

Market Classification Framework for E-Waste Recycling: A Data-Driven Strategy for Global Mapping

Thesis by
Gianfranco Pizzuto Allende

In Partial Fulfillment of the Requirements for the Course of
Microeconomics

Supervised by
Professor Luigi Marengo



LUISS GUIDO UNIVERSITY
Rome, Italy

MANAGEMENT AND COMPUTER SCIENCE

Defended 06/03/2025

ABSTRACT

This thesis develops a data-driven framework to classify countries based on the maturity of their electronic waste management ecosystems. By combining different indicators across regulatory, infrastructural, environmental, and socioeconomic dimensions, four country typologies were identified: Advanced Generators, Developing Systems, Emerging Potential, and Mature Circular Leaders.

A case study comparing Mexico and France demonstrates the model's practical value. Despite Mexico's higher volume of electronic equipment placed on the market, France's more formalized collection and certification systems place it in a more advanced cluster. Underscoring the importance of infrastructure and regulation over raw volumes.

The framework, supported by interactive dashboards, offers a transparent and adaptable tool for benchmarking, policymaking, and investment prioritization. It contributes to ongoing global efforts in e-waste management, circular economy development, and environmental policy innovation.

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to Professor Luigi Marengo for his invaluable guidance, insightful feedback, and continuous support throughout the development of this thesis.

A special thank you goes to my parents, Gianfranco Pizzuto and Alejandra Allende, whose unwavering support and encouragement have been essential throughout my studies.

Luigi Pizzuto, who gave me the opportunity to explore the e-waste sector and whose guidance played a key role in shaping the ideas behind this work.

Sebastian Barriga, whose mentorship greatly influenced my analytical thinking and inspired many of the skills applied in this thesis.

Finally, I would like to thank my siblings Carlo, Piero, and Alexa Pizzuto and Beatrice Conti for their personal support, motivation, and presence throughout this journey.

This work would not have been possible without the contribution and encouragement of all those mentioned above.

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Chapter I

INTRODUCTION

Electronic waste (e-waste) is the fastest-growing waste stream in the world. In 2022 alone, global e-waste generation was above 62 million metric tonnes, yet only 22% was officially documented as formally collected and recycled.¹ E-waste contains valuable materials such as gold, copper, and rare earth elements, alongside toxic and hazardous substances that can pollute air, soil, and water if improperly managed. While many countries have begun addressing this issue through regulation, infrastructure development, and awareness campaigns, the approaches remain short, leading to a significantly higher waste production than recycled.

Some countries have established national legislation, extended producer responsibility systems, and formal recycling infrastructure. Others continue to rely heavily on informal sectors or lack enforcement capacity. This variation reflects different levels of institutional maturity, economic development, environmental awareness, and resource availability.

Understanding these differences is crucial for global examination, policy comparison, and identifying shared challenges. However, there is currently no structured framework to systematically classify countries based on the difference of their e-waste ecosystems.

1.2 Problem Statement

Despite growing international awareness and data availability, there is no standardized framework to classify countries based on the maturity and characteristics of their e-waste ecosystems. Existing studies often focus on regional statistics, or performing a series of mathematical equations to calculate approximate generated waste. These methods do not focus on integrating multiple dimensions (e.g. regulatory, infrastructural, environmental, and economic) into a classification system.

This lack of a data-driven structure makes it difficult to classify countries, identify peer groups, or study policy effectiveness comparatively. A country with low collection rates, for instance, may share infrastructure issues with another, despite having different regulations. Without a structured classification method, such insights are hard to detect or act upon.

1.3 Objective

The goal of this thesis is to design a multi-dimensional classification framework to group countries based on their e-waste generation and management characteristics. Specifically, the study aims to:

- Identify and collect key indicators across four dimensions: E-Waste Generation & Monitoring, Waste Infrastructure & Policy, Macroeconomic & Structural Readiness, and Microeconomic & Trade Enablers.

- Normalize and score each country along these dimensions using publicly available data.
- Apply clustering and classification techniques to reveal distinct country profiles.
- Interpret these profiles to offer a deeper understanding of global patterns, challenges, and structural similarities.

1.4 Research Questions

This thesis will be guided by the following research questions:

1. What are the most relevant indicators for describing a country's e-waste ecosystem?
2. How can these indicators be used to build a consistent, data-driven classification of countries?
3. What clusters or typologies of e-waste ecosystem maturity emerge from the analysis?
4. How do countries in similar or different regions compare within and across these classifications?

1.5 Significance of the Study

This research contributes to global environmental and circular economy efforts by offering a replicable model that supports strategic decision-making for recycling companies, investors, governments, and development agencies. Facilitates smarter allocation of resources for recycling infrastructure, and encourages balanced, data-based expansion strategies for sustainable electronics recovery globally.

By producing a transparent, indicator-driven country classification, this study aims to accelerate progress toward more effective e-waste recycling systems worldwide.

Chapter II

LITERATURE REVIEW

Electronic waste has come to be the defining environmental and policy challenge of the 21st century. With over 62 million metric tonnes (Mt) generated globally in 2022, and projections suggesting a rise to 110 Mt by 2050 if no substantial interventions occur. E-waste continues to grow faster than any other waste stream. This growth is driven by a variety of different factors, including technological innovation, increased consumer demand, the rise of AI, and current digitalization trends (e.g IoT systems).¹

The clear attributes of e-waste; as both an environmental threat and a source of valuable secondary raw materials, underline its strategic relevance. Electrical and electronic equipment (EEE) contains high concentrations of precious metals, rare earth elements, and recyclable plastics, but also hazardous substances such as lead, mercury, and brominated flame retardants. Poorly managed e-waste represents not only a public health risk but also a lost economic opportunity.²

2.2 Global Flows and Transboundary Movement

E-waste flows are global, and often cloudy. Ideally, these materials should circulate within formalized systems through regulated collection, responsible treatment, and material recovery. However, as shown by numerous studies and field investigations, actual flows diverge substantially from this norm.

The Basel Convention established a framework to properly classify and keep track of exported e-waste, classifying it as a hazardous material. However, according to the Global Transboundary E-waste Flows Monitor, up to 30% of used electronic goods shipped across borders are likely illegal, given that the transport of hazardous material involves higher regulation and compliance methods. An example being used is the transport of non-functional devices being falsely labeled as reusable and ending up in countries with poor infrastructure to recycle the waste.⁴ For instance, the Basel Action Network's (BAN) GPS-tracking project revealed that around 40% of e-waste dropped off with U.S. recyclers was exported, with 93% of those exports ending up in developing countries; predominantly in Southeast Asia and West Africa.⁵ These flows typically bypass environmental controls and are handled in informal settings, where open burning and acid leaching are common practices, leading to higher carbon emissions and health hazards for the workers of these recycling facilities.

Such leakages not only damage environmental safety but also distort global recycling markets. Informal processing can offer cheaper services than compliant treatment facilities, creating downward pressure on prices and contributing to a “race to the bottom”.⁶

Apart from growing policy awareness and technological advances, major challenges remain. In many low and middle-income countries, the informal sector dominates. Meanwhile, high-income countries, despite having formal infrastructure and extended producer responsibility schemes, still experience significant waste leakages. Even certification systems like R2 and e-Stewards have limitations, as some certified recyclers continue to engage in practices that violate international standards.

