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How big is circular economy potential on Caribbean islands considering e-waste?

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A R T I C L E I N F O

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A B S T R A C T

While excessive use of electronics and the resulting e-waste is a global problem, the situation is even more acute on small islands as bounded systems and the enormous costs associated with shipping it elsewhere. Dumping e-waste on islands can cause pollution of ground and surface water and degradation of coastal and marine resources. Yet, research that supports island governments to deal with their e-waste is scarce. This paper explores the viability of a circular economy (CE) and asks whether this could be a promising solution for islands to tackle their e-waste challenge. In pursuit of this aim, the CE potential of e-waste is analyzed on five Caribbean islands: Aruba, Barbados, Grenada, Jamaica, and Trinidad and Tobago. The resource quantity of e-waste generated between 2020 and 2025 is estimated, and the economic value is assessed for the embedded materials. Using sensitivity analyses, three scenarios of exploitable e-waste and their potential economic values were calculated, considering the recovery of 20%, 50%, or 100% of e-waste stocked on the islands between 2001 and 2019. Expert interviews were conducted to identify existing e-waste management practices, if any. The results reveal that more than 317.4 kt of secondary materials would be available for recovery, comprising a significant amount of base and precious metals, such as aluminum, copper, silver, gold, and palladium. The estimated economic value of these materials is estimated to be more than $546 million. However, according to the sensitivity analysis, if these islands had started the recovery of resources in early 2001, this value would almost triple to $1,430 million - equivalent to nearly 30% of the total gross domestic product (GDP) from mining and quarrying in the entire Caribbean community, from just these five islands. Due to economies of scale that limit smaller nations, regional co-operations and initiating industrial symbiosis would be essential for desirous islands to shift to a CE. CE can support resource self-sufficiency on islands and bring several social, environmental, and economic benefits. This research is the first to provide an island-specific perspective to help decision-makers manage e-waste flows by including participatory CE implementation methods.

1. Introduction

The development and widespread use of Electrical and Electronic Equipment (EEE) have enabled technological, social, educational, and communicational advances; however, they have also raised new sustainability challenges. Several environmental impacts occur over the entire lifecycle of electronic products, such as resource depletion, human toxicity, and pollution risks (Köhler and Erdmann, 2004; Song et al., 2012; Biganzoli et al., 2015. Extraction and primary production of metals usually require considerable energy (Oguchi et al., 2011) and lead to significant upstream emissions (Dutta et al., 2016). Electronics are composed of a mix of materials, mainly plastics and common metals (Nowakowski and Mrówczyńska, 2018), as well as precious and rare earth elements (Cucchiella et al., 2015; Oguchi et al., 2011; Tansel, 2017). The geopolitical distribution of natural resources, such as the rare elements, used in different EEE, also raises concerns about future scarcity, supply disruption, or increasing price of these materials (Habib, 2015). Moreover, electronics may contain hazardous materials like lead and mercury, which can cause harmful environmental and health impacts at products' end-of-life (EoL) (Chen et al., 2011; Kiddee et al., 2013). The swift evolution of technology and planned obsolescence are amongst the main causes for the significant rise in material consumption in the EEE industries and the corresponding e-waste generation (Bakker et al., 2014; Luhar and Luhar, 2019).)

Waste management is a significant challenge in Small Island Developing States (SIDS) (Fuldauer et al., 2019). The few studies that exist have raised serious concern on the waste problem faced on islands (Noll

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List of abbreviations

Ag	Silver
Al	Aluminum
Au	Gold
CARICOM	Caribbean Community and Common Market
CE	Circular economy
Cu	Copper
EEE	Electrical and Electronic Equipment
EoL	End-of-life
EPR	Extended Producer Responsibility
EU	European Union
Fe	Iron
GDP	Gross domestic product
IS	Industrial Symbiosis
kt	kilo tonne (1000 tonne)
PCB	Printed circuit board
Pd	Palladium
SIDS	Small Island Developing States

et al., 2019; Shah et al., 2019; Fuldauer et al., 2019; Camilleri-Fenech et al., 2018; Mohee et al., 2015; Telesford, 2020; Saito, 2013; Eckelman and Chertow, 2009; Skordilis, 2004). The e-waste generation rate from a sample of five Caribbean nations was significantly higher (nearly up to four times higher) (Mohammadi et al., 2021) than the average global rate (i.e., 6.1 kg/cap in 2017) (Baldé et al., 2017). Sustainability challenges are reported to be more immediate and acute on small islands than other landmasses (Deschenes and Chertow, 2004), coupled with waste mismanagement. The improper discarding of e-waste and lack of EoL management systems also result in coastal pollution, biodiversity loss, and a decrease in the natural population. Islands are home to rich and rare biodiverse systems. They harbor 20% of all plant, bird, and reptile species found globally, where 7 out of 10 coral reef concentrations, and 12 of 18 centers of marine endemism surround islands (Butler, 2016; UN-OHRLLS, 2015). Together with Latin America, the Caribbean is home to 40 percent of the world's biodiversity (UN-OHRLLS, 2015; Saget et al., 2020). The e-waste stocked in the region can be a major threat to these hotspots if poorly managed.

Boundedness, isolation from markets, limited land area, and higher costs of infrastructure are crucial factors that restrict sustainable development in many SIDS (Deschenes and Chertow, 2004; Eckelman and Chertow, 2009; Briguglio, 1995; Eckelman and Chertow, 2013, 2014; UNEP, 2008; IPCC, 2014). The lack of effective waste management systems on most SIDS, and by extension, the availability of reliable data, restricts meaningful planning and sustainable action (Simpson, 2012; Eckelman et al., 2014). In addition, SIDS are confronted with limitations in recycling and resale opportunities, lack of policies, and barriers to exporting waste to other countries (Camilleri-Fenech et al., 2018; Fuldauer et al., 2019), thereby requiring innovative solutions (UNEP, 2019).

New approaches such as CE may help nations improve resource security and reduce environmental and health impacts. Islands can serve as living labs and hubs of innovation for a shift towards resource circularity, an approach that could slow down the increasing and alarming trend in global material consumption (Schaffartzik et al., 2014) while reducing biodiversity loss and land and ocean pollution. By deploying Aruba, Barbados, Grenada, Jamaica, and Trinidad and Tobago as cases, this research explores the potential and viability of a CE on islands and asks whether this could be a promising solution for islands to tackle their e-waste challenge. Based on the data from the literature, the mass of secondary resources available for recycling is estimated using the material composition of different EEE categories. Next, the economic value of embedded materials is calculated on the basis of material composition at the category level and the average market price of each material. Expert interviews provide further insights into the existing practices, the potential for CE, and sustainability in general. This paper provides the first SIDS-specific perspective on e-waste and makes a business case to policymakers for sustainability.

2. Recent research on e-waste and circular economy (CE)

CE is seen as an effective strategy to promote sustainable development. There is no single definition of the CE concept (Kirchherr et al., 2017) or no clear indication of when and who initiated it (Winans et al., 2017). It has been mentioned that the primary school of thoughts referring to 'closed loops' and 'cradle to cradle'; were used as early as 1976 by Walter Stahel (Stahel, 1981; Preston, 2012; Ellen MacArthur Foundation (EMF), 2013). A widely cited definition is from Ellen MacArthur Foundation (2016), where CE is conceived as a restorative or regenerative system, which aims to maintain products and their materials and components at their highest efficiency and value at all times, while "distinguishing between technical and biological cycles". While the goal of CE is on achieving sustainability on a system level, existing CE research and practice are mostly at the level of products and eco-industrial parks for cost-saving, such as minimize raw material intake, design eco-friendly goods that are easy to dismantle and reuse, utilize recyclable materials in products, but also lengthen the lifecycle of products through repair, and recycling or recovery of waste (Van Buren et al., 2016). In other words, the CE concept has been highly considered by scholars and practitioners at the micro-system level, usually to benefit individual enterprises (Sauvé et al., 2016; Kirchherr et al., 2017).

The strong applicability of CE has been highlighted for electronic goods given their increasing volumes (e.g., Ellen MacArthur Foundation (EMF), 2013, 2015, 2016; Nowakowski and Mrówczyńska, 2018; Ongondo et al., 2011; Ottoni et al., 2020) and the importance of critical and precious materials exist in e-waste (e.g., Chancerel et al., 2009; Coughlan et al., 2018). In a recent review by Islam et al. (2020), advances in the metal recovery methods from e-waste were reviewed, and the applicability of microbial bioleaching approaches was emphasized. The necessity for the transformation of EEE through the CE has been emphasized, to minimize resource consumption, and to prolong product lifespan through reuse, repair, and remanufacturing (e.g., Bakker et al., 2014; Ottoni et al., 2020; Reike et al., 2018; Zlamparet et al., 2017). The recovery of secondary raw materials from e-waste has become of high interest (Cossu and Williams, 2015); however, attempts to reduce e-waste volumes, repair, and reuse of EEE have been limited globally (Forti et al., 2020).

