resources

Communication

The Link between e-Waste and GDP—New Insights from Data from the Pan-European Region

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Abstract: Waste electrical and electronic equipment (WEEE) is difficult to sustainably manage. One key issue is the challenge of planning for WEEE flows as current and future quantities of waste are difficult to predict. To address this, WEEE generation and gross domestic product (GDP) data from 50 countries of the pan-European region were assessed. A high economic elasticity was identified, indicating that WEEE and GDP are closely interlinked. More detailed analyses revealed that GDP at purchasing power parity (GDP PPP) is a more meaningful measure when looking at WEEE flows, as a linear dependency between WEEE generation and GDP PPP was identified. This dependency applies to the whole region, regardless of the economic developmental stage of individual countries. In the pan-European region, an increase of 1000 international $ GDP PPP means an additional 0.5 kg WEEE is generated that requires management.

Keywords: WEEE; electrical and electronic waste; estimation of WEEE flows; gross domestic product; GDP at purchasing power parity; economic elasticity; decoupling

1. Introduction

The sustainable management of waste electrical and electronic equipment (WEEE), or e-waste, is one of the major environmental challenges of the 21st century [1,2]. WEEE contains both hazardous and precious components, and is a rapidly growing waste stream [3–5]. The responsible collection and recycling of WEEE reduces environmental harm [6,7] and facilitates the recovery of valuable materials [8–10], including rare earth elements and other critical raw materials (e.g., indium and gallium) that are of vital importance for modern economies [11–14]. The recycling of WEEE is a complex task requiring an effective technical infrastructure and managerial framework [15,16], and it has potential to generate significant economic wealth from recovered rare and important metals [12,17,18]. By way of example, the economic potential for recycling waste printed circuit boards (WPCBs) from WEEE collected from EU households alone, was estimated to be 3–6 thousand million EUR (profitability as net present value) for 2030 [19]. However, it should be noted that large quantities of WEEE are subject to complex transboundary movements that result from both legal and illegal activities [20–22], and flows from high-income countries to low- or middle-income countries can create risk to human health and the environment, especially when low-standard rudimentary methods are used to process WEEE [23,24].

Understanding e-waste generation and the best options for managing the material flows requires considerable effort [25–28]. One of the central challenges in planning sustainable WEEE management schemes remains the task of predicting current and future quantities of e-waste [29–32]. Although a framework for assessing quantities of e-waste in EU countries exists, further improvement would benefit all regions [2]. Elsewhere, including in the wider pan-European region, there is a lack of reliable data and an insufficient assessment of WEEE flows [31].

For material flows that show a close link to the gross domestic product (GDP), i.e., materials with high economic elasticity, quantities can be assessed based on economic data. For e-waste, economic elasticity was previously assumed or documented for some countries [32–35], but an assessment based on larger data sets is not yet available. Therefore, this work evaluates the relationship between e-waste and GDP in the countries in the pan-European region. In identifying a correlation, it is possible to determine the economic elasticity of WEEE and, if the elasticity is high, to estimate WEEE arisings based upon the standardized parameter, GDP. The present work builds upon the pan-European assessment of the Global Environmental Outlook (GEO-6) of the United Nations Environment Programme (UNEP) [2] by exploring the relationship between WEEE and GDP, determining WEEE economic elasticity and deriving a method for assessing WEEE flows. The findings provide a simple methodology for predicting the generation of e-waste in the context of growing economies.

2. Materials and Methods

In the present work, the countries of the pan-European region, as classified by UNEP [2], were studied. However, five of the smallest countries (Andorra, Holy See, Liechtenstein, Monaco, San Marino) were excluded due to the paucity of WEEE data [31], with the resulting analysis, thus being applied to 50 countries (Table 1). The pan-European region is characterized by its high diversity both in terms of size of individual countries and their economic developmental stage. As such, the data set obtained ranges widely and extends the scope of this study.

Table 1. Domestic waste electrical and electronic equipment (WEEE) generation in 2014 in 50 countries of the pan-European region [31].