2.3 Gaps in Measurement and Statistical Infrastructure

Perhaps the most persistent and important challenge is the lack of reliable, harmonization, and comprehensive data. Accurate statistics on e-waste generation, collection, and treatment are scarce, inconsistent, or outdated in many countries. Only 41 countries worldwide are known to compile official e-waste statistics using standardized methods.²

This data deficiency comes from several factors:

Lack of Harmonization: Definitions, classification systems (e.g., UNU-KEYS, EU-WEEE categories), and data reporting protocols differ across jurisdictions, complicating cross-country comparability.

Unreported or Informal Flows: Informal collection and trade of e-waste often occur outside of official systems and are therefore excluded from national statistics.⁴

Lifespan Uncertainties: Calculating the amount of WEEE generated (WG) requires accurate data on the lifespans of products. These vary considerably based on product type, usage context, and socioeconomic conditions, making forecasting imprecise.⁹

Limited Institutional Capacity: Many countries, particularly in the Global South, lack the institutional frameworks and technical tools to monitor e-waste flows systematically.²

These data challenges limit the ability to compare countries, identify trends, and evaluate policy effectiveness.

2.4 The Need for Systematic Classification

Current research and reporting tend to focus either on global compilations or individual case studies. While valuable, these approaches often overlook the broader structural patterns and typologies that could emerge from structured cross-country analysis. A small number of recent studies have attempted to correlate e-waste generation with development indicators such as GDP, literacy, and internet penetration. For instance, Kalia et al. (2021) found that in developing countries, higher internet penetration was associated with higher e-waste generation, while in developed countries, higher literacy rates corresponded with reduced e-waste volumes.¹⁰

These findings suggest that e-waste generation and management outcomes could correlate with broader variables, including policy presence, urbanization, and market maturity. Yet, to date, no study has produced a global classification framework that integrates multiple indicators across regulatory, infrastructural, environmental, and socioeconomic dimensions. This represents a key gap in data, and the primary motivation for the current research.

Chapter III

DATA AND INDICATORS

To enable a structured classification of countries by the maturity of their e-waste ecosystems, this chapter identifies and describes the indicators used in the analysis. These indicators were selected to capture both direct and indirect aspects of e-waste generation, trade, and management performance. The approach is designed to compensate for data gaps by incorporating proxy variables known to correlate with e-waste activity.

The indicators are grouped into four main dimensions: *E-Waste Generation & Monitoring*, *Waste Infrastructure & Policy*, *Macroeconomic & Structural Readiness*, and *Microeconomic & Trade Enabler*. Together, they allow for the normalization and clustering of countries into comparable typologies, regardless of whether detailed e-waste data exists for every country.

3.2 Indicator Framework

E-Waste Generation & Monitoring

This category includes indicators that capture the total volume and characteristics of e-waste generated by country or region. Including but not limited to the amount generated, formally collected, categories of waste, etc. This foundational information is used to estimate the potential size of the e-waste recycling market. Data from international sources such as the Global e-waste monitor (GEWS) provide country-level profiles on generation volumes, collection efforts, and relevant legislative context.¹²

Waste Infrastructure & Policy

Indicators in this category reflect each country's institutional and infrastructural capacity to manage e-waste effectively. This includes the number of formally certified processing facilities, the presence and detail of legal frameworks governing e-waste, and the overall strictness of environmental regulations. Data was obtained from GEWS, Sustainable Electronics Recycling International, the International Telecommunication Union, and the Organisation for Economic Co-operation and Development.^{12 13 14 15}

Macroeconomic & Structural Readiness

This category measures broader national conditions that influence the feasibility and scalability of investment in e-waste recycling. Indicators include GDP, GDP per capita, population and national spending on education, the latter serving as a proxy for human capital development. These metrics are sourced from the World Bank, ITU, and the United Nations.^{16 17 18 19}

Microeconomic & Trade Enablers

This category focuses on localized industrial capacity, specifically on manufacturing of computer, electronic and optical products and electrical equipment. Countries with a developed electronics-related manufacturing base are more likely to support domestic e-waste collection and recycling efforts. Data for this category was sourced from the United Nations Industrial Development Organization, which tracks industrial output by sector.²⁰

The full variable description and type is available in *Appendix A*.

3.3 Data Availability and Normalization Strategy

Due to variable data coverage across countries, the classification will use the most recent available data (typically 2018 to 2022). Indicators will be normalized using min-max scaling to ensure comparability across units and scales. Where direct e-waste metrics are missing, proxy-based estimation models will be explored using correlated socioeconomic indicators.

This comprehensive dataset forms the foundation for clustering countries into e-waste ecosystem typologies in the following chapter.

Chapter IV

METHODOLOGY

This chapter dives into the analytical steps taken to develop a global classification of countries based on their e-waste recycling readiness. The approach integrates data preprocessing, indicator normalization, dimension scoring, and unsupervised machine learning, using Python for analysis and Power BI for visualization.

4.2 Data Preparation and Cleaning

The initial dataset contained country-level data from 2018 to 2022, covering variables across e-waste generation, collection rates, policy presence, economic conditions, and infrastructure proxies. Each row represents a country-year combination, enabling time-series analysis.

Key cleaning steps included converting values, and dropping rows missing essential values such as population or e-waste generation. Variables with limited availability (e.g., environmental policy stringency or education spending) were preserved, as their partial contribution still enhanced the analysis.

In addition to the transformed data, the original version of the data was retained and later imported into Power BI to allow for unfiltered country-level exploration and temporal comparison.

4.3 Normalization of Indicators

To standardize data across different units, Min-Max normalization was applied to all numeric fields, except those already expressed as ratios (e.g., e-waste collection rate). This transformation scaled all features to a 0 to 1 range, enabling a standard structure of the data for the clustering algorithm. The categorical values (yes/no) were also converted into binary form for the algorithm to take into account.

4.4 Construction of Composite Dimension Scores

Normalized indicators were grouped into the selected four dimensions to summarize each country's e-waste ecosystem and assigned a specific score (0 to 1) per each class:

- *Generation & Monitoring*: Indicators for e-waste per capita, formal collection rates, and EEE placed on the market.
- *Infrastructure & Policy*: Presence of R2-certified facilities and national legislation (including EPR and recycling mandates).
- *Macroeconomic Readiness*: GDP, GDP per capita, education investment, and environmental policy stringency.
- *Microeconomic Enablers*: Industrial production indices related to electronics and computer-related goods.

Each dimension score was computed as the mean of available indicators in that group for each country-year. Missing values within a dimension were handled via partial averaging to retain maximum coverage.

4.5 Correlation Analysis

A correlation matrix of the four composite scores was generated to verify their independence as shown in *Figure 1*. Generation and Macroeconomic Readiness were highly correlated ($r \approx 0.76$), as high-income countries typically generate more e-waste. Infrastructure showed moderate correlation with macroeconomic scores, while Microeconomic Enablers were weakly correlated with the rest, confirming their diverse contribution to the clustering algorithm.