The Global E-waste Monitor in 2020 has discussed the e-waste challenge and elaborated solutions for creating a CE, emphasizing global e-waste collection and recycling (Forti et al., 2020). Few studies have assessed the e-waste sector from a CE perspective at the country level, but none for island nations, evaluating the material composition and potential revenues from material recovery. These studies aim to help the optimization of the EoL products' collection for a CE. For instance, Cesaro et al. (2018) has assessed the elemental composition of e-waste and has overviewed the e-waste management systems in some EU and non-EU countries. Another study in Denmark has mapped the EEE flows and examined the economic viability of prioritizing reuse (Angouria-Tsorochidou et al., 2018). Parajuly and Wenzel (2017) have also investigated the potential for a CE of e-waste in Denmark and identified the potential revenues from the reuse and recycling of the EoL electronics. Islam and Huda (2019) and Cucchiella et al. (2015) have also evaluated the material composition and economic value of e-waste for different products. Most of these CE studies in e-waste management research have focused only on one aspect of the CE, mainly recycling, and disregarded other aspects, namely reducing, repairing, and reusing.

Herat and Agamuthu (2012) examined e-waste management challenges in Asian countries, conducting a literature review, highlighting four significant areas of concern: (1) an emphasis on end-of-life management operations; (2) limited environmentally sound e-waste handling; (3) e-waste shipping across borders; (4) the informal recycling sector as a problematic social and environmental hurdle. More recently, Shittu et al. (2020) identified three main areas of concern in e-wase management through reviewing the literature: (1) lack of regulations; (2) the partial provision of formal systems for e-waste collection and treatment; (3) escalation of global e-waste generation due to the increased ownership and obsolescence. In the Indian context, a study by Garg (2021) highlighted that e-waste mitigation could be beneficial if it focuses on the proper execution of e-waste policies, directives, and regulations. Conducting a literature review, Cesaro et al. (2018) overviewed e-waste generation trends, composition, and the legislative framework for its handling. It is suggested that the emphasis should be on improving the characterization, collection, treatment, and global e-waste trades and the related health and environmental impacts. Malinauskaite and Erdem (2021) analyzed the EU's CE strategy considering the 'rule utilitarianism' approach and intergenerational justice. They argued that the current measures concerning competition law, consumer protection law, and environmental law are insufficient to deal with planned obsolescence (Malinauskaite and Erdem (2021)).

A notable shortcoming in existing studies proposing CE at the macro-level (e.g., country, continent) is a lack of a comprehensive approach that includes the role of stakeholders and their inclusion in sustainable management of resources. Considering the immediacy and acuteness of sustainability challenges on islands and addressing this literature gap, this study will explore opportunities for CE of e-waste, including reduce, reuse, repair, and recycle dimensions, along with an analysis of an enabling environment and relevant stakeholders.

3. Methodology

The five Caribbean SIDS selected for this study are Aruba, Barbados, Grenada, Jamaica, and Trinidad and Tobago. Together they represent around 11% of the Caribbean population, 7% of the land area, and exhibit diverse portfolios such as human and economic development, key economic sectors, and geographical spread in the Caribbean Sea (The World Bank, 2019). Together with their diverse portfolios, these islands have very diverse e-waste generation rates that allow for an understanding of e-waste dynamics, their management, impact on the environment, and CE potential in varying socio-economic contexts. According to our previous estimations (Mohammadi et al., 2021), among these islands, Aruba has the highest e-waste generation rate per capita of 27 kg/cap, followed by Barbados (19 kg/cap), Trinidad and Tobago (17 kg/cap), Grenada (12 kg/cap), and Jamaica (5 kg/cap), in 2020. From 2020 to 2025, the estimated volume of generated e-waste would be around 148.5 (kt) in Trinidad and Tobago, 106.9 (kt) in Jamaica, 33.6 (kt) in Barbados, 18.6 (kt) in Aruba, and 9.7 (kt) in Grenada.

The research was conducted in three steps to estimate the material composition of e-waste and its economic value in the five island nations, and their potential for CE. First, we estimated the mass of materials such as precious and base metals found in e-waste that are available for recycling from 2020 to 2025; second, estimate the potential economic value of these materials considering the current market values; and third, conduct semi-structured interviews with professionals in solid waste management sector on these islands to identify challenges and opportunities with regards to achieving a CE for e-waste in the five Caribbean islands. Finally, three sensitivity analyses are performed to examine the uncertainty of the results obtained.

The material composition and economic assessment cover the following e-waste categories:

1) Temperature exchange equipment (e.g., fridges, freezers, air conditioners, cooled dispensers)
2) Screens and monitors (e.g., laptops, cathode ray tube monitors, flat display panel monitors and TVs)
3) Lamps (e.g., compact fluorescent lamps, led lamps, special lamps)
4) Large equipment (e.g., dishwashers, washing machines, dryers, leisure equipment, professional medical equipment)
5) Small equipment (e.g., microwaves, vacuum cleaners, personal care equipment, video recorders)
6) Small IT and telecommunication equipment (e.g., desktop personal computers, routers, mice, keyboards, printers, phones)

This paper considers the e-waste generation rate from 2020 to 2025. This is because of an assumption made that no e-waste stock is available on these islands for recovery from previous years up to 2020. Any e-waste generated prior to 2020 had been mainly dumped into the landfills. This assumption will be tested using three sensitivity analyses to evaluate what could happen in alternative contexts where stocked e-waste could be recovered.

3.1. Quantifying e-waste material composition

The e-waste estimation in our previous research (Mohammadi et al., 2021) was based on EU-10 categories, which are first converted to the EU-6 categories for the purpose of this study. This conversion would help compare the results with other studies conducted in several countries based on the European Union guidelines (e.g., Kumar et al., 2017; Parajuly et al., 2017b). Then, the mass of secondary resources available for recycling in each e-waste category was estimated using the average material composition, retrieved from Magalini et al. (2015). The analysis considered five material types: base metals (Aluminum (Al), Copper (Cu), Iron (Fe)), precious metals (Silver (Ag), Gold (Au), Palladium (Pd)), plastics, glass, and other materials. The availability of secondary materials from each e-waste category in a given year is calculated using the following equation (1):

$$M_{j\ (t)} = \sum_{i=1}^{n} E_{i\ (t)} \cdot C_{ij} \tag{1}$$

$M_{j\ (t)}$= The total secondary material resource "j" available in e-waste in the year "t"
$E_{i\ (t)}$= The e-waste amount of the "i" category in the year "t"
C_{ij}= The composition of secondary material resource "j" in the "i" e-waste category

3.2. Economic value of embedded materials

The economic value of recyclable materials within e-waste can be estimated using the mass of embedded materials and related market prices. Market prices are highly volatile and fluctuate continuously over time. At the time of this analysis, the best available data regarding the market price of different metals found in e-waste was for 2019 using different stock exchange websites such as the London Metal Exchange (London Metal Exchange, n.d.) and Comext (Comext, n.d.). The latest reliable prices for plastics and glass were only available for 2018. The average yearly prices of embedded materials are calculated using the data demonstrated in Table 1. The highest market value is related to Pd, whereas glass has the lowest value. The economic value for the category of 'other materials' is not evaluated, as this category contains very different material types, and identifying the mass and market value of these materials was not feasible given the time and data constraints at the time of this study.

The estimated material composition of each e-waste category is multiplied by its market price, as shown in Table 1, to identify the total material value per tonne of material for each product category. The economic value of each product category (P) is calculated using equation (2), considering the mass content (tonne) of the category multiplied by the market value of the primary material (USD/t):

Table 1
The average market values of the embedded materials within e-waste.

MATERIAL	AVERAGE ANNUAL MARKET VALUE (USD/T)	YEAR
PALLADIUM (Pd)	61,729,387	2019
GOLD (Au)	48,290,385	2019
SILVER (Ag)	557,660	2019
COPPER (Cu)	5,308	2019
ALUMINUM (Al)	1,504	2019
PLASTICS	1,200	2018
IRON (Fe)	275	2019
GLASS	50	2018

The market values have been retrieved for 2019 from the London Metal Exchange ("London Metal Exchange: Market data," n.d.) and Comext ("Comext: datasets," n.d.); next, the average yearly prices of embedded materials are calculated.

$$P = \sum_{i=1}^{n} p_i . M_i \tag{2}$$

P = The total material value per tonne for each product category (USD/t)
M_i = The mass of the material "i" in the product category in tonnes
p_i = The unit price of primary material "i" (USD/t)
n = The total number of materials in a product category

3.3. Expert interviews

Eight expert interviews were conducted with academics and professionals in the solid waste management sector of the five islands to understand how ''reduce, reuse, and recycling'' of EEE are nationally facilitated. The interviewees were requested to provide the information in the context of their professional position. The information obtained from these interviews would help better understand the current situation on islands and provide practical recommendations for developing proper e-waste management systems. Interviewees were selected based on their expertise, ensuring that they had high enough level of knowledge and experience to provide information about the current CE and e-waste management strategies in their countries. All interviewees had at least three years of experience in the solid waste management sector as an academic, e-waste broker, or manager in waste management companies or non-governmental organizations (NGOs).

A set of seven open-ended questions were used for each expert interview. The initial questions posed to them allowed the interviewees to lead the discussions around the CE of e-waste on each island, providing them with the flexibility to share information they considered relevant. The key questions were; 1) Are there any national e-waste management and CE policies in place?; 2) Are people aware of their role in the CE practices (focusing on e-waste)?; 3) Are any companies or organizations operating in the e-waste dismantling sector?; 4) What are the major e-waste recycling activities?; 5) What are the major e-waste ''reduce and reuse'' activities on the island?; 6) Is there any co-operation with other countries for recycling operations?; and 7) What are the challenges in implementing a CE approach on the island (focusing on e-waste)?

