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Out with the old, out with the new – The effect of transitions in TVs and monitors technology on consumption and WEEE generation in Sweden 1996–2014

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ABSTRACT

The recycling of Waste Electrical and Electronic Equipment (WEEE) is important due to its content of valuable and hazardous compounds. This study investigates the case of the recent technology change within television sets (TVs) and monitors, its impact on the generation of WEEE, and the implications for the recycling industry. In particular, material flow analysis for the time series of 1996–2014 for TVs and monitors by type of technology (CRT, Plasma and LCD) in physical units is combined with empirical data on product lifespans. The number of consumed TVs and monitors has grown exponentially. As a result, despite a 3-fold reduction in the weight of the products, the weight of the corresponding WEEE is also growing exponentially. Out with the old, out with the new – a peak in WEEE from both CRT and flat-screen displays is expected during 2014–2020, due to the simultaneous obsolesce of the last wave of CRT products and the short-lived flat-screen products that substituted the CRTs. The lifespans of LCD and LED TVs were found to be three times shorter than of the CRT TVs, with many TVs discarded while still functional. This is the consequence of two events – replacement of the CRT TVs in combination with lifestyle purchases of TVs, i.e. the premature replacement of flat-screen displays with new sets with extra-large screens and/or new features. The throughput of TVs and monitors consumed has been estimated annually from 2014 until 2040, by quantity and type of device, as well as by component and material type. The annual economic value of the corresponding secondary materials, by material type, has also been estimated. The point in time when the final disposal of CRT products is likely to take place has been identified and should be noted by the recycling industry. Among the important contributions of this study to the accounting and predicting of amounts and types of WEEE are the lifespan distributions, size and weight distributions, and material composition for TVs and monitors of different technology. Directions for method application in other countries are given.

1. Introduction

The increasing variety of electronic devices, their penetration in all parts of the world, and their ever decreasing lifespan has led to an exponential growth in Waste Electrical and Electronic Equipment (WEEE) globally, with collection and recycling rates far below the desirable (UNEP, 2013). The fastest rate of increase is observed in developing countries, with a 50% annual increase in some countries (UNEP, 2013). However, in the EU WEEE is also expected to grow, by an annual rate of 2.5–2.7%, until 2020, which would generate 12.3 million tonnes of WEEE by 2020 (Huisman et al., 2007).

The WEEE contains over 1000 different substances, which fall into "hazardous" and "non-hazardous" categories (Pinto, 2008). The presence of elements such as lead, mercury, arsenic, cadmium, selenium, hexavalent chromium and flame retardants causes WEEE to be classified as hazardous waste and the dismantling or incineration of WEEE is considered toxic (Widmer et al., 2005). On the other hand, the presence of metals such as copper and aluminum, as well as precious metals such as silver, gold, platinum, palladium among others, makes recycling of the WEEE and recovery of these materials economically attractive (Cucchiella et al., 2015).

Estimations of the types, quantities and material composition of the WEEE are necessary in order to support its safe end-of-life management, to develop appropriate collection and recycling facilities and to inform environmental policy. As part of this study,

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Elkretsen (branch organization for WEEE collection and recycling companies in Sweden) and Stena Recycling, the dominant WEEE recycling company in Sweden, were interviewed (Berg, 2015). According to Elkretsen, the planning of collection and recycling capacities for WEEE requires three major types of analysis: projections of mass flow of products over time, the age of the products, and their content in terms of glass, plastics and elements (metals, etc.). However, the components contained in the WEEE should also be investigated due to the consequences of technology changes, such as the change from Hg-lights to LEDs in flat-screen TVs, and because of a growing interest in recycling of the components.

In this paper we investigate the particular case of trends in the consumption of TVs and PC monitors and the corresponding WEEE generation. In the last decade, the market for TVs and PC monitors experienced a technology shift and product substitution from Cathode Ray Tube (CRT) to Liquid Crystal (LCD) and Plasma displays (also known as flat-panels). The first commercial LCD TV was available on the market in 1988, and in 2007 sales of LCD televisions surpassed sales of CRT TVs worldwide for the first time (McGlaun, 2008). There are several reasons why it is important to study this phenomenon: as an example of technology shift and product substitution; to identify impacts on the use and disposal phases of both CRT and LCD products and, most importantly, to describe and assess the effect on WEEE generation and its implications for the recycling industry. The patterns and amounts of generated WEEE could be expected to change as a result of product substitution. In addition, the construction, materials and elements – both hazardous and valuable – vary between the CRT and flat-screen products, which means that different handling and recycling processes are required. As an example, the displays of CRT TVs can contain several kilograms of hazardous lead. There is a particular technique for the transport and disassembly of CRT TVs, and for separating the lead from the glass in displays (Stena, 2014). The LCD technology, on the other hand, may contain mercury, which must also be handled in a particular way (Boeni et al., 2012). LCD TVs also contain a considerable number of other materials that can be recycled, such as Fe, Al, Cu and plastic (Cucchiella et al., 2015). In order to develop a suitable recycling technology and infrastructure for flat-screen WEEE, the expected generation times and volumes need to be known.

