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ABSTRACT

Waste from Electrical and Electronic Equipment (WEEE or e-waste) is regarded as one of the fastest growing waste streams in the world and is becoming an emerging issue owing to adverse consequences on the natural environment and the human health. This research article reveals the presence of a strong linear correlation among global e-waste generation and Gross Domestic Product. The obtained results indicate that the best fit for data can be reached by comparing e-waste collected volumes and GDP PPS. More in detail, an increase of 1000 GDP PPS means an additional 0.27 kg of e-waste collected and 0.22 kg of e-waste reused/recycled. Furthermore, for each additional citizen, there will be an increase of 7.7 kg of e-waste collected and 6.2 kg of e-waste reused/recycled. The better collection of e-waste acts an important role concerning the circular economy, and it can be an advantageous approach. Therefore, e-waste could be considered as an opportunity for recycling or recovery of valuable metals (e.g., copper, gold, silver, and palladium), given their significant content in precious metals than in mineral ores.

1. Introduction

Waste from Electrical and Electronic Equipment (WEEE or e-waste) is considered as the fastest increasing stream of waste in the world (Guo and Yan, 2017; Zeng et al., 2017b). The increasing publications in the recent two decades (Fig. S1 in Supplementary content (SC)) indicate that e-waste management has become a global and emerging issue, from developing countries to industrial nations (Awasthi and Li, 2017; Li et al., 2015; Sthiannopkao and Wong, 2013). The generated quantities of e-waste are highlighted owing to its fundamental significance in both new policies definition and process development. In principle, the experts described e-waste generated amounts like a logical effect of the technological progress, especially in developed countries (Song et al., 2016). The main idea was that it is useless trying to estimate future e-waste generation because there are so many factors influencing these amounts that there are very few chances to give a real value (Cucchiella et al., 2016b; Zeng et al., 2016). The same issue can be described for yearly growth rates. The list of obsolete products considered as e-waste is so variegated and numerous that there are too many different customer behaviours to consider for doing a real estimation of trends (Guo and Yan, 2017; Tran et al., 2016). As evidenced in some work (Cucchiella et al., 2015), the disruptive innovation characterizing some technological product, together with new environmental measures and critical materials restrictions, modified the natural obsolescence of some electrical and electronic equipment (EEE), by actively increasing their substitution rate. A typical example reported in the literature is about the technological shift between cathode-ray tube and liquid-crystal display screens (Sun et al., 2016).

Recently, some authors started in studying the possible presence of any mathematical relation among e-waste generated volumes and the anthropogenic behaviour in developed (and developing) countries (Duan et al., 2016; Song et al., 2017). For example, Kumar et al. (2017) evaluated the relationship among e-waste generated volumes, national Gross Domestic Product (GDP) and population. Kusch and Hills (2017) refined the previous results by considering GDP at Purchasing Power Standards (PPS) – instead of usual GDP – for limiting/standardizing the effect of different purchasing powers in different nations taken into account during their work.

GDP-PPS is an artificial currency unit, that analyses factors of each country to define a number on a person's standard of living within that country. For this reason, GDP PPS is better than usual GDP (Coccia, 2010; Dennett, 2014). However, the analysis of data characterizing e-waste volumes, including—collection, reuse and recycling with macro-variables are not well analysed in literature. Given a vast difference between generated and collected volumes subject to both illegal flows of WEEE (Li et al., 2013), absence of standardized measuring systems (Ongondo and Williams, 2011), and population habits (Wang et al., 2011), it is of utmost importance to have two distinct views of the context. In general terms, generated

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volumes are those amounts that, usually, are estimated through statistical data by experts (Garlapati, 2016; Ongondo et al., 2015). Given the previous issues, real data on these amounts are very challenging to gather. As opposite, collected volumes are those numbers that are measured by national governments and that give a correct idea of the real recycling performance of nations (Nelen et al., 2014; Salhofer et al., 2016). However, both generated and collected volumes refer to waste amounts prior to their treatment. Instead of reuse, recycling and recovery are resorted to waste amounts after their treatment (Robinson, 2009). Reused/recycled numbers refer to wastes that, after treatment, can directly re-enter within the traditional value chain (e.g., plastics, wood, glass, metals). Recovered amounts, instead refer to wastes that – given their physical features – cannot re-enter in the value chain and must be incinerated for the production of green energy (Bovea et al., 2016; Golsteijn and Valencia Martinez, 2017). This way, it is important to distinguish the two measures also when there is a need to define a new performance parameter.