3.4. Sensitivity analysis

In the sensitivity analysis, three other possible scenarios have been considered and analyzed. Due to the lack of proper e-waste management on these five islands, it was assumed that people might have kept at least part of their e-waste as hibernating stock in their homes. For the small IT and telecommunication equipment category, the retained amount could be much higher as people tend to keep old devices for a longer time, mainly due to the small size of products in this category (e.g., Borthakur and Govind, 2017; Ylä-Mella et al., 2015). Thus, to test the sensitivity of our results to the assumption of no e-waste generated before 2020 available for resource recovery, three sensitivity analyses were conducted: a) adding the 20% hoarded e-waste comprising all categories from 2001 to 2019; b) adding the 50% stockpiled e-waste for Small IT and Telecommunication Equipment category and 20% hoarded e-waste for the other five categories; and c) 100% of the e-waste generated on these islands, from 2001 to 2019, is available for materials recovery. This comparison helps demonstrate approximately how much resources these nations have lost by neglecting the recovery of secondary resources from e-waste.

4. Results

In this section, we discuss the results for each island across all six EEE categories: 1) temperature exchange equipment, 2) screens and monitors, 3) lamps, 4) large equipment, 5) small equipment, and 6) small IT and telecommunication equipment. Findings from the expert interviews are also presented with respect to the current e-waste management practices, the challenges, and the opportunities of implementing a CE framework on the islands.

4.1. Material composition

The material composition of e-waste generated on the five case islands from 2020 to 2025 is shown in Fig. 1. The total mass of recoverable materials from e-waste on these islands is estimated at around: 148.5 kt for Trinidad and Tobago, 106.9 kt for Jamaica, 33.6 kt for Barbados, 18.6 kt for Aruba, and 9.7 kt for Grenada. The distribution of secondary resources embedded in different product types follows mostly the same pattern on all island cases. The small equipment is the largest category, comprising 35.5%–46.3% of the total materials found in e-waste on all islands. The small equipment category is mostly comprised of plastics (32%) and Fe (31%), while glass content is estimated to be around zero. The mass of Ag and Au in this category is 0.007 (kt) and 0.001 (kt), respectively.

The temperature exchange equipment makes up the second-largest category, contributing 18.6%–26.5% of secondary resources on the five Caribbean islands. The share of the aggregated material composition of the temperature exchange equipment category is 26.5% for Barbados and is 18.6% for Trinidad and Tobago. The temperature exchange equipment is mostly composed of Fe (31.8 kt) and plastics (14.1 kt) and does not contain any precious metals and glass. The third-largest e-waste category considering the mass of secondary resources is large equipment, comprising 14.2%–19.4% of the total mass of secondary materials. The share of recoverable materials from large equipment is largest for Barbados (19.4%), while it is the lowest for Aruba (14.2%). This category mainly contains Fe (21.3 kt), Al (4.9 kt), and plastics (4.9 kt). Around 0.011 kt of Ag can also be recovered from this product category on the five islands.

The next category is the small IT and telecommunication equipment, in which the share of recoverable materials is highest for Grenada (11.3%) and lowest for Aruba (8.4%). The major recoverable materials from this category (considering the mass) are plastics (15.5 kt) and Fe (6 kt). Based on our estimations, around 0.008 (kt) of Ag, 0.002 (kt) of Au, and 0.001 (kt) of Pd can be recovered from this category. The screens and monitors category comprises 4.3%–9.9% of the total materials in e-waste available for recycling. The estimated share of accumulated materials found in this category is largest for Trinidad and Tobago (9.9%) and smallest for Barbados (4.3%). Plastics (7.4 kt) and Fe (6.8 kt) are the heaviest materials in this category. Besides this, approximately 0.002 (kt) of Ag, 0.0009 (kt) of Au, and 0.0003 (kt) of Pd can be recovered from this product category. The last category of lamps constitutes the lowest share of embedded materials, with the highest being in Barbados (3.1%) and lowest in Aruba (0.63%). Glass is the heaviest material (4 kt) contained in this category, followed by Al (1.3 kt), and plastics (1.2 kt).

Overall, Fe and plastics are the most common materials contained in

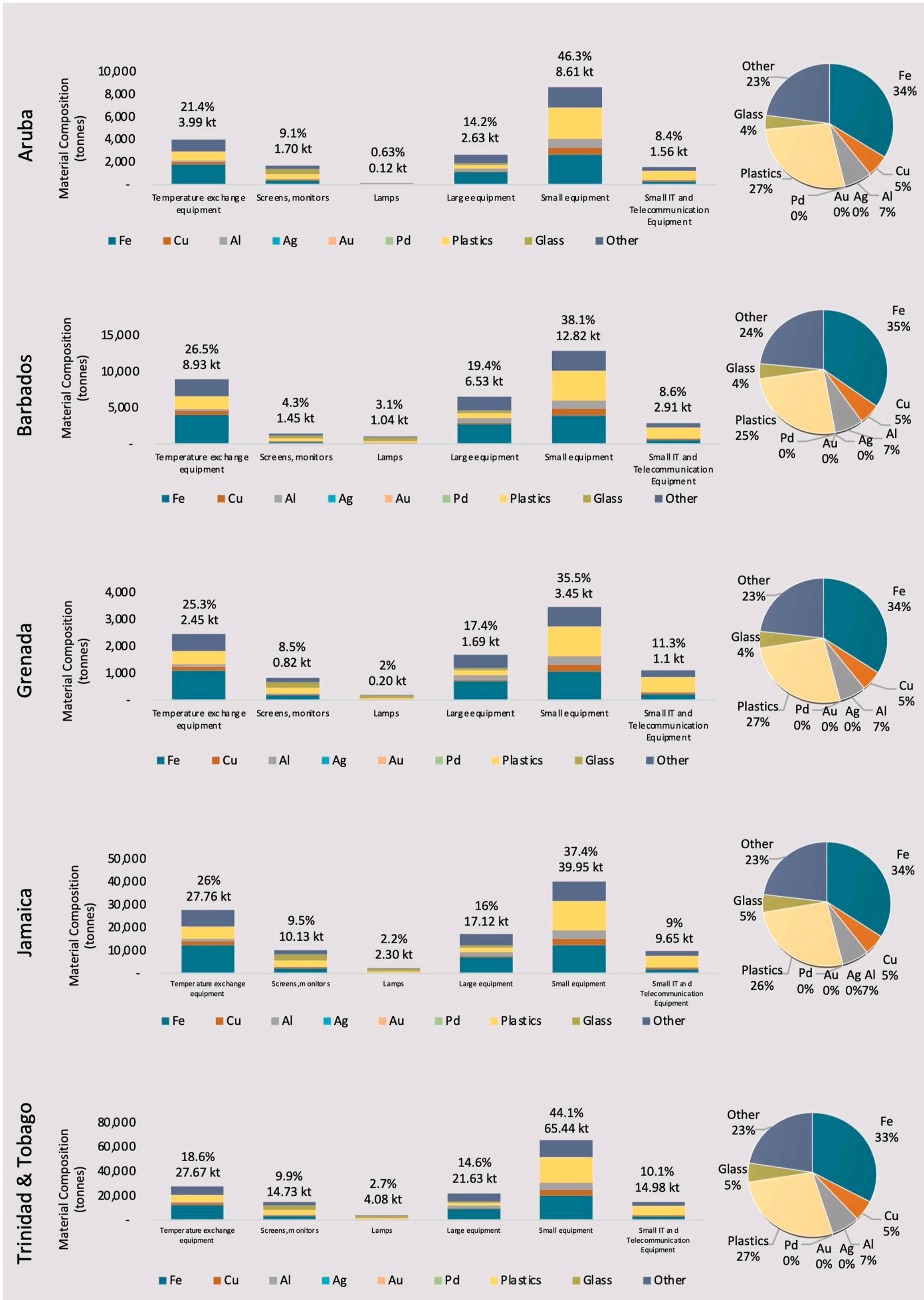

Fig. 1. The material composition of generated e-waste in each island from 2020 to 2025 (The mass of available resources in each e-waste category was estimated using the average material composition retrieved from Magalini et al. (2015)).

different categories of e-waste, whereas precious metals (Ag, Au, and Pd) have the least mass in e-waste. The majority of precious metals are concentrated in the categories of small IT and telecommunication equipment, small equipment, and screens and monitors.

4.2. Potential economic value

The estimated economic value of different materials embedded in the six categories of e-waste is presented in Fig. 2, for 2020 to 2025. The estimated total economic value of the recoverable materials is more than \$546 million, and around 40% of this value seems to come from Au. The top three materials contributing to economic value are Au (40%), plastic (19%), and Cu (16%). Au is mainly contained in small IT and telecommunication equipment (0.002 kt), small equipment (0.0013 kt), and screens and monitors (0.0009 kt). Plastics are contained in all categories (10% in lightning equipment to 51% in small IT and telecommunication

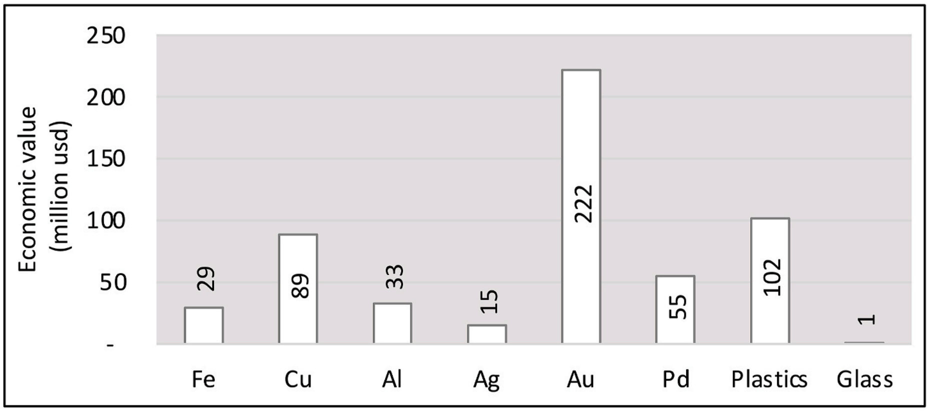

Fig. 2. Estimated economic value (in million USD) of the materials embedded in e-waste for all five islands (from 2020 to 2025).

equipment). Plastics are mostly embedded in small equipment (41.6 kt), small IT and telecommunication equipment (15.5 kt), and temperature exchange equipment (14.1 kt). Here, the estimated plastic content can be recovered if it can come out as a clean fraction. Plastics have meager recycling rates (Habib, 2015; Parajuly et al., 2016) due to a number of factors such as the type of polymers used in plastics and contamination to impurities (e.g., Hahladakis and Iacovidou, 2019). Therefore, efficient separation and purification methods can impact the estimated resource recovery rate and costs.