WEEE Generation per Country in 1000 Metric Tons					
Western Europe		*Central Europe*		*Eastern Europe and Caucasus with RUS*	
Germany (DEU)	1769	Poland (POL)	397	Russian Federation (RUS)	1231
The United Kingdom (GBR)	1511	Romania (ROU)	197	Ukraine (UKR)	258
France (FRA)	1419	Czech Republic CZE)	157	Belarus (BLR)	72
Italy (ITA)	1077	Hungary (HUN)	125	Azerbaijan (AZE)	48
Spain (ESP)	817	Bulgaria (BGR)	77	Georgia (GEO)	21
The Netherlands (NLD)	394	Slovakia (SVK)	62	Armenia (ARM)	16
Belgium (BEL)	242	Croatia (HRV)	48	Republic of Moldova (MDA)	6
Sweden (SWE)	215	Lithuania (LTU)	34	*Central Asia*	
Switzerland (CHE)	213	Slovenia (SVN)	31	Kazakhstan (KAZ)	131
Austria (AUT)	188	Latvia (LVA)	22	Uzbekistan (UZB)	45
Portugal (PRT)	171	Estonia (EST)	19	Turkmenistan (TKM)	22
Greece (GRC)	171	Cyprus (CYP)	14	Tajikistan (TJK)	7
Norway (NOR)	146	*Southeastern Europe with TUR, ISR*		Kyrgyzstan (KGZ)	7
Denmark (DNK)	135	Turkey (TUR)	503		
Finland (FIN)	118	Israel (ISR)	138		
Ireland (IRL)	92	Serbia (SRB)	56		
Luxembourg (LUX)	12	Bosnia and Herzegovina (BIH)	21		
Iceland (ISL)	9	Albania (ALB)	20		
Malta (MLT)	6	FYR Macedonia (MKD)	13		
		Montenegro (MNE)	4		

Data for WEEE for 2014 was retrieved from the Global E-waste Monitor [31] (Table 1). The values were calculated from trade data on EEE (electrical and electronic equipment) with assumptions of how the equipment became waste [31]: Statistics for EEE were extracted from trade data for the period 1995 to 2012 as found in the UN Comtrade database, whereas for EU countries the data was taken from Eurostat; average product lifespan was considered for individual product categories to derive discarding probabilities over time; whereas the average weight per appliance type was used to calculate the overall amount of WEEE generated in 2014. The methodology employed is described in more detail in the Global E-waste Monitor [31]. Table 1 shows, in absolute figures, that the main producers of domestic WEEE in the pan-European region today are Germany, UK, France, Italy and the Russian Federation.

All GDP data were retrieved from the official online database of the World Bank [36,37]. GDP data was also for the year 2014, except for three countries (Luxembourg, Malta and Switzerland), for which the most recent data was from 2013. Key parts of the analysis were performed in September 2015 as part of the working schedule of the UNEP GEO-6 regional assessment [2]. Due to the scope of the GEO-6 report, only selected findings were published [2], namely WEEE generation per capita in the countries, and WEEE totals for sub-regions and the region as a whole. This work uses the same data used in the UNEP report [2].

The earlier study [2] showed that average domestic WEEE generation in the region for 2014 amounted to around 14 kg per capita, with large variations between individual countries: In Western Europe, generation per capita (21 kg) was about twice the average for Central Europe, was nearly three times that of South Eastern Europe, Eastern Europe and the Caucasus, and was nearly seven times greater than for Central Asia. These results suggested the existence of a close correlation between domestic WEEE generation and GDP in the pan-European region.

To further explore the dependency between WEEE quantities and GDP (economic elasticity), a regression analysis was applied in two modes to analyze the data sets of the 50 countries of the pan-European region:

- WEEE quantity (domestic WEEE generation per capita) against nominal GDP (per capita) of the country
- WEEE quantity (domestic WEEE generation per capita) against GDP at purchasing power parity (GDP PPP; per capita) of the country

Nominal GDP is most commonly used to assess the economic status and economic growth of a country. It expresses the monetary value of all the finished goods and services produced within a country's borders in a specific time period at current market prices. GDP per capita is derived by dividing the total GDP of a country by its total population (i.e., number of inhabitants). To enable comparison among countries, national currencies need to be converted to one common currency, such as the US dollar. Nominal GDP per capita does not reflect differences in the cost of living and the inflation rates of individual countries. Purchasing power parity (PPP) considers price level differences across countries and adjusts for differences in the cost of living. PPP is based on assessing how much (goods or services) one unit of a country's currency will purchase, and therefore indicates the actual purchasing power of the countries' inhabitants at parity. GDP PPP is derived from nominal GDP by using purchasing power parity rates and is expressed in international dollars (a hypothetical unit of currency that has the same purchasing power parity that the US dollar has in the United States). Nominal GDP and GDP PPP are both standard parameters, published by the World Bank on an annual basis for the countries of the world [36,37].