Considering the global challenges subject to e-waste, this paper aims to reach two objectives: (1) the mathematical relationship among economic growth, population, and e-waste amount, concerning the 28 European countries during the year of 2009–2014, will be examined in six case-studies such as GDP PPS and collected amount, GDP PPS and reuse & recycling amount, population and collected amount, population and reuse & recycling amount, GDP PPS per capita and collected amount per capita, GDP PPS per capita and reuse & recycling amount per capita. And (2) the future projection of e-waste amount will be uncovered with a comparison among 28 European countries.

2. Materials and methods

This section is structured as follows. Section 2.1 will present a general discussion about circular economy principles. Section 2.2 will link these principles with European governmental actions, evidencing current and future strategies regulated by the EU Commission towards the sound management of e-waste. Section 2.3 will demonstrate a state-of-the-art analysis on e-waste management, uncovering the existing literature gaps. Finally, Sections 2.4 and 2.5 will describe the model used within this work, proposing assumptions and input data at the base of its functioning.

2.1. Circular economy

The CE system originates from eco-industrial development theory and thought (Geng et al., 2012). It is based on the 'win-win' philosophy in which economic opportunities and environmental protection can co-exist (Park et al., 2010). The great challenge of CE is to overcome the linear 'take, make and dispose' economic model (McDowall et al., 2017).

CE aims to reduce both virgin materials input and wastes output through closing resource flow loops in a sustainable way (Islam, 2017). This topic is multidisciplinary, and it is a solution to series of challenges such as resource scarcity, waste generation, environmental pollution and economic opportunities providing by waste (Lieder and Rashid, 2016; Winans et al., 2017). This system is analysed by industrial actors and researchers in several contexts, as (i) eco-industrial park, (ii) waste-to-energy supply chain, and (iii) waste-to-resource supply chain (Chiang and Pan, 2017).

The first is a critical research issue in the field of recycling economy (Zhao et al., 2017) and the eco-industrial park is an effective way to promote the sustainable development and CE (Zeng et al., 2017a). The second field of research aims to create synergies with energy and climate policy without compromising the achievement of higher reuse and recycling rates (Cucchiella et al., 2017). The waste-to-energy supply chain has the potential to conjugate energy demand, waste management, and greenhouse gas emission (Pan et al., 2015). Also, waste-to-resource supply chain has the goal to resolve the issues of waste management and CO_2 emissions and in addition to recovering critical and valuable materials (Pan et al., 2017). A social analysis defines that some values such as trust behaviour, waste cognitive domain, and environment engagement, are necessary to develop these systems (Ceglia et al., 2017).

Industrial waste reuse contributes to both economic growth and carbon emission reduction, even if the environmental benefits are mitigated when the economy is less developed (Zhang et al., 2016a). CE is considered an alternative to today's linear business model. However, the definition of the benefits of CE in many business sectors is not yet entirely defined. Two critical pathways promoted by CE are reuse and recycling and consequently, e-waste management represents a segment of potential interest (Parajuly and Wenzel, 2017) and e-waste is defined as an important resource of the circular economy agenda (Golsteijn and Valencia Martinez, 2017).

2.2. EU policy measures supporting circular economy and e-waste management

The European Union re-knowns the importance of a correct recovery of e-waste for many years. A new version of the WEEE Directive entered into force on 13 August 2012, obliging the Commission to adopt a common methodology for the calculation of EEE placed on the national market in each Member State and of e-waste generated. The collection target until 2015 was set to 4 kg per capita of e-waste coming from households, representing about 2 million tonnes per year, out of around 10 million tonnes of e-waste generated annually in the EU. Given the expected increase of generation volumes (around 12 million tonnes of e-waste) and responding to a legal requirement, the EU Commission reviewed the current WEEE Directive by fixing new scopes, new deadlines and options for collection rates and new recovery targets. To this aim, the year 2019's targets are set to 65% of equipment's sold (against 45% of the previous version of the WEEE Directive), or 85% of total e-waste generated. This change in targets could guarantee around 10 million tonnes of e-waste (or roughly 20 kg per capita) collected in the EU in 2020. Each nation will be free to measure collected volumes either in terms of EEEs put on the market or wastes generated. Given the high relevance of these changes, the Commission will help Member States in identifying and exchanging good practices in the implementation of the WEEE Directive. To this aim, according to what expressed by Ongondo et al. (2011), "WEEE Calculation Tools" will be shared with Member States, supporting them in the calculation of WEEE collection rates. This measure will help EU nations in:

(i) standardizing the treatment and recycling of materials;
(ii) ensuring uniform conditions in the calculation of the WEEE collection rates;
(iii) reporting to the Commission on the achievement of the collection targets starting from the reference year 2016.