Cu is the third-largest contributor to the economic value, which is mainly contained in small equipment (9.1 kt), temperature exchange equipment (4.2 kt), and small IT and telecommunication equipment (1.5 kt). Another interesting contribution to the economic value could come from Pd (10%), mostly concentrated in small IT and telecommunication equipment and screens and monitors. The economic value of recoverable Al is around $33 million, which can be found in all categories but is mainly contained in small (11.7 kt) and large equipment (4.9 kt). Fe is also a common material widely used in all EEE categories; however, the most substantial quantity of this base metal can be recovered from small equipment (40.3 kt), temperature exchange equipment (31.8 kt), and large equipment (21.3 kt). The potential value from the recovery of glass is very low compared to other materials ($1 million).

The overall resource recovery and economic potential from e-waste on the five islands are demonstrated in Fig. 3. By converting the e-waste generated between 2020 and 2025 on the five islands into secondary resources would fetch them $546 million. The exploitable materials from e-waste and the economic value can significantly vary depending on the type of product, the EoL management system, and the available recycling technology (Parajuly et al., 2017b). Among these islands, the e-waste generated in Trinidad and Tobago is the largest and contains the highest quantities of secondary resources (148.5 kt). The economic value of these resources can be up to $266 million. Jamaica has the second most quantities of materials (106.9 kt) and the associated economic value ($179 million). Barbados and Aruba can also recover around 33.6 kt and 18.6 kt of secondary resources, with the economic value of $52 million and $32 million, respectively. Grenada, which has the lowest population, can recover 9.7 kt of materials from e-waste with a value of roughly $17 million.

The mass of embedded precious metals (Pd, Au, and Ag) within e-waste is around 0.034 kt, only comprising 1% of the total resources found in e-waste. However, more than 40% of the economic value ($242 million) could come from the recovery of these precious metals. The precious metals are concentrated in printed circuit boards (PCBs). Therefore, proper dismantling and handling of PCBs would require efficient recycling and recovery of these resources (Ardente et al., 2014).

We compared the results of this research with a study in Denmark (Parajuly et al., 2017b). The estimated population of Denmark is around 5.8 million for 2020, and the estimated total population of these five islands is around 4.9 million in the same year. Parajuly et al. (2017b) estimated that in Denmark, from 2020 to 2025, around 486 (kt) of material could be recovered from e-waste, with approximately $816 million (or €720 million) economic value. Our estimation reveals that over the same period, 317 (kt) of materials can be recovered in these five SIDS with a total value of $546 million. This comparison shows that the average economic value of each kilo tonne of material in Denmark was $1.68 million (at the time of the study in 2017), and now it is around $1.72 million in the Caribbean. The difference between these two values

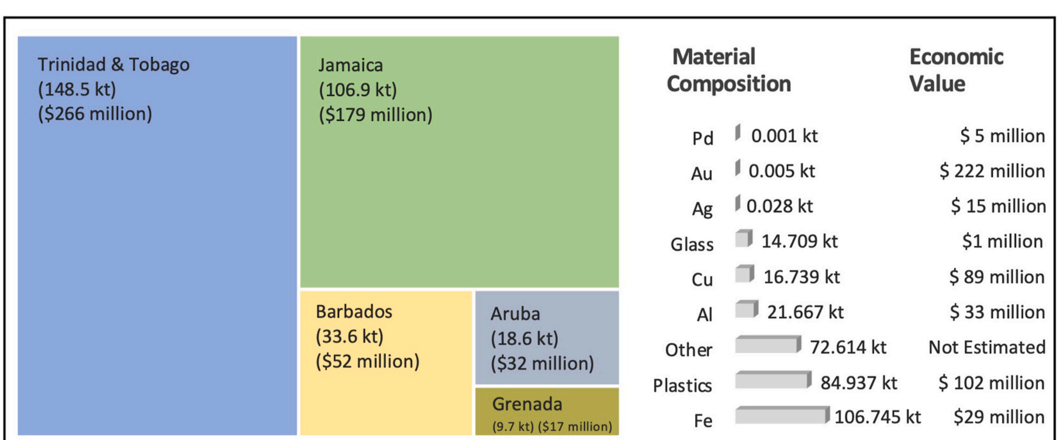

Fig. 3. The mass of accumulated secondary resources in e-waste (in kt) and the associated economic value of these materials (in million USD) from 2020 to 2025.

can be explained by the significant increase in gold prices in recent years ("Government of Canada: Gold facts," 2020). The study in Denmark indicates that Au and plastic carry more than half of the total economic value, which is also true for the Caribbean islands' case. In both studies, the next key metal is Cu representing around 15% of the potential economic value for Denmark and 16% for the Caribbean.

4.3. Results of the sensitivity analysis

Fig. 4 compares the estimated economic values and material composition of the e-waste (excluding the category of other materials) with three sensitivity analyses for our cases. In the first sensitivity analysis, it was assumed that 20% of the e-waste generated from 2001 to 2019 is still stockpiled on islands and is available for materials recovery. Adding this 20% hoarded e-waste, the economic value can increase from $546 to around $723 million. In the second sensitivity analysis, it was assumed that 50% of the e-waste for small IT and telecommunication equipment, as well as the 20% of e-waste for the other five categories, are still retained. The second sensitivity analysis shows that economic value can increase to around $1,124 million (up by around 205% compared to the base scenario). However, if these islands had started the recovery of secondary resources in early 2001 (the third sensitivity analysis), they could have gained around $1,430 million worth of economic value by the end of 2025. It is worth noting that the aggregated material composition in Fig. 4 is not a hundred percent. The category of 'other materials' is excluded from the economic value estimation.

Our sensitivity analyses assume that due to the lack of a proper e-waste management system, around 470 (kt) of materials or $883 million in economic value was lost on these islands between 2001 and 2019. Some old stockpiled e-waste might still be available for recycling in some islands. The sensitivity analyses reveal that recovery of the hoarded secondary resources can still considerably increase material and value benefits. Regional and national authorities would require taking on-time actions through planning, funding, and constructing the necessary facilities to avoid future material and value loss.

4.4. Current e-waste management situation on islands

Table 2 summarizes the responses of the eight waste management experts to the questions we asked. From their inputs, it could be argued that, as of now, there are no specific national practices devoted to achieving the CE of e-waste on these five islands. Barbados and Jamaica's governments have recognized the e-waste problem, and efforts are being made to address the issue by putting in place policies and regulations. In 2015, the National Solid Waste Management Authority in Jamaica launched a pilot project to collect specific e-waste categories to provide the necessary information for Jamaica's e-waste policymaking. However, no particular progress has been made so far. Besides, all experts mentioned that there is minimal awareness about CE practices for proper e-waste management in these islands. There are some programs for raising public awareness (mainly about plastics and paper wastes), but progress on e-waste still lags behind.

Disaggregating and exporting some materials or components (mainly computer components, base metals, and plastics) to other countries are the only practices that have been implemented in four out of five islands. Two e-waste brokers in Barbados and Trinidad and Tobago try to repair, refurbish or upgrade some types of products, including computers and laptops for reuse, but these efforts are small. Repair activities take place for other electronic categories too, but the challenge of availability and high price of spare parts limits the range of products that can be repaired. People usually buy cheaper electronics with a lower lifetime because, in general, the market price of these products on islands is higher than on the mainland due to shipping costs and taxes. Currently, there is no specific co-operative program between these islands and other countries to develop regional e-waste recycling. The ABC Islands (Aruba, Bonaire and Curaçao) have signed a pledge in 2016 to increase co-operation for waste recycling, but there is no particular program for e-waste. According to the interviews, the difficulties confronted by these islands for implementing the CE practices (focusing on e-waste) can be labeled into three main categories: lack of awareness, economies of scale, and government support.

5. Discussion

5.1. Is there an opportunity for a circular economy (CE) on caribbean islands?

Our findings reveal that the mass and economic value of embedded materials within e-waste have the potential to advance recycling opportunities in the Caribbean if one of the countries can construct a facility to serve multiple islands. The findings strongly support the recycling aspect of the CE. Iron, plastics, and aluminum represent the majority of the total mass of secondary materials (213 kt) that can be found in e-waste. However, the mass of precious metals (Pd, Au, and Ag) within e-waste is less than 1%, and more than half of the economic value comes from the recovery of these precious metals. Improving e-waste collection and recycling practices in the Caribbean would help decrease the imports of virgin raw materials. Recycling and treating the e-waste in an environmentally sound manner would also help elude the losses of economically valuable materials that just end up in landfills.