The most common approach to predicting WEEE generation is by combining flows data with lifespan data for the products in a method named Product Flow Analysis, developed by Oguchi et al. (2008). The objectives, procedures and level of detail vary between different studies. Some studies rely on a typical average lifespan for TVs and PC monitors and disregard the specific characteristics of individual countries, year of production and type of technology. Average lifespans for the different technologies and types of products have been provided for Japan (Oguchi et al., 2008), the Philippines (Peralta and Fontanos, 2006) and Lithuania (Gurauskiene and Stasiskiene, 2011). There is a lack of distinction between the different TV technologies in some studies (Yang et al., 2008), and other studies do not take into account the introduction of flat-screen TVs on the market (Tasaki et al., 2004; Zhang et al., 2000). One of the studies (for Europe) discusses technology substitution from CRT to LCD (Fakhredin and Huisman, 2013). Detailed identification of the materials with potential for recycling present in a typical device has been the subject of some studies, with particular emphasis on critical metals and the economic value of materials (for example, Cucchiella et al., 2015 and Buchert et al., 2012). Others also study the breakdown of the TVs and PC monitors in components that are sent for dedicated recycling technologies (Salhofer et al., 2011).

To the best of our knowledge no other study has consolidated the necessary data and methods available to project the generation of WEEE caused by TV and monitor consumption as well as the available secondary resources. In particular, the typical lifespans, product weights, components, material composition, and economic values necessary for such projections can be useful for various stakeholders. In addition, as shown in this paper, all of these variables change over time and require ongoing evaluation.

This paper has the following objectives: (i) to contribute to the consolidation of available methods for forecasting the amounts of discarded TVs and monitors by technology type; (ii) to account TV and monitor consumption in Sweden from 1996 to 2014 and forecast the material types and quantities that will be available for recycling as a result of this consumption; (iii) to identify when the final CRT disposal is likely to occur in Sweden; (iv) to project quantities of future flat-screen disposal and (v) to describe possible implications of the transitions in TV and monitor technology for waste management.

2. Method

For durable goods, the sale and end-of-life stages are separated in time by a lifespan ranging from a few years to decades. Time series of material flow analysis (MFA) are necessary in order to describe the behavior of the system over time (e.g.: Patrício et al., 2015). In this study, time series of 19 years, from 1996 to 2014, have been accounted for the consumption of TVs and monitors. A lifespan modeling approach was used to estimate the corresponding WEEE flows (e.g.: Oguchi et al., 2008; Mueller et al., 2007; Polák and Drápalová, 2012). This approach combines inflows calculated based on historical EEE consumption statistics with the typical lifespan of different commodities (Murakami et al., 2010). In Fig. 1, a scheme of the method is presented.

The lifes pan is the key variable for describing the dynamics of product use, and in particular for forecasting future availability of resources for reuse, recycling or recovery. In this study, the lifespan is set to the domestic service lifespan, defined as the period of time from initial manufacture until the point in time when a product is disposed of by the final owner (Murakami et al., 2010). The study was performed for Sweden and annual resolution of MFA data was considered.

Step 1

The model applies an internationally accepted nomenclature to systematically assess the flows, the Combined Nomenclature classification (CN), used for foreign trade data. In the CN classification, each product type is assigned an 8-digit classification code, the codes can then be aggregated into a larger groups of products. In this step, CN codes for the products covered by this study were selected – televisions and monitors divided by technology type. For monitors, only devices used in automatic data processing systems were considered. During the study period, numerous changes were made to the CN codes, as a result of changes in technologies. These have also been taken into account.