However, the ability to reach these new requirements is also a direct responsibility of people living in each Member State (Wang et al., 2011). The increase in e-waste recovery in a nation is primarily a question of changing the mentality of people by activating their willingness in household recycling habits (e.g., through dedicated training campaigns) and not only an issue related to the lack of infrastructures (Wang et al., 2016a, 2016b).

2.3. Literature review

Prosperity-related regression models for total municipal solid waste (MSW) generations in European cities were evaluated (Beigl et al., 2008; Ciacci et al., 2017). GDP per capita [measured in US-$ purchasing power parity (PPP), 1995 prices] was the most significant parameter. Furthermore, the MSW generation module was considered as an econometric model, consisting of a system of multiple linear equations for each city group (Beigl et al., 2004).

A review on Directive 2002/96 highlighted the relationship between e-waste and GDP and also for this typology of waste a linear regression was evaluated. The amounts of e-waste per person (variable *y*) were linked with GDP per person (variable *x*). Eleven countries were considered, and the following linear regression ($y = 0.000566 \times x$) was obtained with the coefficient of determination (R^2) equal to 0.5485. This value is low, but the authors defined as the linear relation was substantially feasible to quantify the future amounts of e-waste generated (Huisman et al., 2008). An update of this work was proposed by Huisman (2010), who confirmed this correlation. In particular, EEE put on Market per person versus GDP PPS per person and e-waste per capita versus GDP PPS per capita have a value of R^2 equal to 0.896 and 0.9188, respectively. Recent works explored again this relationship. For instance, Kumar et al. (2017) analysed fifty countries on a global scale, and they did not propose an equation concerning the linear regression, while R^2 was defined for several case studies regarding e-waste generated:

- Total e-waste and e-waste/inhabitant vs GDP are 0.9583 and 0.0563, respectively.
- Total e-waste and e-waste/inhabitant vs population are 0.3897 and 0.0504, respectively.
- Total e-waste and e-waste/inhabitant vs GDP per capita are 0.0113 and 0.8327, respectively.

Consequently, e-waste and GDP have a direct correlation, while the population doesn't present a significant one. The coefficient of determination is high when homogeneous variables (e.g., e-waste vs GDP or e-waste/inhabitant vs GDP per capita) are evaluated. Kusch and Hills (2017) analysed 50 countries of the pan-European region and highlighted as PPP or PPS consider price level differences across countries and adjust for differences in the cost of living. Like already underlined in the introductory section, given the different price levels in countries, a cross-country comparison through the use of GDP PPS is proposed. The relationship between e-waste generated per capita (variable *y*) and GDP PPP per capita (variable *x*) is evaluated, and the mathematical formula describing the linear correlation is $y = 0.4892 \times x$, with R^2 equal to 0.9285. A high economic elasticity defines as e-waste and GDP PPP are closely interlinked. These works analysed e-waste generation, but collection levels can differ significantly from generated volumes. The difference depends mainly upon four aspects: (i) illegal flows; (ii) no attention of citizens towards environmental problems; (iii) absence of regulations; and (iv) inadequate number (or location) of collection centres (Cucchiella et al., 2016a). Furthermore, both current recovery performance and recyclability measurement procedures are yet insufficient to contain the annual increase of generated waste (Tao et al., 2017; Zhang et al., 2016b) and so the calculation of e-waste reused and recycled is extremely relevant (Rosa and Terzi, 2016; Zeng and Li, 2016).

