Original Article

WM&R

Waste Management & Research
2023, Vol. 41(10) 1539–1548

DOI: 10.1177/0734242X231165242
journals.sagepub.com/home/wmr
SAGE

Towards the definition of WEEE recycling targets in Ecuador. A case of study for mobile phones

Iván Vidal[1], Gabriela Sucozhañay[1], Melanie Haupt[2] and Paúl Vanegas[1,3]

Abstract

The rise of consumption patterns of electrical and electronic equipment (EEE) and the generation of waste EEE (WEEE) has been strongly increasing globally. Recycling rates (RRs) are one of the main indicators for monitoring the progress towards a circular economy and establishing recovery and treatment schemes. For this reason, this study discusses the setting of recycling targets for WEEE in Ecuador, using mobile phones as a case study. Firstly, the generation of mobile phone waste from 2012 to 2018 is estimated based on literature review. The most appropriate model for estimating WEEE generation is selected according to the applicable market conditions, input requirements and available data. Then, the composition of a mobile phone is determined through an extensive literature review. Based on these results, the materials' environmental impact and potential economic value are approximated using the ReCiPe Endpoint (H, A) method and the prices of virgin materials, respectively. The estimation shows that in Ecuador an average of 2 million devices are discarded every year, which represents an interesting source of resources but currently does not have appropriate management. Ecuador has implemented regulatory frameworks in favour of the integral management of these wastes. However, mass-based collection targets still appear to be the only available measure. Therefore, national results on electronics recycling do not allow adequate monitoring of progress towards a circular economy and largely neglect environmental aspects and economic potential.

Keywords

Collection rates, recycling rates, WEEE management, mobile phones, circular economy

Received 3rd October 2022, accepted 14th February 2023 by Associate Editor Mario Grosso.

Introduction

The modern lifestyle has been strongly influenced by the introduction of electrical and electronic equipment (EEE). These devices have changed the way humans interact, communicate, entertain and learn (Nnorom and Osibanjo, 2009). However, the massive consumption of these devices, the rapid technological advances and their accelerated obsolescence rate have generated an alarming growth in its waste flows (waste EEE (WEEE); LeBel, 2016; Richter, 2016). According to the E-waste monitor, approximately 53.6 million metric tonnes (Mt) of WEEE were generated in 2019. This amount is expected to exceed 74 Mt in 2030, since the global quantity of discarded devices is increasing at an alarming rate of almost 2 Mt per year (Forti et al., 2020).

WEEE is a potential source of valuable materials as its composition includes base and precious metals. Nevertheless, several components have hazardous and toxic substances that pose a risk to the environment and human health when are inadequately managed (Cesaro et al., 2019). Enabling the development of an effective WEEE management system requires knowing its composition, the total number of devices discarded over time, as well as to identify its disposal pathways (Kosai et al., 2020; Kumar et al., 2017). Establishing a solid knowledge basis on waste flows further enables setting collection, recovery and recycling targets that increase the contribution of waste management to the circular economy (Ott, 2008). The European Community, through the WEEE Directive, has been leading the WEEE management worldwide for years, establishing technical indicators to monitor the efficiency of Member States' management systems (Cucchiella et al., 2015; European Commission, 2015a). The most common indicators used for this purpose include material flow-based indicators such as collection rate (CR) and

[1]Space and Population Department, University of Cuenca, Cuenca, Ecuador
[2]Chair for Ecological Systems Design, Institute of Environmental Engineering (IfU), Zurich, Switzerland
[3]Faculty of Chemical Sciences, University of Cuenca, Cuenca, Ecuador

Corresponding author:
Paúl Vanegas, Faculty of Chemical Sciences, University of Cuenca, Avenue 12 de Abril, Cuenca 010203, Ecuador.
Email: paul.vanegas@ucuenca.edu.ec

recycling rate (RR), which are often not clearly defined and may lead to some confusion. CRs denote the ratio between the mass of material collected and the material initially consumed, which only reflects the input of materials into recycling systems and not the secondary material produced. RRs can be divided into intermediate RRs, which reflect the ratio of mass of sorted material to the material initially consumed, and final RRs, which represent the ratio of the mass in secondary products to the material initially consumed (Haupt et al., 2017). RRs are a frequently used measure to evidence the degree of resource use efficiency and circularity progress (Horta Arduin et al., 2020). However, RR statistics usually report CRs instead, so the assessment of recycling targets in relation to their environmental and economic consequences is not properly reflected (Haupt et al., 2017).

Within the European Union (EU), the action plan for the circular economy includes the objective of a harmonized definition of RRs based on the last recycling step inputs, which is defined as the mass that enters the final recycling process divided by the mass of material consumed in a country (European Commission, 2015a). Although this is an improvement over tracking for CRs alone, only final RRs consider both material quality and quantity losses throughout the recycling chain.