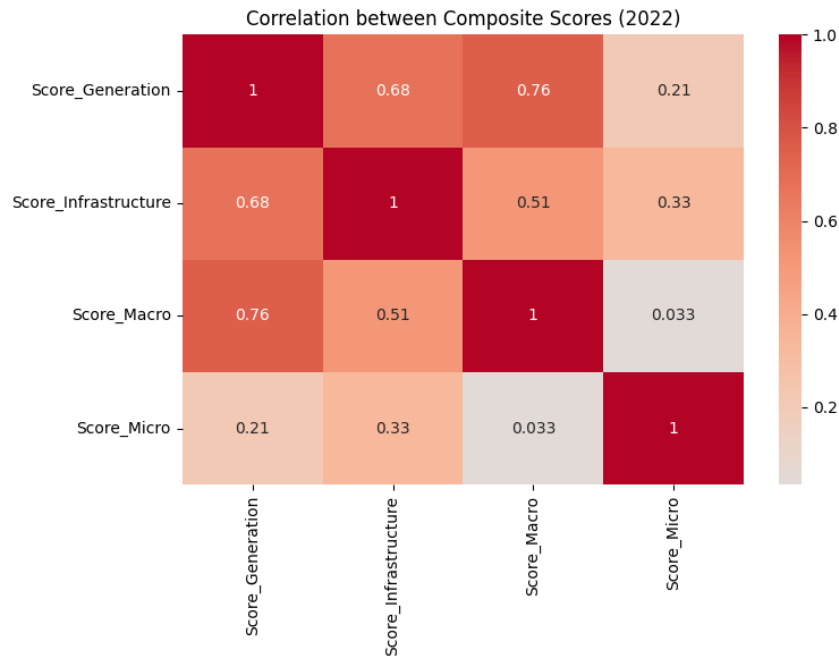


Figure 1: Correlation between Composite Scores (2022)

This analysis validated the inclusion of all four scores in the clustering process.

4.6 Clustering Analysis (2022)

Unsupervised clustering was performed using the K-Means algorithm applied to 2022 data. This machine learning algorithm classified the countries into different categories. The Elbow Method and Silhouette Score were used to test different values of k . Based on visual diagnostics and domain knowledge, a four cluster solution ($k = 4$) was selected, offering meaningful distinctions between country typologies.

The resulting clusters were interpreted as follows:

Cluster 0, Advanced Generators: High-income, high-tech countries with moderate collection systems (e.g., USA, Canada).

Cluster 1, Developing Systems: Emerging markets with growing e-waste activity and limited infrastructure (e.g., India, Brazil).

Cluster 2, Emerging Potential: Countries with mid-level readiness and uneven progress across dimensions (e.g., Mexico, Indonesia).

Cluster 3, Mature Circular Leaders: Mature, policy-driven systems with strong recycling infrastructure (e.g., France, Sweden).

A visual map of the classified countries was created using Power BI and is shown in *Figure 2*.

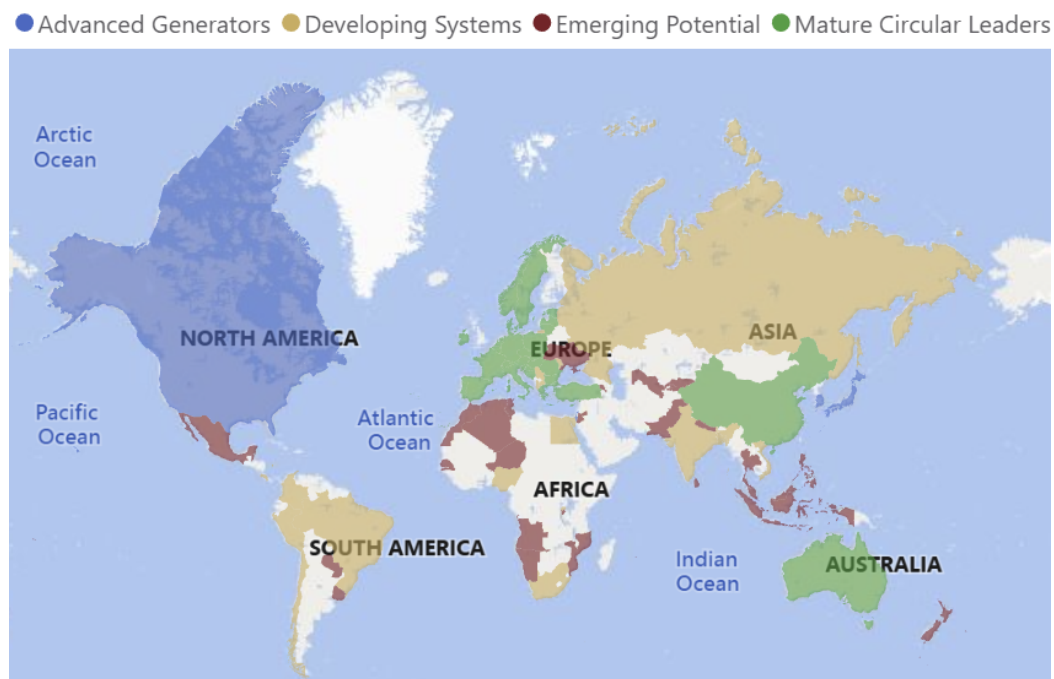


Figure 2: Countries Classified by Cluster

A complete list of countries assigned to each cluster is provided in *Appendix B*.

4.7 Visualization in Power BI

Two main interactive dashboards were developed in Power BI to visualize and interact with the data:

The *Cluster Overview Dashboard*, built using the 2022 cluster-labeled dataset, provides a visual summary of global e-waste readiness. It includes a filled world map to quickly identify each country's cluster, bar charts to compare average scores across dimensions, and cards highlighting key indicators. A country table and regional filters allow exploration across areas, and diving deeper into specific county insights. The dashboard is a practical tool for identifying strategic priorities and regional trends of the countries classified at a glance.

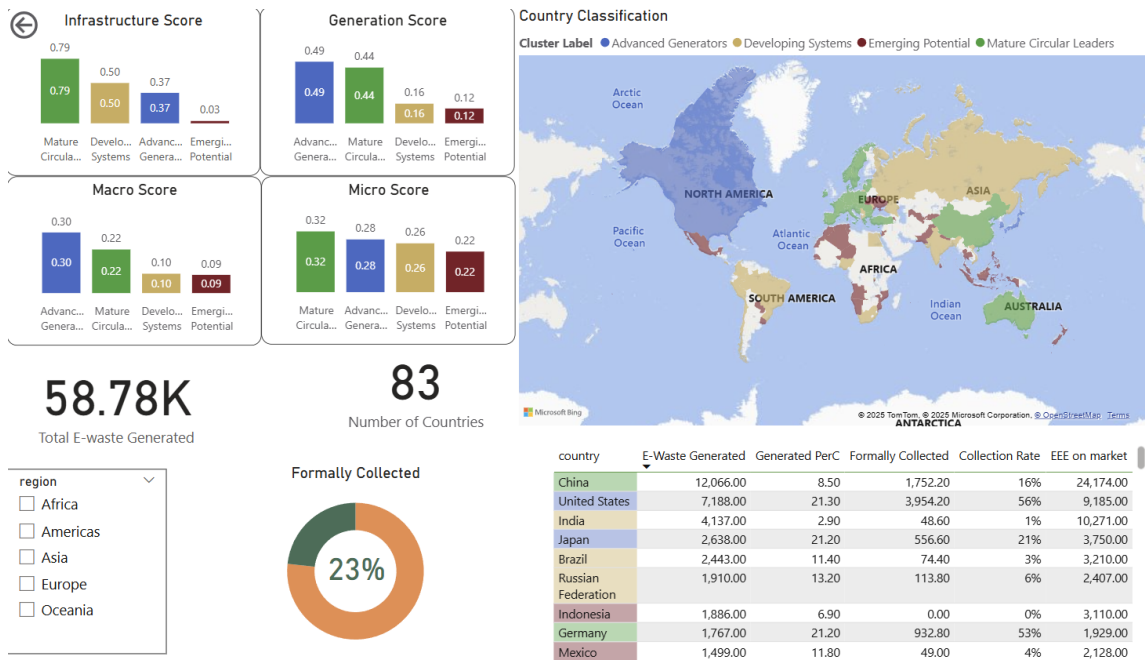


Figure 3: Clusters Overview Dashboard Power BI

The *Country Dashboard*, built using the original dataset, enables exploration of both raw and normalized indicators across all countries and years. Can track temporal changes in e-waste generation, collection, and policy readiness, independent of cluster assignments. With flexible filters, it allows for detailed country-level comparisons. Making it especially useful for deeper analyses, such as the Mexico/France case study presented in the following chapter.