2.4. Model assumptions

A state-of-the-art analysis proposes a simple linear regression between e-waste and GDP PPS. Linear regression is the most basic type of regression and commonly used for predictive analyses. It is a way to model the relationship between two variables and propose the dependent variable values as a function of the independent variables (Mudd et al., 2014). Starting by a set data points (x_i, y_i), it is hypothesized that Eq. (1) describes the linear relationship between *x* and *y*. The goal is to find the best-fitting straight line (called regression line) through the points - Eq. (2). The dependent variable is determined by two components: (i) structural and (ii) Random. In fact, independent variables are never perfect predictors of the dependent variables. The regression line minimizes the total error and the typical procedure to find this line is the least-squares method - Eq. (3). The minimization problem is solved by the calculation of one regression coefficient - Eq. (5) - and one constant - Eq. (6). R^2 defines the goodness of fit of a model. It varies from 0 to 1 and an R^2 of 1 indicates that the regression line perfectly fits the data – Eq. (7) (Lane et al., 2014; Seltman, 2012). F-test defines the statistical significance of the model parameters. It is used to test the null hypothesis that the variances of two sets of data are equal and is verified if F value (F) is greater than F critical value (Fcrit) – Eqs. (10), (11). F critical is calculated in according to reference tables. Finally, this test proposes also a P-value (P), that defines the probability to have F lower than F critical under the null hypothesis (Maddala and Lahiri, 2009).

$$y_i = a + bx_i + e_i \tag{1}$$

$$y = a + bx \tag{2}$$

$$\min_{a,\ b} \sum_{i=1}^{N} {e_i}^2 \tag{3}$$

$${e_i}^2 = \sum_{i=1}^{N} \left(y_i - a - bx_i\right)^2 \tag{4}$$

$$b = \sum_{i=1}^{N} \left(x_i - \overline{x}\right)^* \left(y_i - \overline{y}\right) / \sum_{i=1}^{N} \left(x_i - \overline{x}\right)^2 \tag{5}$$

$$a = \overline{y} - b\overline{x} \tag{6}$$

$$R^2 = \left(\left(\overline{xy} - \overline{x} * \overline{y}\right) / \sqrt{\left(\overline{x^2} - \overline{x}^2\right)^* \left(\overline{y^2} - \overline{y}^2\right)}\right)^2 \tag{7}$$

$$S_x^2 = (1/(N-1))^* \sum_{i=1}^{N} \left(x_i - \overline{x}\right)^2 \tag{8}$$

$$S_y^2 = (1/(N-1))^* \sum_{i=1}^{N} (y_i - \bar{y})^2 \quad (9)$$

$$F = S_x^2/S_y^2 \quad (10)$$

$$\text{Fcrit} = f\,(\text{dof, level of significance}) \quad (11)$$

where y is dependent variable; a is constant; b is regression coefficient; x is independent variable; e is prediction error; i is observation; N is number of data points; a horizontal bar over a variable indicates its average value; S_x^2 is variance of x; S_y^2 is variance of y and dof is degrees of freedom.

The aim of this article is to uncover the relationship between all types of e-waste volumes with both national GDP PPS and population.

2.5. Input data

In light of uncertainty of input data, output values may be unreliable due to the non-homogeneity of this information (Schoer et al., 2012). The statistical office of the European Union (Eurostat) solved this issue and, within the paper, the proposed input values come from this source (Eurostat, 2017):

- GDP PPS [Economy and finance → National accounts → Annual national accounts → Main GDP aggregates].
- Population [Population and social conditions → Demography and migration → Population change – Demographic balance and crude rates at national level].
- E-waste collected [Environment and energy → Environment → Waste → Waste streams → WEEE by waste operations].
- E-waste reuse & recycling [Environment and energy → Environment → Waste → Waste streams → WEEE by waste operations].

The latest year available is 2014 in Eurostat, and 2020 is chosen as target year for evaluating the future projection of e-waste. Given that the 2015–2020 interval is composed of five periods, consolidated data referred to the 2009–2014 period are evaluated. Multiplying six variables and twenty-eight nations for each variable means a total number of data points equal to one hundred and sixty-eight. However, there are twenty-six missing data concerning four countries (e.g., Croatia, Cyprus, Italy, and the United Kingdom). Consequently, the effective number of data points analysed in this work is different.

Input values of the EU 28 in 2014 for each key-variables are proposed as follows: population (SC Table S1); GDP PPS (SC Table S2 and SC Table S3); e-waste collected (SC Table S4 and SI Table S5) and e-waste reuse & recycling (SC Table S6 and SC Table S7). Total values of the EU 28 are proposed in Table 1, in which the compound annual growth rate (CAGR) is defined for all the examined key-variables. Eurostat proposed also the value of GDP PPS of the EU 28 in 2015 that is equal to 14,714 billion. In this way, CAGR calculated for the 2009–2014 period is 2.6% and 3.0% in the 2009–2015 one.

Table 1
Trends of key-variables in EU 28 in the year of 2009–2014 (Eurostat, 2017).