In Ecuador, no WEEE recycling targets have been formulated, and the development of collection targets has been scarce. In 2013, the national post-consumer WEEE policy was presented, which established post-consumer guidelines regarding the management of disused EEE within the framework of the application of the principle of extended responsibility and the active participation of the state and the population (Ministerio del Ambiente, 2013a). As a result, the first collection target in the country's history was established for WEEE, specifically for mobile phones, at 3% (Ministerio del Ambiente, 2013b). This target was complemented by an incentive in the import quota, which encouraged the interest of importers, exceeding the collection targets until 2016, when the incentive was eliminated and a significant reduction in the number of units collected was observed (Ministerio del Ambiente, 2018). Then, in 2018, the United Nations Industrial Development Organization presented, through the Global Environment Facility, the 'Electronic Waste Project in Latin America' (PREAL). It is an initiative that involves 13 countries, including Ecuador, that seeks to strengthen and harmonize key aspects of public policies related to WEEE management and establish regional cooperation and knowledge exchange. At the national level, the project supports the implementation of policies and training of technical staff and government officials (Proyecto PREAL, 2018). Within this framework, in 2022 the Ministry of Environment, Water and Ecological Transition of Ecuador presented the 'Instructive for the application of the extended responsibility in the integral management of Waste Electrical and Electronic Equipment of domestic origin', which proposed an initial collection target for WEEE of 0.5% and kept mobile phone collection targets at 3% (Ministerio del Ambiente Agua y Transición Ecológica, 2022a, 2022b). This supposes a first attempt to articulate and regulate importers, assemblers and manufacturers to encourage the development of a WEEE management system and a national WEEE policy for the country. However, a better comprehension of the system is needed, and other aspects such as technical recycling capacity, environmental impact or potential economic revenues should be taking into account when establishing collection targets. Likewise, this ministry agreement contemplates the training of more than 50,000 base recyclers for the subsequent commercialization of the materials obtained from these waste streams, as currently the informal sector represents most of the workforce of the WEEE management chain, and its work is not recognized by the government or society. In addition to WEEE, some other related regulations have been proposed, such as the law of inclusive circular economy, which promotes the sustainable management of waste and supports the transition to a circular economy and the incorporation of vulnerable groups (Asamblea Nacional, 2021).

This study discusses the setting of recycling targets for WEEE, according to four key factors: waste generation, waste composition, potential economic value and environmental impact. For waste generation, a case of study of mobile phones is used, and a simplified model for WEEE estimation is selected based on applicable market conditions, input requirements and previous identified available data in Ecuador. Then, mobile phones composition is determined by a literature review. Finally, the potential economic value is calculated using virgin material prices, and the environmental impact is approximated by the ReCiPe Endpoint (H, A) method.

Materials and methods

Mobile phone waste estimation

There are many different methods available in literature for estimating WEEE generation, which vary depending on the applicable market conditions and input requirements. Input–output analysis (IOA), which describes the relations and dynamics among product sales, stocks and lifespans is the most frequently used (Araújo et al., 2012). Many variations of IOA have been conducted, such as market supply, consumption and use or time step (Araújo et al., 2012) (Li et al., 2015; Wang et al., 2013). A detailed description of these models is presented in Table 1.

These models were compared based on their applicable market conditions and input requirements. Most of them can be applied to both saturated and dynamic markets and use sales and a constant lifespan. Since waste flows emerge slowly as a consequence of both wear and technological obsolescence as well as early failure of recently sold appliances (Peeters et al., 2017), using a constant lifespan cannot properly forecast its generation. In order to make the WEEE estimation more accurate and considering the official data available in Ecuador, the methodology presented here is based on the Stock and Lifespan model. It combines time-series stock data with lifespan distributions to estimate waste flows (Müller et al., 2009).

Available data in Ecuador. Mobile phone data in Ecuador is scarce and often inconsistent. There is no national production of mobile phones. The entry of these devices into the country is

Table 1. Description of relevant methods in literature for WEEE estimation.

Method name	Description	Equation		Applicable market conditions[1]		Input requirements						References
						Stock[2]		Sales[2]		Lifespan[3]		
				S	D	D	C	D	C	A	D	
Time step	WEEE equals sales minus the difference between stocks in the last two consecutive years.	$WEEE(t) = S(t) - St(t) - St(t-1)$ $S(t) = I(t) + P(t) - E(t)$	- $S(t)$ = sales - $St(t)$ = stock - $I(t)$ = importations - $P(t)$ = production - $E(t)$ = exportations.	X	X		X	X				Yu et al. (2010b), Araújo et al. (2012), Lau et al. (2013), Wang et al. (2013), Oguchi et al. (2008), United Nations Environment Programme, (2007)
Consumption and use	WEEE is estimated by dividing the stock in an evaluation year t by the average lifespan.	$WEEE(t) = \frac{H(t)Nh(t)W}{L}$	- $H(t)$ = number of households - $Nh(t)$ = saturation level per household - W = average weight of EEE (tons) - L = average lifespan (years).	X		X				X		Widmer et al. (2005), Araújo et al. (2012), Lau et al. (2013), Schluep et al., (2012)
Distribution Delay (Market supply)	WEEE generation is estimated by multiplying product sales in all historical years with their respective obsolescence rates in evaluation year.	$WEEE(t) = \sum_{n=no}^{t} S(n) f(n,t)$	- $S(n)$ = product sales in year n - $f(n,t)$ = obsolescence probability in year t for a product sold in year n.	X	X				X		X	Polák and Drápalová (2012), Yang and Xu (2008), Melo (1999), Tasaki et al. (2004), Peeters et al., (2017)
Simple Delay (Market supply)	WEEE generation in a year t is equal to sales in year t minus sales in year $t-L$ (t minus average lifespan.)	$WEEE(t) = S(t - L)$	- $S(t)$ = sales - L = average lifespan (years)	X				X		X		Lau et al. (2013), Wang et al. (2013), United Nations Environment Programme (2007), Van der Voet et al., (2002)
Mass balance/ Carnegie Mellon (Market supply)	WEEE generation estimated based on number of sales, reused and stored EEE and their respective average lifespans.	$WEEE(t) = S(t - L) + R(t - Lr)$ $+ Sr(t - Ls)$	- $S(t-L)$ = sold quantities - $R(t-Lr)$ = reused quantity - $Sr(t-Ls)$ = stored quantity - L = average lifespan (years) - Lr = average lifespan of reuse (years) - Ls = average time of storage (years)	X	X				X	X		Kang and Schoenung (2006), Peralta and Fontanos (2006), Dwivedy and Mittal (2010), Steubing et al., (2010)
Leaching model	WEEE generation is estimated as a fixed percentage of the total stock divided by the average product lifespan.	$WEEE(t) = St(t) / L$	- $St(t)$ = stock - L = average lifespan (years)	X			X			X		Araújo et al. (2012), Robinson (2009), Chung (2012), Van der Voet et al., (2002)
Stock and Lifespan	WEEE is estimated by combining time-series stock data with lifespan distributions of products.	$WEEE(t) = \sum_{t=to}^{n} St(t) L(p)(t,n)$	- $St(t)$ = stock - $L(p)(t,n)$ = Probability that a product acquired in year t will become waste in year n.	X	X		X				X	Zhang et al. (2011), Müller et al. (2009), Walk, (2009)

[1] S = Saturated and D = Dynamic on Applicable Market Conditions.
[2] D = Discrete and C = Continuous on Stock and Sales.
[3] A = Average and D = Distribution on Lifespan.

