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Electronic waste in the Caribbean: An impending environmental disaster or an opportunity for a circular economy?

Elham Mohammadi*, Simron Jit Singh, Komal Habib

Faculty of Environment, University of Waterloo. 200 University Ave West, Waterloo, Ontario, N2L3G1, Canada

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ABSTRACT

Islands are bounded systems, often plagued with several sustainability challenges of limited land and resource availability, as well as pressing waste management issues. Despite these known problems, research aiming to help develop proper e-waste management systems for small island nations is scarce. Focusing on five Caribbean island states, this study provides the first comprehensive view of e-waste generation trends in an island context and explores the factors driving those trends. The study estimates Electrical and Electronic Equipment (EEE) flows for the five island cases over a period of 60 years (1965–2025), including e-waste that these flows have and will generate. A dynamic material flow analysis (MFA) approach has been used to estimate these flows and stocks for 206 product types. The results show that the five Caribbean islands produced double the e-waste per capita per year, i.e., 13 kg/cap/year compared to global average of 6.1 kg/cap/year in 2016. The aggregated amount of e-waste generated per year on these five islands seems to significantly rise in future: from 27,500 tonnes in 2010 to an estimated amount of 59,000 tonnes in 2025. This considerable estimated e-waste generation rate, when not properly managed, is not only harmful for the local environment, but also translates into considerable health impacts and loss of valuable resources. From a sustainability perspective, small islands should consider moving away from a linear to a circular economy that will limit waste generation as well as reliance on the supply of virgin materials from outside.

1. Introduction

In 2019, approximately 53.6 million metric tonnes (Mt) of electrical and electronic waste (e-waste) was generated globally, however, only 17.4% was recycled properly (Forti et al., 2020). E-waste is defined as any end-of-life (EoL) piece of equipment that depends on electric currents or electromagnetic fields to function properly and includes all components, sub-assemblies and consumables that constituted the product at the time of discarding (The Council of European Union, 2012). The electrical and electronic equipment (EEE) contains a number of valuable materials that are lost due to insufficient and inefficient recycling of e-waste (Schluep et al., 2009). Apart from valuable materials, a number of electronic items, such as computer hard disk drives and smart phones contain critical raw materials e.g., rare earth elements based permanent magnets i.e., neodymium-iron-boron (NdFeB) magnets, which are lost during the pre-processing of e-waste (Habib, 2019; Habib et al., 2015). The increasing number of electronic products, the swift evolution of technology, low initialization cost, improved purchasing power, and planned obsolescence are among the main causes for the significant rise in e-waste (Luhar and Luhar, 2019). In 2006, the European Commission reported that e-waste was growing by 3–5% per year in the European Union, around three times faster than solid waste (Savage et al., 2006). A recent UN report still highlights e-waste as one of the fastest-growing solid waste streams in the world, which is estimated to grow from 75 million tonnes in 2030 to 111 million tonnes by 2050 (Parajuly et al., 2019).

E-waste is not only one of the fastest-escalating waste streams in the world with respect to quantity, it is also a significant contributor to toxicity (Chung et al., 2011). Discarding this large and growing quantity of electronics will have lasting consequences on our planet due to the pollution caused by landfilling and artisanal recycling (Chen et al., 2015). Artisanal recycling is an informal recycling method in which manual sorting, dismantling and open burning of e-waste is performed mainly without safety precautions (Ilankoon et al., 2018). Different EEE contain various hazardous materials that are harmful to human health and also to the environment. Huge quantities of e-waste retain toxic substances such as copper, lead, chromium, and cadmium (Kumar et al., 2017); consequently, illegal or improper recycling of e-waste may cause serious health issues. For example, when some e-waste recycling areas in China were studied, approximately 35% to 39% of children living in

* Corresponding author.
E-mail address: elham.mohammadi@uwaterloo.ca (E. Mohammadi).

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these areas were found to have above 10 μg L^{-1} blood lead levels (Wang et al., 2012), which is considered harmful limit by the World Health Organization (World Health Organization, 2010).

Managing this fast-escalating and hazardous waste stream requires data and statistics on the quantities of e-waste being generated. However, merely 20 percent of countries in the world collect international data on e-waste, and only Europe has regular and harmonized statistics. Recently, the United Nations University (UNU) developed a comprehensive overview of the global e-waste for the year 2016 to help countries establish their e-waste statistics (Balde et al., 2017). A year later, in 2018, UNU published a guideline document of the methodological steps (Forti et al., 2018) to help future researchers to apply the model in their e-waste estimations. The UNU model followed the methodology developed by Wang et al. (2013), who first proposed to use the Weibull distribution and sales-stock-lifespan method for e-waste generation estimation (Islam and Huda, 2019). This method was later applied in other researches, such as the study by Johnson et al. (2018) for Ireland and Parajuly et al. (2017) in Denmark.

Based on the Basel Convention Regional Centre (BCRC) report in 2016, improper e-waste discarding and processing in the Caribbean islands results in a severe decline in environmental quality, causes biodiversity loss, and a decrease in the natural population. Despite this assertion, none of the Caribbean countries have laws and regulations addressing e-waste (BCRC, 2016; Balde et al., 2017). Very few non-governmental stakeholders, like the International Telecommunications Union (ITU) (ECLAC, 2018) and the BCRC (BCRC, 2016) in the Caribbean, have embraced the e-waste challenge and are addressing the related concerns (Riquelme et al., 2016). A report on the e-waste management policy framework was published for Jamaica by Telecommunications Management Group in 2017 (Roldan, 2017), focusing on very few product types. Earlier a study by the BCRC (2016) identified the local stakeholders involved in e-waste management in Suriname. A comprehensive overview of the global e-waste (2016) by UNU contains a very limited number of SIDS, only providing the e-waste amount for the year of 2016. There is still quite limited information on the generated e-waste amount in this region (BCRC, 2016) and there is no holistic overview of the problem and recommended solutions. Therefore, research on e-waste in Small Island Developing States (SIDS) is very scarce.

To address the gap in e-waste evaluation studies for islands and especially for the Caribbean, the e-waste generation amount is estimated in this study, focusing on five island nations: Aruba, Barbados, Grenada, Jamaica, and Trinidad and Tobago. The main objective of this study is to estimate the flows and stocks of EEE from 1965 to 2025, and the resulting e-waste on these islands from 2000 to 2025. To gain insights into the drivers behind these trends, the e-waste generation amount over time is correlated with GDP, and total population. It is expected that a better understanding of e-waste patterns, types and pressures generated will help re-evaluate the appropriateness of existing policies, and asses the necessity for a transformation in legislative and infrastructure requirements.

2. The challenge of waste management on small islands

Simply described, islands are landmasses surrounded by water and often characterized as closed and bounded systems. Islands make up 3% of the Earth's land area, harbour 20% of all plant, bird and reptile species. The Caribbean is classified as one of the world's most biodiverse regions (Myers et al., 2000). It provisions about 13,000 species of endemic plants, 469 reptiles, 170 amphibians (UN-OHRLLS, 2015), 148 birds, and 49 mammals (Kairo et al., 2003). A major threat to these hotspots of biodiversity is hazardous waste that is often poorly managed and ends up in terrestrial and marine ecosystems.

Small Island Developing States (SIDS) around the world are struggling with an increasing rate of waste (Mohee et al., 2015), including the 16 SIDS in the Caribbean region. SIDS are a distinct group of 38 UN and 20 Non-UN Member states sharing unique vulnerabilities to social, economic, and environmental issues (UN-OHRLLS, 2015). The average waste generation of SIDS is around 2.30 kg/cap/day (includes waste generated by tourists), which is much higher compared to the global average of 1.55 kg/cap/day (UNEP, 2019b). Shortcomings in the waste collection, transfer, and transport, namely outdated collection vehicles and narrow- inaccessible roads (Mohee et al., 2015), makes it more challenging to manage the high waste generation rate in these islands. Moreover, three out of the world's 50 largest dumpsites are located in SIDS, however the generated waste mainly ends up in marine areas and dumpsites (UNEP, 2019b).

Waste management is a global problem. According to Haas et al. (2015), the planet currently generates 41 Gt of waste annually, which is 66% of total materials entering the economy each year. On a global scale, recycling is very modest, amounting to only 4% of the inflows (*ibid*). The severity of waste generation and management is much higher in SIDS, given their unique vulnerabilities such as narrow resource-base economies (UN-OHRLLS, 2015) and restricted ability to metabolize the generated waste streams (Shah et al., 2019). These limitations can be also coupled with the restricted geographical, ecological, and social capacity of the island systems (*ibid*). Focusing on waste-related issues, some documented impacts of waste mismanagement on small islands are damage to the marine and environment, resource loss, increasing greenhouse gas emissions (GHGs), in addition to the continuous nuisances of littering and treatment facilities (Camilleri-Fenech et al., 2018). Moreover, inadequate waste management in small island states can have severe impacts on human health, atmospheric, terrestrial, freshwater, and coastal environments, as well as having severe effects on different economic sectors such as tourism, fishing and agriculture (UNEP, 2019b).

