Waste Management 46 (2015) 28–39

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Forecasting waste compositions: A case study on plastic waste of electronic display housings

Jef R. Peeters [a,*], Paul Vanegas [a,b], Karel Kellens [a,c], Feng Wang [d], Jaco Huisman [d], Wim Dewulf [a], Joost R. Duflou [a]

[a] KU Leuven, Department of Mechanical Engineering, Celestijnenlaan 300A, Box 2422, 3001 Leuven, Belgium
[b] Center for Environmental Studies, University of Cuenca, Campus Quinta Balzay, Av. Victor Manuel Albornoz, Cuenca, Ecuador
[c] KU Leuven, Technology Campus Diepenbeek, Agoralaan Gebouw B, 3590 Diepenbeek, Belgium
[d] United Nations University, Institute for the Advanced Study of Sustainability, UN Campus, Platz der Vereinten Nationen 1, 53113 Bonn, Germany

ARTICLE INFO

Article history:
Received 9 June 2015
Revised 14 September 2015
Accepted 15 September 2015
Available online 1 October 2015

Keywords:
Forecasting
Electronic displays
Waste electrical electronic equipment (WEEE)
Plastic recycling

ABSTRACT

Because of the rapid succession of technological developments, the architecture and material composition of many products used in daily life have drastically changed over the last decades. As a result, well-adjusted recycling technologies need to be developed and installed to cope with these evolutions. This is essential to guarantee continued access to materials and to reduce the ecological impact of our material consumption. However, limited information is currently available on the material composition of arising waste streams and even less on how these waste streams will evolve. Therefore, this paper presents a methodology to forecast trends in the material composition of waste streams. To demonstrate the applicability and value of the proposed methodology, it is applied to forecast the evolution of plastic housing waste from flat panel display (FPD) TVs, FPD monitors, cathode ray tube (CRT) TVs and CRT monitors. The results of the presented forecasts indicate that a wide variety of plastic types and additives, such as flame retardants, are found in housings of similar products. The presented case study demonstrates that the proposed methodology allows the identification of trends in the evolution of the material composition of waste streams. In addition, it is demonstrated that the recycling sector will need to adapt its processes to deal with the increasing complexity of plastics of end-of-life electronic displays while respecting relevant directives.

1. Introduction

The global middle class is predicted to grow from 1.8 billion people in 2009 to 4.9 billion by 2030 (Pezzini, 2012). This is expected to result in a significant increase in consumption, including a growing demand for electrical and electronic equipment (EEE). In turn, the total lifespan of most EEE is decreasing due to the rapid succession of technological innovations (Bakker et al., 2014). As a result, waste of electrical and electronic equipment (WEEE), also referred to as e-waste, will strengthen its position as one of the fastest growing waste streams, which encompasses an increasing spectrum of products containing a broad variety of materials.

The magnitude of current and future e-waste flows has been thoroughly assessed by prior research. Several methods to forecast the amount of waste that will emerge have been developed, as described in Chancerel (2010), Polák and Drápalová (2012). These methods have been applied to forecast e-waste generation in several regional and national studies (Polák and Drápalová, 2012; Huisman et al., 2012; Yang et al., 2008; Dwivedy and Mittal, 2010; Chung et al., 2011; Zhang et al., 2011; Araújo et al., 2012). However, the results of these studies are mainly aimed to provide a baseline to optimize planning of e-waste policies, management of take-back systems and monitoring of legislative implementation (Beigl et al., 2008). Notwithstanding that the implementation of adequate e-waste policies and proper management of take-back systems are crucial elements toward a circular economy, the development and implementation of innovative recycling processes are as essential to achieve this objective. Such innovations are needed to lower the environmental impact of waste treatment and to increase resource efficiency in an economically viable manner. However, in order to steer this important innovation and related development of new recycling processes, more detailed information is required on the challenges that recycling companies will encounter to separate and refine materials with a high efficiency

* Corresponding author.
E-mail address: Jef.peeters@kuleuven.be (J.R. Peeters).

http://dx.doi.org/10.1016/j.wasman.2015.09.019
0956-053X/

from future waste streams. In addition, recycling companies need information on the material composition of future waste streams to properly evaluate the economic viability of the implementation of these new and innovative recycling processes.

Such a forecast of the evolution in material composition is only of value for those products, sub-assemblies or components of which the material composition has drastically changed. This is the case for many products, such as, for example, vehicles as a result of the gradual introduction of electrified solutions for road transportation, photovoltaic (PV) modules due to the development of new PV technologies and printed wiring boards (PWBs) and LCD modules of which the composition has been demonstrated to evolve (Yamane et al., 2011; Kolias et al., 2014). This research is illustrated by means of a case study on the evolution of EoL plastics of housings of electronic displays, which is expected to rapidly and strongly change in the coming years. One of the reasons for this evolution is the recent development in legislation, which progressively required more fire safety for electronic displays. This has resulted in the application of more flame retardants (FRs) in plastics tailored to the use in housings of electronic displays. In addition, the variety of plastics used in electronic displays has significantly increased as a result of the availability of new polymer blends, additives and composite materials. Furthermore, the share of plastics used in electronic displays has increased due to the availability of these new plastics, which enable the use of plastics for applications for which in the past only metals or ceramics could be used.

In consequence of the wider variety of plastics used, as well as the increasing use of FRs in electronic displays, the complexity of the plastics from this waste stream will substantially increase. As a result, some plastic types will only be present in relatively small concentrations for which it will not be possible to achieve the required economies of scale to make the separation of these plastics economically viable. In addition, the performance of material separation processes decreases when the complexity of the waste composition input increases (Tange et al., 2012). Nevertheless, the separation of plastics with a high purity is a prerequisite for using plastic recyclates in applications similar to the original product category, commonly referred to as closed loop recycling. From an environmental perspective closed loop recycling is preferred over incineration (with energy recovery) and landfilling. Plastics recycling indeed reduces the need for natural resources and avoids the environmental burdens caused by plastics production and incineration or land filling (Patel et al., 2000; Dodbiba et al., 2008; Böni et al., 2010; Nelen et al., 2014). When plastics can be recycled in a closed loop system, it is in most cases also possible to market these plastic recyclates at a higher price. Therefore, closed loop plastic recycling offers a significant business potential and opportunities for job creation. Consequently, recycling companies need to improve their processes to coop with this ongoing evolution. To enable developers of plastic separation technologies and recycling companies to evaluate investments, a good insight in the evolution of the plastic composition is essential. However, at present only limited data with insufficient detail concerning the concentration of different plastics and FR types are available for current waste streams (Salhofer et al., 2012; Morf et al., 2005) and no data are available on the composition of future plastic waste streams.

Therefore, this article presents a methodology to forecast the evolution of the material composition of a waste stream. This methodology is based on an input–output analysis of both the product and material level, in contrast with prior research which only considers the product level (Polák and Drápalová, 2012; Wang et al., 2013). For this analysis, a detailed characterization of the plastics present in different waste streams was performed. The proposed methodology makes use of parameters which are available in literature for a broad variety of product categories, such as parameters defining the product lifetime distribution. Furthermore, the presented methodology is used to forecast the evolution of the plastic composition in Belgium and Europe for both historic waste of cathode ray tube (CRT) and the upcoming waste of Flat Panel Display (FPD) TVs and monitors. These four case study products demonstrate that plastic compositions strongly depend on the product category, and how the plastic composition can rapidly change as the result of legislative requirements.

2. Experimental exploration

2.1. Materials

The presented research focuses on electronic displays, because the material composition of this waste stream has drastically changed, as a result of new legislation and the shift from CRT to FPD technologies (Peeters et al., 2012). Compared to other waste streams, such as cooling appliances, the plastic waste of electronic displays represents a more complex waste stream, because it contains a higher diversity of plastics. FPD TVs and monitors contain on average 31 wt% and 25 wt% plastics respectively (Vanegas et al., 2014; Peeters et al., 2014), whereas CRT TVs and monitors contain 21 wt% (Huisman et al., 2001) and 23 wt% plastics respectively (Berkhout and Hertin, 2004). For FPD TVs and monitors respectively 15% and 5% of the plastics are used in the front covers and 45% and 40% in the back covers (Peeters et al., 2013a). The other 40–55% of the plastics of FPD TVs are used in the Liquid Crystal Display modules to diffuse and polarize the backlight. The focus of the presented case studies is on the back cover, because it has been demonstrated to be one of the largest components of electronic displays with a high complexity for recycling (Peeters et al., 2014; Ryan et al., 2011).

Despite the fact that TVs and monitors are designed to perform a similar function and have similar product architectures, they are very different in size and are used at different locations. Because of the difference in use locations, these products are subject to different fire safety regulations. The European legislation (EN 60065:2002/A11:2008) obliges the use of fire-safe housings for TVs from 2010 onwards. This can be achieved by using a housing produced from a material, which is non-flammable or flame retardant by itself, such as metals. However, this is mostly achieved by adding FRs to plastics. For monitors there is no legislation in the EU related to fire-safety.

