Final Report - CSE6242 Spring 2025

Data Visualization and Analysis of Metal Recycling from E-waste, based on UN SDGs

Team 7
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Abstract

Electronic waste (e-waste) represents a rapidly escalating global challenge, characterized by its complex composition, potential environmental hazards, and significant untapped resource value, particularly in metals. This project addresses the critical need for enhanced understanding and visualization of e-waste dynamics to inform policy and promote circular economy principles aligned with UN Sustainable Development Goals (SDGs) 11 and 12. We developed an automated data collection pipeline using Python (Requests, BeautifulSoup) to scrape comprehensive statistics (2018-2022) for continents, regions, and countries from the Global E-waste Statistics Partnership. The collected data, encompassing generation (total and per capita), EEE put on market, and formal collection rates, was processed using Pandas and visualized using GeoPandas, Matplotlib, and Contextily. Key findings reveal stark geospatial disparities, with Europe exhibiting high per capita generation and the highest collection rates, while vast regions in Asia and Africa show critically low collection (<5-10%). Temporal analysis highlights a consistent global increase in e-waste generation outpacing the slow growth in formal collection, thereby widening the resource circularity gap. This data-driven analysis underscores the urgency for improved e-waste management infrastructure, design-for-recycling strategies, and targeted policy interventions, especially in developing regions.

1 Introduction

Electronic waste (e-waste), discarded electrical and electronic equipment (EEE), is a rapidly growing global waste stream, reaching 62 million tonnes in 2022 and projected to exceed 74 million tonnes by 2030 Baldé et al., 2024. Despite containing valuable metals (e.g., gold, copper) constituting an "urban mine" Kastanaki and Giannis, 2022, formal collection and recycling rates remain critically low globally (22.3% in 2022), leading to resource loss and environmental hazards from improper disposal Baldé et al., 2024; Pamminger et al., 2021. Effective e-waste management through enhanced recycling is vital for resource conservation, mitigating pollution, fostering a circular economy, and achieving UN Sustainable Development Goals (SDGs), particularly SDG 12 (Responsible Consumption and Production) and SDG 11 (Sustainable Cities) Jose et al., 2024; Onete et al., 2020.

However, the lack of accessible, systematically visualized longitudinal data hinders effective policy-making and progress tracking. Addressing this gap, this project aimed to:

1. Systematically collect global e-waste statistics (2018-2022) from the Global E-waste Statistics Partnership (GESP) via automated web scraping.
2. Process and structure the data for analysis.
3. Visualize geospatial patterns (generation per capita, collection rates) and temporal trends (global generation vs. collection).
4. Quantify and illustrate regional/continental disparities.
5. Contextualize findings within the framework of UN SDGs and circular economy principles.

2 Literature Survey

This project is informed by literature spanning e-waste monitoring, circular economy principles, life cycle assessment (LCA), design considerations, and regional analyses. Authoritative reports like the Global E-waste Monitor Baldé et al., 2024 establish the scale of the problem and provide the foundational data utilized here. LCA studies confirm the significant environmental advantages of repair, refurbishment, and recycling over primary production, particularly due to high impacts from material extraction Jose et al., 2024; Pamminger et al., 2021. The economic potential of recovering critical raw materials from this "urban mine" is also well-documented Apple Inc., 2024; Kastanaki and Giannis, 2022.

Design choices significantly impact end-of-life management, with trends towards technological obsolescence hindering repair and circularity Barros and Dimla, 2021. Conversely, "Design for Recycling" principles are crucial upstream interventions Chakraborty et al., 2022. Consumer behavior studies indicate that factors like perceived value and environmental knowledge influence adoption of circular practices like purchasing refurbished goods, though awareness gaps persist Bigliardi et al., 2022; Onete et al., 2020.