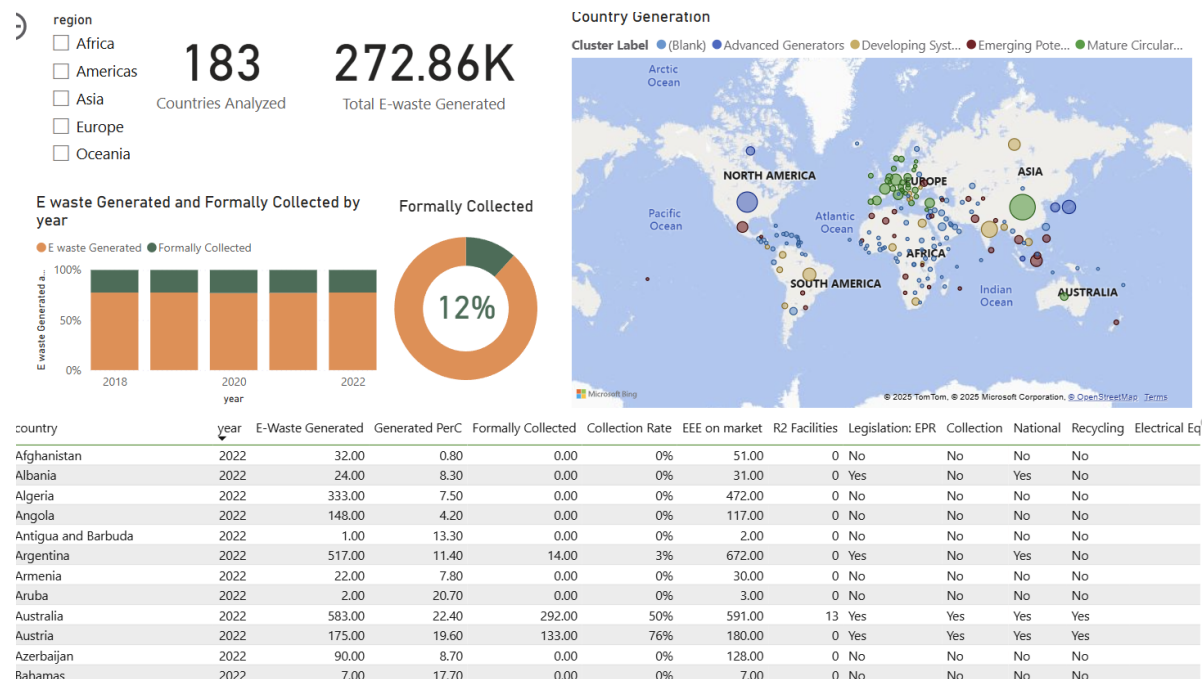


Figure 3.1: Countries Dashboard Power BI

This two-dashboard structure allows for a global typology analysis and country-specific insight. More visuals were created in the Power BI dashboard that will help conduct specific research on the case study of the following chapter, full dashboards are available in *Appendix C*.

4.8 Considerations and Limitations

All dimension and indicator scores were equally weighted to maintain transparency and avoid subjective bias. Clustering was performed for a single year (2022) to ensure time-consistency and minimize data gaps.

Missing values in composite scores were handled using mean averaging, which preserves country participation while slightly reducing precision for countries with sparse data. Additionally, some indicators such as EPS and industrial production had limited country coverage, which may affect comparability.

The Power BI dashboards provide a flexible front-end for policy exploration and investment analysis, while the Python-based methodology ensures replicability and clarity.

Chapter V

RESULTS AND LOCAL ANALYSIS

Building upon the global clustering framework developed in *Chapter IV*, this chapter shifts focus toward country-specific insights. The objective is to explore how two countries from different clusters (*Mexico* and *France*) differ in terms of their e-waste ecosystem, despite both playing significant roles in global electronics consumption and waste generation.

While France was classified as a *Mature Circular Leader*, Mexico fell under the *Emerging Potential* group. This distinction reflects not only differences in economic development but also variation in infrastructure maturity, policy enforcement, and industrial readiness.

This section begins with a side-by-side comparison of the composite dimension scores, followed by a time-series analysis of key indicators, a breakdown of e-waste types and a comparison of legislation of the chosen countries. The aim is to uncover structural differences and identify areas of opportunity for policy development or infrastructure investment in developing countries like Mexico.

5.2 Comparative Profile of Composite Scores

To show the diversity in e-waste readiness across countries, this section compares *Mexico* and *France* using their 2022 composite dimension scores.

The comparison highlights significant differences across the four dimensions as shown in *Figure 4*.

Dimension	Mexico (Score)	France (Score)
Generation & Monitoring	0.23	0.58
Infrastructure & Policy	0.21	0.8
Macroeconomic Readiness	0.17	0.21
Microeconomic Enablers	0.26	0.21

Figure 4: Mexico vs France Composite Scores

France consistently scores higher across three of the four dimensions, particularly in *Infrastructure & Policy*, where its score (0.80) is far superior than Mexico's (0.21). This reflects France's maturity in establishing e-waste legislation, formal collection networks, and certified facilities.

In *Generation & Monitoring*, France also leads with a score of 0.58, compared to 0.23 for Mexico, indicating more advanced tracking of e-waste and electronics placed on the market. Interestingly, Mexico slightly outperforms France in the *Microeconomic Enablers* dimension. This could suggest that while France benefits from mature public systems, Mexico may have untapped private-sector or industrial

capacity that hasn't yet translated into a formal industrial potential that is fully supported by regulation or infrastructure.

The *Macroeconomic Readiness* scores for both countries remain relatively low, with a slight advantage for France. This suggests that while economic strength contributes to e-waste readiness, it is not the dominant driver compared to infrastructure and policy frameworks.

These differences in composite scores provide a high-level view of system maturity. The next sections will delve deeper into time-series performance, collection outcomes, and category-level differences to better understand the structural gaps and opportunities in each national system.

5.3 Time-Series Analysis

The evolution of e-waste readiness in Mexico and France over the period 2018 to 2022 reveals not only their structural differences, but also how their respective systems responded to changing industrial and policy contexts.