In addition to the regression analysis, WEEE intensities for each country and of the region were calculated. WEEE intensity indicates total domestic e-waste generation in a country (or region) per total GDP of that country or region (here as kg WEEE per $1000 GDP). Again, nominal GDP and GDP PPP were applied. The waste intensity represents an alternative way to easily assess how a higher GDP is linked to a higher flow of the waste [38,39]. A constant WEEE intensity indicates that WEEE and GDP are closely coupled via a linear relationship. This means that as GDP grows, more WEEE is generated by a constant rate; whereas, a declining WEEE intensity means that the growth in GDP might still be accompanied by an increasing WEEE flow, but not at a constant rate.

Where average values for sub-regions or the whole region are provided, the values indicate total WEEE quantity in the sub-region or region (sum of WEEE amounts in the respective countries) divided by the denominator of interest in the context (i.e., total number of inhabitants of the country group or total GDP of the country group). Data sets for regression analysis include values of single countries only, and no average values.

3. Results

3.1. WEEE Generation and GDP

Figure 1 shows that a close correlation between WEEE generation per capita and GDP exists, both when considering nominal GDP per capita and GDP PPP per capita. Based on the complete data set, the coefficient of determination (R^2) is higher for the version shown in Figure 1a. This might suggest a better fit of the data obtained from plotting WEEE against nominal GDP in the region. However, the results further demonstrate that if the assessment of WEEE economic elasticity is based on using GDP PPP data, a linear correlation between WEEE generation per capita and GDP PPP per capita is described. This linear dependency allows for a simple mathematical equation to articulate the relationship between WEEE and GDP PPP (see Section 3.2). In exploring the results further, Luxembourg can be considered as an exception that does not fit the relationship observed. Luxembourg is a small country with an unconventional economic situation, as its economy is heavily dominated by the financial sector, resulting in unusually high GDP values per capita [40]. At the same time, an unusual number of the country's citizens live and work abroad [40]. Luxembourg was therefore excluded when deriving the mathematical formula describing the linear correlation between WEEE and GDP PPP (Section 3.2).