Different studies have emphasized the constraints causing the mismanagement of the waste in island nations. As described by Eckelman et al. (2014), islands confront six common obstacles setting up waste management systems: lack of available land and financing resources, vulnerability to extreme weather events, higher operational expenditures, small market sizes, and changing community norms. Fortuitously, rehabilitation of landfills and dumpsites is feasible for island nations, and it has proved successful. One of the examples often quoted as an effective climate-resilient landfill is the Namara site in Fiji (UNEP, 2019b). However, recycling and recovery of materials is challenging in islands due to the lack of available market for recycled resources and the distance from larger markets (Zsigraiová et al., 2009). Moreover, in densely populated and tourist dependent islands, it is challenging to find a suitable location for waste treatment (Agamuthu and Herat, 2014) and landfill sites often exposed to the view of tourists (Eckelman et al., 2014).

The field industrial ecology applied to islands offers several useful practices for tracking and planning of waste management (Eckelman et al., 2014), that can be used by islands. The threats of waste can also be opportunities following a transition from linear to a circular economy to achieve the UN Sustainable Development Goals (UNEP, 2019b). However, from a material stock and flow perspective, only a handful of studies have been conducted on island waste to date: the material, energy and waste flows of tourist sector for Grenada (Telesford, 2014; Telesford and Strachan, 2017); material flow analysis of waste management in Oahu (Eckelman and Chertow, 2009); and material flow and carbon footprint analysis of municipal waste management in the Maltese (Camilleri-Fenech et al., 2018). Recently a study by Noll et al. (2019) used a dynamic stock-driven model for different infrastructures and buildings on Samothraki from 1971 to 2016 to provides a systematic view of construction and demolition waste (CDW) on this island.

3. The study area: five island nations in the Caribbean

Five Caribbean Small Island Developing States (SIDS), namely

Aruba, Barbados, Grenada, Jamaica, and Trinidad and Tobago, were selected for this study. Together, they represent diverse profiles in the region such as size, location spread, economic prosperity, population density, and geography. These five SIDS comprise 11% of the Caribbean population and 7% of the Caribbean land area, while being geographically spread across the Caribbean crescent, from east to the west.

Jamaica and Aruba are the most and least populated countries, among these five island cases, with 2,920,853 and 105,366 residents respectively in 2017 (The World Bank, 2019). Jamaica's land area is around 10,991 km^2 whereas Aruba only lies on 180 km^2. Barbados has the highest population density, with 665 people per km^2, and Jamaica and Trinidad and Tobago are least densely populated, with 270 people per km^2. Comparing these countries based on economic and development performances, it is notable that Aruba has the highest GDP per capita of $25,630 (in 2017) and also the highest Human Development Index (HDI) of 0.908, which is last measured in 2009 (Hastings, 2009). On the other hand, in 2017 Jamaica has the lowest HDI of 0.732 between these cases (The World Bank, 2019). In the Caribbean, the service sector that mainly corresponds to tourism, transport, government, and financial sectors has the highest share in national GDP (The world bank, 2019). However, the contribution of these countries to the regional tourism sectors varies. In 2014, Trinidad and Tobago was the main contributor to CARICOM's GDP in service sector with an approximate share of 30%, and Grenada had the lowest share of 1.5% (Regional Statistics Programme Caribbean Community Secretariat, 2016). These economic and demographic differences might influence the EEE consumption pattern of these five countries that will be discussed further.

4. Methods and data sources

Currently, the Caribbean lacks any baseline data related to the annual quantity of EEE consumption and the corresponding e-waste amount generated. Therefore, it has been considered crucial to evaluate the past and prospective regional levels of e-waste generation over time.

In order to quantify the current and future e-waste generation on the Caribbean islands, dynamic Material Flow Analysis (MFA) is applied as method, using the Weibull distribution function that is also known as Sales-Stock-Lifespan model (Wang et al., 2013). MFA is a systematic assessment of the material flows and stocks, based on the mass balance principle, within space and time boundaries (Brunner and Rechberger, 2004). This method had been applied in several studies for analysis and evaluation of e-waste management systems formerly (Streicher-Porte et al., 2005; Gurauskiene and Stasiškiene, 2011; Steubing et al., 2010; Habib et al., 2015; Parajuly et al., 2016, 2017). For MFA modelling, static or dynamic approaches can be used for quantifying the e-waste volume. Static MFA model is within a time scale of one year, however dynamic model assesses past, present, and future stocks and flows (Müller et al., 2014). Dynamic MFA is capable of providing a more in-depth understanding of the e-waste system by taking into account the actual EEE sales statistics and then coupling the data with product lifespan distribution (Islam and Huda, 2019). Wang et al. (2013) utilized the Weibull distribution function in dynamic MFA for e-waste estimation in the Netherlands. Thereafter, this method was applied by other researchers for other countries (Balde et al., 2017; Parajuly et al., 2017; Song et al., 2017).

The categorization of e-waste in this study is based on the methodological principles and guidelines set by the Sustainable Cycles (SCYCLE) Programme of the United Nations University (2018) and the study by Forti et al. (2018). The EEE corresponding to 206 Harmonised System (HS) codes as per UN COMTRADE database were first aggregated to 54 product categories to allow using the available lifetime distribution data for these 54 categories. As the next step, these 54 categories were aggregated into 10 main e-waste categories (EU-10) to show the results in clear and consistent manner. The EU-10 classification of e-waste is based on the directive 2012/19/EU of the European Parliament on e-waste (The Council of European Union, 2012). These categories include: large household appliances (LHA), small household appliances (SHA), IT and telecommunications equipment (ITE), consumer equipment excluding photovoltaic panels (CE), lighting equipment (LE), electrical and electronic tools (EET), toys, leisure and sports equipment (TLSE), medical devices (MD), monitoring and control instruments (MCE), and automatic dispensers (AD).

4.1. Estimating the annual EEE Put-on-Market (PoM)

The amount of EEE products sold to a consumer or Put-on-Market (PoM) is estimated using MFA for 54 EEE types on five island nations from 1965 to 2025. PoM is defined as “any supply of a product for distribution, consumption or use on the market in the course of a commercial activity, whether in return for payment or free of charge” (Forti et al., 2018, p. 37). Intended for these estimations, the trade data for different EEE was retrieved from published import and export statistics (UN COMTRADE, 2019). The maximum lifespan of a product is considered to be 30 years (Islam and Huda, 2019), within which the probability of all products becoming absolute is approximately more than 98% for the given α and β values. At the time of this research, the annual trade data had been only published for 2001 to 2017. Thus, the PoM growth rate for each island from 2001 to 2017 has been used to back-cast the historic data from 1965 to 2001. Moreover, to forecast the PoM amount by 2025, the EEE market is assumed to be saturated where PoM quantities are expected to remain largely unchanged from 2017 to 2025.

The material flows for islands logically fall into two main categories: (1) imports from other countries, and (2) export or re-export to other nations. UN Comtrade (2019) defined re-export as “exports of foreign goods in the same state as previously imported”, and it was mentioned that the re-exports are to be included in the country exports. Therefore, re-exports are taken into consideration in the export statistics. There are no major domestic EEE production, resale, reuse, or official recycling strategies in these islands up to this date. Thus, it is assumed that PoM is approximately equal to the physical trade balance, which is (PoM = Import – Export). The export amount in the same year is deducted from the imports to estimate the amount of PoM that stays in the island for a specific residence time and then reaches its end-of-life.

4.2. Calculating annual e-waste generated amounts

The e-waste generation estimation in this study has been conducted based on dynamic MFA model, using the Weibull distribution function. The lifespan profile of the products in this model are defined by the shape (α) and scale (β) parameters; (α) is also called characteristic life parameter and (β) is the slop of the probability distribution. Forti et al. (2018) have made available α and β values for 54 categories of EEE products in different EU countries. Due to the lack of specific product lifespan data in the Caribbean region, the lifetime parameters are obtained from the study by Baldé et al. (2018). The calculated PoM of different EEE categories across their lifespans is modelled by Weibull distribution function using MATLAB software and Microsoft Excel. The Weibull function is widely used to estimate e-waste generation for all EEE product types.