Composite Score Evolution

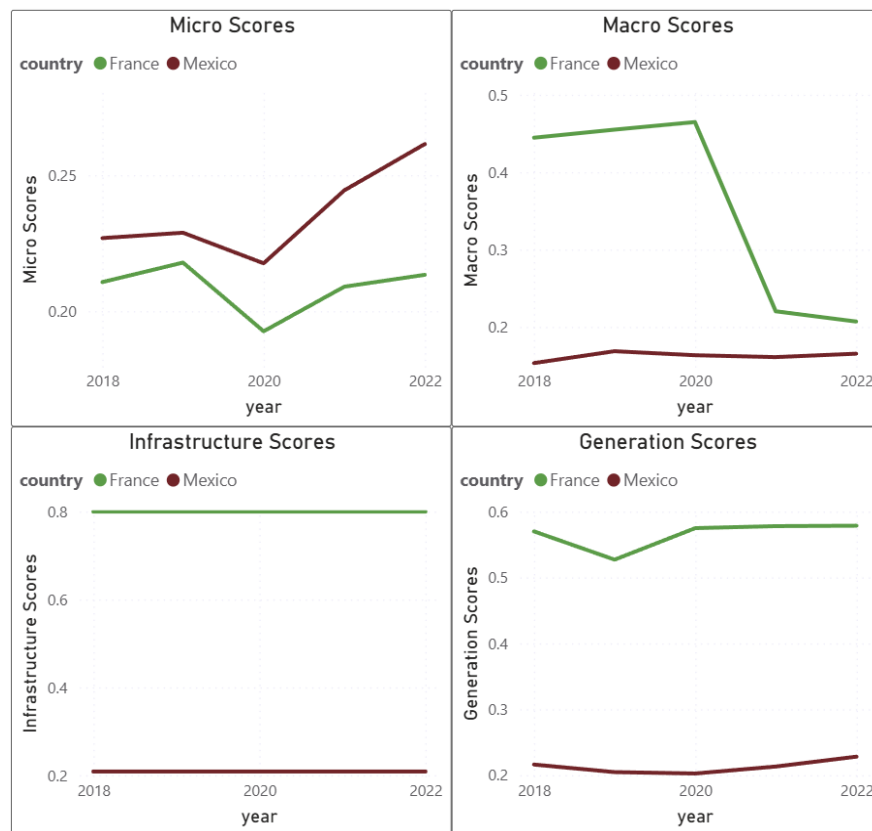


Figure 5: Mexico vs France Composite Scores by Year

As shown in *Figure 5* France demonstrates stable high performance across Infrastructure and Generation scores throughout the timeline. Its infrastructure score remaining consistently strong, reflects a mature system supported by established regulations and formal recycling facilities. Generation scores also held steady, indicating that France maintains a well-monitored flow of electronic equipment and waste. However, a noticeable decline occurred in its Macroeconomic Readiness score after 2020. While not directly explained in the dataset, this drop could relate to broader post-pandemic budget reallocations that affected education or other macroeconomic factors like GDP.

Mexico, in comparison, maintained low scores in infrastructure, macro dimensions, and generation throughout the period, with a slightly upward trend in the latter. However, one shift stands out; the *Microeconomic Enablers* score increased after 2020, with a significantly higher slope than France. This change could suggest a growing domestic activity in electronics-related manufacturing and a higher volume of devices entering the market.

EEE on Market

Another key finding comes from the trends in *EEE placed on the market*. While Mexico consistently placed more electronics on the market than France, this difference widened significantly after 2020. France shows a downward trend, while Mexico's curve rebounds noticeably.

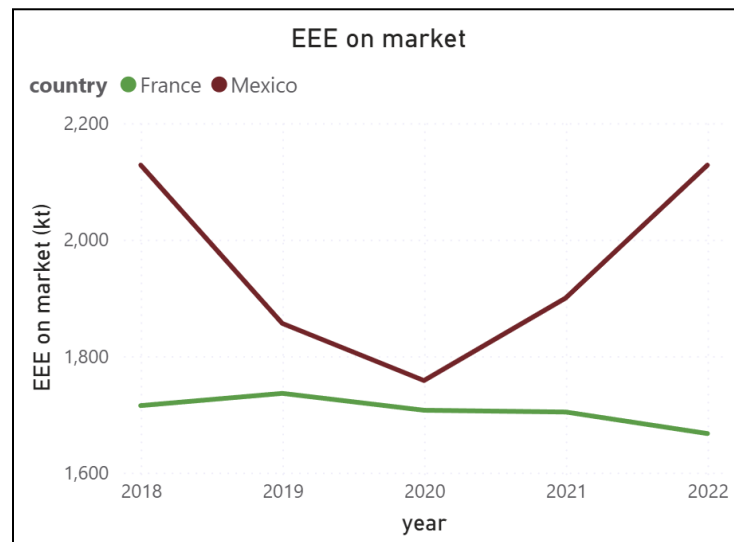


Figure 6: Mexico vs France EEE put on market by Year

This drift may be partially attributed to the economic effects of the COVID-19 pandemic. France's dip could reflect reduced consumer spending or delayed production in institutional sectors during lockdowns. Alternatively, Mexico's manufacturing sector (particularly in consumer electronics and electrical equipment as shown in the micro scores of *Figure 4*) may have played a growing role in global supply chains, possibly driven by nearshoring trends, given the increasing regional demand during the recovery period, and the rising geopolitical instability between the U.S. and China.

The increase in Mexico's electronics production and placement on the market highlights potential, but also emphasizes the urgency of scaling its formal collection systems. Without corresponding growth in infrastructure or regulation, the environmental and social burden from this growing volume could worsen.

Formally Collected E-Waste

Perhaps the most persistent and striking gap between the two countries lies in formal collection rates. France maintained a stable collection rate of around 60% over the entire five-year period, with most of its generated e-waste entering formal channels. Mexico, on the other hand, remained stuck at just 4%, with insignificant improvement despite increasing volumes.

Formal Collection Rates		
Year	Mexico	France
2018	4%	61%
2019	4%	46%
2020	4%	60%
2021	4%	60%
2022	4%	60%

Figure 7: Formal Collection Rate Mexico vs France

This reinforces the statement that *policy maturity* and *infrastructure*, rather than economic growth alone, determine the effectiveness of e-waste management systems. Even as Mexico's electronics production and consumption expands, its lack of structure to channel waste into formal recycling structures presents a clear bottleneck, and a potential area for investment or policy innovation.

Summary Insight

The time-series view confirms that France maintains consistent performance, with minimal variation mostly in infrastructure indicators. Mexico shows early signs of growth in industrial and consumer electronics, but without a corresponding rise in policy or infrastructure capacity. The collection rate gap illustrates how readiness is not only a function of what is produced or consumed, but of what is recovered.

These insights reinforce the cluster classification, while setting the stage for a deeper dive into the specific *categories of e-waste* and how both countries manage them.

5.4 E-Waste Category Breakdown

Further than the overall volumes and scores, the types of e-waste generated in each country reveal structural differences in manufacturing capacities, consumption patterns, device lifecycles, and industrial usage. This section, as shown in *Figure 8*, compares the category-level distribution of e-waste between Mexico and France in 2022, highlighting which streams dominate and where intervention efforts may differ.