Step 2

In the second step, the product consumption was accounted by technology type, using the MFA indicator Domestic Material Consumption in the year t: $DMC_t = Imports_t + Industrial\ Production_t - - Exports_t$. The balance was expressed in metric tonnes and units. Eq. (1) is an example of how the DMC was accounted for LCD TVs (CN 85287240) in 2012.

$$DMC_{CN\ 85287240} = IMP_{CN\ 85287240} + IP_{CN\ CN\ 85287240} - EXP_{CN\ CN\ 85287240}$$
$$DMC_{CN\ 85287240} = 1778702 + 0 - 1096905 = 681797\ units \quad (1)$$

with DMC = Consumption, IMP = Imports, IP = Industrial Production, EXP = Exports, CN = Combined Nomenclature

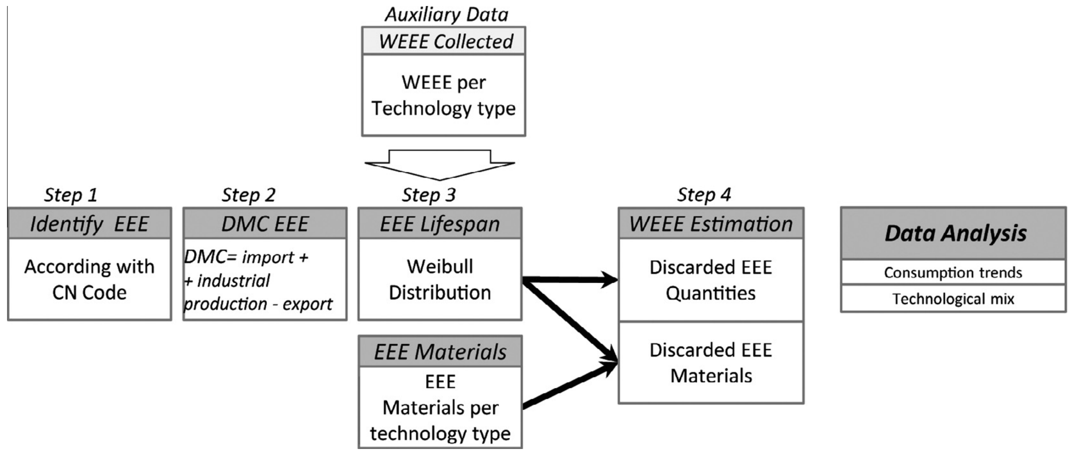

Fig. 1. The MFA method for TV and monitor consumption, at product and material level and by technology type. EEE – Electric and Electronic Equipment, CN – Combined Nomenclature (see Section 2), DMC – Domestic Material Consumption (see Section 2), Weibull Distribution see (Section 3.2).

Sales figures for TVs in Sweden in 1981–2013 were used to cross-check the MFA results. The sales data was also used to identify the dimensions of the sold TVs, based on the length of the diagonal of the screen in inches: small screen <25″; medium screen 25″–39″; large screen 40″–49″ and extra-large screen >49″. These figures were used to further analyze the trends in TV consumption.

Step 3

To forecast the WEEE, distribution functions ($f(t)$) for product lifespans (in years) were fitted to empirically obtained lifespans (Methodology 1 in Oguchi et al. 2010). An empirical database of lifespans developed as part of a study on WEEE collected in Sweden was used (El-kretsen, 2013). This database contained data for different time periods between 2011 and 2013 (88 collected LCD TVs, 141 CRT TVs, 401 LCD Monitors and 832 CRT Monitors). The database included the type (CRT or LCD), weight, components, year of production and year of collection, which made it possible to calculate the lifespan by subtraction of the year of production from the year of collection.

A Weibull distribution function was shown to well describe the lifespan of EEE (Melo, 1999; Elshkaki et al., 2005; Polák and Drápalová, 2012). In this paper, the Weibull distribution for TVs and monitors is tested for three different technologies – LCD, Plasma and CRT.