Furthermore, the type of FRs applied in electronic displays has also shifted due to developments in legislation on Persistent Organic Pollutants (POP) Council Decision 2006/507/EC, 2004. As a result, no POPs can be found in flat panel displays, which were placed on the market after the restriction of POPs. The POPs which were being used most in CRT TVs and monitors are the BrFR C-Octabromodiphenyl ether (OctaBDE) used with acrylonitrile–butadiene-styrene (ABS – $(C_8H_8{\cdot}C_4H_6{\cdot}C_3H_3N)_n$) and BrFR DecaBDE used with High Impact PolyStyrene (HIPS – C_8H_8), which can potentially break down into the POP pentaBDE (European Chemicals Bureau and European Commission, 2003). The Restriction of Hazardous Substances (RoHS) directive forbids the use of the BrFRs DecaBDE, C-OctaBDE and penta BDE above 1000 ppm in EEE in Europe. However, the application of the BrFR DecaBDE in EEE will be re-evaluated in August 2017. Furthermore, according to the European legislation on Registration, Evaluation, Authorization and Restriction of Chemicals (REACH), the BrFR Hexabromocyclododecane (HBCD) can no longer be applied for EEE after August 2015. However, HBCD was only rarely used in EEE. It should be noted that the BrFRs Tetrabromobisphenol-A (TBBPA), Tris(tribromophenoxy)triazine (TTBPT), Brominated

Epoxy oligomers/polymers with or without end capping (BEOs), Ethane bis(pentabromophenyl) (EBP), Brominated Carbonate Oligomers (BCOs) and Ethylene bis(tetrabromophthalimide) (EBTBP) can and are still commonly applied, often in combination with metal oxide synergists, typically antimony oxide, in electronic displays (Flame Retardant Association, 2014).

As a consequence of these legislations and the pressure of non-governmental organizations to ban BrFR, the concentration of the Phosphorus based (P)FRs Resorcinol Diphenyl Phosphate (RDP) and Bis-phenol Diphenyl Phosphates (BDP) in WEEE is rapidly growing (Wäger et al., 2011). These PFRs can only be added to the copolymers poly-carbonate (PC – $C_{16}H_{14}O_3$)/ABS (up to 25 wt% ABS), HIPS/ Poly (p-Phenylene) Ether (PPE – C_8H_8O) (30–70 wt% PPE) or ABS/ Poly(methyl methacrylate) (PMMA – $C_5H_8O_2$). Because of this interdependency between FRs and polymer type, the type of plastics and FRs used in electronic displays is also expected to substantially change. Table 1 provides an overview of the FRs found in the plastic housings of CRT and FPD TVs and monitors that comply with the most stringent V0 requirements of the UL 94 flammability standards (UL 94, 2012).

2.2. Methodological approach

Several forecasting methods have been used in prior research to forecast the amount of waste that will be generated. These methods can be classified as time-series models, factor models, econometrics analysis and input–output models (Li et al., 2015). The time-series models involve the use of historical data and their distribution to extrapolate future waste trends by the use of exponential smoothing, linear extrapolation, trend analysis or periodic approaches (Walk, 2004). Factor models use factors, such as the number of households and the household penetration grade, to predict the waste generation based on causal relationships (Walk, 2004). Econometric analysis models are similar to factor models using causal relationships with econometric indicators, such as the gross domestic products, to predict waste generation. The advantage of these models is their limited demand for data. However, with these forecasting methods it is not possible to determine the characteristics of the waste generated based on the characteristics of the products placed on the market.

In contrast, with input–output models the waste generated is forecasted based on the number of products supplied to the market and their age. Input–output models are so far the most frequently used models to forecast waste generation and many model variations exist. However, most of these input–output models, such as the time step method, market supply method and Carnegie Mellon method (Araújo et al., 2012; Wang et al., 2013; Li et al., 2015), assume that products are discarded after a constant lifetime. Nevertheless, to correctly forecast the material composition of waste streams it is crucial to account for the variation in the product lifetime. In addition, it is important to take into account that the market of electronic equipment is dynamic. Thus, the lifetime of electronic products can significantly evolve over time, for example as the result of the introduction of a new technology.

For these reasons, the presented methodology is based on the distribution delay forecasting method presented by Chancerel (2010). A distribution delay forecasting method, also referred to as a market supply model, uses sales and average lifetime distribution data to forecast the amount of waste that will be discarded. The challenge to forecast emerging waste streams with a distribution delay method is to obtain detailed and reliable data on the historic numbers of products that were sold. In addition, the number of products that will be placed on the market in the near future should also be taken into account to make a correct forecast. This is of main importance when there is a steep increase in the number of sales, since in this case the arising waste stream will contain a significant share of the early failing products coming from the large number of new generation products. The quantity $FQ_{(yw)}$ of EoL products that will have to be treated in year *yw* can be calculated by means of a distribution delay forecasting method with formula (1):

$$FQ_{(yw)} = \sum_{0}^{ys=yw-1} (D_{(ys,yw)} * QP_{(ys)}) * S_{(yw)} \quad (1)$$

In this equation, the number of products that will have to be treated in year *yw* is forecasted by taking into account the share of the discarded products $S_{(yw)}$ that will be collected for recycling in year *yw*. The total quantity of products that will be discarded in year *yw* is calculated by adding up the number of products sold in in the different years *ys* that will be discarded in year *yw*. The quantity of products sold in year *ys* that will be discarded in *yw* is forecasted by multiplying $QP_{(ys)}$, which is the total quantity of products sold in the year *ys*, times the probability $D_{(yp,yw)}$ that a product produced in year *ys* will be discarded in year *yw*.

Since fluctuations in consumer behavior or technology shifts can result in a significant under- or overestimation of the forecasted quantity of EoL products that will emerge, it is for most products advised to take into account a time dependent lifespan distribution. Different probability functions, such as Normal and Lognormal, can be used to represent the lifespan distribution. However, prior research indicates that the Weibull function produces the best fit of the lifespan distribution of most products, including CRT TVs (Walk, 2009). In addition, a Weibull distribution is characterized by relatively simple calculations and is easier to fit onto actual lifetime data (Melo, 1999). Therefore, in the proposed methodology the probability that a product sold in *ys* is discarded in *yw* is calculated by using a Weibull distribution, which is defined by a time dependent shape parameter $\alpha_{(ys)}$ and scale parameter $\beta_{(ys)}$ Polák and Drápalová, 2012; Van Schaik and Reuter, 2004. The shape parameter $\alpha_{(ys)}$ determines the velocity at which the failure rate decreases (<1) or increases (>1) over time and the scale parameter $\beta_{(ys)}$ determines the average product lifetime.

$$D_{(ys,yw)} = \frac{\alpha_{(ys)}}{\beta_{(ys)}} \left(\frac{yw - ys}{\beta_{(ys)}}\right)^{\alpha_{(ys)}-1} e^{-\left(\frac{yw-ys}{\beta ys}\right)^{\alpha_{(ys)}}} \quad (2)$$

To forecast the material composition of products, sub-assemblies or components in a waste stream their material composition needs to be accounted for. In case there is an evolution in the product material composition, it is necessary to take into account the composition of future generations of products that will be placed on the market. The composition of the waste stream is defined with the following formula:

$$FC_{(yw,i)} = \sum_{0}^{ys=yw-1} (D_{(ys,yw)} * QS_{(ys)} * M_{(ys)} * C_{(ys,i)}) * S_{(yw)} \quad (3)$$

In this formula, the probability to be discarded $D_{(ys,yw)}$ is multiplied with the number of products sold $QS_{(yp)}$ in *ys*, the total average mass $M_{(ys)}$ of the product, sub-assembly or component in *ys* and the material fraction for the considered material $C_{(ys,i)}$ in *ys*. $C_{(ys,i)}$ is the average percentage of material *i* used in the product, sub-assembly or component in *yp*. The material composition can either be based on data from Original Equipment Manufacturers (OEMs) or on results of waste sampling experiments, as described in Section 2.6. The total amount of material *i* that will be discarded in *yw* is then calculated by making the sum of the amount of material *i* in all the products produced before *yw* that will be discarded in *yw*. Finally, the total amount of material *i* that will have to be treated is calculated by taking into account the share of the discarded products $S_{(yw)}$ that will be collected in *yw*.

Table 1
Types of FRs most commonly used in housing plastics of CRT and FPD monitors and TVs.