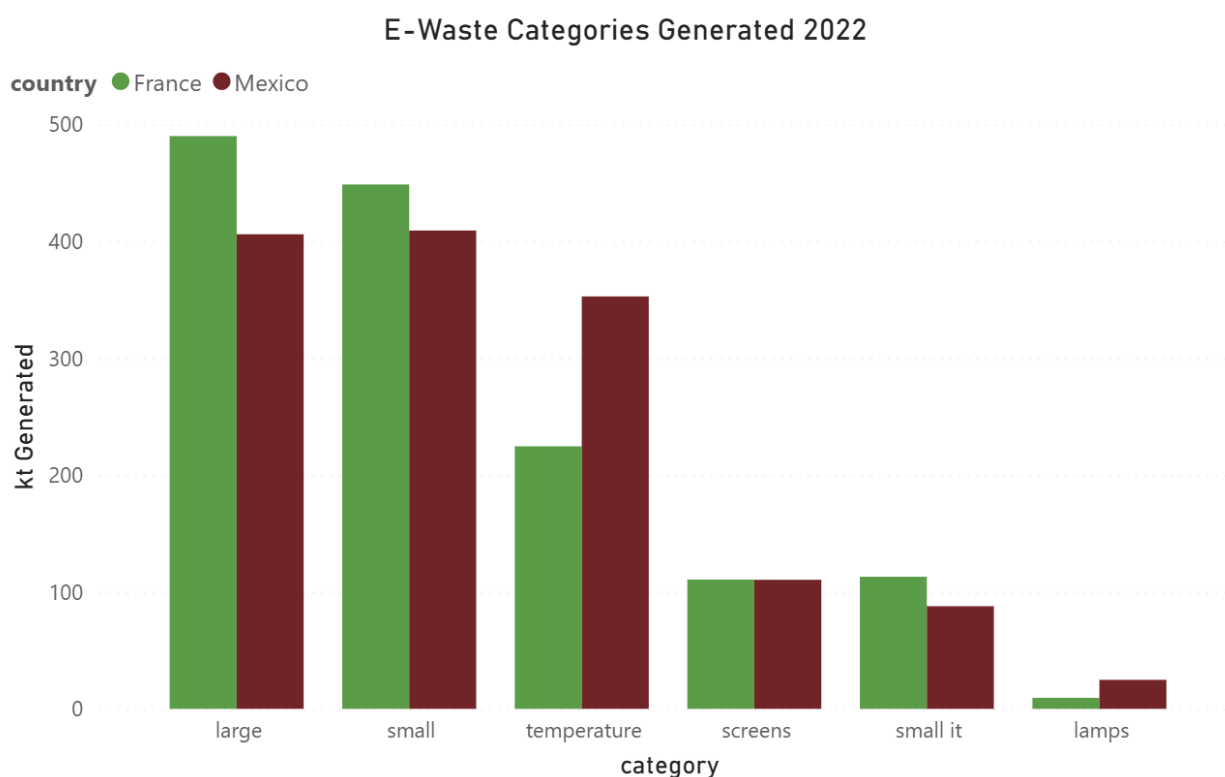


Figure 8: E-Waste Generated by Category in 2022 Mexico vs France

Key Differences

The most striking gap lies in *temperature exchange equipment* (e.g., refrigerators, air conditioners), where Mexico generates over *140 kt more* than France. This may reflect a warmer climate driving broader use of A/C and cooling devices, more frequent device turnover or less efficient repair/reuse markets. This category also poses greater environmental risks due to the hazardous material in refrigerants and insulation foams, emphasizing the urgency of formal collection systems in Mexico.

France leads in *large equipment*, *small IT*, and *small equipment*, likely due to higher penetration of home appliances and digital devices per household. This could also suggest France has a more developed production system and greater demand for small and more complex electronics. However, Mexico's numbers are close behind, especially in *small equipment*, which nearly matches France's output. By

comparison, Mexico focuses more on the production of simpler electronics, such as lamps, whose volume is almost three times higher than in France. Interestingly, both countries produce the same volume of e-waste from screens (116 kt), indicating similar TV and monitor saturation rates.

For more detailed data the full table is available in *Appendix D*.

Takeaway Insight

France and Mexico share similar waste volumes in many categories, yet France's higher formal collection rate means these streams are more likely to be safely handled. In Mexico, rising volumes, particularly in temperature and lamp categories, pose growing environmental risks if not properly collected and treated.

This breakdown provides a more specific lens on system gaps, and supports targeted recommendations in the next chapter on how Mexico might prioritize infrastructure or policy upgrades across specific categories.

5.5 Policy & Infrastructure Gaps

Despite similar volumes of e-waste, as seen before Mexico and France differ significantly in how effectively they manage, regulate, and process this waste. These differences are strongly reflected in the policy and infrastructure indicators.

Legislative Coverage

As of 2022, France has full legislative coverage across all key areas of e-waste regulation; including collection, recycling, national legislation, and Extended Producer Responsibility (EPR). In contrast, Mexico lacks formal legislation in three out of four areas: it only reports having national legislation, but no collection mandates, EPR schemes, or recycling requirements.

This legal difference directly influences operational outcomes. France's established policy framework creates accountability and incentives for both producers and consumers to engage with formal waste systems. Mexico's limited legislation leaves a critical governance gap, restricting the ability of both public and private sectors to scale formal collection efforts.

Infrastructure and Institutional Readiness

The infrastructure picture is equally revealing. While the dataset reports zero *R2-certified* facilities in France, this does not reflect a lack of capacity. France operates under the *WEEE Directive*, and is home to 215 treatment centers that fulfill equivalent roles in the European context.

Mexico, by contrast, is listed with only 13 *R2-certified* facilities, with a territorial area three times as big as France; this means waste has to travel further to be recycled which leads to higher costs and more fuel spent on transportation. Mexico's infrastructure score remains flat at 0.21, suggesting that the presence of facilities alone is not sufficient, without national systems to regulate flows and enforce usage, even certified infrastructure may be underutilized or unevenly distributed.

France also maintains a much higher Environmental Policy Stringency (EPS) Index, scoring above 4.5 in every year, while Mexico remains below 1.6. This reinforces the idea that beyond regulation, France actively prioritizes environmental outcomes at the policy level, integrating e-waste into broader sustainability agendas.

For more detailed data the full table is available in *Appendix E*.

Key Takeaway

The data shows that France's maturity results from an integrated system, legislation, infrastructure, and environmental ambition work in alignment. In contrast, Mexico's system is fragmented. Even as industrial capacity and electronics demand rise, policy and infrastructure have not adapted, leaving formal collection stagnant at 4%.

Bridging this gap will require more than infrastructure expansion, it will depend on coordinated policy development, enforcement mechanisms, and public-private collaboration to transition from scattered management to a circular model.

The comparative analysis between Mexico and France reveals how structural, legislative, and infrastructural differences shape e-waste outcomes, even when generation volumes are similar. These findings highlight both the risks and the opportunities that exist in emerging systems like Mexico's. The following chapter summarizes the key insights from this research and outlines strategic recommendations to support more effective global e-waste management.

Chapter VII

CONCLUSIONS AND IMPLICATIONS

This thesis set out to build a replicable, data-driven framework for classifying countries based on the maturity of their e-waste ecosystems. The methodology, combining multidimensional indicators and clustering analysis, successfully identified four distinct country typologies that reflect structural realities across regulation, infrastructure, economic readiness, and market dynamics.

What surprised me most during this process was how accurately the classification mirrored my personal knowledge of global recycling systems. The model's ability to group countries with similar structural challenges (even in the absence of complete data) validated both the indicator design and the power of data normalization and unsupervised machine learning methods like clustering.

That said, a few countries challenged expectations. For example, I initially thought China would appear among *Advanced Generators*, given its collection rate and economy is similar to that of the US, but given its infrastructure policies it was classified in the *Mature Circular Leaders* along with France and Germany. Similarly, I assumed Mexico would fall under *Developing Systems*, but its cluster classification as *Emerging Potential* highlights the weight of its growing electronics market compared to its limited (but existing) certified infrastructure. This made me realize how regulatory structures and enforcement mechanisms heavily influenced classification, sometimes more than raw volumes.

One key insight from the Mexico-France comparison was the detachment between electronics production and collection readiness. Despite Mexico having a higher volume of electronic equipment placed on the market than France, its formal collection rate remained extremely low. This mismatch points out the importance of building systems that not only manage waste, but also track and recover it formally.

6.2 Implications for Stakeholders

For Policymakers

For developing countries like Mexico, I believe the first step must be a *structured and decentralized collection system*. Ideally managed at the state or municipal level. Much of the e-waste currently moves through informal channels, which limits visibility and increases environmental and health risks.

