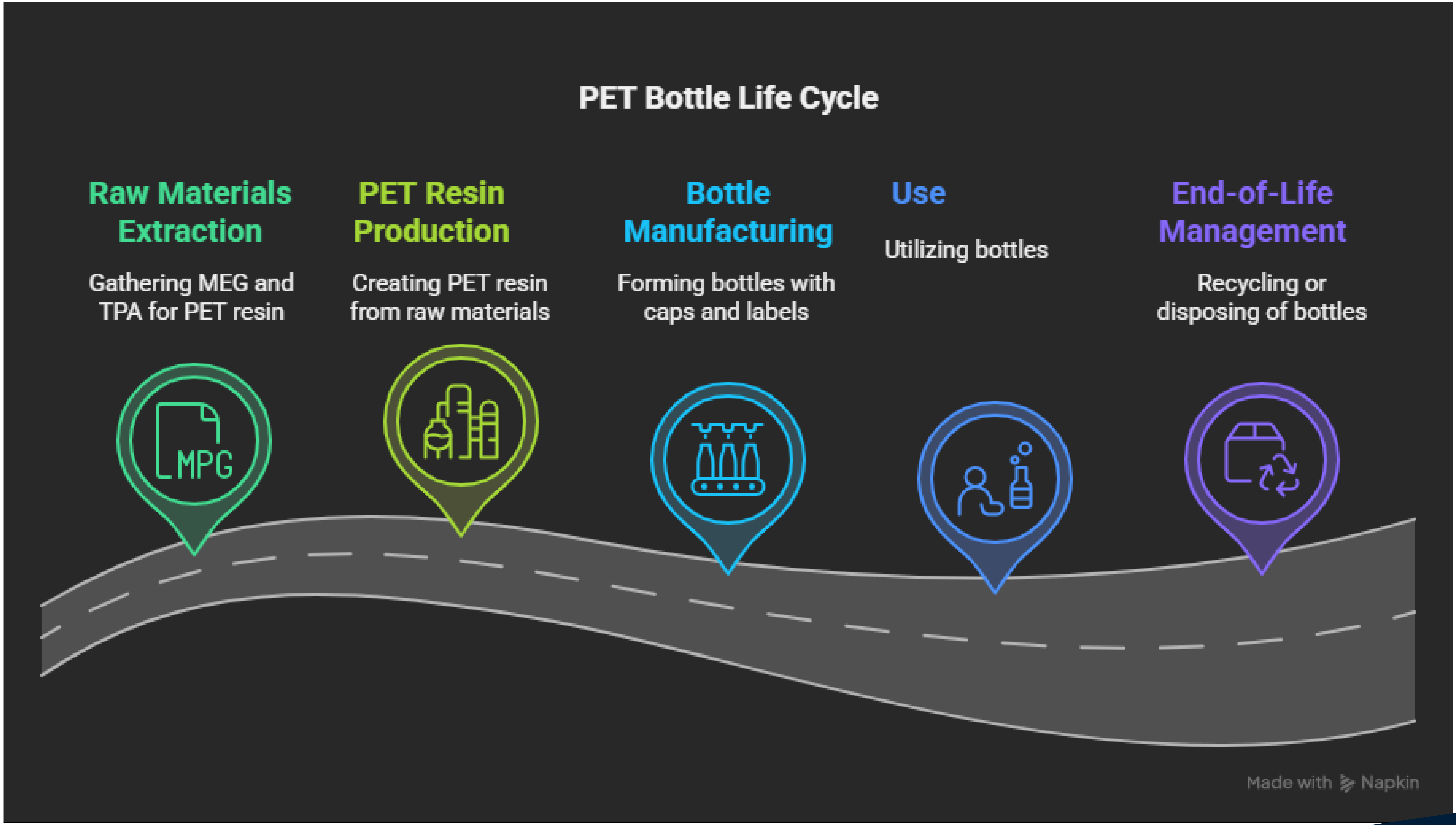


LIFE CYCLE ASSESSMENT

Life Cycle Assessment (LCA) analyses a product's environmental impact from extraction to disposal.