The amount of e-waste generated for each year is calculated using the following equation. The estimated e-waste amount using this model is in tonnes and has been converted into the number of units as well.

$$E\_WASTE_{(y)} = \sum_{n=1}^{206} P_{n(1965)}{}^{*}f_{n(y-1965)} + P_{n(1966)}{}^{*}f_{n(y-1966)} + \ldots + P_{n(y-1)}{}^{*}f_{n(y-1)}$$

Where

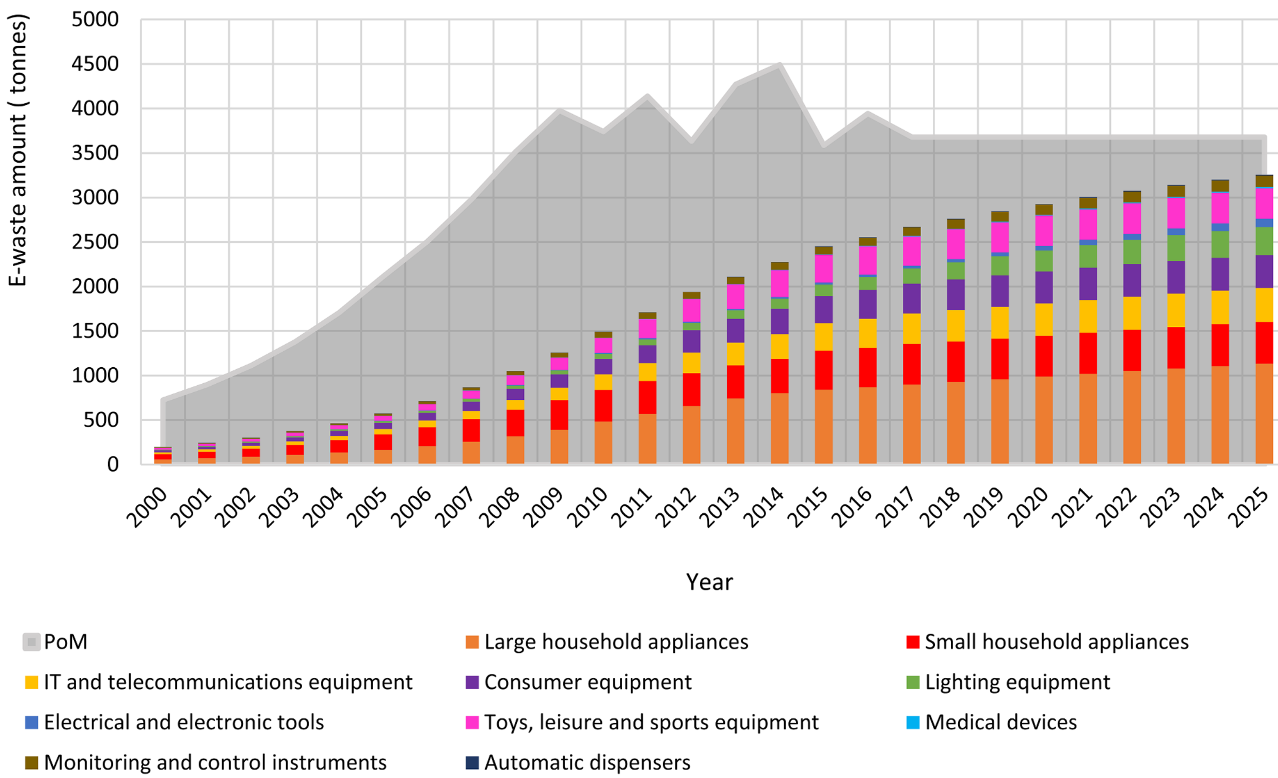

Fig. 1. Amount of electrical and electronic equipment's Put-on-Market (grey area) and the corresponding e-waste (bars) for Aruba from 2000 to 2025.

$E\_WASTE_{(y)} =$ amount of e-waste generated in year y
$n =$ categories of e-waste according to 206 Harmonised System (HS) codes
$P_{n(y)} =$ amount of EEE Put-on-Market for category n in year y
$f =$ failure rate using α and β.

4.3. E-waste generation in number of units

The EEE sales, import and export data are usually provided in the number of units of products. Therefore, the estimated amount of e-waste generation in metric tonnes has been converted into the number of pieces using the weight of 54 EEE categories provided by Forti et al. (2018). Forti's report listed the weight of the 54 product types for EU-28 countries over six different years: 1995, 2000, 2005, 2010, 2015 and 2016. The average weight for each category has been calculated and used in this research assuming that the EEE weights are not significantly different between EU and Caribbean countries.

4.4. Data collection

To capture the trade data for EEE, the published import and export statistics are obtained from the United Nations commodity trade statistics database and/or national statistical institutes. Trade data for five islands is retrieved from UN COMTRADE (2019) and for Grenada, the quantities are triangulated with the data received from the statistics department of this island. These EEE trade data are obtainable from 2001 to 2017, while the data for previous and subsequent years is not available. At the time of this study, the data for Aruba and Trinidad and Tobago is available only for 2005 to 2017 and 2001 to 2015. For the years, where the trade data is not available, the PoM growth rate is used to estimate the EEE amount. Moreover, at the time of conducting this research, the trade data for three out of 54 UNU Keys: 0002 (Photovoltaic Panels), 0502 (Compact Fluorescent Lamps), and 0505 (Led Lamps), were not available in UN COMTRADE database and therefore were not included in calculations.

4.5. Sensitivity analysis

To test the sensitivity of the results to the assumptions made, sensitivity analysis is conducted to visualize the impact of changing a variable on actual results. An important assumption made in this study is regarding the PoM volume, where the EEE market is assumed to be saturated and expected to remain largely unchanged from 2017 to 2025.To demonstrate the sensitivity of the model to this assumption (saturation assumption of PoM quantity from 2017 to 2025), the annual put-on-market is forecasted for 2017 to 2025 using the PoM growth rate for each island. Then the Weibull function is used again to estimate the e-waste generation, considering the new scenario. Comparing the new e-waste quantification results with the initial results expresses the sensitivity of the model to the market saturation assumption.

5. Results

The annual amounts of Put-on-Market (PoM) for Electrical and Electronic Equipment (EEE) under 10 categories have been estimated and provided below for each island from 2000 to 2025. The results have been presented by country, highlighting through each figure the electrical and electronic equipment's PoM (shown in grey areas) and the corresponding e-waste (shown in bars). The trade data is not still available on the UN COMTRADE database for 2018 and later, therefore these estimates are based on the saturation assumption. Here the saturation assumption indicates that PoM will not change significantly from 2017 to 2025. Detailed annual quantities of EEE's PoM and generated e-waste under the 10 categories for each island case is provided in the *supplementary material* (SM), along with the total distribution of e-waste under different category types.

5.1. Aruba

It is estimated that the total electrical and electronic equipment's PoM in Aruba is around 84,856 tonnes over the years of 1965 to 2025.

Fig. 1 shows an increasing PoM trend from 2000 to 2009 in which the annual put-on-market quadrupled in 2009 in comparison to 2000. Then it fluctuated for 4 years due to two recessions in 2009–10, followed by another recession in 2012. The PoM reached the highest point of 4492 tonnes in 2014 and declined again in 2015. This fall was due to the financial recession of the country which weighed on the fiscal position (IMF, 2019). The electronic equipment's PoM in the last 9 years (2017-2025) assumed to remain steady at the level of 3680 tonnes. Accordingly, the corresponding annual accumulation of e-waste in Aruba ranges from 196 tonnes in 2000 to 3256 tonnes in 2025. The e-waste generation growth rate on this island is estimated to have an upward trend in upcoming years. This trend will slow down from a growth rate of 24% in 2000 to one of 1.5% in 2025. The quantity of annual e-waste generation is expected to rise from 2845 tonnes to 3256 tonnes between 2019 and 2025. Besides, around 36.5 kt of electronics is estimated to remain as in-use stock on these islands by the end of 2025, which will be discarded by the user in future years.

5.2. Barbados

Fig. 2 shows the quantity of EEE's PoM and the resultant total e-waste in Barbados from 2000 to 2025. The annual put-on-market amount on this island is raised from 3824 tonnes in 2000 to 6467 tonnes in 2016. PoM quantity reached the highest volume of 7879 tonnes in 2006 and then fluctuated for 10 years. It is assumed that the PoM amount maintains the same level of 6467 tonnes after 2016 for the next 9 years. The corresponding e-waste generation on this island had a surge at the beginning of the 21st century when it had an annual growth rate of 32%. It is estimated that the yearly e-waste generation on Barbados will increase from 5341 tonnes in 2019 to 5780 tonnes in 2025. During this period, the growth rate will have an increasing trend, which is projected to slow down by half to around 1% in 2025. More than 70 kt of in-use stock will remain on this island by the end of 2025.

5.3. Grenada

The estimated quantity of total electrical and electronic equipment's PoM in Grenada is about 44,657 tonnes for the years of 1965 to 2025. Fig. 3 shows the PoM volumes for each category and the projected corresponding e-waste amount for the period between 2000 and 2025. As shown below, the EEE trade balance or put-on-market dipped in 2005 with a total of 437 tonnes and peaked in 2017 with a total of 2939 tonnes. The dramatic PoM fall in 2005 was due to Hurricane Ivan, which caused widespread damage in Grenada in 2004 (The World Bank, 2005). The estimations show that the PoM had an upsurge in the beginning of the 20th century, with over 130% annual growth rate. The put-on-market is assumed to stay static at the volume of 2939 tonnes from 2017 to 2025. These evaluations show that the annual e-waste generation will increase from 18 to 1909 tonnes during the years of 2000 to 2025. Although the e-waste generation growth rate will slow down from 15% in 2018 to around 6% in 2025, it still will have an upward trend. By the end of 2025, more than 25.5 kt of in-use stock will remain on this island.