Table 2. Imports and exports of mobile phones in Ecuador from 2011 to 2017 (Senae, 2018).

Year	Importations (units)	Exportations (units)	Total (units)
2011	3,156,928	35,346	3,121,582
2012	1,940,109	9172	1,930,937
2013	2,103,003	29,160	2,073,843
2014	2,227,279	47,861	2,179,418
2015	2,071,735	4317	2,067,418
2016	1,266,702	904	1,265,798
2017	2,052,998	2950	2,050,048

done through imports registered by the national customs service and through unauthorized channels or contraband, of which no national entity keeps a registry. The main official sources of information are described as follow:

- Telecommunications Regulatory and Control Agency (ARCOTEL): It provides data about the number of active phone lines in Ecuador. However, this information does not differentiate between old, not disabled lines and active lines and does not contain information on people using two lines on the same device so translating this data into telephone units would be unreliable.
- National Institute of Statistics and Census (INEC): It presents data about mobile phone users, which are presented in the National Survey of Employment, Unemployment and Underemployment in the Information and Communication Technologies (TIC) section. Nonetheless, this information represents only the number of mobile phone users instead of the number of devices.
- Ecuadorian National Customs Service (SENAE): It provides information about imports and exports of mobile phones using the Common Tariff Nomenclature of the Andean Community (NANDINA). However, they do not have registers of illegal contraband mobile phones.

Stock. Official data presented by Ecuadorian National Customs Service was used to determine the stock. Imports and exports (assembled and exported units) were considered to calculate the consumption of devices from 2011 to 2017 as presented in equation (1). The total amount of incoming devices is presented in Table 2.

$$T_t = I_t - E_t \quad (1)$$

where T_t is the consumption in time t. I_t is the national importations in time t and E_t is the national exportations in time t.

It is important to mention that a considerable number of mobile phones enters the national market through smuggling. However, there is no available statistics about smuggling activities; therefore, illegally imported devices cannot be considered in this study.

Lifespan. The establishment of a product's lifespan is complex as it is influenced by the lifestyle and consumption habits of the evaluated population. Some smartphone manufacturers, such as Apple or HTC, indicate in their environmental reports a lifespan of 3 years for their devices (Apple, 2014; HTC, 2013), which is the same as the average time found in the literature (Duygan and Meylan, 2015; Suckling and Lee, 2015). In Ecuador, no formal studies have been found that determine the useful life of mobile phones, although some interviews, blogs and informal reports (grey literature) mention useful lives for mobile phones between 2 and 3 years. On the other hand, in some Latin American realities, similar in market trends and cultural aspects related to consumer usage habits, such as Colombia, it is suggested that the average life of these devices is 3 years (Ott, 2008). The Weibull function is the most used to represent lifespan distributions of EEE, as it has been proved to produce the best fit of lifespan (Davis et al., 2007; Müller et al., 2007; Terazono et al., 2006; Walk, 2009). However, it requires specific shape and scale parameters, which are not available for Ecuador in literature. This article, therefore, uses a normal distribution to represent the lifespan of mobile phones, considering an average lifespan of 3 years with a standard deviation of 1.25 years. The probability density function covers 99% of the inputs after 6 years. Since the waste generation of each year is composed of the entries of the previous 6 years – to calculate the number of mobile phones that were discarded from 2012 to 2016 – it is necessary to know the total number of devices that entered the market from 2006 to 2010. Due to the lack of official information, these entries were approximated using the average of known quantities from 2012, 2013, 2014, 2015 and 2017. The 2011 and 2016 quantities, being the highest and lowest respectively, were excluded as outliers.

Multidimensional assessment

This section aims to describe the composition of mobile phones and estimate the environmental impact and potential economic value of the materials, allowing a comparison of recycling targets according to mass and environmental impact or economic value. Although the composition of mobile phones varies according to product age, design and manufacturer, all phones have the same general structure, which includes housing, display, keypad (not on smartphones), printed wiring board (PWB) and battery (Yu et al., 2010a). In Ecuador, no formal studies have been conducted to determine the composition of mobile phones. In this study, four main smartphone components were considered: display, PWB, housing and battery, and their composition was estimated

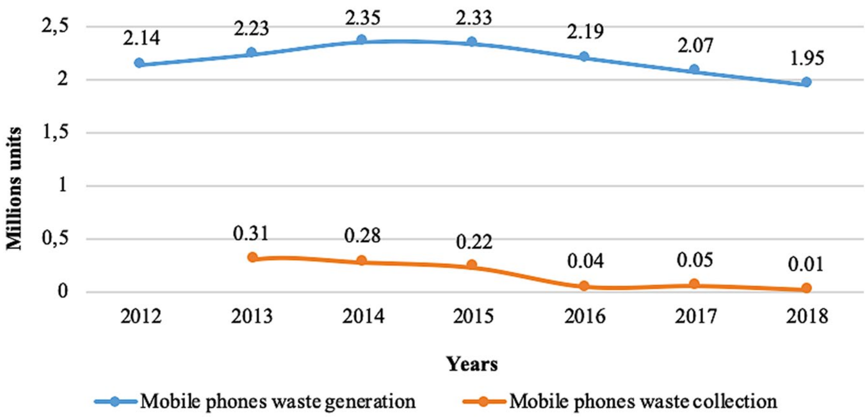

Figure 1. Mobile phones waste generation and end-of-life phone collection from 2012 to 2018.