Regional disparities in e-waste management infrastructure and policy effectiveness are substantial Kastanaki and Giannis, 2022; Slabe-Erker et al., 2023, often correlating with economic development levels. Data analysis and visualization techniques, including geospatial methods Chen et al., 2023, are essential for understanding these complex dynamics. While existing studies address specific aspects or regions, this project contributes by systematically collecting and visualizing the most recent (2018-2022) comprehensive GESP dataset across global, continental, and regional scales, providing an updated, accessible overview of current trends and disparities crucial for informing policy and research.

3 Methodology: Data Collection, Processing, and Visualization

A systematic workflow involving automated data collection, processing, and visualization was implemented using Python.

3.1 Data Collection

E-waste statistics (2018-2022; Continents, Regions, Countries) were scraped from the Global E-waste Statistics Partnership website (https://globalewaste.org/country-sheets/) using a custom Python script (`DataCollect.py`). The script utilized the **Requests** library (with session objects and automatic retries via `HTTPAdapter` for robustness against network/server issues) and **BeautifulSoup4** for parsing HTML. The process involved:

1. Fetching the main directory page and identifying category lists (Continent, Region, Country) by HTML ID.
2. Iterating through entity links within each category.
3. Accessing each entity's detail page and identifying links for the target years (2018-2022) via the `.yclick` CSS class.
4. Fetching each entity-year page and extracting key metrics (Population, E-waste Generated [kt, kg/capita], EEE Put on Market [kt, kg/capita], E-waste Formally Collected [kt], E-waste Collection Rate [%], E-waste Imported/Exported [kt]) by targeting specific HTML tags and classes. A helper function handled number parsing, including commas and 'n/a' values.
5. Aggregating extracted data into a list of dictionaries.
6. Implementing delays (`time.sleep`) between requests for polite scraping.

The collected data was saved in timestamped CSV and JSON formats.

3.2 Data Processing and Geospatial Integration

The scraped data was loaded into a **Pandas** DataFrame for cleaning and structuring. Numeric columns were converted to appropriate types, handling potential errors (`errors='coerce'`). To enable geospatial analysis, the country-level data was merged with a world boundaries shapefile (Natural Earth 110m Admin 0 Countries) using **GeoPandas**. Country name alignment between the e-waste data and the shapefile was achieved using a predefined mapping dictionary applied to a new 'Name_mapped' column, joined against the shapefile's 'ADMIN' column. Antarctica was excluded. Aggregations (e.g., summing country data for global totals per year) were performed using Pandas where necessary.

3.3 Data Visualization

Multiple visualization types were generated using Python libraries to illustrate key findings:

- **Choropleth Maps:** Created with **GeoPandas** and **Matplotlib** to show spatial distribution of metrics (e.g., collection rate %). **Contextily** provided basemaps. Appropriate color maps (`cmap`) and classification schemes (`scheme='Quantiles'` or fixed ranges) were used, with legends and styling for missing data (`missing_kwds`). Axes were hidden for clarity (See Figure 1).
- **Line Charts:** Generated with **Matplotlib** to display temporal trends (e.g., global generation vs. collection over 2018-2022). Markers indicated annual points, and shaded areas (`fill_between`) highlighted gaps (See Figure 2).

- **Bar Charts:** Utilized **Matplotlib** for comparing metrics across categories (e.g., continents). Dual axes were employed to compare metrics with different units (kg/capita vs. %) simultaneously. Bar labels provided exact values.

These visualization choices aimed to effectively communicate spatial patterns, temporal evolution, and categorical comparisons within the dataset.

4 Results and Discussion

The automated data collection pipeline successfully retrieved 1085 records covering Continents, Regions, and Countries for the years 2018 through 2022 from the GESP website. The structured dataset, encompassing metrics like population, e-waste generation (total and per capita), EEE put on market (total and per capita), and formal collection rates, formed the basis for subsequent analysis and visualization. Key metrics for selected major entities are summarized in Table 1.