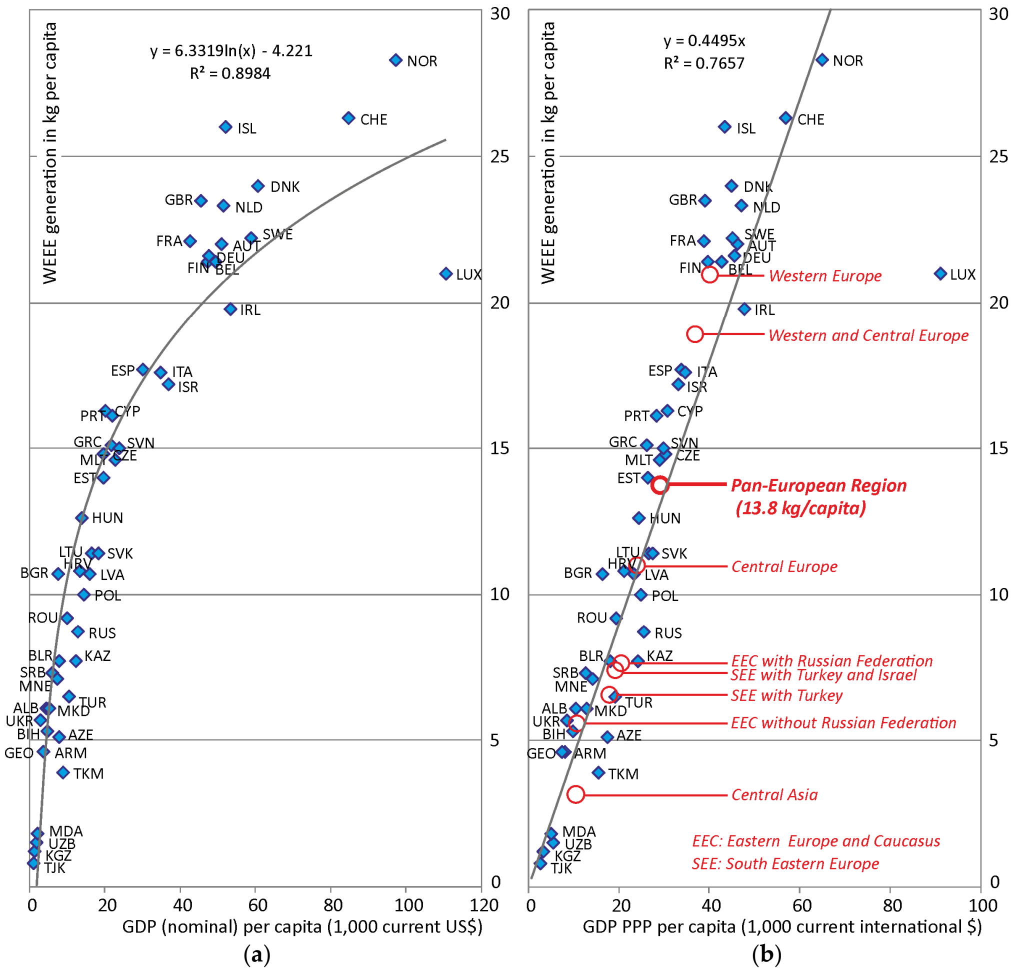

Figure 1. Domestic e-waste generation in 2014 in 50 countries of the pan-European region: (**a**) WEEE generation per capita depicted against nominal GDP; (**b**) WEEE generation per capita depicted against gross domestic product at purchasing power parity (GDP PPP) per capita (in addition, the average values of WEEE generation per capita in the sub-regions are shown); Note: Figure 1b was partially published previously [2].

3.2. Linear Correlation between WEEE Generation and GDP PPP

The findings suggest that if GDP PPP is known, WEEE generation can easily be calculated through a simple linear correlation. When assuming that the regression line passes through the origin, the correlation is described by the equation of the linear regression in Figure 2:

$$y = 0.489x$$

with

y: annual WEEE generation in kg per capita, and

x: annual GDP PPP per capita in thousand current international $

At $R^2 = 0.93$, the coefficient of determination indicates a good fit with the data points. The low *p*-value confirms that application of the linear regression fits the data well.

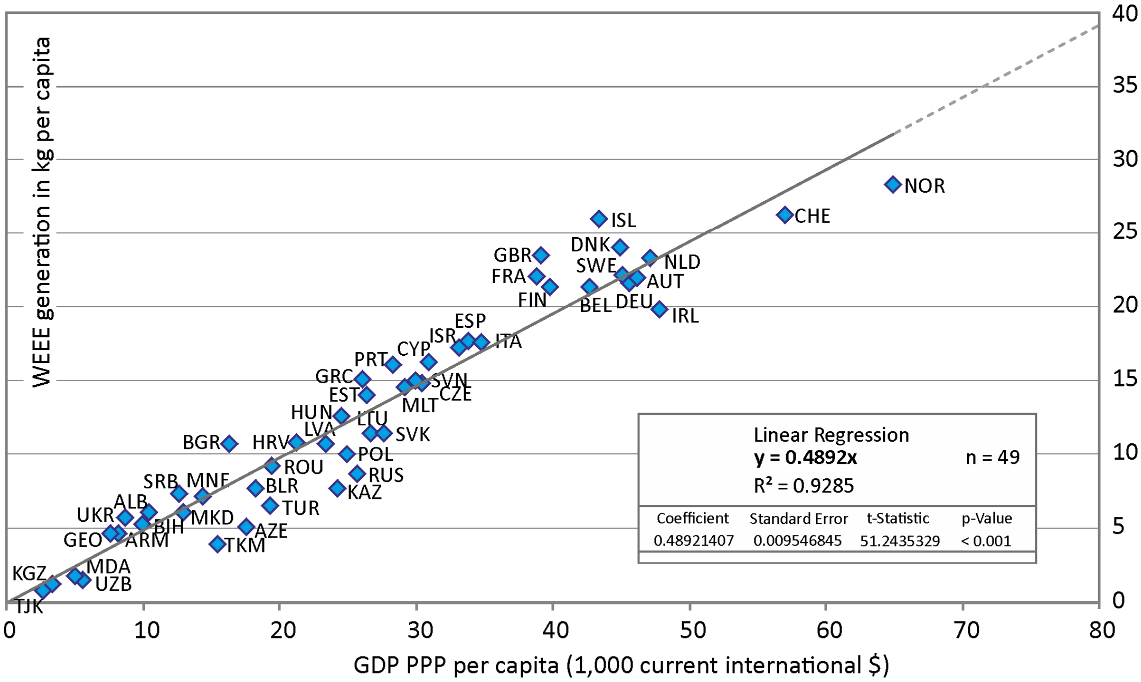

Figure 2. Linear correlation of domestic e-waste generation and GDP PPP (year 2014, 49 countries of pan-European region).