based on a literature review. Then, virgin material prices were used to estimate its potential economic value. Finally, the environmental impact was calculated using the ReCiPe Endpoint (H, A) method based on the 3.6 Ecoinvent database (cut-off system model). It is important to mention that in this study, impacts associated with the manufacture of the components or the use of the device are not estimated since the analyses proposed are only related to the potential impact and recovery of the materials.

Results

Mobile phone waste estimation

The obtained estimation curve of mobile phones waste is presented in Figure 1. It shows that on average 2 million mobile phones were discarded annually in Ecuador between 2012 and 2018. However, according to official data from the Ecuadorian environmental ministry, only 916,002 units, less than 7%, were collected during the same period (Ministerio del Ambiente, 2018). CRs varied between 13% in 2013 and below 1% in 2018. These results represent a first approximation of the mobile phone waste generation in the Ecuadorian reality.

Multidimensional assessment

The results of the literature review show that a mobile phone is made of roughly 40 elements, with a total environmental impact of 651 millipoints (mPts) (ReCiPe 2016) and potential economic revenue of $2.35. Although the PWB contributes 30% to the overall mass, it is responsible for 70% and 59% of its environmental impact and economic value, respectively. A summary of these results is presented in Table 3.

The multidimensional assessment is presented in Figure 2, which depicts the elements within a mobile phone according to its mass proportion (sphere size), environmental impact (*x*-axis) and potential economic value (*y*-axis). It highlights that fractions with high mass shares do not necessarily represent the major environmental impact and economic value within a smartphone.

Recycling rates. A simplified scheme of a WEEE management system is presented in Figure 3, which shows the differences between CR and RR in measuring material ratios.

Boxes indicate the main processes through a simplified WEEE management system. o represents disposal channels different to separate collection, l_1 indicates removed impurities and yield losses, whereas l_2 and l_3 represent material losses due to recycling treatment efficiencies. The dotted line represents the system boundaries for CR, and the dashed line indicates the system boundaries of the RR.

Based on this scheme and for practical purposes, a mass-based RR scenario of 40% with the following assumptions is discussed. Firstly, a CR of 70% and an average pre-processing and end processing efficiency of 57% for all materials are assumed. Secondly, all devices are considered to enter the system in one piece. Thirdly, 60% is used as a maximum recyclable mass percentage per mobile phone unit due to the presence of non-valuable elements and non-recyclable fractions.

The proposed mass-based RR could be achieved by recycling the mass-wise dominating materials of mobile phones (Al, Fe, Cu, Co, Cr, Ni and ABS). However, this mass-based strategy fostered by current RR targets would only allow for a recovery of 18% of the potential economic value and avoids 13% of the environmental impact, since precious metals such as Au or Ag, which have the highest economic value and environmental impact, are found in minimal fractions and would not be recovered (see the details in Table 4).

The elements shown are those with the highest mass fractions. The mass-based target proposed in this scenario can be achieved by recycling these materials. However, the elements with the highest potential economic value and environmental impact are not recovered since they are found in minimal fractions.

Discussion

This study highlights the importance of different factors when establishing recycling targets. In this sense, knowing the generation of WEEE as well as its composition, environmental impact and economic value constitutes the starting point for the

Table 3. Multidimensional assessment of a mobile phone unit.

Component	Element	Mass (g)	Environmental impact (mPts)	Economic value ($)
Screen	Al	2.67	3.31	0.006
	In	0.01	2.18	0.002
	K	0.33	0.22	0.0001
	Si	8.12	65.95	0.0135
	Sn	0.29	29.38	0.0057
Battery	Al	2	2.48	0.004
	C	19.85	0.17	0.022
	Co	6.59	51.83	0.501
	Li	0.87	4.50	0.017
PWB	Ag	0.34	61.25	0.177
	Al	0.47	0.58	0.001
	As	0.01	n/a	0.00002
	Au	0.014	189.63	0.566
	B	0.44	0.82	0.0003
	Bi	0.02	n/a	0.0003
	Ca	0.44	0.19	0.002
	Cl	0.01	n/a	0.000011
	Cr	4.94	21.69	0.014
	Cu	7.84	41.11	0.052
	Dy	0.001	n/a	0.0002
	Fe	18.63	11.74	0.0013
	Ga	0.01	0.16	0.003
	Mg	0.65	2.13	0.001
	Mn	0.29	2.59	0.001
	Mo	0.02	2.26	0.00052
	Nd	0.135	n/a	0.0078
	Ni	2.72	17.71	0.038
	P	0.03	n/a	0.000003
	Pb	0.04	0.10	0.0001
	Pd	0.015	61.01	0.458
	Pr	0.036	n/a	0.0044
	S	0.44	0.03	0.000044
	Sb	0.033	0.32	0.029
	Si	0.0135	0.11	0.0033
	Sn	0.37	37.48	0.007
	Ta	0.02	0.83	0.0037
	Ti	0.3	1.02	0.0015
	V	0.04	n/a	0.0014
	W	0.02	n/a	0.0006
	Zn	0.69	3.697	0.002
Casing	Al	26	32.222	0.055
	Plastic (ABS)	5	2.580	0.35

The environmental impacts are presented in terms of millipoints (mPts) using the ReCiPe method (ReCiPe H/A, total impact 2016) and the database Ecoinvent v3.6. ABS: Acrylonitrile Butadiene Styrene.

proper establishment of these targets. In Ecuador, available information on WEEE generation is scarce, and official databases do not provide the required information for the application of estimation models. Hence, one of the contributions of this study is the adaptation of an estimation model using the information available in the country. This first estimation of mobile phone waste generation provides essential data for establishing a waste management system. The results show that, on average, 2 million mobile phones were discarded annually in Ecuador between 2012 and 2018. According to official data from the Ministry of Environment, less than 7% of the total was collected in the same period, evidencing the absence of an efficient management system and an insignificant CR.