Table 1: Selected E-Waste Data Comparison (2018 vs 2022)

Cat.	Name	Year	Pop (M)	Gen. (kt)	EEE Mkt (kt)	Coll. Rate (%)	Gen. (kg/c)	EEE Mkt (kg/c)
Cont.	Europe	2018	742.7	12278.0	14922.0	43.0	16.5	20.1
Cont.	Europe	2022	742.3	13076.0	14443.0	43.0	17.6	19.5
Cont.	Asia	2018	4539.6	24142.0	49337.0	12.0	5.3	10.9
Cont.	Asia	2022	4677.2	30147.0	56102.0	12.0	6.4	12.0
Reg.	South-Eastern Asia	2018	654.1	3573.0	6442.0	0.0	5.5	9.8
Reg.	South-Eastern Asia	2022	678.4	4362.0	7369.0	1.0	6.4	10.9
Ctry.	China	2018	1414.4	9558.0	22213.0	16.0	6.8	15.7
Ctry.	China	2022	1425.9	12066.0	24174.0	16.0	8.5	17.0
Ctry.	United States	2018	331.0	6768.0	8801.0	58.0	20.4	26.6
Ctry.	United States	2022	337.5	7188.0	9185.0	56.0	21.3	27.2
Ctry.	Germany	2018	82.8	1738.0	1854.0	49.0	21.0	22.4
Ctry.	Germany	2022	83.4	1767.0	1756.0	54.0	21.2	21.0
Ctry.	Japan	2018	126.5	2575.0	3337.0	19.0	20.4	26.4
Ctry.	Japan	2022	124.3	2638.0	3750.0	23.0	21.2	30.2

Note: 'kt'=kilotons; 'Gen.'=Generated; 'Coll.'=Collection; 'Pop.'=Population; 'M'=Millions; 'kg/c'=kg/capita. Full dataset available.

4.1 Key Findings and Visualizations

Analysis of the collected and processed data revealed several critical trends and disparities in global e-waste management between 2018 and 2022:

1. Stark Geospatial Disparities in Formal Collection: As visualized in Figure 1, formal e-waste collection rates in 2022 exhibited extreme variation globally. Europe maintained the highest average rate (43%), with several Western and Northern European countries achieving rates above 50-60%. In stark contrast, vast regions across Africa, Asia (excluding East Asia), and Latin America reported collection rates often below 10%, and frequently near or below 1-2%. This highlights a significant deficit in collection infrastructure and policy enforcement in many parts of the world.

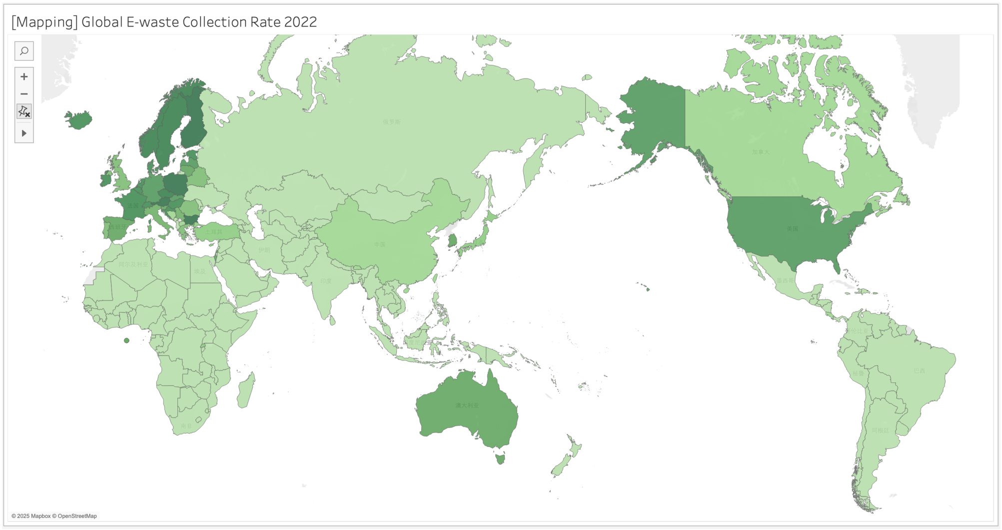

Figure 1: Global Formal E-waste Collection Rate (%), 2022. Darker shades indicate higher collection rates.