Item	2009	2010	2011	2012	2013	2014	CAGR
E-waste collected (ktons)	3446	3525	3554	3474	3524	3601	0.9%
E-waste reuse & recycling (ktons)	2757	2913	2993	2838	2929	2985	1.6%
Reuse & recycling/ collected	80.0%	82.6%	84.2%	81.7%	83.1%	82.9%	
GDP PPS (billion)	12,297	12,817	13,193	13,449	13,559	14,003	2.6%
Population (million)	502.1	503.2	503.0	504.1	505.2	507.0	0.2%

3. Results and discussion

3.1. Correlation model of e-waste volumes and GDP

Starting by the model assumptions defined in Section 2.4 and input data proposed in Section 2.5 (SC: Tables S2, S4, and S6), a regression model for e-waste (distinguished between collected and reused/recycled) and GDP PPS is evaluated in Fig. 1. The number of data points analysed in this comparison is equal to one hundred and sixty-four for e-waste collected vs GDP PPS and one-hundred and fifty-nine for e-waste recycled/reused vs GDP PPS.

By considering both the graph and the related equations, it is possible to say that there is a clearly linear relation between e-waste volumes (variable *y*) and GDP PPS (variable *x*). Results defined that an increase of 1 GDP PPS means an additional 0.27 g of e-waste collected ($y = 0.2701 \times x$) and 0.22 g of e-waste reused/recycled ($y = 0.2199 \times x$). In addition, this relation is strong, given the high R^2 reported in the picture. It is equal to 0.9419 considering e-waste collected vs GDP PPS and 0.9217 with e-waste reused/recycled vs GDP PPS. R^2 has a value near to 1 and consequently, this indicates as the regression line perfectly fits the data. Furthermore, these values are also similar to the ones presented in literature by other experts (Kumar et al., 2017). This relation could be used for estimating future e-waste volumes, independently from the availability of official databases. Another important thing to say is that the relation is not influenced by the time variable (values reported are referred to 2009–2014 period, but also for each year the relationship is verified).

As highlighted in Section 1, also the relationship among two typologies of e-waste with population is evaluated (Fig. 2). Also in this comparison, the number of data-points analysed is the same of one proposed previously (SC: Tables S1, S4, and S6). In fact, the popula-

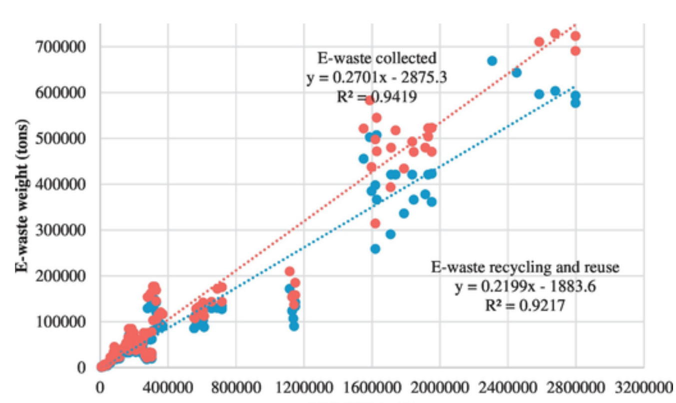

Fig. 1. The correlation between WEEE collection or WEEE reuse & recycling and GDP PPS.

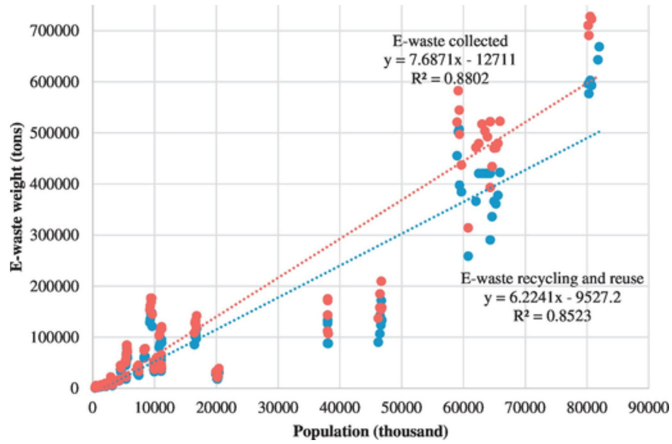

Fig. 2. The correlation between e-waste collection or e-waste reuse & recycling and population.

tion as GDP PPS presents all one hundred and sixty-eight values, but there are four missing data for e-waste collected and nine inputs for e-waste recycled/reused.