Not more than a couple of decades ago, WEEE management was not a priority in Ecuador. In fact, it is still considered an unknown and relatively new waste flow for many of the stakeholders involved in the value chain (CRBAS, 2020). Despite this, it is notorious that in recent years, WEEE management has positioned itself in the country's political and public agenda. In 2022, the 'Regulation for the implementation of extended responsibility in the integrated management of Waste Electrical and Electronic Equipment of domestic origin' was published, representing a starting point for establishing an integrated WEEE management system in the country (Ministerio del Ambiente, 2022a, 2022b). Today, Ecuador is one of the few countries in the region with specific regulations for WEEE, along with Colombia, Mexico, Costa Rica, Brazil, Chile and Peru (Wagner et al., 2022).

A significant milestone of the regulation mentioned above was the establishment of symbolic collection targets amounting to 3% for mobile phones and 0.5% for other EEE placed on the market (Ministerio del Ambiente, 2022a, 2022b). As mentioned in the regional monitoring of electronic waste, in practice, both legal and infrastructure development can be reported through monitoring indicators that provide an overview of the state of WEEE management in a country. More than 97% of electronic waste in Latin America is neither collected nor delivered to authorized facilities. CRs are considered and indicator of progress in WEEE management, which is still in its initial stages. According to the recommendations presented in the report, they should be progressively increased (Wagner et al., 2022). However, as already presented in this study, mass-based targets could lead to poor environmental and economic performance, as materials with bigger fractions do not necessarily reflect these aspects. It is, therefore, recommended to consider environmental and economic sustainability when defining recycling targets in order to make them more meaningful. Recycling targets based on the avoided environmental impact or economic value retention rather than on mass could allow the recovery of fractions such as Au, Sn, Pd or Ag, in addition to mass-dominating fractions such as Al or Fe and are a step towards the circular economy.

Nevertheless, how to reach environmentally and economically meaningful recycling targets in Ecuador continues to be a challenge. In general, recycling practices differ substantially between developed and developing countries. Typically, mechanical size reduction and automatic separation for pre-processing and high-tech refining processes in final processing are the predominant techniques for WEEE management in developed countries (Peeters et al., 2013). Under this scheme, RRs are higher (Manhart, 2011). On the other hand, in developing countries, most treatments consist of manual dismantling followed by inefficient refining techniques due to the limited availability of

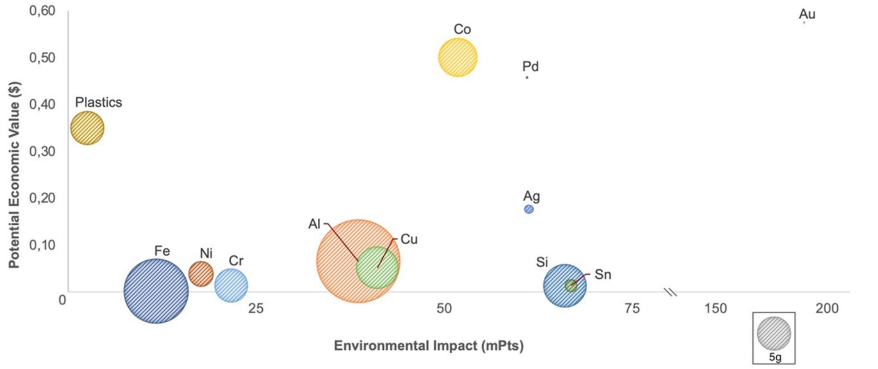

Figure 2. Multidimensional assessment of a mobile phone unit.

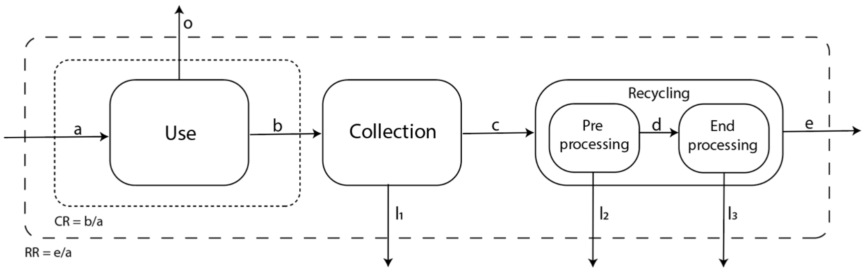

Figure 3. CR and RR differences in measuring material ratios.
Source: Figure adapted from Haupt et al. (2017).

Table 4. Mass-based proposed RR scenario.

Collection rate		Pre-processing and end processing efficiency	RR
70%		57%	40%
Mass-based target (g)		Environmental impact (mPts)	Economic value ($)
Al	12.42	15.40	0.03
Co	2.63	20.68	0.20
Cr	1.97	8.65	0.01
Cu	3.13	16.40	0.02
Fe	7.43	4.68	0.00
Ni	1.09	7.07	0.02
Plastic (Abs)	2.00	1.03	0.14

infrastructure, technological access and investment (Wang, 2014). Specifically in Ecuador, WEEE management starts with collection at the municipal level, mainly by the informal sector (base recyclers and scrap dealers). After collection, the valuable parts are manually disassembled and sold to intermediaries, who sell them to recycling companies. Within these companies, valuable components, such as printed circuit boards, are extracted and exported to international companies, and the non-valuable materials are disposed through unknown channels.