2. Divergent Per Capita Generation Patterns: While total generation is dominated by populous regions like Asia, per capita generation remains highest in developed economies. In 2022, Europe (17.6 kg/capita), Northern America (21.2 kg/capita), and Oceania (16.1 kg/capita) exhibited significantly higher per capita generation compared to Asia (6.4 kg/capita) and Africa (2.5 kg/capita). This suggests differing consumption patterns of EEE relative to population size.

3. Widening Gap Between Generation and Collection: Temporal analysis (Figure 2) clearly shows a consistent upward trend in total global e-waste generation from 2018 to 2022. While total formal collection also increased slightly over this period, its growth rate lagged behind generation. Consequently, the absolute volume of undocumented and likely improperly managed e-waste expanded annually, representing increasing environmental risks and lost resource opportunities.

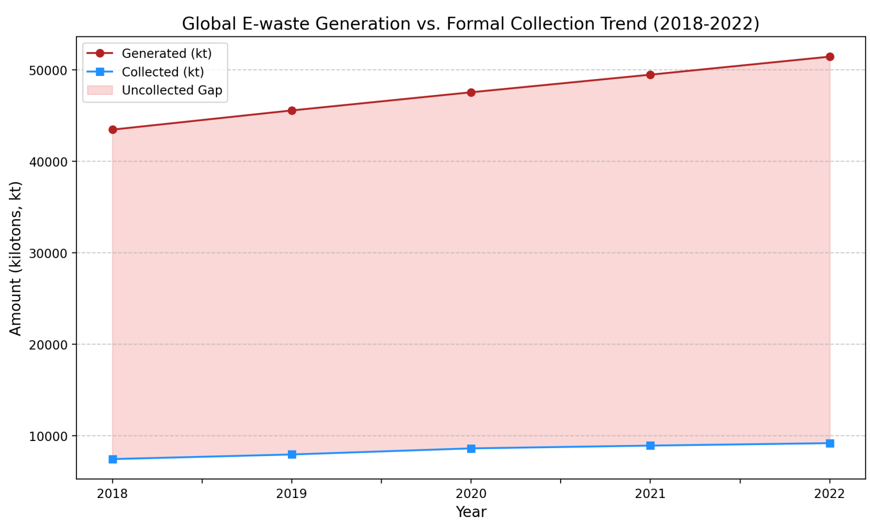

Figure 2: Global E-waste Generation vs. Formal Collection Trend (kt), 2018-2022. The shaded area indicates the growing volume of uncollected e-waste.

4. Continental Performance Synthesis: The continental comparison synthesizes these trends for 2022. Europe stands out with high per capita generation coupled with the highest collection rate. The Americas show similar high per capita generation but a lower collection rate than Europe. Asia, despite lower per capita figures, represents the largest total volume generated but suffers from very low average collection rates. Oceania exhibits high per capita generation but a collection rate comparable to Europe's average (driven largely by Australia/NZ policies). Africa shows the lowest figures for both per capita generation and collection rate.

5. Key Country Dynamics (2018 vs. 2022): Examining major economies (Table 1) reveals nuanced trends. Both China and the United States saw increases in per capita generation (China: 6.8 to 8.5 kg/c; US: 20.4 to 21.3 kg/c), but their formal collection rates remained relatively stagnant or slightly decreased (China: 16.0% constant; US: 58.0% to 56.0%). Germany and Japan exhibited slight increases in both per capita generation and collection rates (Germany rate: 49% to 54%; Japan rate: 19% to 23%).

4.2 Discussion

The visualized data starkly illustrates the uneven global landscape of e-waste management and the lagging progress towards circularity goals outlined in SDG 12.5. The widening gap between generation and formal collection signifies a massive, ongoing loss of valuable secondary raw materials and constitutes a growing environmental burden, particularly in regions lacking adequate management infrastructure.