A healthy relationship between e-waste volumes (variable y) and population (variable x) is confirmed. Values obtained quantified an increase of 7.7 kg of e-waste collected ($y = 7.6871 \times x$) and 6.2 kg of e-waste reused/recycled ($y = 6.2241 \times x$) for each additional citizen. Contrarily to what reported in the literature (Kumar et al., 2017), consequently there is a strong relation between e-waste volumes and population (R^2 equal to 0.88 and 0.82 for collected and reused/recycled, respectively). Even if, these values are lower than previous (Fig. 1), certainly can be assumed that the regression line perfectly fits the data. One possible cause of this difference with existing literature is the alternative set of countries taken into account by this work. In fact, the presence of developing countries within the set of nations considered by other works could have negatively influenced the calculation with nonlinear effects.

Finally, for this sub-section Fig. 3 shows a relation between e-waste volumes and GDP PPS, but this time is calculated per capita. This was done trying to limit the effect of population on both the previous variables. One thing to mention is the absence of Luxembourg among the EU countries taken into account. This choice was done because Luxembourg is a very small country in which the great part of population is represented by foreign company's employees and not by average citizens. The number of data points analysed in this comparison is equal to one hundred and fifty-eight for e-waste collected per capita vs GDP PPS per capita and one-hundred and fifty-three for e-waste recycled/reused per capita vs GDP PPS per capita (SC: Tables S3, S5, and S7).

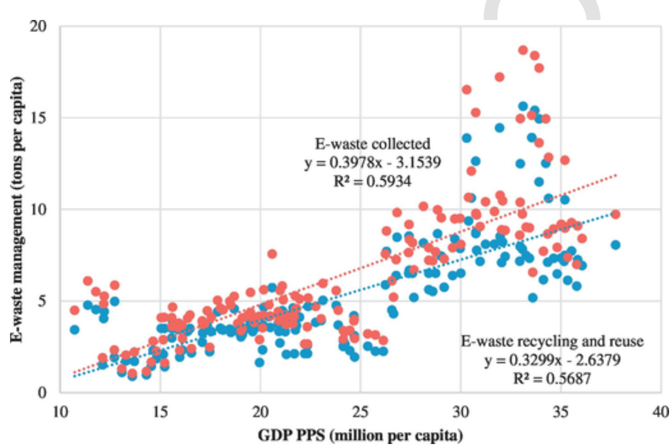

Fig. 3. E-waste per capita vs GDP PPS per capita.

Contrarily to what seen before, in this case, it is not possible to consider a linear relation between e-waste volumes per capita (variable y) and GDP PPS per capita (variable x). R^2 are small, equal to 0.5934 and 0.5687 for e-waste collected and reuse & recycling, respectively. Also in this case, there are differences with what presented in literatures (Kumar et al., 2017; Kusch and Hills, 2017). However, it is possible to say that these deviations are essentially caused by the different GDP considered (PPS instead of normal), years taken into account (range of years instead of single year), nations considered (EU instead of EU plus extra-EU countries) and e-waste volumes taken into account (collected/reused/recycled instead of generated).

The statistical significance of the model parameters is verified for six combinations examined in this work (SC Table S8). In fact, F is always greater than Fcrit considering a level of significance equal to 0.05 (see Section 2.4). The low P-value gives solidity to the obtained results.

3.2. Future projections for EU's e-waste streams

The future management of e-waste requires appropriate methods and technologies to maximize the recovery of materials embedded in these products. Firms involved in this business define own strategy and relative investments according to the size of the market. Thus, two different approaches can be used – Table 2. Both of them are based on historical data, using CAGR as the reference variable. The first one considers e-waste collected and reuse & recycling, that is equal to 0.9% and 1.6% in the 2009–2014 period (Table 1), respectively. Instead, the second one is linked to GDP PPS. This choice is determined by the higher value of the determination coefficient between e-waste and GDP PPS than the one calculated between e-waste and population (Figs. 1 and 2). CAGR of GDP PPS is equal to 2.6% (Table 1) and the linear correlation determines the same growth rate also for e-waste streams. An upload of data proposes a different percentage increase (3.0%), considering the 2009–2015 period as the reference. This value is referred to the European scenario and it is coherent to the global one proposed in the literature. In fact, several works define e-waste as one of the fastest growing waste streams in the world, with an estimated growth rate going from 3% up to 5% per year (Cucchiella et al., 2015; Ongondo et al., 2011).