Focusing on four key stages:

1. Goal & Scope Definition
2. Life Cycle Inventory (LCI)
3. Life Cycle Impact Assessment (LCIA)
4. Interpretation.



PET Bottle Life Cycle
Raw Materials Extraction
Gathering MEG and TPA for PET resin
MPG
PET Resin Production
Creating PET resin from raw materials
Bottle Manufacturing
Forming bottles with caps and labels
Use
Utilizing bottles
End-of-Life Management
Recycling or disposing of bottles
Made with Napkin

LCA FRAMEWORK

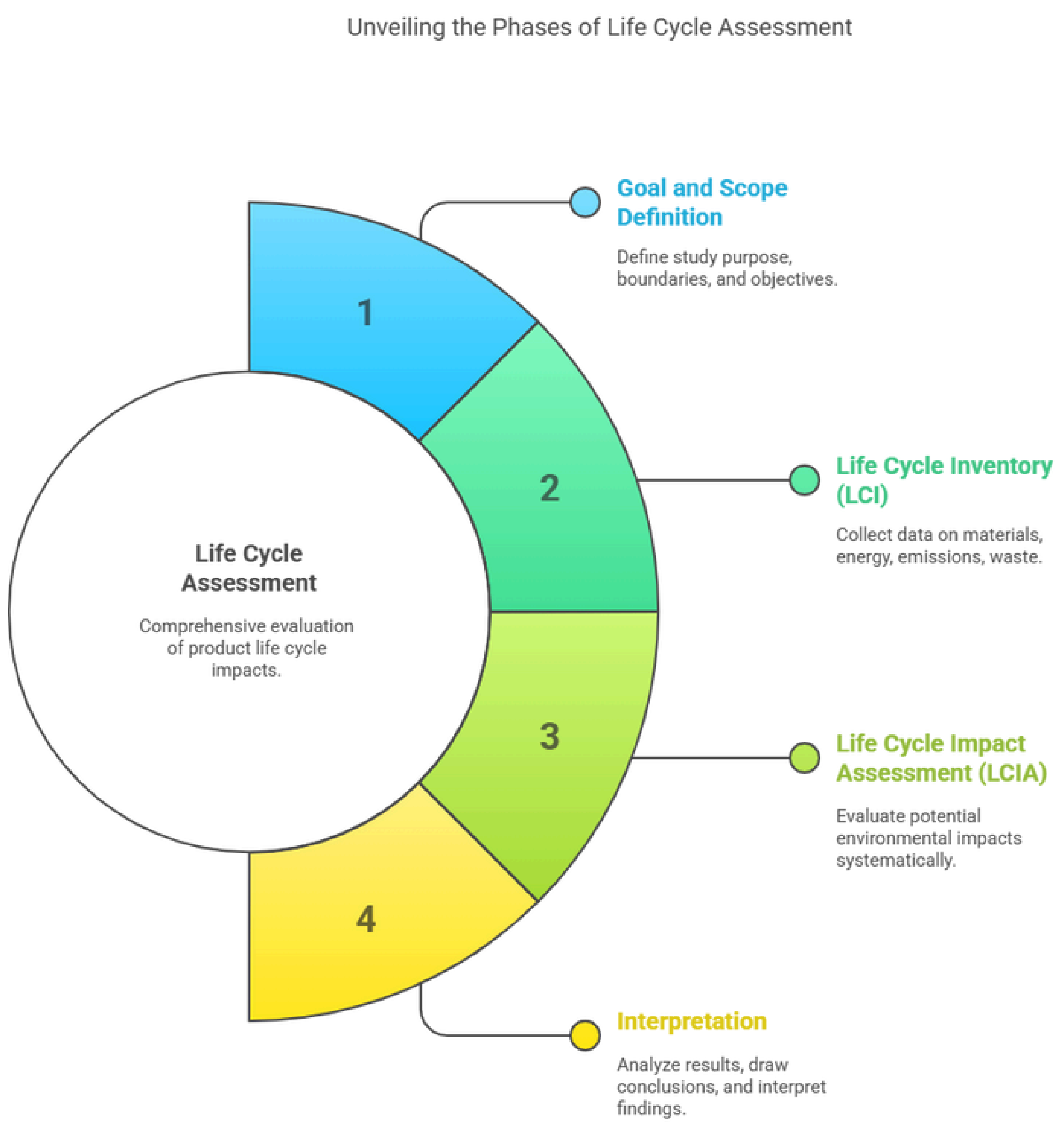
Goal and Scope Definition: Define the purpose and boundaries of the study.

Life Cycle Inventory (LCI): Collect data on inputs (raw materials, energy) and outputs (emissions, waste).

Life Cycle Impact Assessment (LCIA): Evaluate potential environmental impacts.

Interpretation: Analyze results and draw conclusions.