The identified linear dependency signifies that a doubling of GDP PPP is associated with a doubling of WEEE generation.

3.3. WEEE Intensity

While WEEE generation per capita was highest in countries with the largest GDP (see above, Figures 1 and 2), at the same time, WEEE intensity, based on nominal GDP was lowest in high-income countries (Figure 3a). Based on nominal GDP, countries with lower GDP had higher WEEE intensities, whilst in countries with higher GDP the WEEE intensity was lower. This reflects a "saturation pattern" in wealthy countries, where higher economic wealth still results in more EEE put on the market and consequently generation of higher WEEE quantities, but not to the same extent that can be observed in countries with lower economic wealth. For a country with lower income, e.g., with a nominal GDP of 10,000 US$ per capita, an increase of the country's GDP by 1000 US$ will mean an increase in WEEE generation around 0.8 kg or higher. For a high-income country with a nominal GDP of 100,000 US$ per capita, an increase of the country's GDP by 1000 US$ means an increase in WEEE generation by around 0.3 kg, i.e., less than 50% of what is seen in a country with lower income. However, there is considerable variation of the WEEE intensity among countries with lower economic wealth, which obviates a simple general rule.

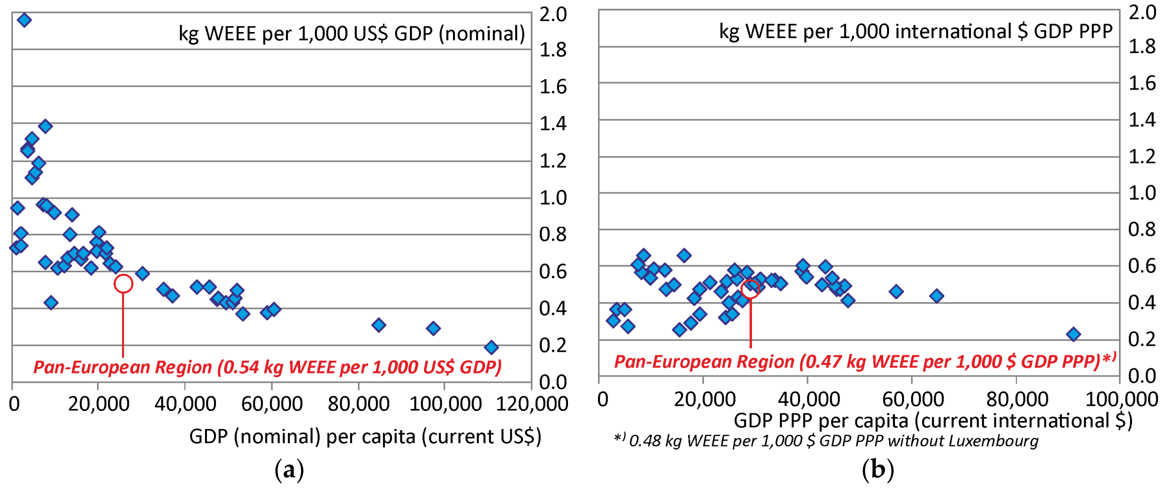

Figure 3. Domestic WEEE intensity in 2014 in the pan-European region (50 countries): (**a**) based on nominal GDP; (**b**) based on GDP PPP.

When looking at WEEE intensities with reference to GDP PPP (Figure 3b), the results show a more uniform picture, again suggesting a simple relationship that applies to all countries, regardless of their economic development stage. Figure 3b shows that WEEE intensities based on GDP PPP are not lower for high-income countries, as had been the case when looking at WEEE intensities based on nominal GDP. In fact, the assessment shows that per unit of GDP PPP, the amount of WEEE is consistent throughout the whole region, regardless of the economic development stage of individual countries. On average, around 0.5 kg WEEE per 1000 international $ GDP PPP are generated. That means that if the GDP PPP of a country increases by 1000 international $, WEEE occurrence will increase by around 0.5 kg, regardless of the economic development status of a country.