The amount of e-waste collected in EU 28 varies from 3797 to 4612 kilotons in 2020, while e-waste quantity of reuse & recycling ranges from 3283 to 3756 kilotons. There is a significant difference between minimum and maximum values although the methods are related to the same variable. From one side, the approach linked to

Table 2
Future projections of e-waste streams in EU 28.

Parameter		2015	2020
CAGR E-Waste	E-waste collected (kilotons)	3633	3797
	E-waste reuse & recycling (kilotons)	3033	3283
Linear correlation vs GDP PPS	E-waste collected (kilotons)	3879	4417
	E-waste reuse & recycling (kilotons)	3158	3597
Linear correlation vs GDP PPS (upload)	E-waste collected (kilotons)	3971	4612
	E-waste reuse & recycling (kilotons)	3234	3756

GDP PPS highlights a greater growth and is justified by its linear correlation with e-waste streams. From the other side, this approach has the limit to consider the same growth rate for two typologies of e-waste. A sustainable approach requires initially minimizing the production of e-waste, but not always data concerning e-waste generated are known. Consequently, a high value of e-waste collected represents a good performance considering the rapid increase of e-waste. The following step is represented by maximization of better environmental performances regarding the treatment of e-waste collected. Data proposed in Table 1 are not confident. In fact, at least 80% of e-waste collected is also reused or recycled, but there is a downward trend (e.g. equal to 84.2% in 2011 and decreasing to 82.9% in 2014). A specific trend characterizes each European country, and the decision maker is able to estimate future streams according to the methodology proposed in this work.

3.3. A comparison of e-waste performance of European countries

The linear correlation of e-waste and GDP PPS allows comparing all the 28 EU countries. Taken 2014 as the reference, the benchmarking is represented by the average European value. Only Italy and Cyprus are referred to 2013. Three indicators are proposed (Fig. 4):

- GDP PPS per capita.
- E-waste collected per capita.
- E-waste reuse & recycling per capita.

Results highlight as eleven countries (e.g., Austria, Belgium, Denmark, Finland, France, Germany, Ireland, Luxembourg, Netherlands, Sweden, and the United Kingdom) have higher values than EU 28 ones in all the three indicators examined. Luxembourg is the leading in GDP PPS per capita with 74.6 million per capita. Both the Ireland and the Netherlands follow, with 37.7 and 36.1 million per capita, respectively. EU 28 average value is equal to 27.6 million per capita. Considering the other two indicators, the first positions are occupied by other countries. Sweden has 14.9 kg of e-waste collected per capita and 12.5 kg of e-waste reused and recycled per capita. Denmark and Finland follow, with 12.7 and 12.1 kg of e-waste collected per capita, respectively. EU 28 average value is equal to 7.1 kg per capita. These two countries have inverted positions concerning e-waste reuse and recycling per capita (10.6 and 10.5 kg per capita, respectively). The EU 28 average value is equal to 5.9 kg per capita. Concerning other seventeen countries with values lower than EU 28 ones, Italy and Lithuania present a unique situation. However, the first one has a value greater than the EU average only for two typologies of e-waste per capita and the second for e-waste collected per capita.

The analysis has also been conducted in previous years (from 2009 to 2013), and the results are confirmed. It is possible to highlight:

(i) Eight countries (Austria, Belgium, Denmark, Finland, Germany, Ireland, Luxembourg and Sweden) have always values greater than European average.
(ii) United Kingdom presents the same situation, however there are lacking data concerning e-waste reuse and recycling in four years.
(iii) Values of The Netherlands are lower only in 2009 for both the typologies of e-waste;
(iv) E-waste collection, reuse and recycling values in France are greater than EU 28 ones from 2011 and 2014, respectively.
(v) Data of e-waste available for Italy in 2014 are lower than average European ones, but they are not considered due to their any homogeneity with previous years.

3.4. The value of e-waste for the circular economy

An economic analysis of 14 common categories of WEEE has underlined the potential value of bringing e-waste streams into the circular economy. They are estimated to be equal to two billion Euros in the year 2014 for the European market (Cucchiella et al., 2015). The presence of valuable and critical materials plays a key role. However, as defined in Section 2.1, this potential is not completely perceived. In fact, Europe currently loses around 600 million tonnes of waste materials (European Commission, 2017). E-waste can generate serious dangers to human health and the environment if not well-handled (Awasthi et al., 2016; Wang et al., 2017). The idea is that e-waste can support the development of circular economy is verified when they are treated by recycling facilities covering all efficiency standards (economic, environmental, governance, health and technological).