In order to create a sustainable scenario for WEEE management in developing countries, the Solving the E-waste Problem (StEP) Initiative proposed the Best-of-2-Worlds philosophy. It provides a pragmatic solution by creating a cooperation network, which integrates local pre-processing in developing countries, where mobile phones waste can be manually dismantled and some low technical requirement materials can be obtained, with end-processing of complex and hazardous fractions in developed countries where state-of-the-art technology is available. This scheme has proved to be environmentally and economically favourable (Wang et al., 2012).

To achieve WEEE management objectives, regional cooperation schemes, where countries lacking technical capacities join together to strengthen management systems, could be very helpful. In this context, the PREAL project assists 13 Latin American countries, both technically and financially. At the regional level, the project seeks to harmonize critical aspects of WEEE policies and to strengthen regional cooperation and knowledge sharing by promoting policies that will enable optimal recycling and utilization of recycled materials, the generation of decent jobs and employment opportunities (Wagner et al., 2022).

Finally, even though the establishment of recycling schemes supposes a substantial step towards the development of WEEE management systems in developing countries, other value retention strategies such as reuse, repair or refurbish need to be deeply explored. These circular economy strategies should coexist in order to maximize environmental, economic and social benefits (Achillas et al., 2010).

Since there is a significant potential for reuse of WEEE (Bovea et al., 2016; Parajuly and Wenzel, 2017), the setting of separate targets could suppose opportunities for resource savings and job creation. Considering the local scenario, where reuse practices and second-hand markets are widespread and there is a strong presence of the informal sector, there is a great opportunity to incorporate WEEE value retention schemes (Vanegas et al., 2014; Parajuly et al., 2017). However, there are several barriers in the establishment of reuse targets that need to be addressed, including difficulties to track flows, the costs of logistics or the lack of legislation (European Commission, 2015b; McMahon et al., 2019). In the absence of regulatory frameworks, priority is typically given to recycling practices, as they are usually the simplest and least costly, so the introduction of modest mandatory targets for producers could support the development of reuse schemes as observed on the case of Spain, the first country to set reuse goals in the EU (McMahon et al., 2019; Ministry of Agriculture, Food and Environment, 2015). In addition, assessment methods that consider environmental, economic and social aspects should be performed to provide a more comprehensive understanding on how to properly define these targets in the future.

Conclusions

This study discussed the establishment of WEEE recycling targets in Ecuador using mobile phones as a case study and based on four key factors: waste generation, waste composition, potential economic value and environmental impact. It was found that on average, 2 million devices were discarded annually in the country from 2012 to 2018, but less than 7% of this waste flow was formally collected during the same period. Although currently symbolic collection goals for WEEE exist, recycling targets are required in order to measure the management system performance and progress towards a circular economy more properly. It was found that mass-based only targets could lead to poor environmental and economic performance, since elements with the highest potential economic value and environmental impact, typically precious metals, are found in minimal fractions. Therefore, in addition to mass, it is necessary to include these aspects to establish more meaningful goals. These factors could be extended to other EEE, although the waste generation and its composition should be determined for each specific device.

Since the technological capabilities for WEEE recycling in Ecuador are limited, meeting recycling targets requires the development of schemes that can be adapted to local conditions. In this sense, the regional cooperation promoted by the PREAL project, or the international StEP Initiative, which proposed the Best-of-2-Worlds philosophy could provide a pragmatic solution to maximize the efficiency of materials recovery, while having a better environmental performance and generating higher economic income.

Finally, some of the limitations of this study include the scarcity of data for the application of more accurate WEEE estimation models. As the management of these waste flows in Ecuador is at an initial stage, only symbolic mass-based collection targets have been established, which depreciate the environmental and economic aspects. In future research, it would be important to analyse waste management schemes that facilitate the implementation of indicators that show more effectively the progress towards a circular economy. Similarly, it would be important to evaluate in greater depth the participation of the informal sector in WEEE management systems in developing countries. In this regard, the research team behind this study is carrying out the Responsible and Sustainable e-waste Management in Cuenca/Ecuador (ResCuE) project[1], with the aim of design and implement, a sustainable and replicable e-waste management system that integrates repair, reconditioning and takes into account environmental, social and economic impacts.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This research was carried out under the project 'Enhancing the Social Value of the Circular Economy in Latin-American', funded by the Flemish Interuniversity Council (VLIR), the Research Direction of the University of Cuenca (DIUC) and the Research Vice-rectorate of the University of Cuenca (VIUC), supported by the Swiss National Science Foundation (SNSF) as part of the scientific exchange of Dr Melanie Haupt.

ORCID iD

Iván Vidal https://orcid.org/0000-0002-7825-6087

Note

1. For more details visit https://www.rescue.ec

References

Achillas C, Moussiopoulos N, Karagiannidis A, et al. (2010) Promoting reuse strategies for electrical/electronic equipment. *Proceedings of Institution of Civil Engineers: Waste and Resource Management* 163: 173–182.

Apple (2014) *iPhone 6 Environmental Report*. Apple Inc.

Araújo MG, Magrini A, Mahler CF, et al. (2012) A model for estimation of potential generation of waste electrical and electronic equipment in Brazil. *Waste Management* 32: 335–342.

Asamblea Nacional (2021) Ley Orgánica de Economía Circular Inclusiva. Quito: Registro Oficial.

Bovea MD, Ibáñez-Forés V, Pérez-Belis V, et al. (2016) Potential reuse of small household waste electrical and electronic equipment: Methodology and case study. *Waste Management* 53: 204–217.