The high collection rates in Europe correlate with long-standing implementation of policies like the WEEE Directive, suggesting policy effectiveness, though even here, significant room for improvement exists. The stagnation or slow progress in collection rates for major generators like the US and China, despite their increasing per capita generation, is particularly concerning given their large contribution to the total e-waste volume.

These findings emphasize the critical need for:

- **Infrastructure Investment:** Substantial investment in robust collection and recycling infrastructure is imperative, especially in developing nations across Asia, Africa, and Latin America.
- **Policy Harmonization and Enforcement:** Strengthening and enforcing e-waste policies, potentially including effective Extended Producer Responsibility (EPR) schemes globally, is crucial. International cooperation is needed to address transboundary e-waste flows.
- **Design for Circularity:** Encouraging EEE design that facilitates repair, refurbishment, and material recovery is a vital upstream intervention Barros and Dimla, 2021; Chakraborty et al., 2022.
- **Bridging the Data Gap:** Continued and improved data collection and reporting, potentially including better tracking of the informal sector and specific material flows, is necessary for monitoring progress and refining strategies.

The data clearly indicates that while high-income countries generate more e-waste per person, they often possess more effective (though still imperfect) systems for managing it. Addressing the global e-waste challenge requires tackling both high consumption levels in developed nations and inadequate infrastructure in developing ones.

5 Conclusion and Future Work

5.1 Conclusion

This project successfully developed and deployed an automated pipeline to collect comprehensive e-waste statistics (2018-2022) from the Global E-waste Statistics Partnership. Through processing and visualization using Python libraries (Pandas, GeoPandas, Matplotlib), we illustrated critical global trends, stark regional disparities, and the persistent challenge of low formal collection rates failing to keep pace with escalating generation. The findings provide a clear, data-driven confirmation of the widening circularity gap in e-waste management and underscore the urgent need for enhanced policy, infrastructure, and design interventions globally to achieve sustainable resource management aligned with UN SDGs.

5.2 Limitations

The analysis relies on the accuracy and methodology of the GESP data, which involves modeling and estimation, particularly for regions with limited primary data. The dataset frequently lacked reliable data on transboundary e-waste movements (import/export marked 'n/a'). The web scraping script's longevity depends on the stability of the source website's structure. Furthermore, this study does not quantify the significant role of the informal e-waste processing sector, which impacts both resource recovery and environmental/health outcomes, especially in developing regions. The analysis remains primarily descriptive, identifying correlations and trends rather than establishing causal relationships.

5.3 Future Work

Several avenues exist for extending this research:

1. **Material Flow and Economic Analysis:** Integrate specific metal composition data (e.g., from the Urban Mine Platform or LCA literature) with the collected tonnage data to estimate the economic value of metals lost in uncollected e-waste streams regionally and globally.
2. **Policy Effectiveness Analysis:** Conduct comparative studies correlating specific policy implementations (e.g., EPR start dates, specific collection targets) with changes in collection rates within countries or regions over a longer time series, potentially using econometric methods.
3. **Predictive Modeling:** Develop forecasting models to project future e-waste generation and collection trends based on historical data, EEE sales patterns, population growth, and socio-economic indicators.
4. **Informal Sector Integration:** Incorporate available estimates or develop methodologies to account for the scale and impact of the informal e-waste recycling sector.
5. **Interactive Platform Development:** Enhance the accessibility and exploratory potential of the data by developing a more comprehensive interactive web-based dashboard (e.g., using Dash/Plotly or expanding Tableau work).

Team Contribution

Zhiyuan Xia, as the sole member of Team 7, was responsible for all aspects of the project lifecycle, including conceptualization based on course requirements, literature review, development and execution of the Python-based data collection script, data cleaning and processing, geospatial analysis, generation of all visualizations (maps, line charts, bar charts), and the compilation of project deliverables including the proposal, progress report, final report, and poster.

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