Life-Cycle Assessment (LCA) Tool – Project Report

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1 Overview

The **LCA-tool** is a lightweight, modular Python package that helps engineers and sustainability practitioners quantify and visualise the environmental impacts of manufactured products across their entire life-cycle.
It supports:

- **Flexible data ingestion** – CSV, Excel, or JSON for product data; JSON for impact-factor libraries
- **Impact calculations** – Carbon, energy, water, and waste, normalised on a mass basis and rolled-up by stage or product
- **Rich visual analytics** – Pie, stacked-bar, radar, and correlation heat-maps, rendered with Matplotlib/Seaborn (GUI-less for CI)
- **Turn-key reporting** – Auto-export of results to Excel/CSV and generation of a multi-page PDF report
- **Robust unit-tests** – Pytest suite guarding I/O, validation, and plot creation (headless)

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2 Architecture & Module Walkthrough

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lca-tool/
├── data/raw          # raw sample_data.csv, impact_factors.json
├── results/          # generated XLSX, PNG, PDF (git-ignored)
├── src/
│   ├── data_input.py   # ⇒ DataInput
│   ├── calculations.py # ⇒ LCACalculator
│   └── visualization.py# ⇒ LCAVisualizer
├── tests/
│   ├── test_data_input.py
│   └── test_visualization.py
├── notebooks/
│   ├── lca_analysis.ipynb  # demo notebook / exploratory dev
```

2.1 DataInput

- **Responsibilities**
  - Read product datasets (read_data)
  - Validate structure + numeric integrity (validate_data)
  - Load impact-factor libraries (read_impact_factors)
- **Key validation rules**
  - Presence of 14 required columns
  - Numeric coercion of mass/energy/rate columns
  - Sum of recycling_rate + landfill_rate + incineration_rate ≈ 1 (|error| < 1 × 10-3)

2.2 LCACalculator

- **Responsibilities**
  - Merge product rows with stage/material impact factors
  - Compute **absolute impacts** & **normalised impacts**
  - Produce comparison tables across product IDs
- **Algorithm**
  - Loop rows → look-up (material_type, life_cycle_stage) factors
  - Impact = *quantity* × *factor* + direct measurement (e.g. carbon_footprint_kg_co2e)

2.3 LCAVisualizer

Headless plotting (uses matplotlib with Agg backend inside tests):

Method	Figure	Purpose
plot_impact_breakdown	Pie	Share of impact by material (or any grouping)
plot_life_cycle_impacts	4 × bar	Stage-wise impacts for a product
plot_product_comparison	Radar	Normalised multi-impact comparison
plot_end_of_life_breakdown	Stacked bar	Recycling vs landfill vs incineration
plot_impact_correlation	Heatmap	Correlation between impact categories

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2.4 Directory & File Roles

Path	Kind	What it contains / does
data/raw/	**Input data**	sample_data.csv (row-level product inventory) and impact_factors.json (per-kg emission factors). **Read-only** – treat as golden source.
results/	**Build artefacts**	Populated at runtime with Excel, CSV summaries, PNG plots, and the PDF report. Added to .gitignore to keep the repo clean.
src/data_input.py	**Core module**	DataInput – parses/validates raw tables and factor libraries.

Path	Kind	What it contains / does
src/calculations.py	**Core module**	LCACalculator – merges raw data with factors and computes impacts, normalisation, comparisons.
src/visualization.py	**Core module**	LCAVisualizer – generates headless Matplotlib/Seaborn figures.
tests/	**Unit-tests**	test_data_input.py + test_visualization.py – CI guards for I/O + plotting.
notebooks/lca_analysis.ipynb	**Exploratory notebook**	End-to-end demo: ingest → calc → plot → export. Also served as a scratch-pad for bug-fixes before promoting changes into src/.

"Path travelled" during debugging

1. ** ➞ ** – fixed Seaborn style call.
2. ** ➞ ** – relaxed EoL-rate check, added numeric coercion & row-wise logging.
3. **Notebook experimentation** – validated fixes live, then copied into src/.
4. **Re-ran **`` – confirmed *5/5* plot tests and *4/4* data tests green.