Cesaro A, Belgiorno V, Gorrasi G, et al. (2019) A relative risk assessment of the open burning of WEEE. *Environmental Science and Pollution Research* 26: 11042–11052.

Chung S-S (2012) Projection of waste quantities: The case of e-waste of the People's Republic of China. *Waste Management & Research* 30: 1130–1137.

CRBAS (2020) *Fortalecimiento de Iniciativas Nacionales y Mejora de la Cooperación Regional para la Gestión Ambientalmente racional de los COP en Residuos de Aparatos Eléctricos y Electrónicos (RAEE) en Países Latinoamericanos [WWW Document]*. Buenos Aires: CRBAS. Available at: https://bcrc-argentina.net.ar/raee-ecuador-2/# (accessed 21 Dec 22).

Cucchiella F, D'Adamo I, Lenny Koh SC, et al. (2015) Recycling of WEEEs: An economic assessment of present and future e-waste streams. *Renewable and Sustainable Energy Reviews* 51: 263–272.

Davis J, Geyer R, Ley J, et al. (2007) Time-dependent material flow analysis of iron and steel in the UK: Part 2. Scrap generation and recycling. *Resources, Conservation and Recycling* 51: 118–140.

Duygan M and Meylan G (2015) Strategic management of WEEE in Switzerland—combining material flow analysis with structural analysis. *Resources, Conservation and Recycling* 103: 98–109.

Dwivedy M and Mittal RK (2010) Estimation of future outflows of e-waste in India. *Waste Management* 30: 483–491.

European Commission (2015a) *Circular Economy Action Plan* [WWW Document]. Brussels: European Commission. Available at: https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en (accessed 21 Dec 2022).

European Commission (2015b) *Study on WEEE Recovery Targets, Preparation For Re-Use Targets And On The Method For Calculation Of The Recovery Targets Final Report*. Brussels: European Commission.

Forti V, Baldé CP, Kuehr R, et al. (2020) *Quantities, Flows, And The Circular Economy Potential The Global E-Waste Monitor 2020*. Tokyo: Global E-waste Statistics Partnership (GESP).

Haupt M, Vadenbo C and Hellweg S (2017) Do we have the right performance indicators for the circular economy?: Insight into the swiss waste management system. *Journal of Industrial Ecology* 21: 615–627.

Horta Arduin R, Mathieux F, Huisman J, et al. (2020) Novel indicators to better monitor the collection and recovery of (critical) raw materials in WEEE: Focus on screens. *Resources, Conservation and Recycling* 157: 104772.

HTC (2013) *HTC One Carbon Footprint Report*. HTC Corporation.

Kang H-Y and Schoenung JM (2006) Estimation of future outflows and infrastructure needed to recycle personal computer systems in California. *The Journal of Hazardous Materials* 137: 1165–1174.

Kosai S, Kishita Y and Yamasue E (2020) Estimation of the metal flow of WEEE in Vietnam considering lifespan transition. *Resources, Conservation & Recycling* 154: 104621.

Kumar A, Holuszko M and Espinosa DCR (2017) E-waste: An overview on generation, collection, legislation and recycling practices. *Resources, Conservation & Recycling* 122: 32–42.

Lau WK-Y, Chung S-S and Zhang C (2013) A material flow analysis on current electrical and electronic waste disposal from Hong Kong households. *Waste Management* 33: 714–721.

LeBel S (2016) Fast machines, slow violence: ICTs, planned obsolescence, and E-waste. *Globalizations* 13: 300–309.

Li B, Yang J, Lu B, et al. (2015) Estimation of retired mobile phones generation in China: A comparative study on methodology. *Waste Management* 35: 247–254.

Manhart A (2011) International cooperation for metal recycling from waste electrical and electronic equipment. *Journal of Industrial Ecology* 15: 13–30.

McMahon K, Johnson M and Fitzpatrick C (2019) Enabling preparation for re-use of waste electrical and electronic equipment in Ireland: Lessons from other EU member states. *Journal of Cleaner Production* 232: 1005–1017.

Melo MT (1999) Statistical analysis of metal scrap generation: the case of aluminium in Germany. *Resources, Conservation & Recycling* 26: 91–113.

Ministerio del Ambiente (2013a) POLITICA DE POST CONSUMO EQUIPOS ELECTRICOS EN DESUSO.

Ministerio del Ambiente (2013b) ACUERDO No. 191.

Ministerio del Ambiente (2018) *RESPUESTA SOBRE SOLICITUD DE INFORMACIÓN RESPECTO A CELULARES USADOS* [WWW Document]. Quito: Ministerio del Ambiente. Available at: https://drive.google.com/drive/u/0/folders/1_bVAJ3SVnCv3ENHRu1dH_7X81y087sb4 (accessed 10 Feb 2022).

Ministerio del Ambiente Agua y Transición Ecológica (2022a) ACUERDO MINISTERIAL N° MAATE-2022-067.

Ministerio del Ambiente Agua y Transición Ecológica (2022b) INSTRUCTIVO PARA LA APLICACIÓN DE LA RESPONSABILIDAD EXTENDIDA EN LA GESTIÓN INTEGRAL DE RESIDUOS DE APARATOS ELÉCTRICOS Y ELECTRÓNICOS (RAEE) DE ORIGEN DOMÉSTICO.

Ministry of Agriculture, Food and Environment (2015) First national target for WEEE preparation for reuse: Spanish Royal Decree 110/2015 of 20 February on waste electrical and electronic equipment. Madrid: Ministry of Ecological Transition and the Demographic Challenge (MITECO).

Müller DB, Kongar E, Cao J, et al. (2007). *Service Lifetimes of Mineral End Uses*. U.S. Geological Survey (USGS).