	Restricted/regulated types of FRs				Non-Restricted types of FRs						
	Br FRs				Br FR					P FR	
	c-Octa-BDE	Deca BDE	HBCD	TBBPA	EBTBP	BCO	BEO	TTBPT	EBP	BDP	RDP
Max concentration	1000 PPM	1000 PPM	No limits		No limit						
Other elements	Sb				Sb					None	
Concentration for V0 (Wäger et al., 2011; Tange and Slijkhuis, 2009)	500–3000 PPM				1200–1800 PPM					800–1200 PPM	
CRT TV	Used with ABS	Used with HIPS		Used with ABS	Used with HIPS	Used with ABS		Used with ABS and HIPS		Used with ABS/ PMMA, PC/ABS and HIPS/PPE	
CRT monitor											
FPD TV	Never applied in FPD monitors and TVs										
FPD Monitor											

2.3. Product sales

The number of electronic displays (CRT/FPD Monitors and TVs) sold in the Belgian market $QS_{(ys)}$ has been registered by the Belgian non-profit collection organization Recupel. Figures for the period 1995–2013 are shown in Appendix A. Recupel was founded in 2001 and started registering the number of EEE products placed on the Belgian market in 2003 by their members, which at that time accounted for more than 99% of all Belgian OEMs and importers of electronic displays. However, for the declaration of the number of products placed on the market, the OEMs and importers of EEE only made the distinction between FPD and CRT for monitors and not for TVs. Therefore, the historic sales and the transition from CRT to LCD TVs for Belgium are based on the information obtained through personal communication with Recupel that since 2007 no CRT TVs have been placed on the Belgian market. The data on the number of electronic displays of Recupel were also crosschecked with the data retrieved from national registers and the data analyzed by Magalini et al. (2014). Crosschecking of the data from these three different sources indicated significant discrepancies. These discrepancies can be explained by the distinct product sales data acquisition methods and data sources used. For this study the data of Recupel are used, since they are believed to be the most reliable data for Belgium. These data are complemented with the data of Magalini et al. for the number of electronic displays that were placed on the Belgian market before 2003.

Market specialists expect a shift in TV replacement cycle from FPD replacement of CRT TVs, to flat panel upgrades with more advanced display technologies, such as LED backlighted and Organic LED (Display Search, 2012). Furthermore, the global TV demand is forecasted to flatten from 2013 onwards, due to the rising household penetration of FPD TVs, the saturation of the market and because of the slowing economic growth (Display Search, 2012). Therefore, the number of FPD TVs and monitors put on the market are assumed to remain constant from 2014 onwards for the presented forecast.

2.4. Product lifetime distribution

Due to the introduction of new display technologies, dynamic modeling of waste flows of electronic displays is required. Since the Netherlands and Belgium have comparable economies, a linear extrapolation of the Weibull parameters for the lifetime distribution of electronic displays in the Netherlands, as determined by Wang et al. (2013) is used in the presented forecast, as shown in Appendix A. These time varying lifetime parameters were determined with a multivariate analysis method, which links product sales, stock and lifespan profiles to construct mathematical relationships between various data points.

2.5. Collection share

The actual share of the discarded products $S_{(yw)}$ that will be collected in yw is a factor which, depending on the scope of the forecast, either represents the efficiency of a regional collection system or the actual market share of a specific recycling plant. The scope of the presented forecast is Belgium. However, since only limited data are available for the numbers of FPDs collected for recycling in Belgium, this factor is based on the collection rates analyzed by Huisman et al. in 2012 for the Netherlands of 39.2% for monitors and 92% for TVs (Huisman et al., 2012).

The share of electronic displays that will be collected for recycling is expected to increase as a result of the higher collection target stipulated in the European WEEE directive of 2012, which will become legally binding in 2016 and prescribes that 45% of the average weight of products placed on the market in the three preceding years must be collected. In 2019 this annual collection target will rise to 65%. As an alternatively to this target, member state can in 2019 also opt to collect 85% of the WEEE generated. Therefore, the collection share for monitors has been assumed to linearly increase from 2012 onwards to 85% in 2019 and to be constant afterward, as shown in Appendix A.

2.6. Housing weight

The amount of materials that will be discarded can be forecasted based on the total weight of products placed on the market. However, to obtain a better insight in the composition of future waste streams, it is advisable to take into account the evolution in the mass of individual sub-assemblies or components. In order to analyze emerging trends in the mass of back covers of electronic displays, the individual weight of back covers was measured. The analyzed linear trends in back cover weight are used for the forecasts of the four case study products.

2.7. Material composition

To determine the average material composition of the plastic housings, a disk with a diameter of 50 mm was cut out of every back cover of the analyzed electronic displays. For every collected plastic sample the color and the type of display was registered by means of visual inspection. The distinction between a TV and a monitor was made based on the presence of an antenna slot. In addition, the product brand, the year of production and the plastic type and FR used in the back cover were registered based on information from the in mold marking or the product label.

Since prior studies have indicated that a substantial share of plastic components are mismarked (Xiuli et al., 2006; Gent et al., 2011), the type of plastics indicated in the product labels was verified by means of Laser Induced Breakdown Spectroscopy (LIBS).

LIBS scanners use a high energetic laser beam to form a plasma and to excite a range of elements to emit light with element specific wavelengths. For the performed experiments the LIBS scanner developed by Bertin Technologies was used. The spectral library used was specially trained with samples from LCD TVs, which enabled to identify both the presence of PFRs and BrFRs, as well as the identification of all plastic types used in housings of electronic displays. To verify the accuracy of the LIBS technology, the plastics of 72 FPD TVs were also analyzed with a Fourier Transform InfraRed (FTIR) scanner to identify their plastic type and with a Sliding-Spark SPectroscopy (SSSP) for the identification of the FRs. With FTIR the mid-infrared absorption spectrum of plastics is analyzed and compares it with those of reference samples stored in a library. For the performed experiments the lab scale Perkin FTIR scanner was used with the standard accompanying spectral libraries. The SSSP thermally vaporizes a small amount of the plastic surface by using high-voltage sparks to activate the different elements present in the plastic, which emit a specific and measurable radiation. For the performed experiments the mIRoSpark hand SSSP scanner developed by the company GUT was used. Results of these analyses indicated that the analyses performed with the LIBS, FTIR and SSSP were highly corresponding. Because of the high accuracy of the LIBS scanner and the possibility to simultaneously analyze the plastic type and presence of FRs, only LIBS analysis results were used within this research.

The SWA-tool developed to enhance the precision and comparability of solid waste analysis states that the minimum sample size should be based on experience of former waste analysis when the variation coefficient of the analyzed waste is unknown (iC consulenten ZT GmbH, 2004). However, the minimal sample size to determine the plastic composition of WEEE with a high confidence level based on individual product analysis has not been assessed in prior research. Therefore, the number of samples collected is determined based on budgetary constraints. To increase the reliability of the data on the material composition of recent and older products the input data on the average material composition $C_{(ys,i)}$ per year of sales are smoothened. This is done by calculating a moving average with the year of production, the precedent year and the succeeding year for every year of which more than 5 data point are available. For the other years, for which too limited data are available, an extrapolation is made from the nearest determined moving average of the material composition.

Since only a limited number of recent FPD TVs were retrieved in the current waste stream, the plastic composition of FPD TVs after 2010 is forecasted based on the preference of material use by different brands and their market share. The material preference is analyzed for all FPD TV brands with a market share in Belgium of more than 5%, as shown in Fig. 1. This analysis demonstrates, for example, that SONY and Philips have only used plastics with phosphorus based FRs.

3. Results

In this section the results of the product analysis and plastic composition analysis of housings of electronic displays are presented, as well as the results of applying the presented methodology to forecast the composition of housing plastics of CRT and FPD TVs and monitors.

3.1. Housing weight

In total, 252 FPD TVs, 60 CRT TVs, 45 FPD monitors and 101 CRT monitors were analyzed after manual disassembly. The results of this analysis, shown in Fig. 2, indicate a significant variation in the weight of back covers of all types of electronic displays, which is due to the wide variety of display sizes, back cover geometries and applied plastic types. Due to the limited number of samples and high variation in back cover weight, only trends with a low significance were identified. However, the performed analysis for CRT TVs confirmed the expected increase in the weight of the back cover due to the increasing display size of later CRT models.

3.2. Waste composition

In total, 56 CRT TVs, 103 CRT monitors, 62 FPD monitors and 269 FPD TVs of the Belgian waste stream were analyzed in September 2014. Of these products the average plastic and FR type are shown in Fig. 3. The performed analyses show that housings of electronic displays are dominated by ABS, HIPS, PC/ABS, HIPS/PPE and ABS/PMMA, and that only a limited share of the plastics of CRT TV housings is PolyPropylene (PP). Furthermore, these results show that FPD monitors are dominated by ABS (63%), CRT monitors by ABS with Br FR (44%) and PC/ABS (39%), CRT TVs by HIPS (50%) and FPD TVs by HIPS with and without Br FRs (13%/28%), HIPS/PPE with P FR (20%) and PC/ABS with P FR (31%). The presented results are well corresponding to the plastic composition of CRT monitors and TVs investigated by Martinho et al. based on the in mold indicted plastic type and NIR analysis (Martinho et al., 2012). Only the share of PC/ABS and HIPS/PPE in CRT TVs analyzed in this research is 2% and 18% higher than reported by Martinho et al. This difference is expected to be because Martinho et al. only analyzed CRT TVs from before 1988, whereas more than 95% of the CRT TVs analyzed in this research are from after 1988. Compared with the analysis reported by Aldian et al., the performed analyses indicate that the share of plastics with a Br FRs concentration of more than 1000 PPM is 5% lower for CRT TVs and 2% lower for CRT monitors. However, the year of production of the analyzed products was not reported by Aldian et al. Furthermore, the performed analysis indicated a substantial difference in the plastic composition of CRT and FPD TVs and monitors, which can explain the variation in plastic composition of plastics separated from mixed WEEE streams reported by Stenvall et al. (2013).