Comparing the results of our study with the recent $33 million investment by the United Arab Emirates (Pereira, 2019) in an e-waste

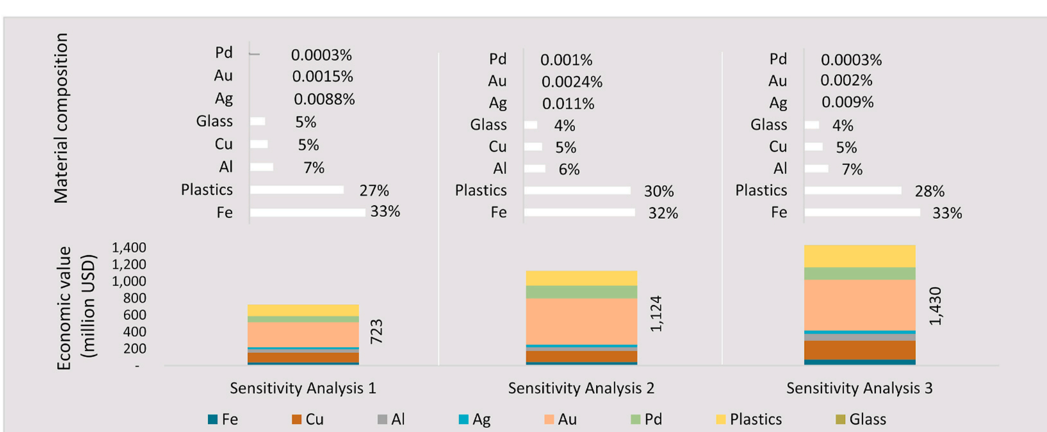

Fig. 4. The comparison of the estimated material composition of the generated e-waste (excluding the category of 'other materials') and the corresponding economic value in the case of three sensitivity analyses.

Table 2
Summary of the findings from the expert interviews.

Focus of the core questions	Aruba	Barbados	Grenada	Jamaica	Trinidad & Tobago
Effective e-waste management policy	None	The e-waste policy is in progress	None	The e-waste policy is in progress	None
Level of awareness about the CE practices	Low	Low	Low	Low	Low
Active companies or organizations in e-waste dismantling	Yes	Yes	No	Yes	Yes
Major e-waste dismantling/ recycling activities	Recovering circuit boards and metals from large household appliances	Recovering circuit boards, plastics, and some metals	Recovering copper from copper wirings	Recovering some metals from e-waste	Recovering plastics, some metals, and computer parts
Major e-waste reuse and reduce activities	None	Repairing or refurbishing monitors and computers on a small scale	None	Repair on a small scale	Reconfiguring computers and laptops for reuse
Co-operation with other countries for e-waste recycling activities	None	None	None	None	None
Major difficulties of implementing the CE approach	Lack of economies of scale, Lack of awareness	Lack of economies of scale, Lack of awareness	Lack of economies of scale, Lack of awareness	Lack of Government support, Lack of awareness	Lack of Government support, Lack of awareness

recycling facility with a capacity of 100 kt per year (Forti et al., 2020) reveals the potential for initiating a recycling project in the Caribbean. Considering that our estimated amounts represent only 11% of the Caribbean population, we can expect at least ten times these quantities to be attained throughout the Caribbean. Investing in "reduce and reuse'' initiatives would be less expensive compared to repair, remanufacture, and recycling (Hall et al., 2017).

Considering the current limited reuse, repair, and refurbishment activities on islands, establishing these initiatives is essential for moving to a CE. Based on the interview findings, raising public awareness and behavioral change can help reduce the increasing EEE consumption in SIDS. In addition, the remaining functionality of the End-of-Use products and components should be recognized by islands to offer reuse and refurbishment opportunities. To make these improvements, SIDS would need to provide a foundation for a proper e-waste management system, such as developing maintenance and repair facilities, enabling policies to reduce reliance on virgin materials while generating new jobs in a CE. Appropriate plans should consider economic performance, social, and environmental inclusiveness.

The CE as an umbrella concept (Blomsma and Brennan, 2017) is interwoven with several other concepts, like Industrial Symbiosis (IS) (Chertow and Ehrenfeld, 2012). Most of the previous CE studies had suggested circularity at the level of industrial parks, including product design (Korhonen et al., 2018). It can be claimed that the success story of IS in other geographies, like Kalundborg in Denmark, can be repeated in the Caribbean if the IS could be implemented efficiently. IS takes into account the co-operation between industries that are located in close proximity and conventionally performed separately (Chertow, 2000). Debnath (2020) argues that the stakeholders of the e-waste industry frequently do not work with external partners, and it is important to integrate their perspectives and engage them in this effort. We also suggest going beyond industry to include economy-wide and inter-sectoral co-operation for an island CE. Partnership with other sectors and integrating them in the supply chain of components could pave the way towards an effective e-waste management system (Debnath (2020)). The main steps towards IS can include collecting the data provided by the companies (material resources and production processes), classification of potential internal and external alternatives for resource valorization, and evaluation of other options such as technical, legal, environmental, and economical feasibility of IS (Cutaia et al., 2020).

The implementation of IS can have a significant impact on reducing environmental burdens and costs in e-waste management in SIDS. Co-operation between different industries can occur in the form of exchanging utilities, materials, by-products, waste, water, energy, information, or joint marketing efforts. IS can create a broad range of opportunities in SIDS, sharing limited available resources and improving industrial sustainability. Spatial planning on islands should consider constructing new industries close to the recycling plants as part of an industrial ecosystem to share resources or to use recovered material as raw materials. IS has proven feasible to use a variety of carbon-rich waste streams (such as waste plastic) as an alternative fuel in cement production (De Queiroz Lamas et al., 2013; Rahman et al., 2013, 2015). Trinidad & Tobago has a cement plant called Trinidad Cement Limited (TCL), with an annual production capacity of 1.2 million metric tons (Millette et al., 2019). IS could make it possible to divert plastic waste from e-waste for use as feedstock in a local cement plant. Moreover, recycled secondary resources can be used to produce value-added products. Manufacturing and trading value-added products would be much more profitable for SIDS than exporting secondary raw materials and contribute to local jobs and ripple through the economy.

5.2. Importance of relevant policies

Appropriate policies and regulations can inevitably play a significant role in e-waste management systems focused on building CE. According to the latest Global E-waste Monitor (2020), 78 countries in the world have policies or legislation governing e-waste. Almost no policies needed to drive e-waste management exist in the Caribbean, either for the islands or the region as a whole, and few nations are currently trying to introduce them.

The e-waste policies should target and engage all stakeholders, from manufacturers and governments to the public. Legislations should aim to establish and improve all aspects of the CE, and not only the efficiency of the recycling chain. However, recycling activities should be carefully designed according to specific local conditions and situations. To stop importing low-quality products, imported EEE must meet the quality standards, and they should be disassembled easily for repair and recycling purposes. Imported electronic products also need to be updatable and reconfigurable. It would be especially crucial for SIDS to monitor and control the transition to a CE, setting the collection and recycling targets. Robust data and information systems would inevitably contribute to support planning for a shift to a CE.

It is essential to move away from a policy where all materials are treated equally to an alternate method for specifying collection targets for different waste streams, specifically different EEE types (Althaf et al., 2019). These targets can be identified based on various factors. Wang and Gaustad (2012) proposed prioritizing electronics with higher economic value, energy-saving potentials, and lower eco-toxicity. Policies emphasizing Extended Producer Responsibility (EPR) should also be developed to manage e-wastes. EPR was introduced based on the polluter-pays principles (Widmer et al., 2005). According to this environmental policy approach, extended responsibility should be attributed to manufacturers at all stages of the product's life cycle, including disposal at their EoL (OECD, 2001). Even when the policies and legislations are enacted in SIDS, enforcement is of high importance to achieve CE.

5.3. Enabling environment

Based on literature review and expert interviews, Fig. 5 identifies potential collaborations, stakeholders, and critical steps for developing efficient e-waste management systems in small island states. Actions and collaborations are required at four different levels: a) regional (such as at the level of CARICOM and the Basel Convention Regional Centre for the Caribbean Region), b) national, c) enterprises and industry, and d) the public.

Moving to a CE of e-waste depends on extensive co-operation and raised awareness among governments, businesses, and the public. Co-operative business models would provide opportunities to combine resources, increase the quantities of recyclable products, and expand business opportunities. Consultation with experts confirms that educational outreach is minimal, involving only a few non-governmental organizations and campaigns focused on plastics and paper, not on e-waste. Increased public, governmental, and stakeholder awareness is needed, with stress placed on behavioral change towards reducing and reusing EEE, as well as proper e-waste disposal.

Regional authorities are expected to take steps toward developing an efficient e-waste management system. Policies need to be formulated for optimal e-waste management and to protect from adverse environmental and health impacts. In this case, the EU guidelines and policies on e-waste can be useful as a benchmark. Based on the expert interviews, harmonized definitions and categories for e-waste would be a fundamental requirement for co-operative management. Previous experiences in other waste sectors have shown that external financing at the initial stages would be beneficial to support the growth of a CE in the region. Therefore, investment plans and incentive and disincentive financial instruments would help to facilitate a thriving e-waste sector in the region.