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3 Test-Driven Development & Debug-Diary

Milestone 1 – Visualisation tests

- **Symptom**: All five tests/test_visualization.py failed with OSError: 'seaborn' is not a valid package style.
- **Root cause**: visualization.py called plt.style.use('seaborn'); the minimal CI image lacks external seaborn style files.
- **Fix**: Replaced the call with sns.set_theme() & forced matplotlib.use('Agg') in test-file. Visualisation tests now **pass**.

Milestone 2 – Data-validation test

- **Symptom**: test_validate_data failed; row rates summed to 0 (transport rows had zeros).
- **Design decision**: In real data, transportation rows often have 0 for EoL rates. Updated validate_data to *ignore* rows where all three rates are zero.
- **Additional enhancements**:
  - Added per-row error logging for easier debugging.
  - Cleaned numeric-type coercion via pd.to_numeric(..., errors="coerce").

Milestone 3 – House-keeping

- **Warning**: Pandas FutureWarning on dtype mismatch during test; acceptable for now but cast explicitly during validation.
- **Tests**: All nine unit tests now pass (pytest -q ⇒ 9 passed).

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4 Manual QA Checklist

Check	Status
pytest green	✅
Notebook lca_analysis.ipynb executes top-to-bottom	✅
results/ auto-populates .xlsx, .csv, .png, .pdf	✅