3.3. Forecasted plastic waste compositions

As shown in Fig. 4, the amount of plastics housings collected from EoL CRT TVs is forecasted to rapidly decrease. This waste stream is mainly dominated by HIPS based plastics of which a substantial share contains P FRs and a small share Br FRs. In contrast, the amount of plastics to be recycled from FPD TVs is rapidly increasing, as shown in Fig. 5. In addition, the complexity of this waste stream is rapidly increasing, as a result of the increasing share of FR plastics.

As shown in Fig. 6, the plastic waste from CRT monitors already significantly decreased, as was confirmed during personal communication with multiple recycling companies. In contrast, the waste of FPD monitors will further increase in the coming years, as shown in Fig. 7. This shift from CRT to FPD monitors is forecasted to result in a shift in the composition of plastic waste from a PC/ABS with PFR and ABS with Br FR dominated mix to a HIPS non-FR and ABS non-FR plastic mix.

4. Discussion

In this section first the reliability of the presented forecasts is discussed. Thereafter, the consequences for the recycling sector of the forecasted evolution in the composition of plastic waste of housings of electronic displays are discussed.

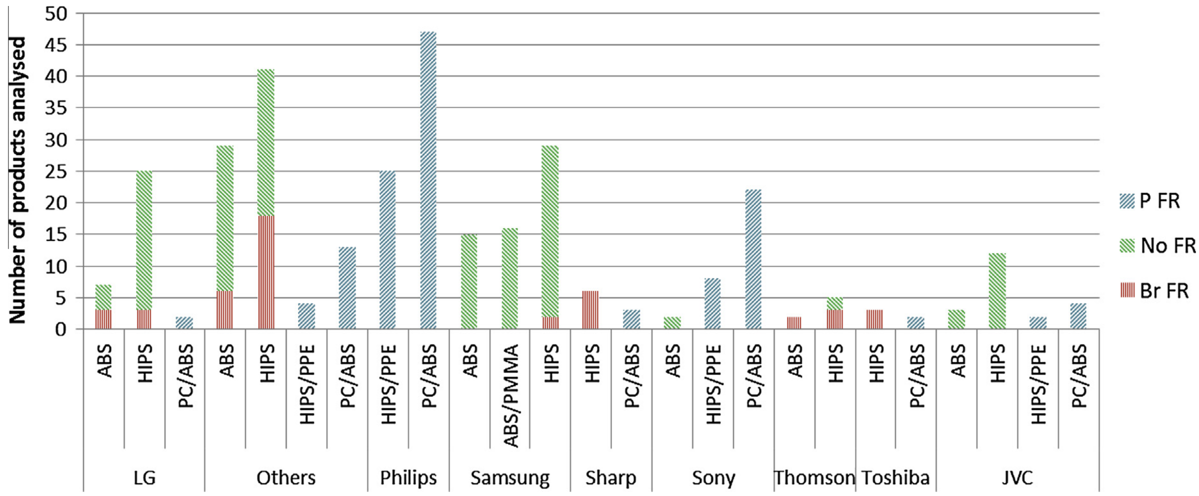

Fig. 1. Plastic and FR preference of FPD manufacturers with a market share larger than 5%.

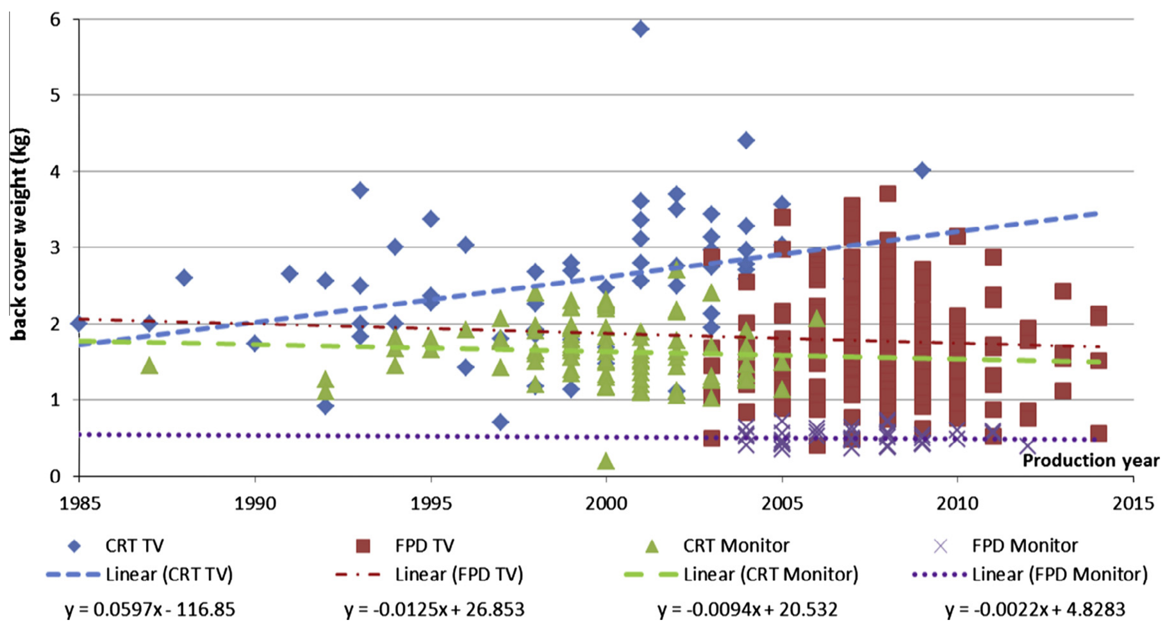

Fig. 2. Evolution of the weight of plastic back covers for FPD and CRT monitors and TVs.

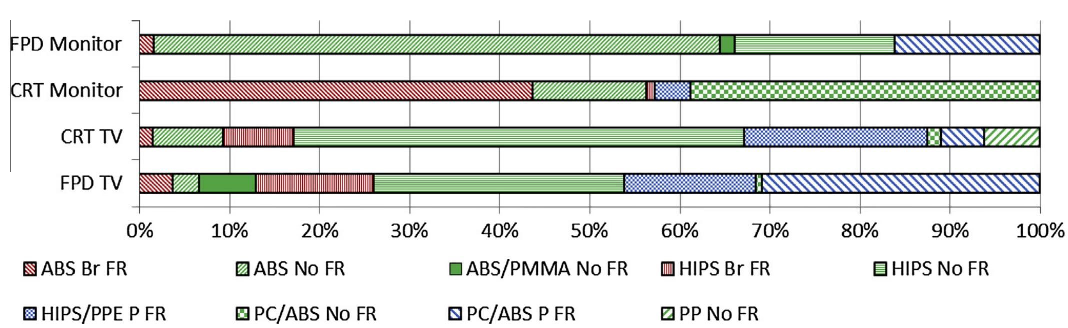

Fig. 3. Results of the LIBS analysis of 56 CRT TVs, 103 CRT monitors, 62 FPD monitors and 269 FPD TVs.

4.1. Reliability

The overall objective of the presented forecasts is to demonstrate the applicability and value of the developed methodology. In addition, the objective of this forecast is to provide insight in the orders of magnitude of the rate at which the amount of plastic housing waste from electronic displays will evolve and to analyze global trends in the evolution of the material composition of this waste stream. The presented forecasts should be interpreted with care, for instance when used for the evaluation of the economic

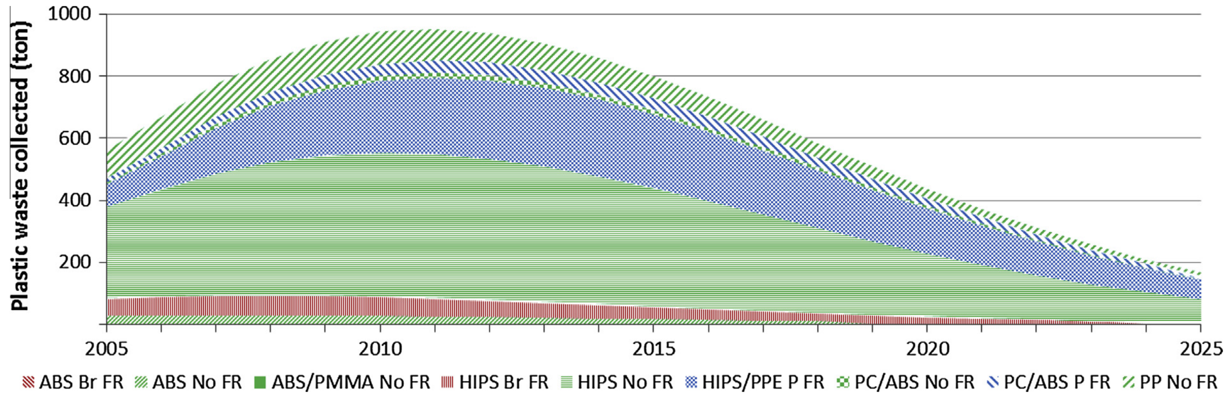

Fig. 4. Forecasted annual amount of plastics from CRT TVs collected for EoL treatment in Belgium.