5.4. Jamaica

It is estimated that the total electrical and electronic equipment's consumption in Jamaica is about 507,624 tonnes between 1965 and 2025. Fig. 4 shows an increasing trend from 2000 to 2008 when the put-on-market tripled. In 2009 due to the great global recession, the EEE consumption decreased by around 25% from 20,988 tonnes to 15,705 tonnes and it decreased steadily for three years, reaching a low of 14,548 tonnes in 2011. There was a dramatic increase in 2016 and the PoM grew by more than 50% and peaked at 26,885 tonnes. The electrical and electronic equipment's PoM in the last 9 years (from 2016 to 2025) assumed to remain steady. Our evaluations show that the corresponding annual e-waste generation amount increased from 563 to 19,775 tonnes between 2000 and 2025. The e-waste generation growth rate in Jamaica is estimated to slow down from 54% in 2000 to around

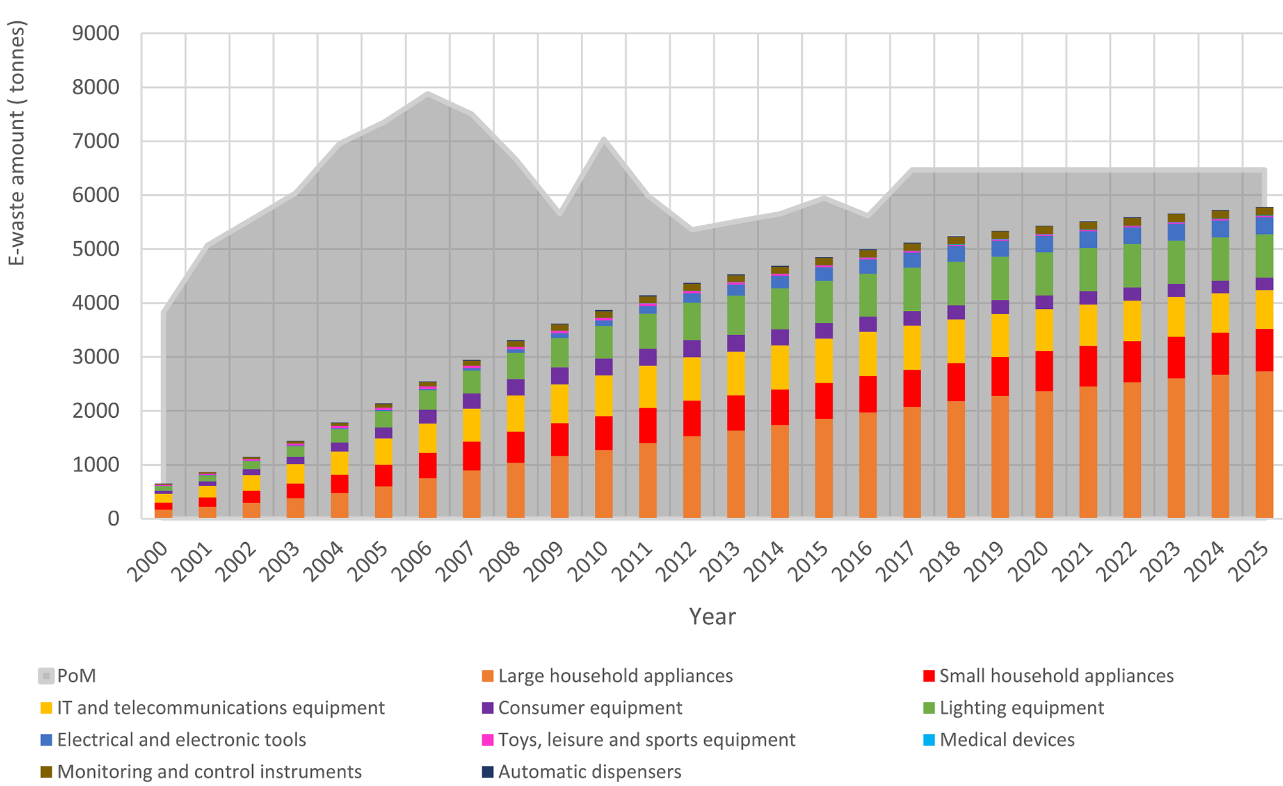

Fig. 2. Amount of electrical and electronic equipment's Put-on-Market (grey area) and the corresponding e-waste (bars) for Barbados from 2000 to 2025.

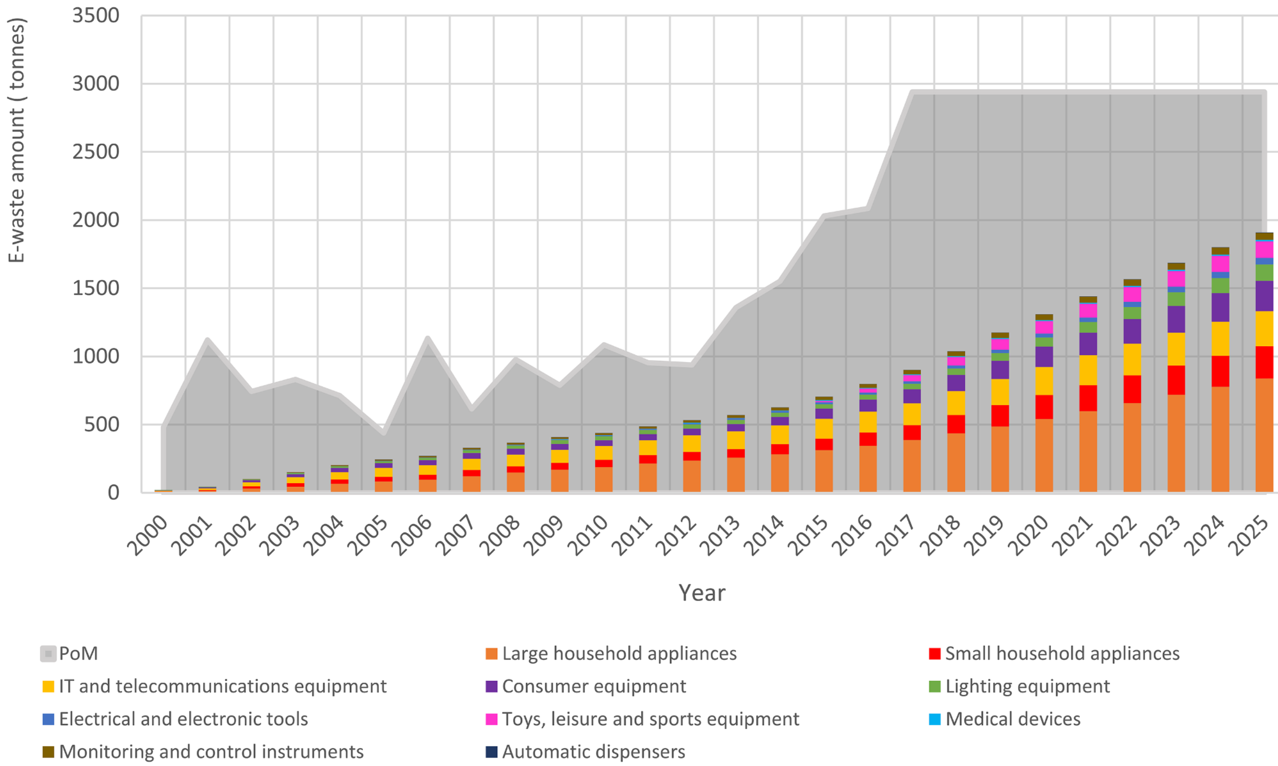

Fig. 3. Amount of electrical and electronic equipment's Put-on-Market (grey area) and the corresponding e-waste (bars) for Grenada - 2000 to 2025.

3.5% in 2025. While the quantity of waste of electric and electronic equipment in this island is still going to increase from 14,818 tonnes to 19,775 tonnes between 2019 and 2025. It is estimated that by the end of 2025, around 256 kt of in-use stock will remain on this island.

5.5. *Trinidad & Tobago*

Fig. 5 illustrates the quantity of electrical and electronic equipment's PoM and the corresponding e-waste amount in Trinidad and Tobago from 2000 to 2025. The annual EEE consumption amount on