National governments should be responsible for setting new policies and standards, ensuring they align with their regional initiatives and regulations. Putting in practice ongoing control and monitoring systems will help to identify any areas not performing to expected levels and determine whether any adjustments are required. A baseline estimation such as e-waste estimation amounts by Mohammadi et al. (2021) can be a starting point to assess the level of success. Compared to other waste streams, e-waste recycling is associated with higher job creation capacity (GreenCape, 2017). Therefore, the development of the e-waste recycling sector on islands is likely to create new employment opportunities. However, capacities need to be expanded in the case of human resources and technological development. The most appropriate technology and environmental practices should be identified for the islands' specific requirements and long-term economically viable development. This infrastructure, as well as the financial support from national and regional sources, would facilitate formulating new initiatives for reducing, reusing, and recycling EEE all around the Caribbean. Developing a market for recycled materials would be a significant step, connecting scattered recycling companies to each other and also connecting buyers and sellers across the Caribbean and elsewhere. Initiating eco-industrial networks and parks would be a significant effort for developing CE, for instance, by selling recycled materials or by-products as a new raw material to various sectors.

The public commitment to CE can be secured through raising awareness, and ambitious public commitments can play an important

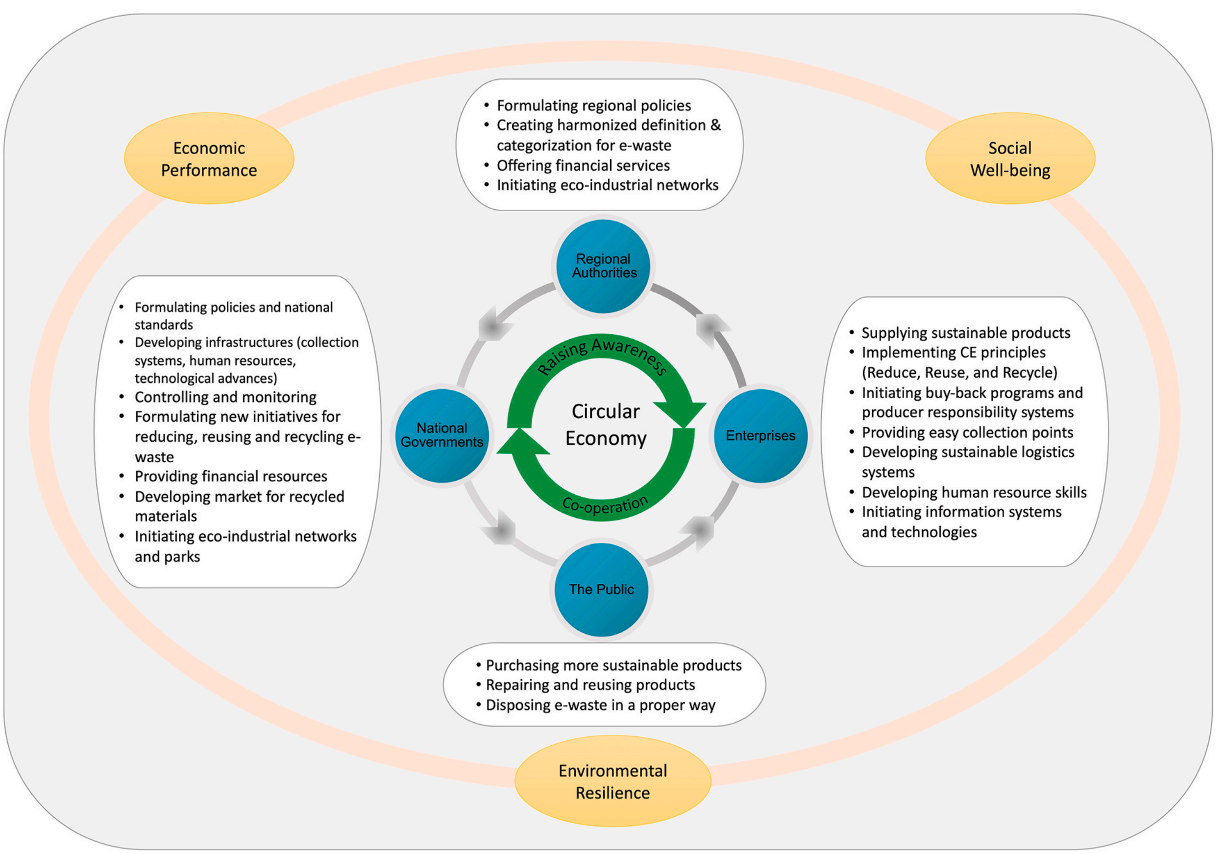

Fig. 5. The potential roles and responsibilities for different stakeholders across scales to facilitate a shift towards a CE.

role in achieving CE. It can set the stage for shifts in collective actions around e-waste, resource management, and sustainability, as well as open the floor for enterprises to invent unique e-waste management solutions for island nations. The public's interest in/support for using sustainable EEE, keeping products in use, repairing, reusing, and proper disposing can unlock the value of CE. However, these can be gained through effective long-term education programs and systems.

Enterprises can play a significant role in reducing the e-waste burdens, supplying high-quality products with longer lifetimes to the remote and island communities. During the interviews, the experts mentioned that people are not often getting high-quality EEE due to remoteness and high shipping costs. Therefore, the average lifetime of products might be shorter than other landmasses. The short lifetime of EEE has boosted the demand for replacement or repair; however, spare parts are available at very high costs, if at all. Products supplied in the region should be designed to fit into the CE; they need to be designed for easy disassembly, should be durable, upgradable, and be offered at reasonable costs.

Expert interviews suggest that no agent or provider currently offers buy-back services in these five islands. Most of the previous efforts to establish take-back services did not succeed because of the high financial burdens, as initiating collection channels and arrangement of reverse logistics require substantial investments. Regional alliances between stakeholders would be the solution to provide buy-back services for all EEE types to clients across the Caribbean. According to the interview findings, lightweight and small devices are usually disposed of in waste bins and mixed with organic and municipal waste. Large household appliances are often dumped illegally (Elgie et al., 2021). Thus, easy access to e-waste collection points and public awareness about the collection services would be advantageous. To enhance transparency and collaboration in the system, a comprehensive e-waste management information system should be designed and developed (e.g., in collaboration with universities or international organizations) for use by municipalities, businesses, e-waste management centers, and other organizations. To implement the required steps, developing human resource skills on circular principles, from reduce and reuse to repair and recycle, would be essential.

6. Outlook and future research

Next to the challenges associated with e-waste on islands, promising opportunities exist. E-waste can be considered a resource mine, and recycling these materials in the Caribbean can be a significant step towards an economy-wide CE. Between 2020 and 2025, more than 317 kt of valuable resources can be recovered from EoL products just on these five small islands, with an estimated economic value of US $546 million. If these islands had started recovering resources in early 2001, this value would almost triple to $1,430 million - equivalent to nearly 30% of the total GDP from mining and quarrying in the entire CARICOM, from just these five islands. While the mass of precious metals (Pd, Au, and Ag) in the e-waste is less than 1%, primarily concentrated in PCBs, this constitutes 44% of the total economic value in our sample. Considering that our sample represents only 11% of the Caribbean population, we can expect US$ 6 billion in revenue to the Caribbean e-waste industry. It is striking to note that the quantity of recoverable materials in the five cases is much larger than the annual volume generated e-waste in some European countries such as Belgium, Sweden, Austria, and Portugal. However, compared to these countries, the Caribbean lags proper strategies for recovering these resources.

Lack of governmental support is recognized as one of the main challenges of e-waste management in the Caribbean; therefore, national and regional authorities need to develop e-waste policies and legislation to deal with the growing problem of EoL products. A transformation to sustainability must also be "just", and so the transition to a CE must be fair and inclusive for workers, firms, and communities for it to be effective. Regional co-operative alliances for an industrial symbiosis or eco-industrial networks will contribute to a robust e-waste management system. These collaborations could bring several sustainability advantages by minimizing energy and raw materials intake, reducing waste, and foster sustainable relationships. Promoting awareness at all levels, governments, businesses, and the public is key to achieve success in reduce and reuse strategies. In the case of SIDS in particular, it can be argued that besides efficiency, the values of sufficiency should be recognized.

Establishing recycling programs and facilities is a small but worthwhile step for islands to meet the full potential of CE. CE can be a multifaceted solution for SIDS, advancing economic, societal, and ecosystem health. It can create new employment opportunities and help in diversifying the island economy. However, a holistic view is necessary to ensure the sustainable development of the EEE sector in SIDS. Appropriate plans are required to develop sustainability standards and support practices with low energy consumption and low emissions. Technological advances should be used as a tool to design processes that prioritize resource efficiency (e.g., water and energy). The e-waste collection and transportation systems should be planned considering the specific sustainability and economic requirements of islands. Inefficient in-country or inter-country transportation can significantly contribute to an increase in emissions and a decrease in CE's expected benefits. Therefore, further research is required to explore sustainable technologies and transportation systems in an island context.

Some limitations should be taken into account when considering the results of this study. The material composition of e-waste is highly heterogeneous and may vary in time and space; therefore, the compositions cannot be determined univocally. Moreover, the market value of the secondary resources in e-waste may vary as it depends on fluctuating market conditions, the grade of materials, and geographical locations. This study provides the basis for further cost-benefit or techno-economic analyses of EoL recycling programs on islands. In future cost-benefit analysis, the costs of neglecting health and environmental burdens arising from e-waste could be included.