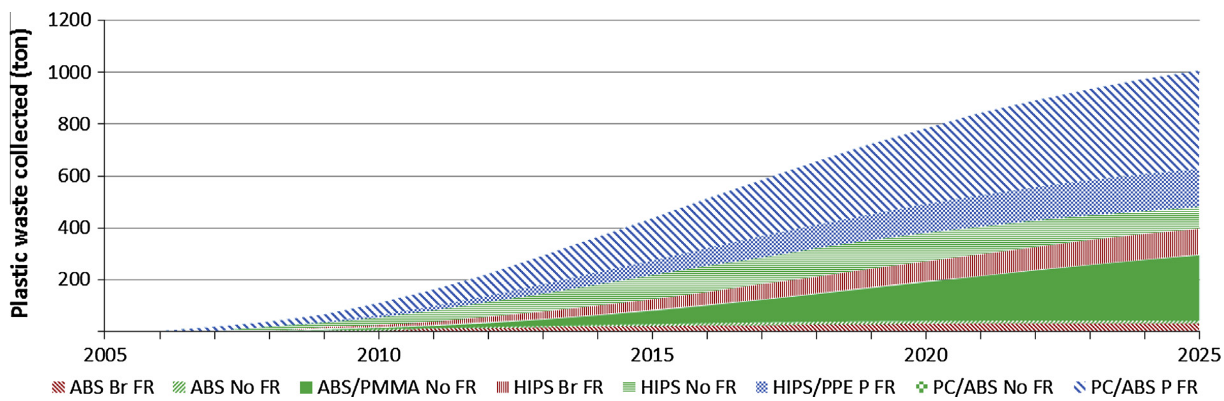

Fig. 5. Forecasted annual amount of plastics from FPD TV collected for EoL treatment in Belgium.

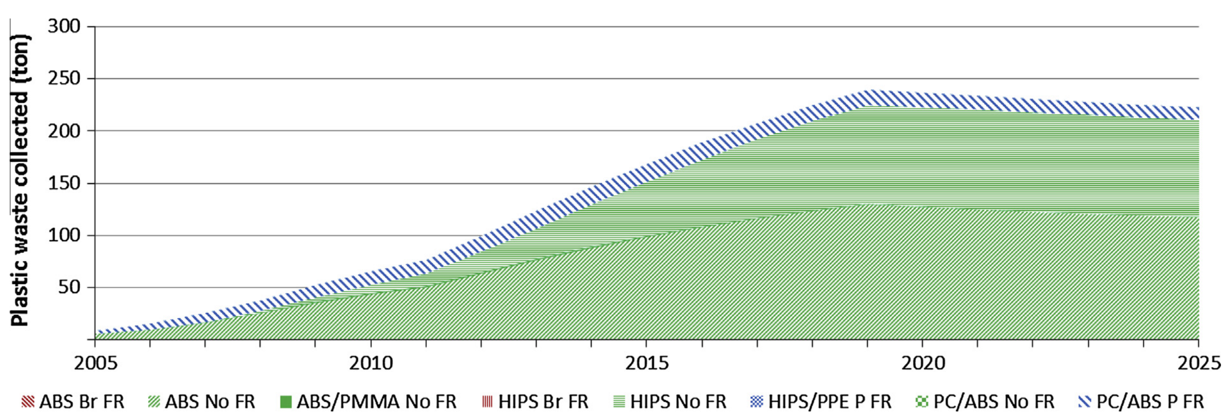

Fig. 6. Forecasted annual amount of plastics from CRT monitors collected for EoL treatment in Belgium.

viability of the implementation of innovative recycling technologies. It should be stressed that the quality of the presented forecast depends on the quality of the available input data and a number of assumptions with respect to future trends in the production of new devices.

For example, data on the material composition of the products placed on the market is essential to forecast the material composition of future waste streams. For this reason, it should be considered that the presented forecasts are based on a representative but also limited number of samples. In addition, the composition analyses have been performed based on mainly early failing products, which failed due to accidents caused by external factors and installation accidents or because of low product quality. There is the possibility that this could influence the analyzed material composition and, accordingly, the forecast. It is indeed possible that, when lower quality products dominate the emerging waste fraction, the analyzed material composition is not a good representation of the average material composition used. However, for the analyzed products there were no indications that this was the case, since many different types of products of different brands, including high quality brands, were retrieved in the analyzed waste streams.

In addition, the accurateness of the lifetime distribution and product sales data are crucial to properly forecast the velocity of

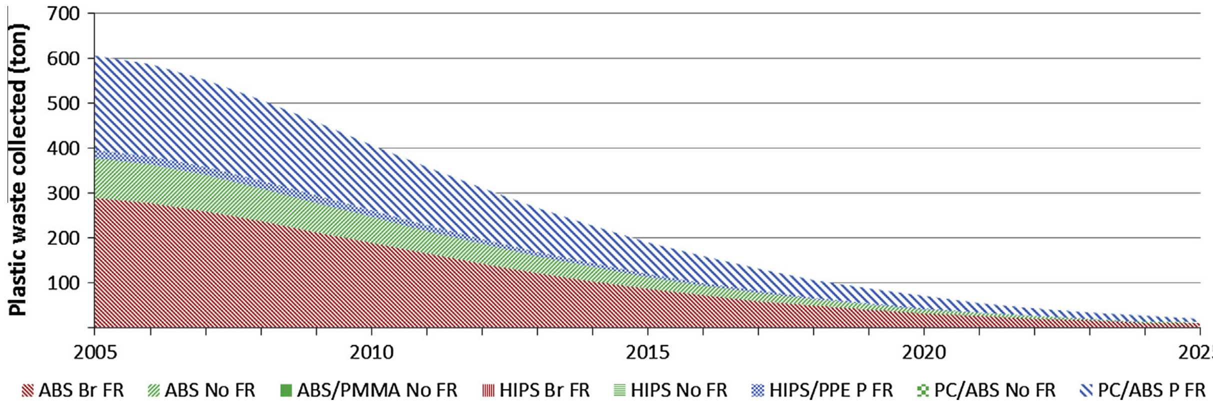

Fig. 7. Forecasted annual amount of plastics from FPD monitor collected for EoL treatment in Belgium.

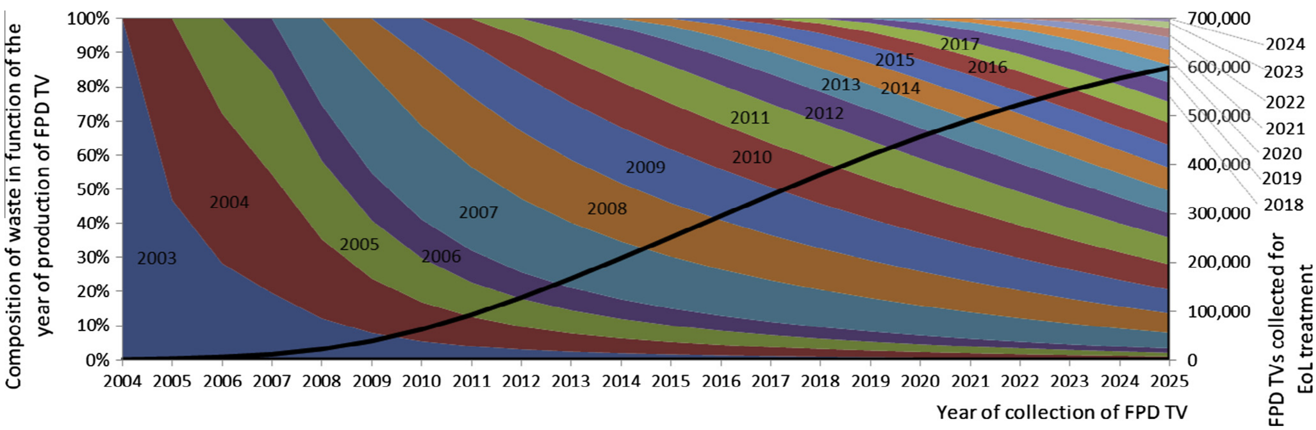

Fig. 8. Year of production of the FPDs TV (in legend) that will be collected for recycling (in the year on the horizontal axis).

the changes in material composition, as well as plastic waste volumes. For these parameters the presented research relied on data from "Recupel" and prior research (Magalini et al., 2014).

Furthermore, changes in the material utilized by OEMS have a significant influence on the forecasted waste composition, whereas the point in time that these changes will influence the waste composition depends on the product lifetime distribution. Therefore, the reliability of the forecasted waste composition should always be evaluated in function of the lifetime distribution of the products under study. In case of the FPD TVs with an average lifetime of approximately 13 years, future changes in the type of plastics used will only influence the forecasted composition to a limited extend. For example, based on the number of FPD TVs placed on the Belgian market and the parameters of the Weibull parameters of the lifetime distribution shown in Appendix A, the FPD TV housing plastic waste in 2025 is calculated with Eq. (1) to originate for approximately 25% of products produced before 2010 and approximately 60% of products produced until 2015, as shown in Fig. 8.