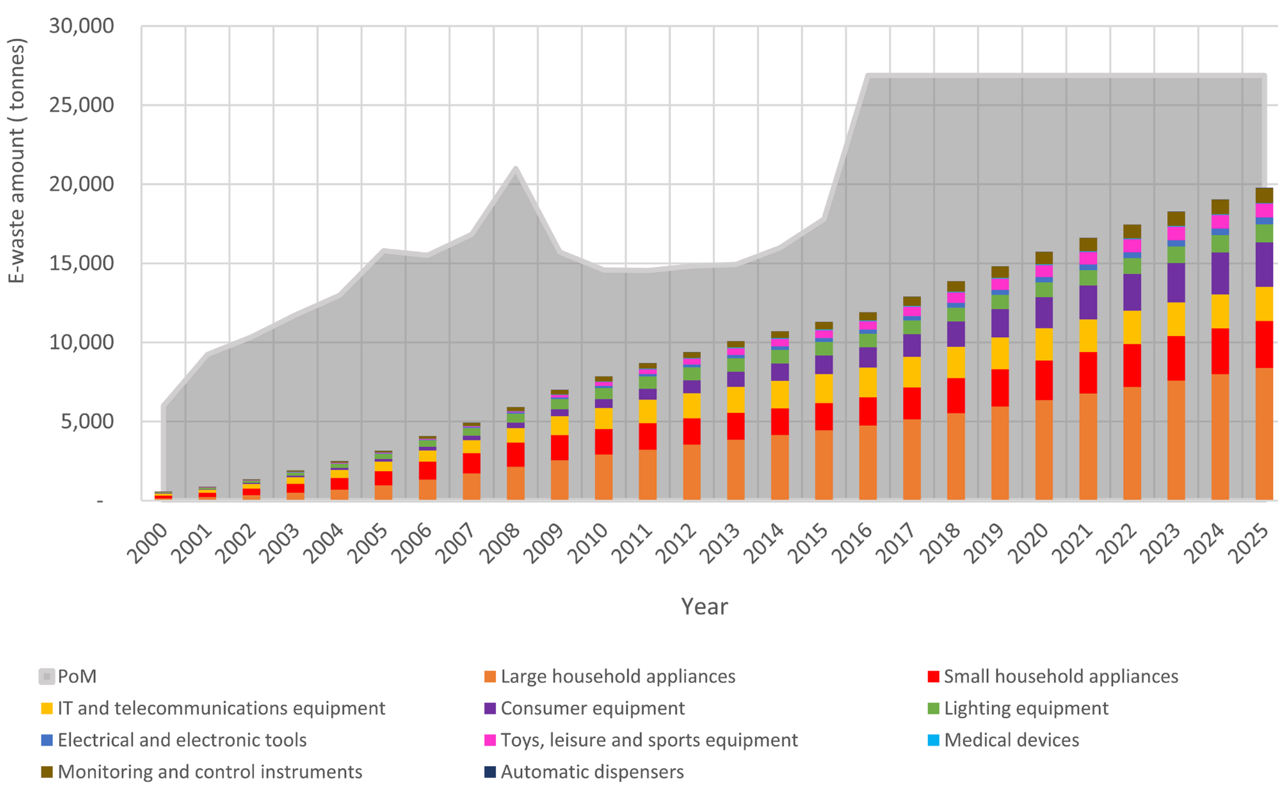

Fig. 4. Amount of electrical and electronic equipment's Put-on-Market (grey area) and the corresponding e-waste (bars) for Jamaica - 2000 to 2025.

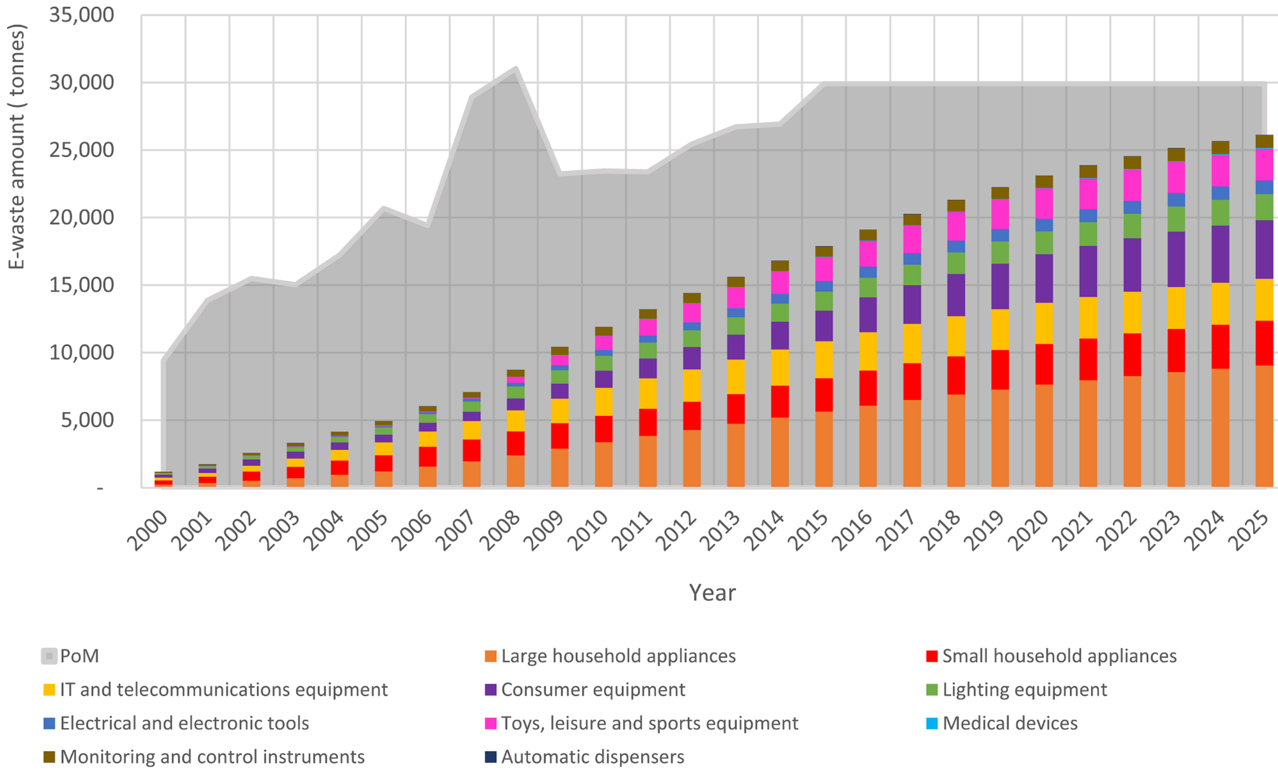

Fig. 5. Amount of electrical and electronic equipment's Put-on-Market (grey area) and the corresponding e-waste (bars) for Trinidad &Tobago - 2000 to 2025.

this island nation increases from 9423 tonnes in 2000 to 29,917 tonnes in 2015. The PoM quantity reached the highest volume of 31,034 tonnes in 2008 and then declined by 25% in the following year and reached 29,917 tonnes in 2015. The trade data for Trinidad and Tobago is only available until 2015, therefore, the EEE's put-on-market amount for the years of 2016 to 2025 is forecasted based on the average PoM growth rate. It is assumed that the PoM amount will maintain the same level of 29,917 tonnes from 2016 to 2025. The commensurate e-waste generation on this island had a surge in the first two years of the 21st century and still has an ascending trend. It is estimated that the yearly e-waste generation on this island will increase from 22,271 tonnes in 2019 to around 26,133 tonnes in 2025. During this period, the e-waste generation rate of growth will still have an upward trend but will be only 1.5% in 2025 compared to 4.5% in 2019. In 2025, the estimated in-use stock on this island will be around 295 kt.

5.6. Results of the sensitivity analysis

The trade data for these islands is mainly available until 2017, and it is assumed that the EEE market can be expected to remain largely unchanged and saturated from 2017 to 2025. As mentioned in Section 4.5 to demonstrate the sensitivity of the model to the saturation (plateaued) assumption of PoM, the annual e-waste generation is forecasted for a second time based on the growing trend assumption. Fig. 6 shows the estimated amount of e-waste using plateaued assumption versus the growing trend assumption, from 2017 to 2025. Considering the plateaued assumption, the estimated e-waste generation will gradually increase and in 2025 it is estimated to only rise by 1% to 6% on these islands. However, replacing the assumption with the growing flow of EEE consumption, the yearly rate of e-waste generation may rise much higher; for instance, in 2025 the rate is estimated to rise by 14%, 16%, 53%, 32% and 29% in Aruba, Barbados, Grenada, Jamaica and Trinidad and Tobago islands respectively. The sensitivity analysis indicates that if the EEE market or PoM continues to expand, the corresponding e-waste amount will rise exponentially in the upcoming years.

6. Discussion

For a cross country comparison, the cumulative amounts of e-waste generation on these islands and the generated e-waste per capita have been demonstrated. It is estimated that Trinidad and Tobago generates the largest e-waste quantity, whereas Grenada produces the lowest amount. Including the population data, Aruba and Jamaica are the biggest and smallest generators of e-waste per capita respectively. To better understand the e-waste generation pattern, data has been compiled with statistical testing on factors of influence. The hypothesis that relatively faster-growing population countries or more economically progressive islands would have higher e-waste generation rates. GDP per capita (in purchasing power parity [PPP]) has also been included to test for affluence, to see if it is a significant driver of e-waste generation.

6.1. Total e-waste generated on the five islands

Between 2019 and 2025, it is estimated that at least 363 kt of new e-waste will be generated cumulatively in these five islands, bringing the total in-use e-waste stock to 683 kt. Getting rid of the newly generated e-waste (of 363 kt) alone would require a total of 14,600 containers, each 20-ft in size (or 6.6 containers a day) leaving these islands. Considering that this amount is generated by only 11% of the Caribbean population, the total e-waste amount from the region is several times fold. Exporting the e-waste imposes two types of costs to an island's economy: 1) collection, handling and shipping costs and 2) the lost opportunity in terms of revenue and income that could potentially be generated from material recycling. There is yet another cost (in terms of social and environmental externalities) that would be borne by countries receiving this e-waste, in most cases the less developing countries.