This is the first study of its kind about the potential for a CE of e-waste in small islands. Regardless of the strong applicability of a CE for electronic goods, utilizing materials from e-waste, either for reuse on the island or for separation and recycling to sell to international markets, has been neglected in previous studies. The sensitivity analyses highlight that the response to the e-waste challenge must be timely to be able to convert the recovery and reuse potential into an opportunity. Each year of inaction would not only result in economic losses but also amplify environmental and health costs. However, achieving the highest level of material recovery and closing the material loop in the region can only be reached through collaborative and long-term efforts at multiple scales.

CRediT authorship contribution statement

Elham Mohammadi: Data collection, Methodology, Writing – original draft. **Simron Jit Singh:** 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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2021.128457.

References

Althaf, S., Babbitt, C.W., Chen, R., 2019. Forecasting electronic waste flows for effective circular economy planning. Resources. Conserv. Recycl. 151, 104362.
Angouria-Tsorochidou, E., Cimpan, C., Parajuly, K., 2018. Optimized collection of EoL electronic products for Circular economy: a techno-economic assessment. Procedia CIRP 69, 986–991.
Ardente, F., Mathieux, F., Recchioni, M., 2014. Recycling of electronic displays: analysis of pre-processing and potential ecodesign improvements. Resources. Conserv. Recycl. 92, 158–171.
Bakker, C., Wang, F., Huisman, J., Den Hollander, M., 2014. Products that go round: exploring product life extension through design. J. Clean. Prod. 69, 10–16.
Baldé, C.P., Forti, V., Gray, V., Kuehr, R., Stegmann, P., 2017. The Global E-Waste Monitor 2017. United Nations University. https://doi.org/10.1016/j.proci.2014.05.148.
Biganzoli, L., Falbo, A., Forte, F., Grosso, M., Rigamonti, L., 2015. Mass balance and life cycle assessment of the waste electrical and electronic equipment management system implemented in Lombardia Region (Italy). Sci. Total Environ. 524, 361–375.
Blomsma, F., Brennan, G., 2017. The emergence of circular economy: a new framing around prolonging resource productivity. J. Ind. Ecol. 21 (3), 603–614.
Borthakur, A., Govind, M., 2017. Emerging trends in consumers' E-waste disposal behaviour and awareness: a worldwide overview with special focus on India. Resour. Conserv. Recycl. 117, 102–113.
Briguglio, L., 1995. Small island developing states and their economic vulnerabilities. World Dev. 23 (9), 1615–1632.
Butler, R., 2016. The top 10 most biodiverse countries. Mongabay. https://news.mongabay.com/2016/05/top-10-biodiverse-countries/.
Camilleri-Fenech, M., Oliver-Solà, J., Farreny, R., Gabarrell, X., 2018. Where do islands put their waste? – a material flow and carbon footprint analysis of municipal waste management in the Maltese Islands. J. Clean. Prod. 195, 1609–1619. https://doi.org/10.1016/j.jclepro.2017.07.057.
Cesaro, A., Marra, A., Kuchta, K., Belgıorno, V., Hullebusch, Van, D, E., 2018. WEEE management in a circular economy perspective: an overview. Global NEST Journal 20, 743–750.
Chancerel, P., et al., 2009. "Assessment of precious metal flows during preprocessing of waste electrical and electronic equipment.". J. Ind. Ecol. 13 (5), 791–810.
Chen, J., Taylor, J.E., Wei, H.H., 2011. Toward a building occupant network agent-based model to simulate peer induced energy conservation behavior. In: Proceedings of the 2011 Winter Simulation Conference (WSC). IEEE, pp. 883–890.
Chertow, M.R., 2000. Industrial symbiosis: literature and taxonomy. Annu. Rev. Energy Environ. 25 (1), 313–337.
Chertow, M.R., Ehrenfeld, J., 2012. Organizing self-organizing systems: toward a theory of industrial symbiosis. J. Ind. Ecol. 16 (1), 13–27.
Comext, June 7, 2020. datasets. Comext. (n.d. Retrieved. https://ec.europa.eu/eurostat/web/main/data/database.
Cossu, R., Williams, L., 2015. Urban mining: concepts, terminology, challenges. Waste Management. (Oxford) 45, 1–3.
Coughlan, D., Fitzpatrick, C., McMahon, M., 2018. Repurposing end of life notebook computers from consumer WEEE as thin client computers–a hybrid end of life strategy for the Circular Economy in electronics. J. Clean. Prod. 192, 809–820.
Cucchiella, F., D'Adamo, I., Koh, S.L., Rosa, P., 2015. Recycling of WEEEs: an economic assessment of present and future e-waste streams. Renew. Sustain. Energy Rev. 51, 263–272.
Cutaia, L., Beltrani, T., Fantin, V., Mancuso, E., Sbaffoni, S., La Monica, M., 2020. Resources audit as an effective tool for the implementation of industrial symbiosis paths for the transition towards circular economy. In: Industrial Symbiosis for the Circular Economy. Springer, Cham, pp. 43–56.
De Queiroz Lamas, W., Palau, J.C.F., de Camargo, R, J., 2013. Waste materials co-processing in cement industry: ecological efficiency of waste reuse. Renew. Sustain. Energy Rev. 19, 200–207.
Debnath, B., 2020. Towards sustainable E-waste management through industrial symbiosis: a supply chain perspective. In: Industrial Symbiosis for the Circular Economy. Springer, Cham, pp. 87–102.
Deschenes, P.J., Chertow, M., 2004. An Island Approach to Industrial Ecology: Towards Sustainability in the Island Context. https://doi.org/10.1080/0964056042000209102, 47, 2, 201-217.
Dutta, T., Kim, K.H., Uchimiya, M., Kwon, E.E., Jeon, B.H., Deep, A., Yun, S.T., 2016. Global demand for rare earth resources and strategies for green mining. Environ. Res. 150, 182–190.
Eckelman, M.J., Ashton, W., Arakaki, Y., Hanaki, K., Nagashima, S., Malone-Lee, L.C., 2014. Island waste management systems: statistics, challenges, and opportunities for applied industrial ecology. J. Ind. Ecol. 18 (2), 306–317.
Eckelman, M., Chertow, M., 2009. Linking Waste and Material Flows on the Island of Oahu, Hawai'i: the Search for Sustainable Solutions. Report Number 21. Yale School of Forestry & Environmental Studies.
Eckelman, M., Chertow, M., 2013. Life cycle energy and environmental benefits of a US industrial symbiosis. Int. J. Life Cycle Assess. 18 (8), 1524–1532.
Elgie, A.R., Singh, S.J., Telesford, J.N., 2021. You can't manage what you can't measure: the potential for circularity in Grenada's waste management system. Resour. Conserv. Recycl. 164, 105170.
Ellen MacArthur Foundation (EMF), 2013. Towards the Circular Economy: Economic and Business Rationale for an Accelerated Transition. Cowes, UK.
Ellen MacArthur Foundation (EMF), 2015. Towards the circular economy: business rationale for an accelerated transition. https://www.ellenmacarthurfoundation.org/assets/downloads/TCE_Ellen-MacArthur-Foundation_9-Dec-2015.pdf.
Ellen MacArthur Foundation (EMF), 2016. Intelligent Assets: Unlocking the Circular Economy Potential.
Forti, V., Baldé, C.P., Kuehr, R., Bel, G., 2020. The Global E-Waste Monitor 2020. Quantities, Flows and the Circular Economy Potential. United Nations University (UNU), United Nations Institute for Training and Research (UNITAR), co-hosted SCYCLE Programme, International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn, Geneva, Rotterdam.
Fuldauer, L.I., Ives, M.C., Adshead, D., Thacker, S., Hall, J.W., 2019. Participatory planning of the future of waste management in small island developing states to deliver on the Sustainable Development Goals. J. Clean. Prod. 223, 147–162.
Government of Canada, June 6, 2020. Gold facts. (2021. Retrieved. https://www.nrcan.gc.ca/our-natural-resources/minerals-mining/minerals-metals-facts/gold-facts/20514.
Garg, C.P., 2021. Modeling the e-waste mitigation strategies using Grey-theory and DEMATEL framework. J. Clean. Prod. 281, 124035.
GreenCape, 2017. Waste economy - 2017 market intelligence report. GreenCape. http://www.green-cape.co.za/assets/Uploads/GreenCape-Waste-MIR-2017-electronic-FINAL-v2.pdf.
Habib, K., 2015. Critical Ressources in Clean Energy Technologies and Waste Flows.
Hahladakis, J.N., Iacovidou, E., 2019. An overview of the challenges and trade-offs in closing the loop of post-consumer plastic waste (PCPW): focus on recycling. J. Hazard Mater. 380, 120887.
Hall, J.W., Thacker, S., Ives, M.C., Cao, Y., Chaudry, M., Blainey, S.P., Oughton, E.J., 2017. Strategic analysis of the future of national infrastructure. In proceedings of the institution of civil engineers-civil engineering. Thomas Telford Ltd 170 (1), 39–47.
Herat, S., Agamuthu, P., 2012. E-waste: a problem or an opportunity? Review of issues, challenges and solutions in Asian countries. Waste Manag. Res. 30 (11), 1113–1129.
IPCC, 2014. Climate change 2014: impacts, adaptation, and vulnerability. Inter-governmental panel on climate change. Geneva. https://doi.org/10.1017/CBO9781107415379.
Islam, M.T., Huda, N., 2019. E-waste in Australia: generation estimation and untapped material recovery and revenue potential. J. Clean. Prod. 237 https://doi.org/10.1016/j.jclepro.2019.117787, 117787.
Islam, A., Ahmed, T., Awual, M.R., Rahman, A., Sultana, M., Abd Aziz, A., et al., 2020. Advances in sustainable approaches to recover metals from e-waste-A review. J. Clean. Prod. 244, 118815.
Kiddee, P., Naidu, R., Wong, M.H., 2013. Electronic waste management approaches: an overview. Waste Manag. 33 (5), 1237–1250.
Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232.
Köhler, A., Erdmann, L., 2004. Expected environmental impacts of pervasive computing. Human and Ecological Risk Assessment 10 (5), 831–852.
Korhonen, J., Honkasalo, A., Seppälä, J., 2018. Circular economy: the concept and its limitations. Ecol. Econ. 143, 37–46.
Kumar, A., Holuszko, M., Espinosa, D.C.R., 2017. E-waste: an overview on generation, collection, legislation and recycling practices. Resour. Conserv. Recycl. 122, 32–42.
London Metal Exchange, June 7, 2020. Market data. (n.d. Retrieved. https://www.lme.com/Market-Data.
Luhar, S., Luhar, I., 2019. Potential application of E-wastes in construction industry: a review. Construct. Build. Mater. 203, 222–240. https://doi.org/10.1016/j.conbuildmat.2019.01.080.
Magalini, F., Wang, F., Huisman, J., Kuehr, R., Baldé, K., Straalen, V., Hestin, M., Lecerf, L., Sayman, U., Akpulat, O., 2015. Study on WEEE Recovery Targets, Preparation for Re-use Targets and on the Method for Calculation of the Recovery Targets. EU Commission.
Malinauskaite, J., Erdem, F.B., 2021. Planned obsolescence in the context of a holistic legal sphere and the circular economy. Oxf. J. Leg. Stud.
Millette, S., Williams, E., Hull, C.E., 2019. Materials flow analysis in support of circular economy development: plastics in Trinidad and Tobago. Resources. Conserv. Recycl. 150, 104436.
Mohammadi, E., Singh, S.J., Habib, K., 2021. Electronic waste in the Caribbean: an impending environmental disaster or an opportunity for a circular economy?. Resources. Conserv. Recycl. 164, 105106.
Mohee, R., Mauthoor, S., Bundhoo, Z.M.A., Somaroo, G., Soobhany, N., Gunasee, S., 2015. Current status of solid waste management in small island developing states: a review. Waste Manag. 43, 539–549. https://doi.org/10.1016/j.wasman.2015.06.012.
Noll, D., Wiedenhofer, D., Miatto, A., Singh, S.J., 2019. The expansion of the built environment, waste generation and EU recycling targets on Samothraki, Greece: an island's dilemma. Resources, Conservation and Recycling, 150(July 2019) 104405. https://doi.org/10.1016/j.resconrec.2019.104405.
Nowakowski, P., Mrówczyńska, B., 2018. Towards sustainable WEEE collection and transportation methods in circular economy-Comparative study for rural and urban settlements. Resources. Conserv. Recycl. 135, 93–107.
OECD, 2001. Extended Producer Responsibility: A Guidance Manual for Governments. OECD, Paris, France.
Oguchi, M., Murakami, S., Sakanakura, H., Kida, A., Kameya, T., 2011. A preliminary categorization of end-of-life electrical and electronic equipment as secondary metal resources. Waste Manag. 31 (9–10), 2150–2160.
Ongondo, F.O., Williams, I.D., Cherrett, T.J., 2011. How are WEEE doing? A global review of the management of electrical and electronic wastes. Waste Manag. 31 (4), 714–730.
Ottoni, M., Dias, P., Xavier, L.H., 2020. A circular approach to the e-waste valorization through urban mining in Rio de Janeiro, Brazil. J. Clean. Prod. 261, 120990.
Parajuly, K., Wenzel, H., 2017. Potential for circular economy in household WEEE management. J. Clean. Prod. 151, 272–285.