In order to improve the quality of the input data on material composition, which in turn results in a more accurate forecast of waste streams, a larger scale sampling of emerging waste streams is required. Another possibility is to increase the information exchange between OEMs and recycling companies on the material composition of products placed on the market. Whereas recently developed technologies could facilitate the systematic sampling of plastic waste streams, information exchange between OEMs and recyclers would enable more accurate long term forecasting of trends in material compositions. The enforcement of such material declaration requirements are currently under discussion for the review of the European Ecodesign Directive. However, to guarantee that the provided data by OEMs can be used to forecast waste stream compositions, it is crucial that these data are gathered in a well-structured database, which allows aggregating the product specific data.

In addition, it should be considered that OEMs will not be willing to supply detailed data until a late stage of the commercial product lifetime. In addition, OEMs are not able to supply data with sufficient detail for historic product sales, since detailed data on material composition has often not been systematically registered by OEMs. Therefore, a combination of data from OEMs and data from the systematic material sampling of arising waste streams is required to forecast waste compositions with higher detail and reliability. Accordingly, the presented forecasting methodology allows a combination of both data sources.

4.2. Implications for the recycling sector

As shown in Fig. 9, the transition from CRT to FPD technology and the implementation of legislation on fire-safe housings for TVs has resulted in changes in the type of plastics and additives applied in electronic display housings. In addition, it is demonstrated that the plastic and FR types used for the housing of the four electronic displays analyzed strongly differ, whereas CRT TVs and monitors or FPD TVs and monitors are often perceived as similar products and are consequently jointly treated at EoL.

One of the main differences is that banned Br FRs are only present in CRT TVs and CRT monitors, which is not the case for LCD TVs and LCD monitors. However, the forecasted share of Br

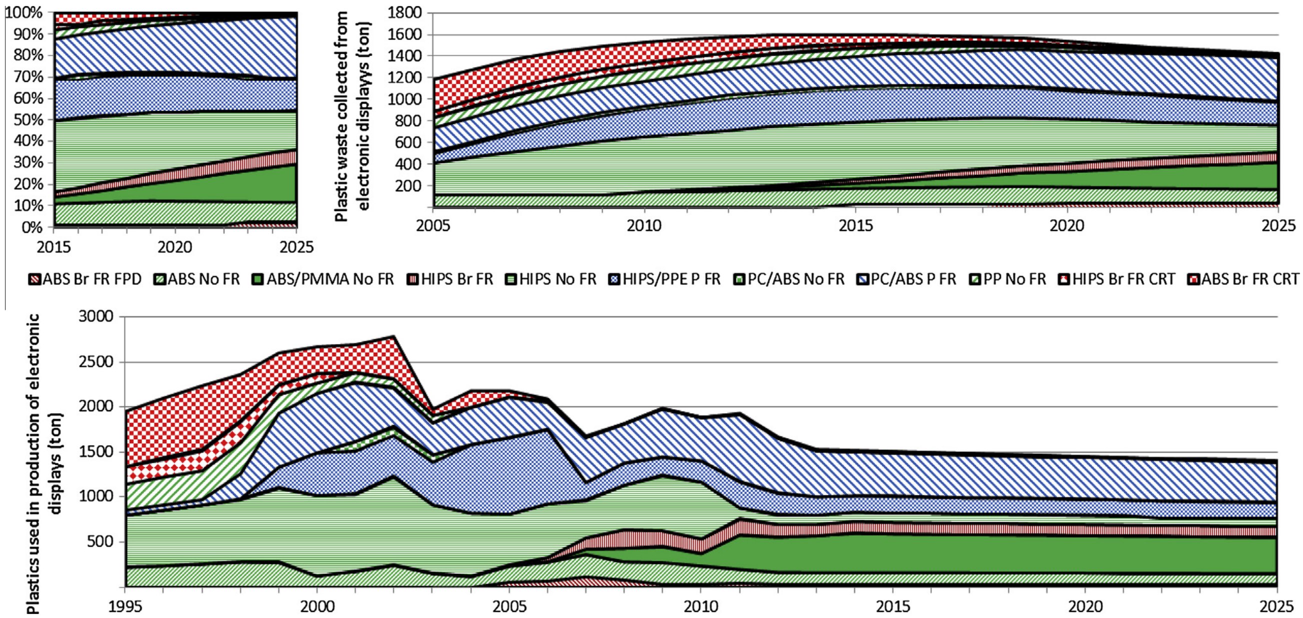

Fig. 9. Annual amount of plastics used in electronic displays placed on the Belgian market and that will be collected for EoL treatment in Belgium.

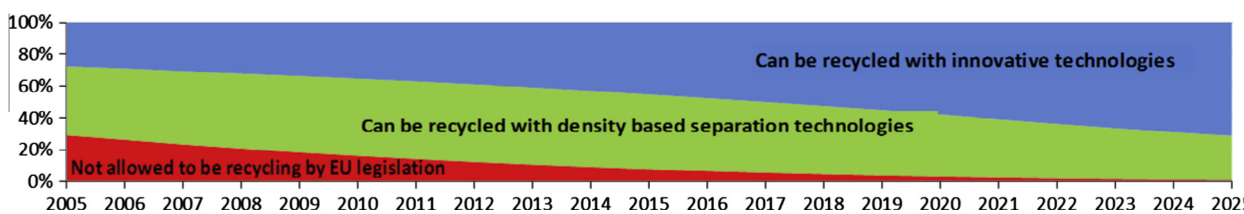

Fig. 10. Forecasted share of plastic from EoL electronic displays in Belgium that can be recycled with different categories of technologies.

FR plastics (as shown in Fig. 9) is forecasted to further reduce from 8% to 1% in 2025. It should be noted that only a share of these Br FR plastics is banned and is not allowed to be recycled in Europe, but the separation in a recycling process of different types of Br FR plastics is nowadays not technically possible. Another difference in the forecasted material compositions is the low presence of FRs in back covers of FPD monitors and CRT TVs. From these products the relatively high share of HIPS and ABS without FRs can be separated with a high efficiency for recycling in commonly applied density based plastic separation processes.

In contrast, high amounts and multiple types of FR plastics are found in housings of EoL FPD TVs. Due to the decreasing number of CRT TVs and the relatively small quantity of back covers of FPD monitors that are forecasted to be collected, the complexity of the plastic waste from housings of electronic displays will significantly increase. However, it is not possible to sort and recycle the FR plastics with a high efficiency with commonly adopted shredder based recycling processes (Tange et al., 2013). Plastics are commonly separated based on their specific density, whereas FR plastics present in FPD TVs are characterized by a wide spread in density, which overlaps with the density of other plastics that are non-compatible for recycling. In addition, PFR plastics have hydrophobic properties, which impede the separation of these plastics based on density. Furthermore, post-shredder separation of housing plastics of FPD TV based on near infrared analysis is not possible due to the high concentration of black plastics used in TVs. Accordingly, separating FR plastics in a size reduction based treatment still requires several technical challenges to be faced, while at the same time high investments are required to separate FR plastics after size-reduction (Peeters et al., 2013b). As a result, it will become increasingly difficult for recycling companies to achieve the material recovery rates put forward in the European WEEE directive.

Prior research has demonstrated that selective removal of PWBs significantly improves the recycling efficiency of the Precious Metals (PMs) present in these boards (Meskers et al., 2009). For this reason and as a result of the rise in PM prices over the last decade, EoL electronics with high grade PWBs are in many cases disassembled (reversible removal) or dismantled (destructive removal) to increase value recovery. In consequence, plastic housings are also systematically removed to access the PWBs, which facilitate the sorting of plastic components based on advanced optical identification techniques, such as LIBS. In addition, Peeters et al. demonstrated that closed loop recycling of the plastic PC/ABS PFR in a disassembly based treatment is technically feasible with recent developed technologies and is economically viable in Europe (Peeters et al., 2013b, 2013c).

Taking into account the limitations of density based plastic separation processes, it can be concluded that in 2005 it was possible to recycle 43% of the housing plastic of electronic displays in a density based recycling process. This percentage could have been increased with 27–71% in the same year when taking into account the plastic separation efficiency of systematic disassembly/dismantling and plastic identification processes. The remaining 29%, which are Br FR plastics, can be considered as non-recyclable. This is due to the fact that it was and still is not possible to separate the Br FR plastics classified as POPs from these Br FR plastics which can be recycled in compliance with EU legislation. As shown in Fig. 10,

Table A1
Number of electronic displays placed on the Belgian market, Weibull parameters of lifetime distribution and collection rate (RED = assumed values).