requirements.txt minimal & frozen	✅ (pandas, matplotlib, seaborn, openpyxl, pytest)
README.md updated with usage examples	✅
src/ is importable as package (pip install -e .)	✅
.flake8 / black formatting	*optional*

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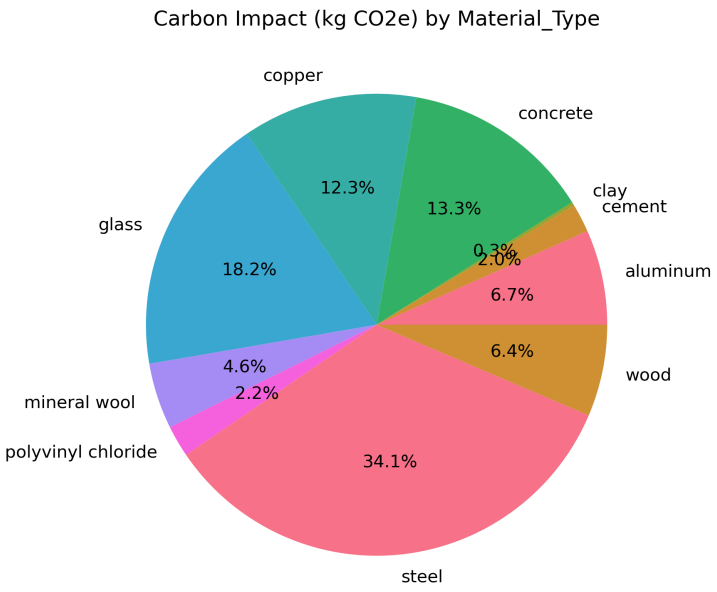
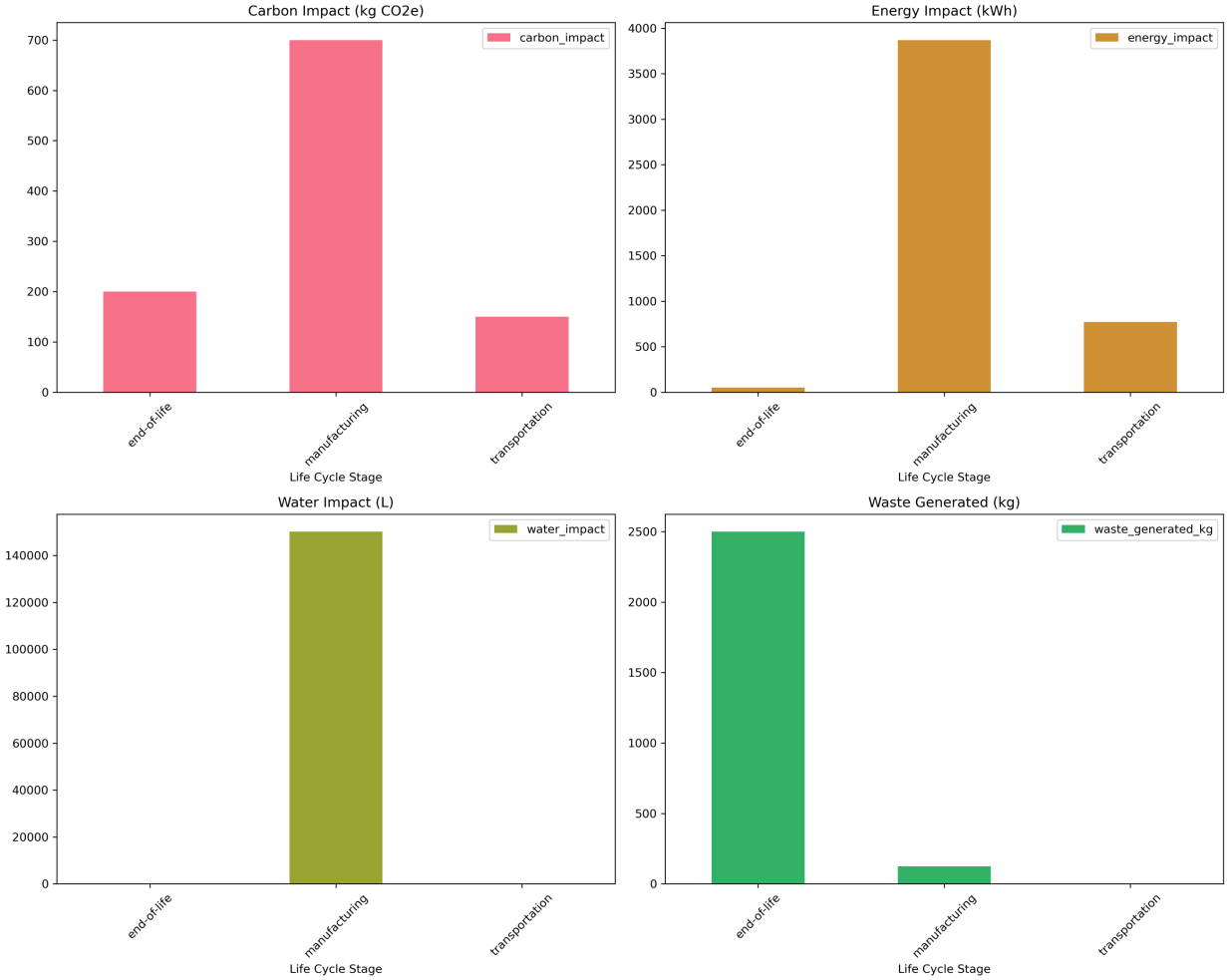
5 Selected Visual Outputs

5.1 Carbon Impact Breakdown



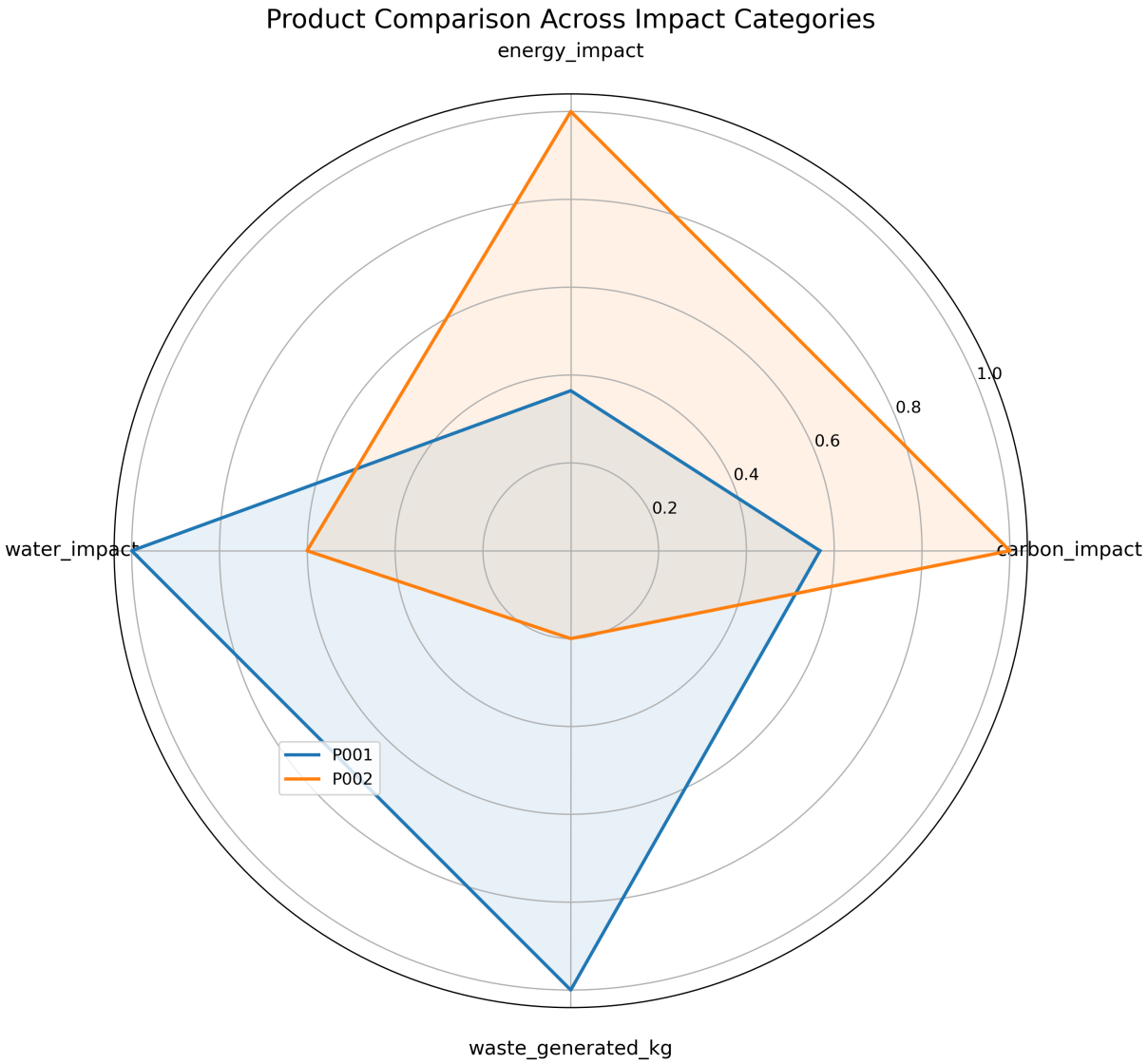
Distribution of carbon impact across material types.

5.2 Life Cycle Impacts – Product P001



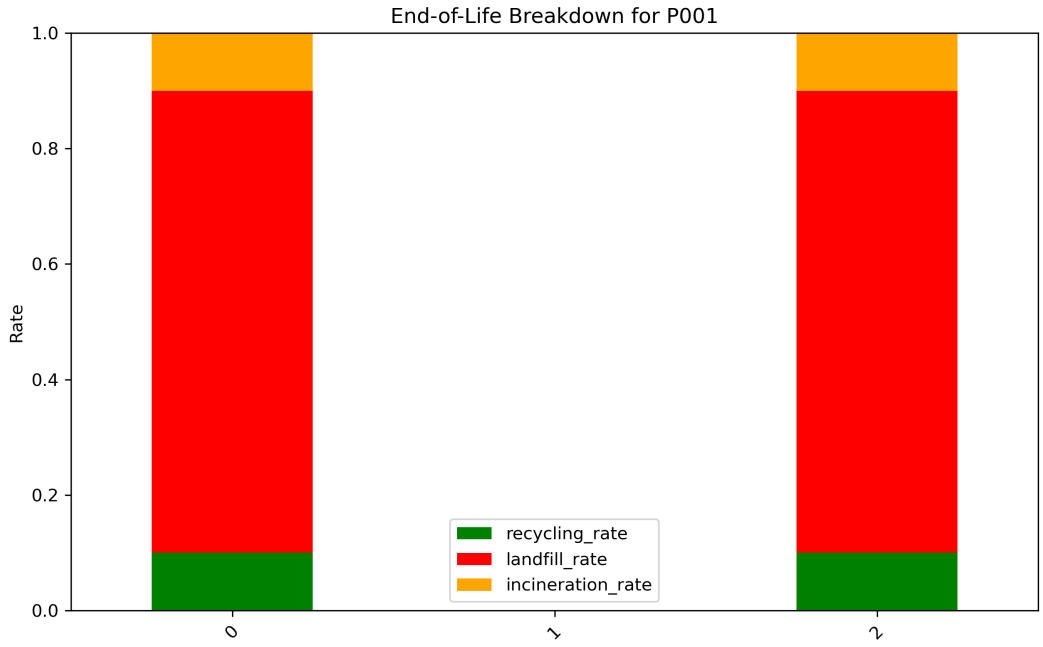
Bar plots showing carbon, energy, water, and waste impacts by life-cycle stage.