Parajuly, K., Habib, K., Liu, G., 2017. Waste electrical and electronic equipment (WEEE) in Denmark: flows, quantities and management. Resources. Conserv. Recycl. 123, 85–92.

Parajuly, K., Habib, K., Cimpan, C., Liu, G., Wenzel, H., 2016. End-of-life resource recovery from emerging electronic products–A case study of robotic vacuum cleaners. J. Clean. Prod. 137, 652–666.

Pereira, N., 2019. Enviroserve launches world's largest e-waste plant in Dubai Industrial Park. https://www.arabianindustry.com/construction/news/2019/mar/21/enviroserve-launches-worlds-largest-e-waste-plant-in-dip-6056986/.

Preston, F., 2012. A Global Redesign? Shaping the Circular Economy.

Rahman, A., Rasul, M.G., Khan, M.M.K., Sharma, S., 2013. Impact of alternative fuels on the cement manufacturing plant performance: an overview. Procedia Engineering 56, 393–400.

Rahman, A., Rasul, M.G., Khan, M.M.K., Sharma, S., 2015. Recent development on the uses of alternative fuels in cement manufacturing process. Fuel 145, 84–99.

Reike, D., Vermeulen, W.J., Witjes, S., 2018. The circular economy: new or refurbished as CE 3.0? exploring controversies in the conceptualization of the circular economy through a focus on history and resource value retention options. Resources,. Conserv. Recycl. 135, 246–264.

Saget, C., Vogt-Schilb, A., Luu, T., 2020. Jobs in a Net-Zero Emissions Future in Latin America and the Caribbean. Inter-American Development Bank and International Labour Organization. Washington D.C. and Geneva.

Saito, O., 2013. Resource use and waste generation by the tourism industry on the big island of Hawaii. J. Ind. Ecol. 17 (4), 578–589.

Sauvé, S., Bernard, S., Sloan, P., 2016. Environmental sciences, sustainable development and circular economy: alternative concepts for trans-disciplinary research. Environmental Development 17, 48–56.

Schaffartzik, A., Mayer, A., Gingrich, S., Eisenmenger, N., Loy, C., Krausmann, F., 2014. The global metabolic transition: regional patterns and trends of global material flows, 1950–2010. Global Environ. Change 26, 87–97.

Shah, K.U., Niles, K., Ali, S.H., Surroop, D., Jaggeshar, D., 2019. Plastics waste metabolism in a Petro-Island state: towards solving a "wicked problem" in Trinidad and Tobago. Sustainability (Switzerland) 11 (23). https://doi.org/10.3390/su11236580.

Shittu, O.S., Williams, I.D., Shaw, P.J., 2020. Global E-waste management: can WEEE make a difference? A review of e-waste trends, legislation, contemporary issues and future challenges. Waste Manag.

Simpson, M.C., 2012. The Caribsave Climate Change Risk Atlas and Climate Change Risk Profile for Saint Lucia. Technical Report. Caribsave, Saint Lucia.

Skordilis, A., 2004. Modelling of integrated solid waste management systems in an island. Resources. Conserv. Recycl. 41 (3), 243–254.

Song, Q., Wang, Z., Li, J., Zeng, X., 2012. Life cycle assessment of TV sets in China: a case study of the impacts of CRT monitors. Waste Manag. 32 (10), 1926–1936.

Stahel, W., 1981. Jobs for Tomorrow: the Potential for Substituting Manpower for Energy. Vantage Press, New York.

Tansel, B., 2017. From electronic consumer products to e-wastes: global outlook, waste quantities, recycling challenges. Environ. Int. 98, 35–45.

Telesford, J.N., 2020. Strategic Sustainability and Industrial Ecology in an Island Context, with Considerations for a Green Economy Roadmap: a Study in the Tourist Accommodation Sector, Grenada (Doctoral dissertation).

The World Bank, 2019. Global population data. Retrieved from. https://data.worldbank.org/. (Accessed 7 January 2020).

UN-OHRLLS, 2015. Small island developing states in numbers: climate change edition 2015. Retrieved from. http://unohrlls.org/custom-content/uploads/2015/12/SIDS-IN-NUMBERS-CLIMATE-CHANGE-EDITION_2015.pdf.

United Nations Environment Programme (UNEP), 2008. Climate Change in the Caribbean and the Challenge of Adaptation. United Nations Environment Programme Regional Office for Latin America and the Caribbean. Technical Report, Panama City, Panama.

United Nations Environment Programme (UNEP), 2019. Small island developing states waste management outlook. Nairobi. https://wedocs.unep.org/handle/20.500.11822/27683.

Van Buren, N., Demmers, M., Van der Heijden, R., Witlox, F., 2016. Towards a circular economy: the role of Dutch logistics industries and governments. Sustainability 8 (7), 647.

Wang, X., Gaustad, G., 2012. Prioritizing material recovery for end-of-life printed circuit boards. Waste Manag. 32 (10), 1903–1913.

Widmer, R., Oswald-Krapf, H., Sinha-Khetriwal, D., Schnellmann, M., Böni, H., 2005. Global perspectives on e-waste. Environ. Impact Assess. Rev. 25 (5), 436–458.

Winans, K., Kendall, A., Deng, H., 2017. The history and current applications of the circular economy concept. Renew. Sustain. Energy Rev. 68, 825–833.

Ylä-Mella, J., Keiski, R.L., Pongrácz, E., 2015. Electronic waste recovery in Finland: consumers' perceptions towards recycling and re-use of mobile phones. Waste Manag. 45, 374–384.

Zlamparet, G.I., Ijomah, W., Miao, Y., Awasthi, A.K., Zeng, X., Li, J., 2017. Remanufacturing strategies: a solution for WEEE problem. J. Clean. Prod. 149, 126–136.