	CRT Monitor				FPD Monitors				CRT TV				FPD TV			
	POM	Scale	Shape	Collection	POM	Scale	Shape	Collection	POM	Scale	Shape	Collection	POM	Scale	Shape	Collection
1995	4,45,008	9.047	1.500	39%		8.000	2.429	39%	5,11,946	14.500	2.246	92%		15.000	2.058	92%
1996	4,91,859	8.961	1.496	39%	812	7.947	2.403	39%	5,29,199	14.310	2.216	92%		15.000	2.058	92%
1997	5,22,443	8.875	1.493	39%	14,989	7.894	2.378	39%	5,47,254	14.120	2.187	92%		15.000	2.058	92%
1998	5,55,287	8.788	1.489	39%	13,403	7.841	2.352	39%	5,65,655	13.930	2.158	92%		15.000	2.058	92%
1999	6,54,665	8.888	1.485	39%	22,378	7.788	2.326	39%	5,79,074	13.740	2.128	92%	216	15.000	2.058	92%
2000	6,48,906	8.988	1.481	39%	32,428	7.735	2.301	39%	5,96,286	13.550	2.099	92%	2,161	15.000	2.058	92%
2001	6,12,717	9.088	1.478	39%	73,206	9.250	2.275	39%	6,13,380	13.360	2.069	92%	21,614	15.000	2.058	92%
2002	6,15,179	9.188	1.474	39%	1,45,148	9.019	2.250	39%	6,24,462	13.170	2.040	92%	43,227	15.000	2.058	92%
2003	5,07,112	9.288	1.470	39%	4,07,986	8.789	2.224	39%	6,35,193	12.980	2.010	92%	86,454	15.000	2.058	92%
2004	4,73,240	8.988	1.466	39%	6,78,030	8.558	2.199	39%	6,87,763	12.790	1.981	92%	2,41,888	15.000	2.058	92%
2005	2,39,611	8.688	1.463	39%	9,43,265	7.470	2.173	39%	7,21,053	12.600	1.952	92%	3,30,648	15.000	2.058	92%
2006	1,31,960	8.388	1.459	39%	10,47,695	7.385	2.109	39%	6,51,775	12.075	1.870	92%	3,45,817	15.000	2.058	92%
2007	97,585	8.088	1.455	39%	8,82,199	7.300	2.045	39%	1,02,565	11.550	1.789	92%	6,72,771	15.000	2.058	92%
2008	63,209	7.788	1.451	39%	9,34,000	7.216	1.981	39%	17,639	11.025	1.708	92%	8,22,106	15.000	2.058	92%
2009	24,482	7.988	1.448	39%	7,77,000	7.131	2.300	39%	40,870	10.500	1.626	92%	8,77,318	15.000	2.058	92%
2010		8.188	1.444	39%	6,86,396	7.032	2.300	39%	20,547	10.364	1.605	92%	9,77,285	15.000	2.058	92%
2011		8.388	1.440	39%	7,58,393	6.933	2.300	39%	5,165	10.227	1.584	92%	9,91,703	15.000	2.058	92%
2012		8.588	1.436	45%	6,27,346	6.834	2.300	45%	650	10.091	1.563	92%	9,09,444	15.000	2.058	92%
2013		8.788	1.433	51%	6,03,335	6.735	2.300	51%		9.955	1.542	92%	10,00,000	15.000	2.058	92%
2014		8.788	1.429	56%	6,03,335	6.636	2.300	56%		9.818	1.521	92%	10,00,000	15.000	2.058	92%
2015		8.788	1.425	62%	6,03,335	6.537	2.300	62%		9.682	1.500	92%	10,00,000	15.000	2.058	92%
2016				68%	6,03,335	6.537	2.300	68%				92%	10,00,000	15.000	2.058	92%
2017				74%	6,03,335	6.537	2.300	74%				92%	10,00,000	15.000	2.058	92%
2018				79%	6,03,335	6.537	2.300	79%				92%	10,00,000	15.000	2.058	92%
2019				85%	6,03,335	6.537	2.300	85%				92%	10,00,000	15.000	2.058	92%
2020				85%	6,03,335	6.537	2.300	85%				92%	10,00,000	15.000	2.058	92%
2021				85%	6,03,335	6.537	2.300	85%				92%	10,00,000	15.000	2.058	92%
2022				85%	6,03,335	6.537	2.300	85%				92%	10,00,000	15.000	2.058	92%
2023				85%	6,03,335	6.537	2.300	85%				92%	10,00,000	15.000	2.058	92%
2024				85%	6,03,335	6.537	2.300	85%				92%	10,00,000	15.000	2.058	92%
2025				85%	6,03,335	6.537	2.300	85%				92%	10,00,000	15.000	2.058	92%

the share of plastics that can be recycled with density based separation technologies is forecasted to decrease to only 28% in 2025. When disassembly/dismantling based treatments and plastic separation based on optical identification are implemented, the share of plastics that can be recycled is forecasted to increase to 99% in 2025.

Consequently, only the adoption of systematic disassembly/dismantling and plastic identification processes will enable to close material loops for housings of electronic displays with a high efficiency. These findings stress the importance of design for disassembly of which prior research has demonstrated the technological and economic viability for FPD TVs (Peeters et al., 2015). Future research will investigate post-disassembly/dismantling plastic separation processes based on advanced optical identification techniques. In addition, the recycling of plastics from multiple categories of WEEE and from EoL vehicles will be targeted in future research, to enable recyclers to benefit from the economies of scale and scope. For the same purpose, also the recycling of other plastic components from these waste streams, such as the light guides and diffusers in LCDs, will be investigated.

The quantification of the plastic separation efficiency, together with the results of the presented research will provide insight on the economic and technologic feasibility of a transition to a circular economy. This evaluation of the economic and technical feasibility of closed loop recycling of plastics will also provide insights on the applicability of existing recycling processes and the potential availability of recyclates considering the rapidly evolving plastic compositions of waste streams. The authors believe that these insights are essential input for legislation makers to define more challenging, but at the same time achievable, requirements for recycling companies than the arbitrary defined recovery and recycling rates of the European WEEE directive. In addition, these insights are essential to define challenging, but at the same time achievable, targets on minimum required percentage of recycled content, as are increasingly adopted by eco-labels and considered to be included in the European Ecodesign directive. This, with the objective to provide the stimuli needed to accelerate the transition to a circular and more sustainable economy.

5. Conclusions and future work

To steer the development of innovative recycling technologies and to enable recycling companies to properly evaluate the economic viability of the implementation of these technologies, insights on the material composition of future waste streams is essential. However, currently only limited information on the material composition of waste streams is available and even less on how the material composition will evolve. To fill this gap, this research presents a methodology to forecast trends in waste material composition.

The presented methodology is used to forecast the evolution of waste of plastic housings from electronic displays in Belgium. These forecasts indicate that different plastic and FR compositions will be found in the waste stream from housings of CRT and FPD TVs and monitors. One of the differences is that only the housing plastics of FPD monitors and CRT TVs will be characterized by a high share of HIPS and ABS without FRs. Consequently, it is possible to separate and recycle the housing plastics of these products with a relatively high efficiency in commonly applied density based plastic separation processes.

In contrast, high amounts and multiple types of mainly FR plastics will be found in housings of EoL FPD TVs and CRT monitors. Since these FR plastics cannot be recycled with commonly applied techniques, the share of housing plastics that can be separated and recycled from electronic displays in a density based process is forecasted to decrease from 43% in 2005 to only 28% in 2025. Conversely, the share of plastics that can be separated and recycled by the application of a disassembly/dismantling based EoL treatment in combination with innovative plastic identification techniques is forecasted to increase from 70% in 2005 to 99% in 2025. Consequently, plastic recycling companies will have to adopt systematic disassembly/dismantling and plastic identification processes to comply with EU legislation and to assure value recovery from these product categories.

By means of the presented case study the applicability of the reported methodology is demonstrated. One of the main advantages of the presented methodology is that it allows forecasting the material composition of the waste stream that will be collected for EoL treatment, whereas prior developed forecasting methods can only be used to forecast waste streams on a product level. Furthermore, the results of this case study demonstrate how the presented methodology can provide valuable insights to both policy makers and recycling companies.

Acknowledgements

The authors acknowledge the Flemish Environmental Technology Platform (MIP) and the Agency for Innovation by Science and Technology in Flanders (IWT) for funding this research. The authors also like to acknowledge the following companies and organizations for collaboration: Recupel, Bertin Technologies, Van Gansewinkel, and the associated members of EFRA.

Appendix A

See Table A1.

References

Araújo, M.G., Magrini, A., Mahler, C.F., Bilitewski, B., 2012. A model for estimation of potential generation of waste electrical and electronic equipment in Brazil. Waste Manage. 32, 335–342.

Bakker, C., Wang, F., Huisman, J., den Hollander, M., 2014. Products that go round: exploring product life extension through design. J. Clean. Prod. 69, 10–16.

Beigl, P., Lebersorger, S., Salhofer, S., 2008. Modelling municipal solid waste generation: a review. Waste Manage. 28, 200–214.

Berkhout, F., Hertin, J., 2004. De-materialising and re-materialising: digital technologies and the environment. Futures 36, 903–920.

Böni, H.W., Hischier, R., Wäger, P., 2010. Incineration vs. recycling of WEEE plastics results of a life cycle assessment study. In: Presented at the 9th International Electronics Recycling Congress Salzburg.

Chancerel, P., 2010. Substance flow analysis of the recycling of small WEEE. Dissertation Thesis. Institut für Technischen Umweltschutz, Berlin.