When excluding Luxembourg, previously identified as an exception (Section 3.1), the analysis shown in Figure 3b results in an average value for the WEEE intensity of 0.48 kg WEEE generated per 1000 international $ GDP PPP, and this is in agreement with the results given in Section 3.2.

4. Discussion

The economic elasticity of commodities and waste flows is usually referenced by the correlation between their quantity and the nominal GDP [39,41–46]. Nominal GDP is the standard parameter to describe the economic growth of a country, which explains its common use in economy-related assessments. For e-waste, a link with GDP was reported or assumed previously for some countries [32–35], and our results, based on data from a larger number of countries, confirms that very strong economic elasticity exists for e-waste. Furthermore, the results show that the economic elasticity is revealed when using nominal GDP for the analysis, and when alternatively using GDP PPP (referring to purchasing power parity). The findings further indicate that for assessing e-waste, GDP PPP is indeed more useful compared to nominal GDP. This is in agreement with findings reported in the literature, for some EU countries [33]. Thus, the buying of electrical and electronical equipment is strongly linked to the purchasing power of consumers in a country, and this explains why the corresponding waste flows show a linear dependency with GDP at purchasing power parity.

Our results provide evidence that the assessment of e-waste quantities in the context of GDP PPP provides a fast and consistent estimation of e-waste quantities based on GDP data. The pan-European region includes countries at different economic developmental stages, as illustrated by GDP levels spanning low- to high-income economies. The linear correlation identified between WEEE generation and GDP PPP applies to the whole region, regardless of the economic development stage of individual countries.

While GDP data are available from the World Bank on an annual basis for the countries of the world, the availability of WEEE data is less reliable. The present study builds on the consistent set of data for the year 2014 from the Global E-Waste Monitor [31], but for countries in regions other than pan-Europe the data given is not as comprehensively covered. Nevertheless, the data available could be used to assess whether the findings of the present work are transferable to other regions and, additionally, whether the findings are applicable more widely, including globally.

There are limitations with the present study, including a potential distortion of e-waste data due to the transboundary movement of e-waste as the actual WEEE flows to be managed can differ from that generated in the country or region of interest. To address this, a more complex assessment is required to the present analysis, which is focused upon how domestic WEEE generation and GDP are linked. As shown, the correlation between domestic WEEE generation and GDP PPP builds on data from one year whereas an analysis over longer time-scales would extend the scope of the study, providing that consistent data for WEEE from the countries of interest is available.

As the decoupling of e-waste generation and economic growth is a major societal challenge, a time-consistent assessment of WEEE data could provide a means to monitor change as it begins to happen.

5. Conclusions

This work provides evidence of a strong link between economic development and the generation of e-waste. WEEE is characterized by high economic elasticity, meaning economic growth will result in a corresponding increase in e-waste. While nominal GDP is usually used to assess the economic elasticity of materials, the results of this study show that GDP PPP is a more meaningful descriptor when looking at WEEE flows.

If the GDP PPP of a country is known, WEEE generation can easily be calculated. The linear dependency identified in this study ($y = 0.00049x$, with y being WEEE generation in kg per capita and x being GDP PPP per capita in current international $) facilitates a rapid assessment of the impact of economic growth on the occurrence of e-waste. The proportionality between GDP PPP and WEEE indicates that if GDP PPP increases by a factor 2, domestic WEEE generation also increases by a factor 2. On average, and regardless of the economic development stage of individual countries, around 0.5 kg WEEE per 1000 international $ GDP PPP are generated throughout the pan-European region. This simple, but fundamental finding can be used in the prediction of future WEEE flows.

The present study contributes to a better understanding of the challenge of e-waste generation in the pan-European region. Whether the relationship between GDP and WEEE identified extends to other regions and in a global context requires further detailed investigation.

To assess the economic elasticity of material flows, this study suggests that GDP PPP should be given more attention. For the economic analysis of WEEE, the application of GDP PPP was shown to be a more meaningful choice than nominal GDP. Further research should address different material flows—both waste streams and commodities—to reveal more contextual detail on GDP PPP as the preferential choice in economic analyses.

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