From the French example, stable recording systems and strict certification frameworks stood out as replicable best practices. Even though France lacks R2-certified facilities, it operates over 200 WEEE treatment centers under national standards, which achieve the same outcomes within a European legal framework. For developing countries like Mexico, adopting a locally enforceable certification scheme could serve as a major milestone.

For Recycling Companies and Investors

From a business perspective, I would prioritize countries that show; a growing base of electronic goods placed on the market, the presence of formal facilities (whether R2-certified or locally recognized), and finally the existence of policy signals, such as mandatory recycling clauses or tax incentives.

In my view, private companies must take a leading role in creating efficient, transparent collection systems, especially in developing countries where regulation is either weak or poorly enforced. This could include providing incentives for businesses that generate e-waste, making formal recycling economically preferable to informal alternatives, even if formal treatment has higher upfront costs.

For Development Agencies

I believe global organizations are doing what they can, but their impact is limited by countries' lack of compliance and poor data infrastructure. One thing that became clear to me during this research is how vague and inconsistent international data can be, even from respected agencies. In many cases, the figures reported are modeled using assumptions that may not reflect ground realities.

A simple, structured data framework that could be applied by any country with minimal training would be an ideal starting point. Decisions can't be data-driven if the data itself is unreliable.

6.3 Limitations and Contributions of the Study

Data was, without a doubt, the biggest constraint. Inconsistent reporting, missing entries, and the absence of centralized databases made the process difficult. I had to rely heavily on web scraping and local code to collect what should be basic national statistics. However, I'm proud of how this thesis turned those limitations into an opportunity. The Power BI dashboards created allow an easy exploration to obtain complex insights, compare country performance, and make more informed decisions.

The core contribution is a framework that is:

- *Transparent*: Built from publicly available indicators,
- *Actionable*: Useful for companies, policymakers, investors, and
- *Flexible*: Capable of adapting as more reliable data becomes available.

Whether used to identify new markets, benchmark national systems, or guide policy priorities, this model offers a solid foundation for global e-waste mapping.

6.4 Areas for Future Research

The main avenues I could add future value to this research include *legal and certification comparisons* across countries to assess whether global standards like R2 truly reflect operational quality in each region. *Best practice documentation* on how leading countries (like France) scaled their collection and recycling networks. *Track transboundary e-waste flows amongst producer and recycling countries*, though these are often mislabeled and hard to verify, and *forms to incentivize producers to favor the formal sector*, especially in countries where cost drives informal behavior.

Finally, for the circular economy, *localized* recycling systems could reduce the environmental cost of transoceanic waste shipments, while transforming waste into high-quality commodity outputs. Which could have a real opportunity for countries with limited natural resources to generate high value materials.

6.5 Final Reflection

The biggest lesson I take from this thesis is that small systemic changes can unlock massive positive impacts. Countries like Mexico already handle large volumes of e-waste, but without formal systems in place, this activity creates environmental risks instead of economic opportunity. Formalization is key.

This work has deepened my conviction that e-waste recycling isn't just an environmental issue, it's a strategic sector for industrial development, public health, and global equity. With the rise of AI, chip cycles are accelerating, and without innovation in material recovery, we'll face increasing pressure on both the environment and supply chains.

E-waste, when recycled properly, can power the next generation of digital infrastructure; sustainably and locally. That's a future worth investing in.

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APPENDIX

A Individual Variable Types Breakdown

A.i GEWS - Countries

Variable	Definition (short)	Type
country	Country name	Categorical (Text)
year	Year of observation	Numeric (Year)
population	Total population	Numeric
e_waste_generated_kt	E-waste generated (kilotonnes)	Numeric
e_waste_generated_per_capita	E-waste per person (kg)	Numeric
e_waste_formally_collected_kt	E-waste formally collected (kilotonnes)	Numeric
e_waste_collection_rate	% of e-waste collected	Categorical (Text %, to convert to numeric %)
eee_put_market_kt	Electrical & Electronic Equipment placed on market (kilotonnes)	Numeric
eee_put_market_per_capita	EEE placed on market per person (kg)	Numeric

Variable	Definition (short)	Type
category_temperature	Waste from temperature exchange equipment	Numeric
category_screens	Waste from screens & monitors	Numeric
category_lamps	Waste from lamps	Numeric
category_large	Waste from large equipment	Numeric
category_small	Waste from small equipment	Numeric
category_small_it	Waste from small IT & telecom equipment	Numeric

Variable	Definition (short)	Type
legislation_national	National-level e-waste laws exist	Categorical (Yes/No)
legislation_epr	Extended Producer Responsibility exists	Categorical (Yes/No)

Variable	Definition (short)	Type
legislation_collection	Legal framework mandates collection	Categorical (Yes/No)
legislation_recycling	Legal framework mandates recycling	Categorical (Yes/No)

Scraped the website to get each individual country data removed countries without population data which by design did not have data in any other category

A.ii SERI - R2 Certified Facilities Number

Variable	Definition (short)	Type
Country	Country name	Categorical (Text)
Number of R2 Facilities	Number of R2 Facilities per country (as of today)	Numeric

Cleaned to count number of facilities by country

A.iii World Bank - GDP Per Capita (Current US\$)

Variable	Definition (short)	Type
Country Name	Name of the country	Categorical (Text)
Country Code	3-letter ISO country code	Categorical (Text)
2018, 2019, 2020, 2021, 2022	GDP per capita in current USD for each year	Numeric (one column per year)

Cleaned and left in N/A Countries, No need to scale

A.iv World Bank - GDP (Current US\$)

Variable	Definition (short)	Type
Country Name	Name of the country	Categorical (Text)
Country Code	3-letter ISO country code	Categorical (Text)
2018, 2019, 2020, 2021, 2022	GDP in current USD for each year	Numeric (one column per year)

Cleaned and left in N/A Countries, No need to scale

A.v World Bank - %of GDP in education

Variable	Definition (short)	Type
Country Name	Name of the country	Categorical (Text)
Country Code	3-letter ISO country code	Categorical (Text)
2018, 2019, 2020, 2021, 2022	% of GDP spent on education for each year	Numeric (one column per year)

Cleaned and left in N/A Countries, No need to scale

A.vii OECD - EPS

Variable	Definition (short)	Type
Country Name	Name of the country	Categorical (Text)
Country Code	3-letter ISO country code	Categorical (Text)
Year	Year recorded	Numeric
EPS	Environmental Policy Stringency Index	Numeric

Cleaned and left in N/A Countries, No need to scale very little data don't know if I will use

A.viii UNIDO - Indices of Industrial Production

Variable	Definition (short)	Type
Country	Name of the country	Categorical (Text)
Year	Year recorded	Numeric
Value	IP Index	Numeric

Average index for production of both Electrical equipment (ac. 26) and Computer, electronic and optical products (ac. 27) two tables

B Full Cluster Country List

Cluster 0 (6 countries):

Canada, Israel, Japan, Republic of Korea, Singapore, United States

Cluster 1 (17 countries):

Albania, Bangladesh, Brazil, Chile, Colombia, Costa Rica, Egypt, India, Moldova, Nigeria, North Macedonia, Peru, Russian Federation, Rwanda, Serbia, South Africa, Viet Nam

Cluster 2 (29 countries):