The e-waste generation distribution (flow) over the five islands is illustrated in Fig. 7 for the period of 2019 to 2025. Trinidad and Tobago will have the highest e-waste generation quantity, while the population and available land area of this island country is less than half that of Jamaica. Therefore, it is expected that Trinidad and Tobago will

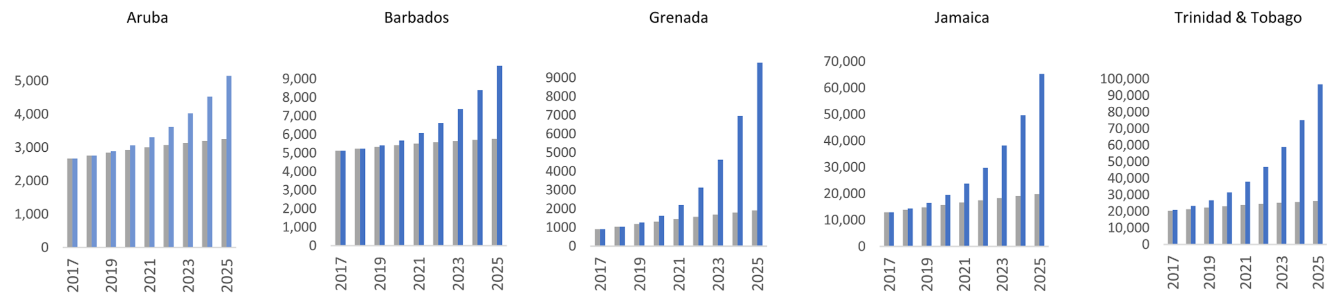

Fig. 6. Comparison of the estimated e-waste amount (tonnes) in five Caribbean islands from 2017 to 2025, considering the plateaued assumption versus increasing trend assumption.

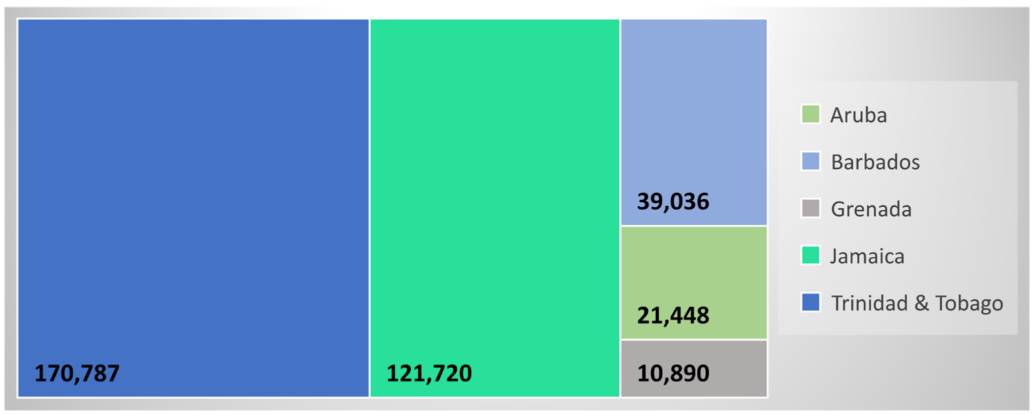

Fig. 7. Estimated volume of e-waste generation (in tonnes) in each island from 2019 to 2025.

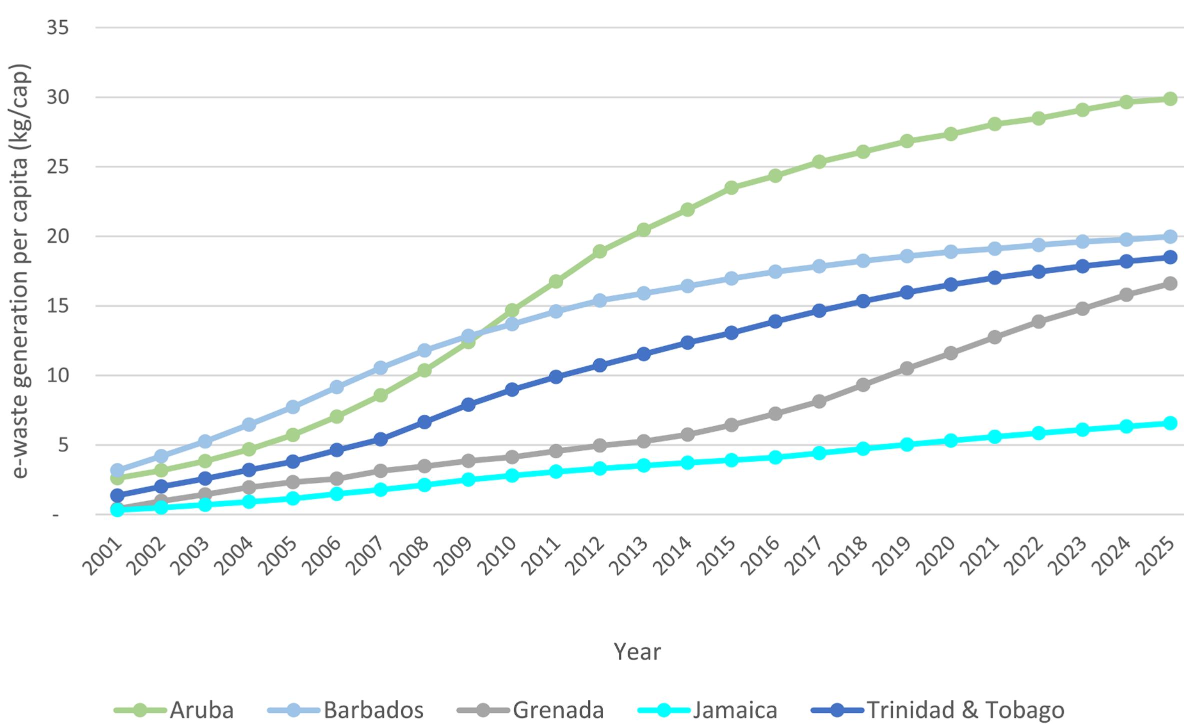

Fig. 8. Comparison of the e-waste generation per capita amount on the five Caribbean islands from 2001 to 2025.

experience higher pressure to deal with the e-waste generation situation. Aruba has the lowest population and land area, but it's e-waste generation potential is estimated to be more than double that of Grenada, with their population size being similar. Considering that the total in-use stock will be more than 683 kt by the end of 2025, that will gradually be discarded, the e-waste situation will remain acute until after 2025.

A recent report by the United Nations University (UNU) presents estimated data on e-waste amounts for a number of countries, including the five island cases considered in this study, in 2019 (Forti et al., 2020). The results presented in this study are similar to the UNU report for Grenada and Trinidad and Tobago, while a difference can be found

Table 1
The correlation coefficient (r) for the relationship between per capita generation of e-waste with the population and the GDP per capita in five SIDS from 2001 to 2017.

Country	*r* value (Population and e-waste generation per capita)	*r* value (GDP per capita and e-waste generation per capita)
Aruba	0.888	0.704
Barbados	0.998	0.862
Grenada	0.987	0.971
Jamaica	0.994	0.887
Trinidad and Tobago	0.995	0.760

for other cases. The estimated amount of e-waste being generated in Aruba, Barbados, and Jamaica is 2.8 kt, 5.3 kt, and 14.8 kt respectively in 2019. In comparison, the amounts reported in UNU report for these islands are 2.2 kt, 3.6 kt, and 18 kt, in 2019. These differences are mainly due to different back-casting and forecasting methods. In this study, the PoM growth rate is used to back-cast the historic data, whereas the UNU study has utilized extrapolation methods.

6.2. E-waste generation rate per inhabitant

The generated e-waste per inhabitant quantity helps to make a cross-country comparison between these five islands. Therefore, to calculate the material flux or e-waste per inhabitant, population data were taken into account from The World Bank (2019). The highest e-waste discarding rate (kg/year per cap) is observed in Aruba with 30 kg per capita for 2025. Barbados, Trinidad and Tobago and Grenada will have 20, 18, and 17 kg e-waste generation per capita in 2025, respectively. Compared to the other four islands, the amount of e-waste per capita is expected to be lowest in Jamaica with 7 kg per person by the end of 2025. Fig. 8 reveals that the e-waste discarding rates profoundly differ across these island nations which can be described by different factors such as economic conditions or population growth. The average e-waste generation rate in these five island nations was over 13 kg/cap in 2016, which is more than two times higher than the average global rate (6.1 kg/cap), which has been estimated by Baldé et al. (2017) for the same year.

6.3. E-waste, GDP and population

The difference between the e-waste generation patterns in these islands can be explained by their population size and the level of affluence (using Gross Domestic Product or GDP per capita as a proxy). Correlation coefficients were calculated to test the relationship between e-waste volumes with population and GDP measures (Table 1). To determine the Pearson correlation coefficient, the estimated e-waste data are used along with the GDP and population data from The World Bank database (2019). E-waste generation amount shows a significant correlation with population and GDP in all SIDS. Contrarily to what reported in a study by Kumar et al. (2017), there is a robust relationship between the amount of e-waste generation per capita and population growth. Kumar and colleagues (2017) stated that there is no significant correlation between the population and the e-waste generation amount. Their study considered the population data for different countries in a specific point of time and was not taken the population growth into consideration. Therefore, it is more reasonable to conclude that the e-waste generation amount has a significant correlation with the population growth rate but not substantially with the population size.

Fig. 9 demonstrates a trend or a pattern of relationship between the GDP and the amount of e-waste generated in these countries from 2000 to 2017 (or 2018 in case actual GDP value is available). The distribution of data around the linear regression line is the lowest for Grenada and demonstrates the limited variability around the regression line (R^2 = 0.963), while in Aruba, the data are more spread around the fitted regression line (R^2 = 0.545). The plot displays that, for most data points, increasing the GPD per capita value causes higher e-waste generation. Therefore, it can be concluded that GDP value is positively linked to the flow of the e-waste in these islands.