Chung, S.-S., Lau, K.-Y., Zhang, C., 2011. Generation of and control measures for, e-waste in Hong Kong. Waste Manage. 31, 544–554.

Council Decision 2006/507/EC concerning the conclusion, on behalf of the European Community, of the Stockholm Convention on Persistent Organic Pollutants, 2004.

Display Search, 2012. Global TV Demand Expected to be Flat in 2013, According to NPD DisplaySearch. <http://www.displaysearch.com/>.

Dodbiba, G., Takahashi, K., Sadaki, J., Fujita, T., 2008. The recycling of plastic wastes from discarded TV sets: comparing energy recovery with mechanical recycling in the context of life cycle assessment. J. Clean. Prod. 16, 458–470.

Dwivedy, M., Mittal, R.K., 2010. Estimation of future outflows of e-waste in India. Waste Manage. 30, 483–491.

European Chemicals Bureau and European Commission, 2003. European Union Risk Assessment Report. Diphenyl Ether, Octabromo Derivative, Luxembourg, 2003.

Eropean Flame Retardant Association, 2014. Flame Retardants used in Enclosures. <http://www.cefic-efra.com/index.php/enclosures>.

Gent, M.R., Mario, M., Javier, T., Susana, T., 2011. Optimization of the recovery of plastics for recycling by density media separation cyclones. Resour. Conserv. Recycl. 55, 472–482.

Huisman, J., Ansems, T., Feenstra, L., Stevels, A., 2001. The QWERTY concept, a powerful concept for evaluating the environmental consequences of end-of-life processing of consumer electronic products. In: Proceedings EcoDesign 2001: Second International Symposium on Environmentally Conscious Design and Inverse Manufacturing, 2001, pp. 929–934.

Huisman, J., van der Maesen, M., Eijsbouts, R.J.J., Wang, F., Baldé, C.P., Wielenga, C.A., 2012. The Dutch WEEE Flows.

iC consulenten ZT GmbH, 2004. Methodology for the Analysis of Solid Waste (SWA-Tool) User Version (Ed.).
Kolias, K., Hahladakis, J.N., Gidarakos, E., 2014. Assessment of toxic metals in waste personal computers. Waste Manage. 34, 1480–1487.
Li, B., Yang, J., Lu, B., Song, X., 2015. Estimation of retired mobile phones generation in China: a comparative study on methodology. Waste Manage. 35, 247–254.
Magalini, F., Wang, F., Huisman, J., Kuehr, R., Baldé, K., Straalen, V.v., Hestin, M., Lecerf, L., Sayman, U., Akpulat, O., 2014. Study on collection rates of waste electrical and electronic equipment (WEEE). Preliminary version, subject to final verification, 2014.
Martinho, G., Pires, A., Saraiva, L., Ribeiro, R., 2012. Composition of plastics from waste electrical and electronic equipment (WEEE) by direct sampling. Waste Manage. 32, 1213–1217.
Melo, M.T., 1999. Statistical analysis of metal scrap generation: the case of aluminium in Germany. Resour. Conserv. Recycl. 26, 91–113.
Meskers, C., Hagelüken, C., Salhofer, S., 2009. Impact of pre-processing routes on precious metal recovery from PCs. In: Presented at the European Metallurgical Conference (EMC), Innsbruck, Austria.
Morf, L.S., Tremp, J., Gloor, R., Huber, Y., Stengele, M., Zennegg, M., 2005. Brominated flame retardants in waste electrical and electronic equipment: substance flows in a recycling plant. Environ. Sci. Technol. 39, 8691.
Nelen, D., Manshoven, S., Vanegas, P., Peeters, J.R., 2014. A multidimensional indicator set to assess the benefits of WEEE material recycling. Accept. J. Clean. Prod.
Patel, M., Thienen, N.v., Jochem, E., Worrell, E., 2000. Recycling of plastics in Germany. J. Resour. Conserv. Recycl., 65–90
Peeters, J.R., Vanegas, P., Dewulf, W., Duflou, J.R., 2012. End-of-life treatment strategies for flat screen televisions: a case study. Sustain. Manufact. 13, 103–108.
Peeters, J.R., Vanegas, P., Duflou, J.R., Mizunoc, T., Fukushigec, S., Umeda, Y., 2013a. Effects of boundary conditions on the end-of-life treatment of LCD TVs. CIRP Annal. Manufact. Technol. 62, 35–38.
Peeters, J.R., vanegas, P., Tange, L., Van Houwelingen, J., Duflou, J.R., 2013b. Closed loop recycling of plastics containing flame retardants. Resour. Conserv. Recycl. 84, 36–43.
Peeters, J., Vanegas, P., Devoldere, T., Dewulf, W., Duflou, J., 2013c. Product clustering for closed loop recycling of flame retardant plastics: a case study for flat screen TVs. In: Nee, A.Y.C. et al. (Eds.), Re-engineering Manufacturing for Sustainability. Springer, Singapore, pp. 383–388.
Peeters, J.R., Vanegas, P., Tange, L., Van Houwelingen, J., Duflou, J.R., 2014. Closed loop recycling of plastics containing Flame Retardants. Resour. Conserv. Recycl. 84, 35–43.
Peeters, J.R., Vanegas, P., Van den Bossche, W., Devoldere, T., Dewulf, W., Duflou, J.R., 2015. Elastomer-based fastener development to facilitate rapid disassembly for consumer products. J. Clean. Prod. 94, 177–186.
Pezzini, M., 2012. An emerging middle class. In: OECD Yearbook (Ed.).
Polák, M., Drápalová, L., 2012. Estimation of end of life mobile phones generation: the case study of the Czech Republic. Waste Manage. 32, 1583–1591.
Ryan, A., O' Donoghue, L., Lewis, H., 2011. Characterising components of liquid crystal displays to facilitate disassembly. J. Clean. Prod. 19, 1066–1071.
Salhofer, S., Spitzbart, M., Maurer, K., 2012. Recycling of flat screens as a new challenge. Waste Resour. Manage. 165.
Stenvall, E., Tostar, S., Boldizar, A., Foreman, M.R.S., Möller, K., 2013. An analysis of the composition and metal contamination of plastics from waste electrical and electronic equipment (WEEE). Waste Manage. 33, 915–922.
Tange, L., Slijkhuis, C., 2009. The classification of WEEE plastic scrap in view of PBB's & PBDE's. An overview of WEEE categories within the current recycling practice. In: European Electronics Recyclers Association (EERA) & European Brominated Flame Retardant Industry Panel (EBFRIP) (Eds.), Brussels, 2009.
Tange, L., Van Houwelingen, J., Hofland, W., Kohl, F., Kearns, M., Salemis, P., Mendad, N., 2012. Recycling of plastics containing flame retardants in electronic waste, a technical and environmental challenge for a sustainable solution. In: PMI Conference, Ghent, Belgium.
Tange, L., Van Houwelingen, J., Peeters, J.R., Vanegas, P., 2013. Recycling of flame retardant plastics from WEEE, technical and environmental challenges. Adv. Prod. Eng. Manage. 8, 67–77.
UL 94. The Standard for Safety of Flammability of Plastic Materials for Parts in Devices and Appliances testing, 2012 (Ed.).
Van Schaik, A., Reuter, M., 2004. The time-varying factors influencing the recycling rate of products. Resour. Conserv. Recycl. 40, 301–328.
Vanegas, P., Peeters, J.R., Dewulf, W., Cattrysse, D., Duflou, J.R., 2014. Disassembly targets for improving resource efficiency: analysis of environmental relevance for flat panel displays. In: Presented at the Care Innovation "Towards a Resource Efficient Economy", Vienna, Austria.
Wäger, P.A., Schluep, M., Müller, E., Gloor, R., 2011. RoHS regulated substances in mixed plastics from waste electrical and electronic equipment. Environ. Sci. Technol. 46, 628–635.
Walk, W., 2004. Approaches to estimate future quantities of waste electrical and electronic equipment (WEEE). Electronic Goes Green.
Walk, W., 2009. Forecasting quantities of disused household CRT appliances – a regional case study approach and its application to Baden-Württemberg. Waste Manage. 29, 945–951.
Wang, F., Huisman, J., Stevels, A., Baldé, C.P., 2013. Enhancing e-waste estimates: improving data quality by multivariate Input–Output Analysis. Waste Manage. 33, 2397–2407.
Xiuli, Q., Williams, J.A.S., Grant, E.R., 2006. Viable plastics recycling from end-of-life electronics. IEEE Trans. Electron. Packag. Manuf. 29, 25–31.
Yamane, L.H., de Moraes, V.T., Espinosa, D.C.R., Tenório, J.A.S., 2011. Recycling of WEEE: characterization of spent printed circuit boards from mobile phones and computers. Waste Manage. 31, 2553–2558.
Yang, J., Lu, B., Xu, C., 2008. WEEE flow and mitigating measures in China. Waste Manage. 28, 1589–1597.
Zhang, L., Yuan, Z., Bi, J., 2011. Predicting future quantities of obsolete household appliances in Nanjing by a stock-based model. Resour. Conserv. Recycl. 55, 1087–1094.