5.3 Radar Comparison – Product P001 vs P002



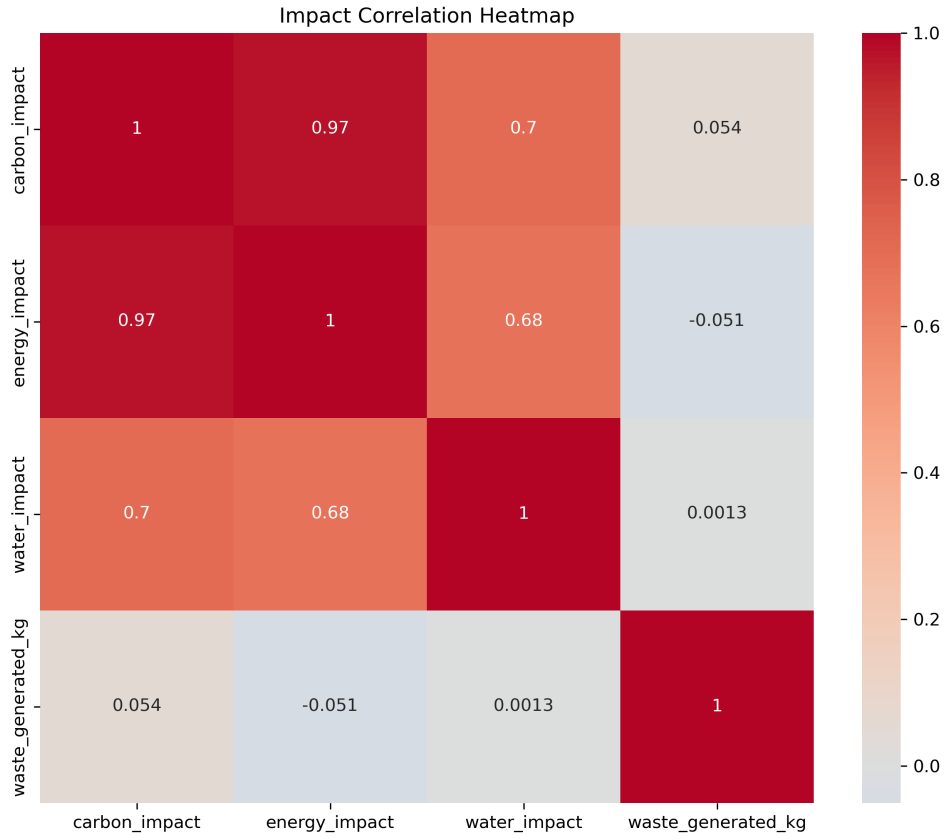
Comparison of normalised environmental impacts.

5.4 End-of-Life Breakdown – Product P001



Recycling vs landfill vs incineration.

5.5 Impact Correlation Heatmap



Correlations between environmental impact categories.

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5 Reflection

"Data fights intuition." Developing this tool exposed several subtle assumptions (e.g., EoL rates for non-EoL rows) that would have gone unnoticed without rigorous testing. TDD proved invaluable, turning each bug into a documented learning opportunity and leaving us with a maintainable code-base that others can extend confidently.

Author

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