A more comprehensive comparison is conducted, that is to look at the effect of GDP per capita and population growth on e-waste generation for each island (Fig. 10). The distinguished positive relationship between population growth and e-waste generation rate suggests that slowing down the purchasing power, and the fall in GDP, can decrease e-waste growth rate. The GDP per capita has been peaked in 2008 and then dropped dramatically; this pattern has been the same for all five countries because of the negative influence of the global financial recession in 2008. The key economic indicators in the Caribbean SIDS were affected by the great recession and especially in the countries

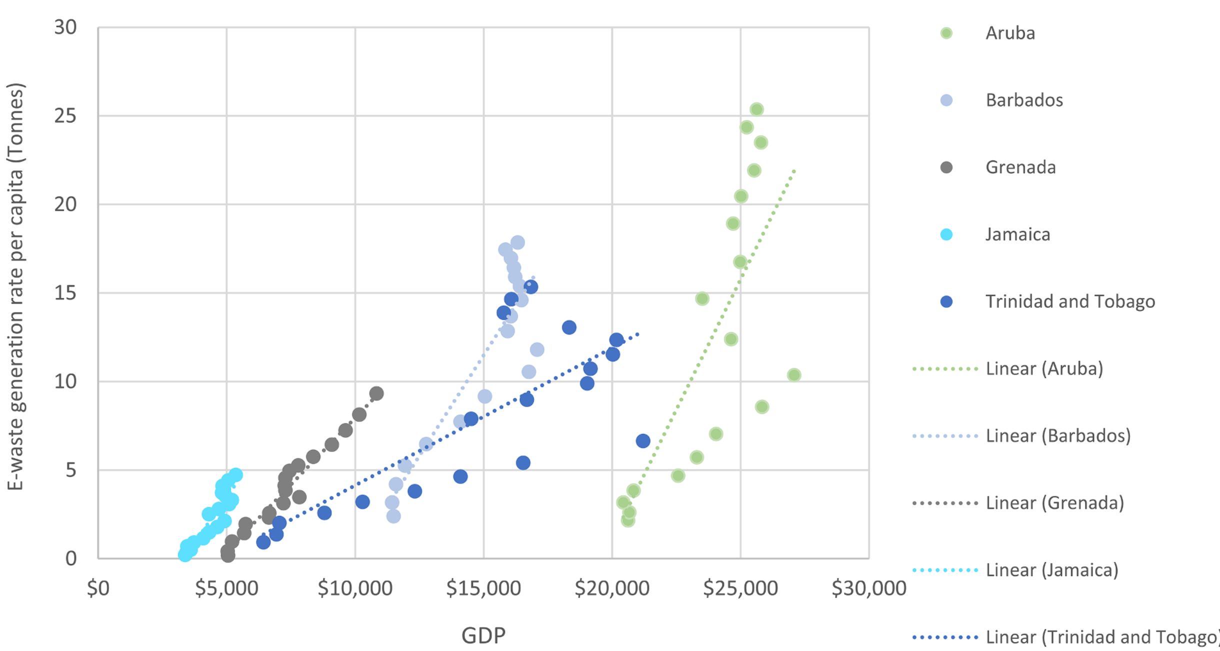

Fig. 9. Scatter plot of e-waste generation per capita versus GDP per capita in five Caribbean islands from 2000 to 2017.

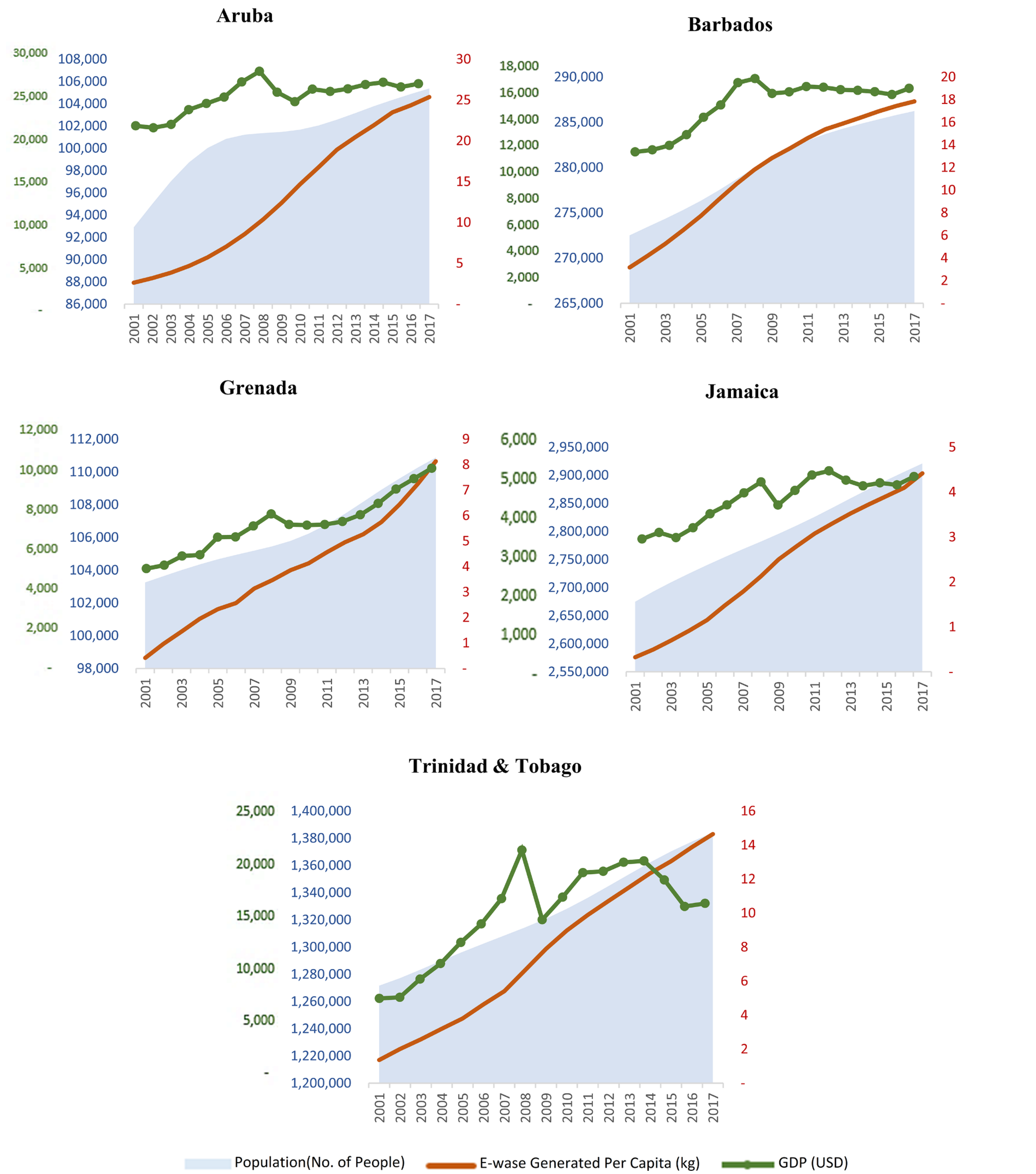

Fig. 10. The relationship between GDP per capita (USD) (in green), population (in blue) and the amount of e-waste generated per capita (kg) (in red) on each island.

which were heavily dependent on tourism (UN ECLAC, 2010). The worst affected countries by this recession were Trinidad and Tobago and Jamaica, with a sharp decline in their GDP (32% and 12%) from 2008 to 2009. This decline took a toll on the average income of the people and caused a falling demand for EEE. As an example, in Trinidad and Tobago, with the highest fall in GDP, e-waste generation rate was decreased from 23% (2008) to 19% (2009) and then 14% (2010). Other factors, such as environmental disasters and financial institutions, also affected the GDP. For instance, GDP per capita has declined in Trinidad and Tobago from 2014 to 2016 due to the sharp decline in oil and gas prices (Grigoli et al., 2019).

In lower-affluence countries with less GDP or declined GDP, such as Grenada and Jamaica, the slope of the e-waste generation line is considerably steeper. Whereas, the slope of the e-waste generation line is more moderate in higher- affluence countries with consistent GDP value, such as Aruba. A higher standard of living in affluent nations results in producing more e-waste whereas, at the same time, the annual e-waste generation growth rate decreases year by year. Decreasing the e-waste generation growth rate is due to reaching the saturation volume and will only shift if products with new technologies emerge in the market. Besides these factors, specific circumstances of islands may influence the e-waste generation rate or change the strength of the

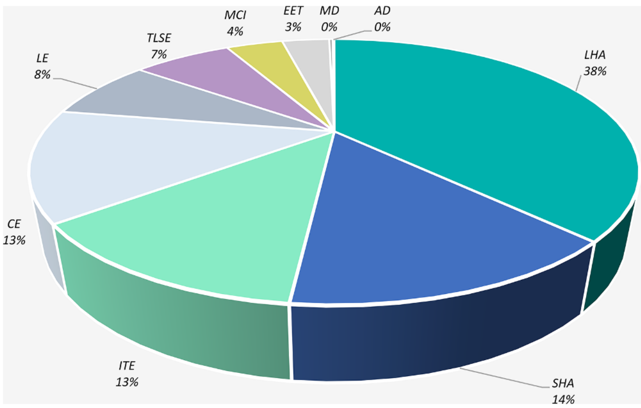

Fig. 11. Categorization of the total e-waste generated (based on weight) into ten categories (EU-10) from 2019 to 2025 on five Caribbean islands. (Large household appliances (LHA), small household appliances (SHA), IT and telecommunications equipment (ITE), consumer equipment excluding photovoltaic panels (CE), lighting equipment (LE), electrical and electronic tools (EET), toys, leisure and sports equipment (TLSE), medical devices (MD), monitoring and control instruments (MCE), and automatic dispensers(AD)).