System boundaries for this study: From raw material extraction to final disposal

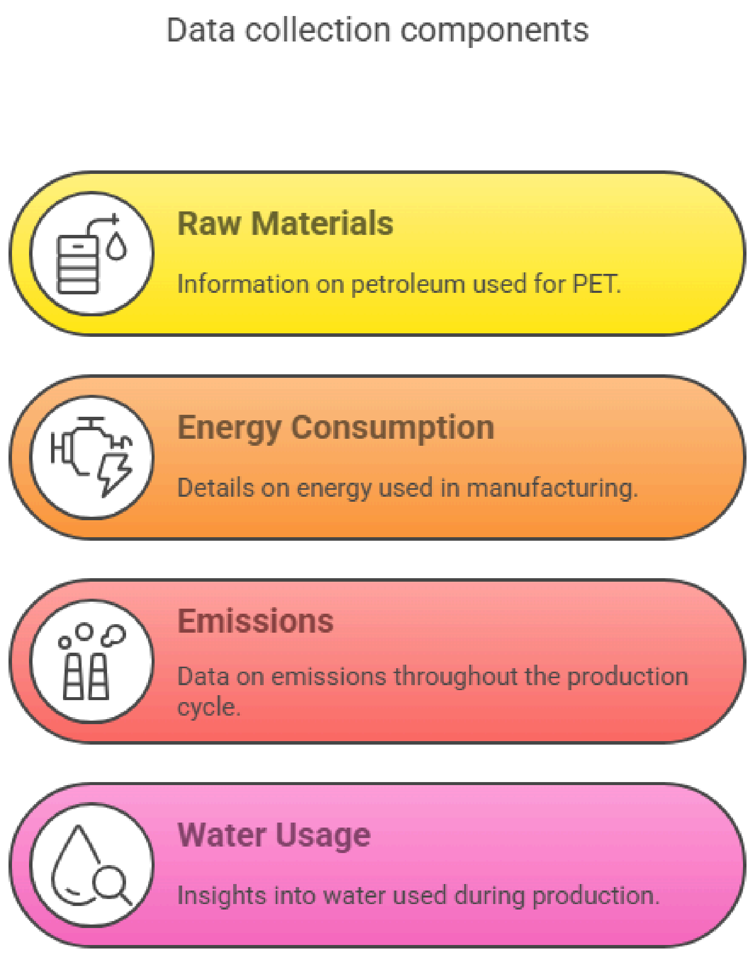


STAGE 1 - GOAL AND SCOPE DEFINITION

- Goal: The goal of this study is to quantify the Global Warming Potential (GWP), electricity consumption, and total energy consumption associated with PET water bottle.
- Scope: Cradle-to-grave analysis, including production, use, and disposal.
- Focus on PET bottles due to their prevalence in global markets.

STAGE 2 - LIFE CYCLE INVENTORY (LCI)

- **Data collection on:**
  - Raw materials: Petroleum for PET production.
  - Energy consumption during manufacturing.
  - Emissions during production, transportation, and disposal. Water usage in production.



Functional Unit

- Functional Unit: 1200 PET bottles (1-liter capacity each)
- Total Weight: Approximately 28.2 kg of PET material (based on 23.5 kg per 1000 bottles)

system Boundary

Raw Material Acquisition --> Manufacturing --> Distribution & Use --> End-of-Life

PET $\longrightarrow$ 23.5 kg per 1000 unit.

so, for 1200 PET Bottles:

$$1000 \longrightarrow 23.5 \text{ kg}.$$

$$1200 \longrightarrow x \text{ kg}$$

$$x = \frac{23.5 \times 1200}{1000}$$

$$x = 28.2 \text{ kg}$$

PET required per 1200 Bottles is equal to 28.2 kg.

CALCULATIONS BY LIFE CYCLE STAGE

1. Raw Material Extraction (Phase I)

Based on the CPCB data for one tonne of PET bottles:

GWP Calculation:
CO_2 emissions per tonne: 591 kg
For 28.2 kg (1200 bottles): 591 × (28.2/1000) = **16.67 kg CO_2-eq**

Energy Consumption:
Energy per tonne: 17,697.6 MJ
For 28.2 kg: 17,697.6 × (28.2/1000) = **499.07 MJ**

Electricity Consumption:
Approximately 22% of total energy is electricity (based on industry averages)
Electricity: 499.07 × 0.22 = 109.80 MJ = **30.50 kWh**

2. Manufacturing (Phase II)

GWP Calculation:

CO_2 emissions per tonne: 72 kg

For 28.2 kg: 72 × (28.2/1000) = **2.03 kg CO_2-eq**

Energy Consumption:

Energy per tonne: 7,765.2 MJ

For 28.2 kg: 7,765.2 × (28.2/1000) = **219.00 MJ**

Electricity Consumption:

Approximately 70% of manufacturing energy is electricity

Electricity: 219.00 × 0.7 = 153.30 MJ = **42.58 kWh**

3. Distribution and Use (Phase III)

GWP Calculation:
CO_2 emissions per tonne: 150 kg
For 28.2 kg: 150 × (28.2/1000) = **4.23 kg CO_2-eq**

Energy Consumption:
Energy per tonne: 914.4 MJ
For 28.2 kg: 914.4 × (28.2/1000) = **25.79 MJ**

Electricity Consumption:
Minimal electricity in distribution (primarily fuel-based)
Estimated electricity: 5% of total energy
Electricity: 25.79 × 0.05 = 1.29 MJ = **0.36 kWh**

4. End of Life (100% Landfill scenario) (Phase IV)

GWP Calculation:
CO_2 emissions per tonne: 188 kg
For 28.2 kg: 188 × (28.2/1000) = **5.30 kg CO_2-eq**

Energy Consumption:
Energy per tonne: 5,274 MJ
For 28.2 kg: 5,274 × (28.2/1000) = **148.73 MJ**

Electricity Consumption:
Approximately 40% of waste management energy is electricity
Electricity: 148.73 × 0.4 = 59.49 MJ = **16.53 kWh**

Life Cycle Stage	GWP (kg CO_2-eq)	Energy (MJ)	Electricity (kWh)
Raw Material Extraction	16.67	499.07	30.50
Manufacturing	2.03	219.00	42.58
Distribution and Use	4.23	25.79	0.36
End of Life	5.30	148.73	16.53
Total	**28.23**	**892.59**	**89.97**

Energy Conversion and CO_2 Equivalent Calculations:

The total energy consumption can be converted to CO_2 equivalents using the standard conversion factor of approximately 0.22 kg CO_2-eq per MJ (based on the CPCB report)

Energy-related GWP: 892.59 MJ × 0.22 = **196.37 kg CO_2-eq**

Direct emissions GWP: **28.23 kg CO_2-eq**

Total GWP: 196.37+28.23= **224.60 kg CO_2-eq**

Carbon Footprint Analysis

The carbon footprint of 1200 PET bottles (1-liter capacity each) can be calculated based on the Global Warming Potential (GWP) throughout its life cycle stages.

Detailed Carbon Footprint by Stage

Life Cycle Stage	Carbon Footprint (kg CO_2-eq)	Percentage of Total
Raw Material Extraction	16.67	7.4%
Manufacturing	130.02	57.9%
Distribution and Use	4.23	1.9%
End of Life	73.68	32.8%
Total	**224.60**	**100%**

Interpretation of LCA Data

Environmental Impact Hotspots

Manufacturing Stage Dominance:

- Manufacturing accounts for nearly 58% of total carbon emissions, primarily from electricity consumption
- The bottle blowing process is particularly energy-intensive, requiring high temperatures and pressures

End-of-Life Impact:

- The end-of-life stage contributes approximately 32.8% of total emissions
- This highlights the critical importance of proper waste management and recycling

Material Efficiency:

- Despite environmental concerns, PET bottles are more material-efficient than alternatives
- A typical 1-liter PET bottle weighs 23.5g, significantly less than comparable glass containers

Energy Consumption Patterns:

- Electricity is the highest contributor to carbon emissions in the production process
- Energy optimization in manufacturing presents the greatest opportunity for carbon reduction

Comparative Environmental Performance

When compared to alternative packaging materials:

1. **Versus Glass**:
    - PET bottles create 80% less solid waste than glass bottles
    - They have 74% lower global warming potential than glass alternatives
    - Glass production requires 5× more energy than plastic production
2. **Versus Aluminum**:
    - PET bottles use 53% less water during production compared to aluminum cans
    - Aluminum production requires twice the energy of plastic bottle production
    - If U.S. consumers chose PET over aluminum for soda, it would conserve 4.4 billion liters of water annually

End-of-Life (50% Recycling, 50% Landfill/Incineration):

Original GWP for 100% landfill/incineration: $188 \times 0.0282 = 5.30$ kg CO_2-eq
Recycling reduces GWP by ~80% (recycling emits only 20% of landfill GWP)