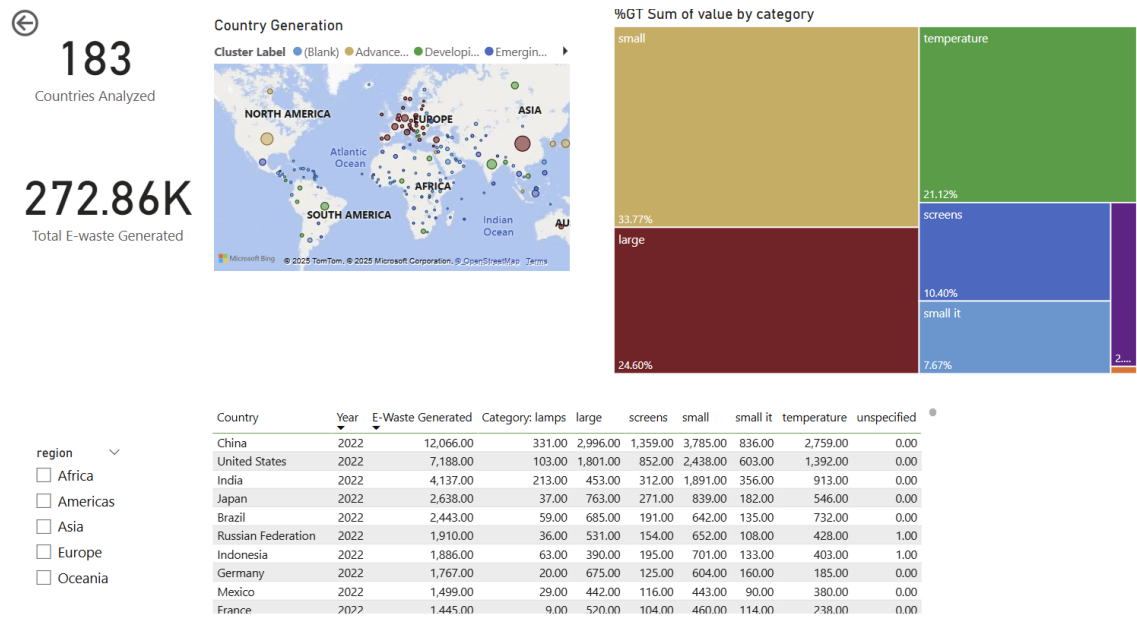
Algeria, Angola, Armenia, Belize, Burundi, Indonesia, Jordan, Kyrgyzstan, Malaysia, Mauritius, Mexico, Morocco, Mozambique, Namibia, Nepal, New Zealand, Niger, Pakistan, Paraguay, Philippines, Samoa, Sao Tome and Principe, Senegal, Sri Lanka, Thailand, Tunisia, Ukraine, Uruguay, Uzbekistan

Cluster 3 (31 countries):

Australia, Austria, Belgium, Bosnia and Herzegovina, Bulgaria, China, Croatia, Cyprus, Czech Republic, Denmark, Estonia, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey

C Power BI Dashboards

C.i Figure 3.2: Category Dashboard

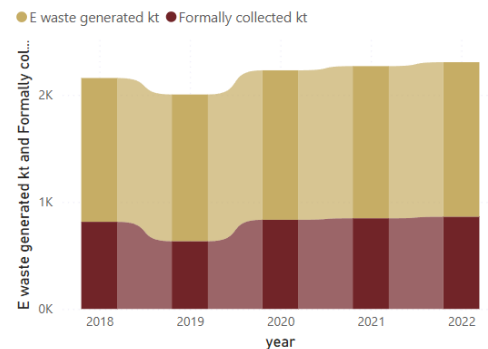


C.ii Figure 3.3: Mexico-France Analysis Dashboard

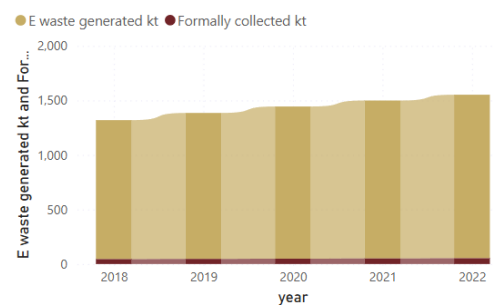
country	year	E-Waste Generated	Generated PerC	Formally Collected	Collection Rate	EEE on market
France	2018	1,344.00	20.90	814.00	61%	1,715.00
France	2019	1,372.00	21.30	632.00	46%	1,736.00
France	2020	1,397.00	21.70	833.00	60%	1,707.00
France	2021	1,422.00	22.00	847.00	60%	1,704.00
France	2022	1,445.00	22.40	861.00	60%	1,667.00
Mexico	2018	1,274.00	10.30	45.00	4%	2,128.00
Mexico	2019	1,338.00	10.70	47.00	4%	1,856.00
Mexico	2020	1,395.00	11.10	49.00	4%	1,758.00
Mexico	2021	1,448.00	11.50	51.00	4%	1,900.00
Mexico	2022	1,499.00	11.80	53.00	4%	2,128.00

country	year	Score_Generation	Score_Infrastructure	Score_Macro	Score_Micro
France	2018	0.57	0.80	0.44	0.21
France	2019	0.53	0.80	0.45	0.22
France	2020	0.57	0.80	0.46	0.19
France	2021	0.58	0.80	0.22	0.21
France	2022	0.58	0.80	0.21	0.21
Mexico	2018	0.22	0.21	0.15	0.23
Mexico	2019	0.20	0.21	0.17	0.23
Mexico	2020	0.20	0.21	0.16	0.22
Mexico	2021	0.21	0.21	0.16	0.24
Mexico	2022	0.23	0.21	0.17	0.26

E waste generated kt and Formally collected kt by year



E waste generated kt and Formally collected kt by year



C.iii Figure 3.4: Mexico-France Scores Dashboard



D Category Table Mexico vs France

country	year	e_waste_generated_kt	Category : lamps	large	screens	small	small_it	temperature
France	2018	1,344.00	10.00	460.00	116.00	436.00	111.00	210.00
France	2019	1,372.00	10.00	475.00	114.00	443.00	113.00	218.00
France	2020	1,397.00	9.00	490.00	111.00	449.00	113.00	225.00
France	2021	1,422.00	9.00	505.00	108.00	455.00	114.00	232.00
France	2022	1,445.00	9.00	520.00	104.00	460.00	114.00	238.00
Mexico	2018	1,274.00	20.00	366.00	105.00	375.00	85.00	323.00
Mexico	2019	1,338.00	23.00	388.00	108.00	393.00	87.00	339.00
Mexico	2020	1,395.00	25.00	408.00	110.00	409.00	88.00	354.00
Mexico	2021	1,448.00	27.00	426.00	113.00	426.00	89.00	368.00
Mexico	2022	1,499.00	29.00	442.00	116.00	443.00	90.00	380.00

E Legislation Infrastructure Mexico vs France

country	year	legislation_collection	legislation_epr	legislation_national	legislation_recycling	R2 Facilities	EPS
France	2018	Yes	Yes	Yes	Yes	0	4.56
France	2019	Yes	Yes	Yes	Yes	0	4.72
France	2020	Yes	Yes	Yes	Yes	0	4.89
France	2021	Yes	Yes	Yes	Yes	0	
France	2022	Yes	Yes	Yes	Yes	0	
Mexico	2018	No	No	Yes	No	13	1.47
Mexico	2019	No	No	Yes	No	13	1.58
Mexico	2020	No	No	Yes	No	13	1.58
Mexico	2021	No	No	Yes	No	13	
Mexico	2022	No	No	Yes	No	13	