The sustainability of EoL strategy is not always guaranteed, given from one side the simultaneous presence of both profitable and non-profitable products and from the other hand the presence of complex and hazardous components. This way, the comparison of economic and environmental aspects continues to be an open issue among the

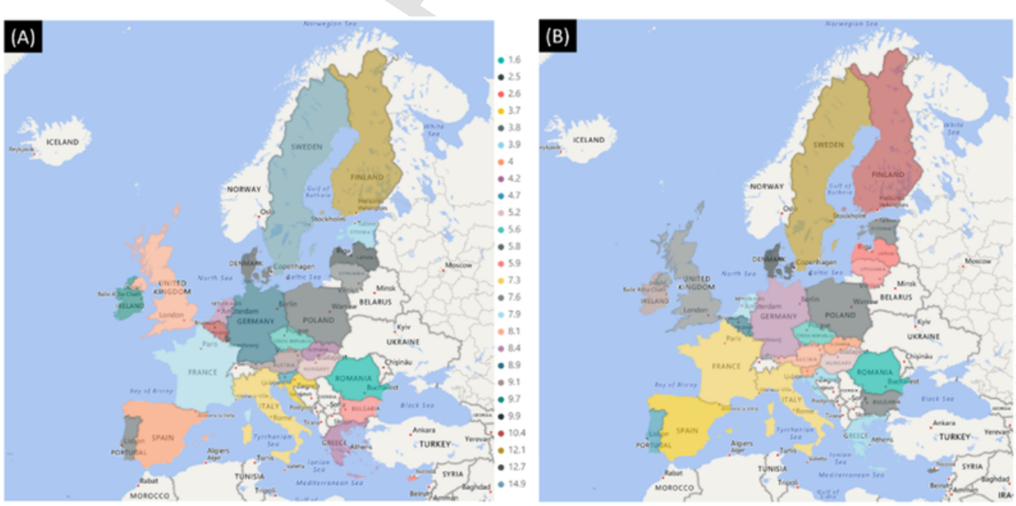

Fig. 4. E-waste treatment in the Europe in 2014 (kg per capita): (A) collection amount; (B) reuse and recycling amount.*(Data source from SC Table S9)*

experts. Also, this work followed the same streamline, by comparing GDP PPS and e-waste volumes (e.g., collected/reused/recycled). From this comparison, interdependence between these variables is evidenced. This way, it was possible to put together economic and environmental aspects. The only constraint is given by the fact that this analysis must be repeated for each product, because of the broad mix of different product categories constituting e-waste.

The interconnections between CE and sustainability attract the attentions of researchers, policy-makers, managers but all citizens. Sustainability is an ideal, in which the future generations have at least the same opportunities of current ones. It is a moral commitment no more deferrable, and the closing-loop of products is the implementation of a good practice oriented to long-term period. Consequently, a model of circular economy based on the exploitation of resources recovered from WEEEs can reach sustainable goals.

4. Conclusions and implications

This research article reveals the presence of a strong linear correlation among global e-waste generation and GDP. The obtained results indicate that the best fit for data can be reached by comparing e-waste collected volumes and GDP PPS. Besides, the current work evidenced as e-waste plays a relevant role in the global economy and their growth rate depends from human behaviours. Although, many directives and policies were deliberated during the last decades trying to limit and control e-waste flows and all of them followed the same paradigm of circular economy. However, if WEEE directives are not followed by dedicated training campaigns about the importance of recovering WEEE, the potential recovery performance of a nation cannot emerge, and supranational targets will continue to be unreachable even if advanced recovery technologies will be adopted.

Considering that both environmental and economic assessments (e.g. life cycle analysis and discounted cash flow analysis) are strongly dependent on volumes taken into account, the chance to make a provision of them becomes fundamental for any kind of investment decision or market analysis. Finally, a quantitative analysis allows evaluating performances in a given period. The comparison of EU nations from 2009 to 2014 allowed the definition of a reference benchmark to be exploited for future performance assessments.

Abbreviations

CE	circular economy
EoL	End of Life
F	F value
Fcrit	F critical value
GDP	Gross Domestic Product
N	number of data points
P	P-value
PPP	purchasing power parity
PPS	Purchasing Power Standards
R^2	coefficient of determination
WEEE	Waste from Electrical and Electronic Equipment

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2017.08.288.

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