GWP Calculation:
50% recycled: $5.30 \times 0.5 \times 0.2 = 0.535.30 \times 0.5 \times 0.2 = 0.53$ kg CO_2-eq
50% landfill: $5.30 \times 0.5 = 2.655.30 \times 0.5 = 2.65$ kg CO_2-eq
Total End-of-Life GWP: $0.53 + 2.65 =$ **3.18 kg CO_2-eq**

Energy Consumption:
Per tonne: 5,274 MJ → $5{,}274 \times 0.0282 = 148.73$ MJ

Assume recycling uses 50% of landfill energy:
Recycled: $148.73 \times 0.5 \times 0.5 = 37.18$ MJ
Landfill: $148.73 \times 0.5 = 74.37$ MJ
Total End-of-Life Energy: $37.18 + 74.37 =$ **111.55 MJ**

Electricity (assume 40% of energy):
$111.55 \times 0.4 / 3.6 =$ **12.39 kWh**

Stage	GWP (kg CO_2-eq)	Energy (MJ)	Electricity (kWh)
Raw Material	16.67	499.07	30.50
Manufacturing	2.03	219.00	42.58
Distribution & Use	4.23	25.79	0.36
End-of-Life (50% rec.)	3.18	111.55	12.39
Total	**26.11**	**855.41**	**85.83**

- Recycling 50% of bottles reduces GWP by 2.12 kg CO_2-eq for 1200 bottles (decreases by 7.5%).
- 37.18 MJ less energy consumed with 50% recycling (decreases by 4.47%) .
- 4.14 kWh less electricity used with 50% recycling (decreased by 4.60%).

Recycling Methods and Challenges

Current Recycling Technologies

1. Mechanical Recycling:
    - Most common method for PET bottle recycling
    - Process involves sorting, washing, grinding, and melting to produce recycled PET (rPET)
    - Limited by contamination issues and degradation of polymer quality after multiple cycles
2. Chemical Recycling:
    - Breaking down PET into its chemical components through depolymerization
    - Produces virgin-quality recycled material but requires more energy than mechanical recycling
    - Enables true circular economy for plastic bottles[4]
3. Solvent-Based Recycling:
    - Emerging technology using solvents to dissolve PET and recover pure polymers
    - Shows promise for producing high-quality recycled plastics with reduced environmental impact[4]
4. Advanced Sorting Technologies:
    - AI and robotics are revolutionizing recycling plant efficiency
    - Automated systems can identify and sort different types of plastics with greater accuracy

Recycling Challenges

1. Collection Infrastructure:
    - Inadequate collection systems in many regions limit recycling rates
    - Only a small fraction of PET waste is properly managed globally[8]
2. Contamination:
    - Labels, adhesives, and mixed materials complicate recycling processes
    - Contaminants reduce the quality and value of recycled PET
3. Economic Barriers:
    - Virgin PET production often costs less than recycled PET
    - Market fluctuations in oil prices affect recycling economics
4. Consumer Behavior:
    - Low consumer awareness and participation in recycling programs
    - Improper disposal of bottles in general waste streams

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Solutions and Alternatives to Plastic Bottles

Reusable Stainless Steel Bottles (Highest Sustainability):
Long-lasting (potential for decades of use)
100% recyclable at end of life
Free from BPA and harmful chemicals
Breaks even with single-use plastic after approximately 50 uses
High initial production energy offset by extended lifetime2

Glass Bottles (High Sustainability):
Infinitely recyclable without quality loss
No chemical leaching into drinks
Higher production energy (5× more than plastic)
Heavier weight increases transportation emissions
Recycled glass reduces energy use by 30%26

Aluminum Bottles and Cans (Moderate Sustainability):
Lightweight and durable
Recycled aluminum reduces energy use by up to 90%
Initial production requires twice the energy of plastic
Significant environmental impact if not recycled2

Plant-Based Plastics (Mixed Sustainability):
Biodegradable alternatives to petroleum-based plastics
Some bottles are edible as well as biodegradable
May still require specialized industrial composting facilities
Can contaminate traditional recycling streams

CONCLUSION

The life cycle assessment of 1200 PET bottles reveals a complex environmental profile with total carbon emissions of approximately 224.60 kg CO_2-eq, predominantly from manufacturing processes and end-of-life management. While plastic bottles present significant environmental challenges, they currently outperform alternatives like glass and aluminum in several impact categories, including global warming potential, water usage, and solid waste generation.

THANK YOU