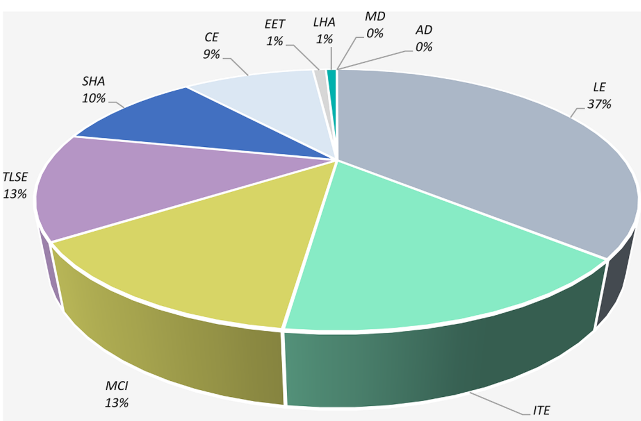

Fig. 12. Categorization of the total e-waste generated (based on number of units) into ten categories (EU-10) from 2019 to 2025 on five Caribbean islands. (Large household appliances (LHA), small household appliances (SHA), IT and telecommunications equipment (ITE), consumer equipment excluding photovoltaic panels (CE), lighting equipment (LE), electrical and electronic tools (EET), toys, leisure and sports equipment (TLSE), medical devices (MD), monitoring and control instruments (MCE), and automatic dispensers(AD)).

relationships, which needs to be studied further in future studies.

6.4. Categorizing e-waste into EU-10 categories

Recognizing the quantity of each e-waste category is of particular importance for developing e-waste recycling strategies. Therefore, to show the e-waste amount in the number of units, the weight of 54 product categories for six years is retrieved from a report by Forti et al. (2018). Then, the average weight of the years is calculated and used to determine the quantity of e-waste generated in the number of units. Fig. 11 determines e-waste distribution at the category level (based on weight) from the date of this study (2019) up to 2025 on five Caribbean islands. The weight of generated e-waste at the large household appliances category level will be the highest, with approximately 38% of the total. The small household appliances and IT and telecommunications equipment categories are the next most cumbersome types, with almost 14% and 13% shares, respectively. Translating estimated e-waste generation volume into the number of units, Fig. 12 shows e-waste distribution at each category level from 2019 to 2025. The lighting equipment category has the highest proportion, with around 152 million pieces over the six years. IT and telecommunication equipment has the second main share with around 65 million pieces. Medical devices and automatic dispensers have the lowest share in either of both calculation models. This information will be useful for the identification of the material recovery, and revenue potential assessments intended for the current or future recycling practices.

6.5. Plateaued versus growing trend assumption: what does the sensitivity analysis tell us?

The results of the sensitivity analysis emphasize that a higher EEE consumption growth rate yields an exponential increasing effect on the amount of e-waste generated in upcoming years. Considering the plateaued assumption, when the consumption achieves the saturation point, the annual e-waste generation rate gradually declines from 2% - 15% in 2017 to 1% - 6% in 2025. However, the e-waste generation amount sharply increases on these islands using the growing trend assumption; the annual growth rate experiences a dramatic upsurge from 2% - 15% in 2017 to 14% - 53% in 2025. This considerable difference between the results of the two scenarios reveal the need for proper strategies aimed at reducing EEE consumption at source. Reducing the amount of consumption will significantly lead to the reduction of waste generation in upcoming years.

The sensitivity results for Grenada shows the highest difference between the plateaued assumption versus the growing trend assumption. E-waste generation in Grenada is estimated to rise from 901 tonnes in 2017 to 1909 tonnes in 2025 if the consumption remains steady over this period. However, assuming the EEE consumption continuously grow by the existing average rate, the e-waste amount will increase sequentially to reach to 10,674 tonnes in 2025. The reason behind this dramatic rise in the e-waste generation amount can be explained by the sensitivity of the model to the amount of PoM. In case such substantial increase in consumption occurs in these islands, there would be a more crucial need for e-waste management purposes. If the e-waste is not managed properly, it would lead to serious environmental problems in the region. This exponential growth can have wider and more complex repercussions on these islands, due to their limited land and resource availability.

7. Will e-waste in the Caribbean become an environmental disaster or an opportunity for a circular economy?

By 2025, it is estimated that the five island cases will have an in-use e-waste stock of 683 kt. Considering that this represents only 11% of the Caribbean population, at least ten times this amount is expected to be generated throughout the Caribbean. The presence of harmful substances as copper, lead, chromium and cadmium in the discarded materials not only threatens human health through improper management, but is also a source of toxic pollution to the vulnerable (is)land and marine ecosystems. These pressures will likely impact other critical sectors on which islands depend, such as tourism and local food security. The recent generous financing from the World Bank's Global Environment Facility (GEF) to reduce toxic waste and chemicals on island environments already sends signals of alarm on this issue (UNEP, 2019a).

Given that the Caribbean region is a hotspot of biodiversity and highly vulnerable to internal and external shocks, individual governments, national and international organizations need put greater efforts to tackle e-waste challenges. The significant amount of e-waste volume relative to island size as well higher per capita as compared to global averages, suggests that urgent attention is given to proper e-waste management in terms of infrastructure, laws and regulations. The e-waste pressure in more populated and affluent SIDS is higher such as in Trinidad and Tobago, but one would expect that they can afford better waste management systems. Due to several limitations, building partnerships would be a crucial ingredient to the successful end of life management in the region to also help smaller and less affluent islands. Because of significantly high e-waste generation rates on these islands, building environmentally sound e-waste dismantling and recycling facilities should be more feasible on a regional level to achieve economies of scale. Starting these facilities will help to reduce the side effects of illegal or improper recycling of e-waste, and it will be an effective mid-to-long-term strategy to move towards a circular economy.

Decreasing the environmental effects of e-waste, a transition from the current linear take- make- waste economy to Circular Economy (CE) will be beneficial for these islands. A linear economy is defined as one where resources are extracted, turned into products and after a short lifetime discarded as waste. Whereas, the Circular Economy (CE) minimizes wastes by closing the loops through recycling, reuse, refurbishment, and remanufacturing (Stahel, 2016). The e-waste management strategy in the region should involve the development of a plan to maximize the reduction of EEE consumption, reusing electronics, and recycling end of life products in an economically viable and environmentally feasible manner. This strategy must consist of a set of guiding principles and action plans for development of policies, financial systems, technologies and skills.

Recycling is a labour- and capital-intensive industry that needs considerable funding and diverse skills for collection, sorting, and processing activities. Despite the financial limitations of SIDS, recycling may provide an economically viable, and ecologically sustainable solution for e-waste management in mid-to-long-term. A profitable regional industry can be developed from recovery of precious and rare metals within e-waste. These islands will require to set up human resource training and development beforehand, expecting the recycling industry to provide different job opportunities in future. The potential for a circular economy in the Caribbean is the subject of our forthcoming article (Mohammadi et al., 2020) assessing the economic feasibility of recycling rare and precious materials from e-waste.

To transition to a more sustainable e-waste management systems, robust data and information systems need to be created by national governments. There is a lack of clarity among different stakeholders on their role and format of reporting data. To keep track of the resource flows more precisely and transparently, harmonization of data sources and reporting method is crucial. Apparent documentation and categorization of the data on EEE sales and consumption, e-waste generation volume, import and export of used EEE and e-waste flows, will help to set the targets and to improve the overall planning and resource recovery from e-waste. Manufacturers and companies should also be encouraged to launch take-back programs to reduce the amount of discarded EEE dumped into the landfills. Moreover, different stakeholders need to take the initiative to increase local community awareness on the issue of e-waste. Effective behavioural change through public awareness about e-waste is of crucial importance. Considering all these aspects, establishing proper e-waste management systems will have a significant impact on decreasing environmental and subsequent public health burdens in long term.

This article is an attempt to offer the first estimate on the electronic and electric products' Put-on-Market (PoM), and the resulting e-waste generated in five Caribbean nations. While more reliable data on the PoM amount and lifetime parameters of electronic products may help refine some of our estimates, we believe that this would not change our overall conclusion and concern around e-waste on small islands. Nonetheless, these gaps provide future research opportunities for conducting regional projects to gather more information and establish a harmonized database addressing these needs. Measuring lifetime parameters and the actual PoM amounts not only for these five island cases but for all Caribbean nations will serve to highlight the importance in establishing a robust regional e-waste management system, and a catalyst for a circular economy.

CRediT authorship contribution statement

Elham Mohammadi: Data curation, Methodology, Writing - original draft. **Simron Jit Singh:** Conceptualization, Supervision, Writing - review & editing. **Komal Habib:** Conceptualization, Methodology, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2020.105106.

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