Müller E, Schluep M, Widmer R, et al. (2009) *Assessment of E-Waste Flows: A Probabilistic Approach to Quantify E-Waste Based on World ICT and Development Indicators*. Dübendorf: Swiss Federal Laboratories for Materials Science and Technology (EMPA).

Nnorom IC and Osibanjo O (2009) Toxicity characterization of waste mobile phone plastics. *The Journal of Hazardous Materials* 161: 183–188.

Oguchi M, Kameya T, Yagi S, et al. (2008) Product flow analysis of various consumer durables in Japan. *Resources, Conservation & Recycling* 52: 463–480.

Ott D (2008) *Gestión de Residuos Electrónicos en Colombia*.

Parajuly K, Habib K and Liu G (2017) Waste electrical and electronic equipment (WEEE) in Denmark: Flows, quantities and management. *Resources, Conservation & Recycling* 123: 85–92.

Parajuly K and Wenzel H (2017) Potential for circular economy in household WEEE management. *Journal of Cleaner Production* 151: 272–285.

Peeters JR, Altamirano D, Dewulf W, et al. (2017) Forecasting the composition of emerging waste streams with sensitivity analysis: A case study for photovoltaic (PV) panels in Flanders. *Resources, Conservation & Recycling* 120: 14–26.

Peeters JR, Vanegas P, Duflou JR, et al. (2013). Effects of boundary conditions on the end-of-life treatment of LCD TVs. *CIRP Annals* 62: 35–38.

Peralta GL and Fontanos PM (2006). E-waste issues and measures in the Philippines. *Journal of Material Cycles and Waste Management* 8: 34–39.

Polák M and Drápalová L (2012) Estimation of end of life mobile phones generation: The case study of the Czech Republic. *Waste Management* 32: 1583–1591.

Proyecto PREAL (2018) *Proyecto Residuos Electrónicos América Latina - PREAL* [WWW Document]. Proyecto PREAL. Available at: https://residuoselectronicosal.org/quienes-somos/ (accessed 10 Feb 2022).

Richter JL (2016) *The complexity of value: Considerations for WEEE, experience from lighting products, and implications for policy*. In: *2016 Electronics Goes Green 2016+ (EGG)*, Berlin, Germany, pp. 1–8. IEEE.

Robinson BH (2009). E-waste: An assessment of global production and environmental impacts. *Science of the Total Environment* 408: 183–191.

Schluep M, Müller E and Rochat D (2012). *E-Waste Assessment Methodology Training & Reference Manual* [WWW Document]. Dübendorf: Swiss Federal Laboratories for Materials Science and Technology (EMPA).

Senae (2018) *Importaciones – Servicio Nacional de Aduana del Ecuador [WWW Document]*. Guayaquil: National Customs Service of Ecuador. Available at: https://www.aduana.gob.ec/importaciones/

Steubing B, Böni H, Schluep M, et al. (2010) Assessing computer waste generation in Chile using material flow analysis. *Waste Management* 30: 473–482.

Suckling J and Lee J (2015) Redefining scope: the true environmental impact of smartphones? *The International Journal of Life Cycle Assessment* 20: 1181–1196.

Tasaki T, Takasuga T, Osako M, et al. (2004) Substance flow analysis of brominated flame retardants and related compounds in waste TV sets in Japan. *Waste Management* 24: 571–580.

Terazono A, Murakami S, Abe N, et al. (2006) Current status and research on E-waste issues in Asia. *The Journal of Material Cycles and Waste Management* 8: 1–12.

United Nations Environment Programme (2007) *E-Waste Vol. 1: Inventory Assessment Manual*. Nairobi: United Nations Environment Programme.

Van der Voet E, Kleijn R, Huele R, et al. (2002) Predicting future emissions based on characteristics of stocks. *Ecological Economics* 41: 223–234.

Vanegas P, Peeters JR, Plessers F, et al (2014) Synergizing industrialized and developing countries to improve resource recovery for E–waste: Case Study Belgium–Kenya. *Procedia CIRP* 15: 283–288.

Wagner M, Baldé CP, Nnorom IC, et al. (2022) *Monitoreo Regional De Los Residuos Electrónicos*. Bonn: United Nations Industrial Development Organization (UNIDO).

Walk W (2009) Forecasting quantities of disused household CRT appliances – A regional case study approach and its application to Baden-Württemberg. *Waste Management* 29: 945–951.

Wang F (2014) *Design for Sustainability Program E-waste: Collect More, Treat Better Tracking Take-Back System Performance for Eco-Efficient Electronics Recycling*. Delft: Delft University of Technology.

Wang F, Huisman J, Meskers CEM, et al. (2012). The Best-of-2-Worlds philosophy: Developing local dismantling and global infrastructure network for sustainable e-waste treatment in emerging economies. *Waste Management* 32: 2134–2146.

Wang F, Huisman J, Stevels A, et al. (2013) Enhancing e-waste estimates: Improving data quality by multivariate Input–Output Analysis. *Waste Management* 33: 2397–2407.

Widmer R, Oswald-Krapf H, Sinha-Khetriwal D, et al. (2005) Global perspectives on e-waste. *Environ Impact Assessment Review* 25: 436–458.

Yang J, Lu B and Xu C (2008) WEEE flow and mitigating measures in China. *Waste Management* 28: 1589–1597.

Yu J, Williams E and Ju M (2010a) Analysis of material and energy consumption of mobile phones in China. *Energy Policy* 38: 4135–4141.

Yu J, Williams E, Ju M, et al. (2010b) Forecasting global generation of obsolete personal computers. *Environmental Science & Technology* 44: 3232–3237.

Zhang L, Yuan Z and Bi J (2011) Predicting future quantities of obsolete household appliances in Nanjing by a stock-based model. *Resources, Conservation & Recycling* 55: 1087–1094.