Step 4

The calculated inflows and distribution functions allow the expected generation of WEEE for each year to be estimated. The future WEEE (W_t) can be expressed as the sum of the result of the distribution function ($f(t)$) for the DMC_t values accounted in Eq. (1) (DMC in tons or number of units) for each year. The WEEE (W_t) can be estimated both in tons and in units, as shown in the Eq. (2):

$$W_t = \sum_{n=ti}^{n=t} DMC_n \cdot f(n) \quad (2)$$

with W = *future WEEE, DMC* = Consumption, $f()$ = distribution function, t = year, ti = initial year

In this study we also present the weights of the main components/materials of TVs and Monitors (i.e. composition). The composition was obtained by dismantling and weighing the components of 189 TVs and 309 monitors, both CRT and LCD devices, with different production years (El-kretsen, 2013, see Supplementary Table 7 for the data). This allowed calculation of the weight ratio for each component by technology type and production year (R_t). In fact, estimating WEEEs by components such as plastics fraction, steel and Printed Circuit Board, can give valuable information, as these can then be passed on to relevant markets for materials recycling (Buchert et al., 2012). To estimate the WEEEs by component (WC_t), the ratio of each component was multiplied by the DMC indicator in weight, accounted in Eq. (1), as well as by the distribution function ($f(t)$), as shown in the Eq. (3):

$$WC_t = \sum_{n=ti}^{n=t} DMC_n \cdot f(n) \cdot R_n \quad (3)$$

with WC = *future WEEE by components*, DMC = Consumption, $f()$ = distribution function, t = year, ti = initial year, R = Ratio of components

Furthermore, this study also estimates the material composition of discarded TVs and monitors (Eq. (4)). To do this, an average composition was assumed, based on a study performed by Cucchiella and colleagues (2015), in which the material composition of several types of EEE is presented, disaggregated into 43 material types. The overall potential revenues are also estimated using the market prices of materials available in the same study.

$$WM_t = \sum_{n=ti}^{n=t} DMC_n \cdot f(n) \cdot RM_n \quad (4)$$

with WM = *future WEEE by materials*, DMC = Consumption, $f()$ = distribution function, t = year, ti = initial year, RM = Ratio of materials

2.1. Limitations and assumptions

A constant lifespan function for each product technology type for all the study years was assumed, based on empirical data. Due to the lack of WEEE data for plasma TVs, it was assumed that Plasma TVs have the same lifespan as LCD TVs. Imported products were assumed to be produced in the year when they were imported.

In this study, it was assumed that all computer systems sold in Sweden include a monitor. There is a specific CN code for systems described as data-processing machines comprising at least one central processing unit, one input unit and one output unit (CN 84714900). The code description does not clarify which types of equipment are included in the systems. It is not clearly stated whether a monitor is included or not, and there is no information on monitor technology. In this particular case, when the consumption of systems was calculated using the DMC indicator, the industrial production was not considered, to avoid double accounting of monitors. The reason is that systems assembled in Sweden usually use imported monitors, as the production of monitors in Sweden is null or negligible. For this reason, the monitors would already have been accounted as individual units. The proportion of CRT and LCD monitors is estimated, using the proportion of monitors collected per technology type, and the year of production of each collected device. Eq. (5) is an example of how the number of CRT and LCD monitors sold as part of systems was calculated.

$$\mathit{CRT\ Monitors\ in\ Systems} = (\mathit{IMP}_{CN\ 87714900} - \mathit{EXP}_{CN\ 87714900}) \times \frac{\mathit{CRT\ Monitors\ Collected}_x}{\mathit{Total\ Monitors\ Collected}_x} \qquad (5)$$

with *CN* 87714900 = *Systems CN code*, *x* = *production year*, *IMP* = *Imports*, *EXP* = *Exports*There is a CN code (CN 85287230) that covers TVs incorporating a video recorder or reproducer. This CN code does not specify the televisions' technology type. Therefore, the TV technology type was estimated based on the proportion of each technology in the available data from the year in question.

3. Results and discussion

3.1. Lifespan distributions

The domestic service lifespan distributions for the studied 1462 discarded TVs and monitors are shown in Fig. 2. The Weibull distribution function appears to provide a good fit for the domestic service lifespan distributions. This means that the obtained Weibull distribution parameters (see Table 1) can be used to forecast the end-of-life for the studied products without any knowledge of the domestic service lifespan distributions.

The CRT TVs average (and median) lifespan is recorded as 15 years, compared to 6 years for the LCD and LED TVs (Fig. 2). While these lifespans are not directly comparable, due to the shorter history of the LCD/LED TVs, the generally shorter lifespans of the latter are also confirmed by the fact that over 40% of the LCD and LED devices are discarded within the first 5 years, but only 20% of the CRT TVs. One reason may be the different technical lifetime of the LCD/LED compared to the CRT technology. However, other factors are likely to be drivers of the shorter lifespans, such as the price, aesthetics and development in peripheral technologies. In particular, the replacement of a product can be triggered by

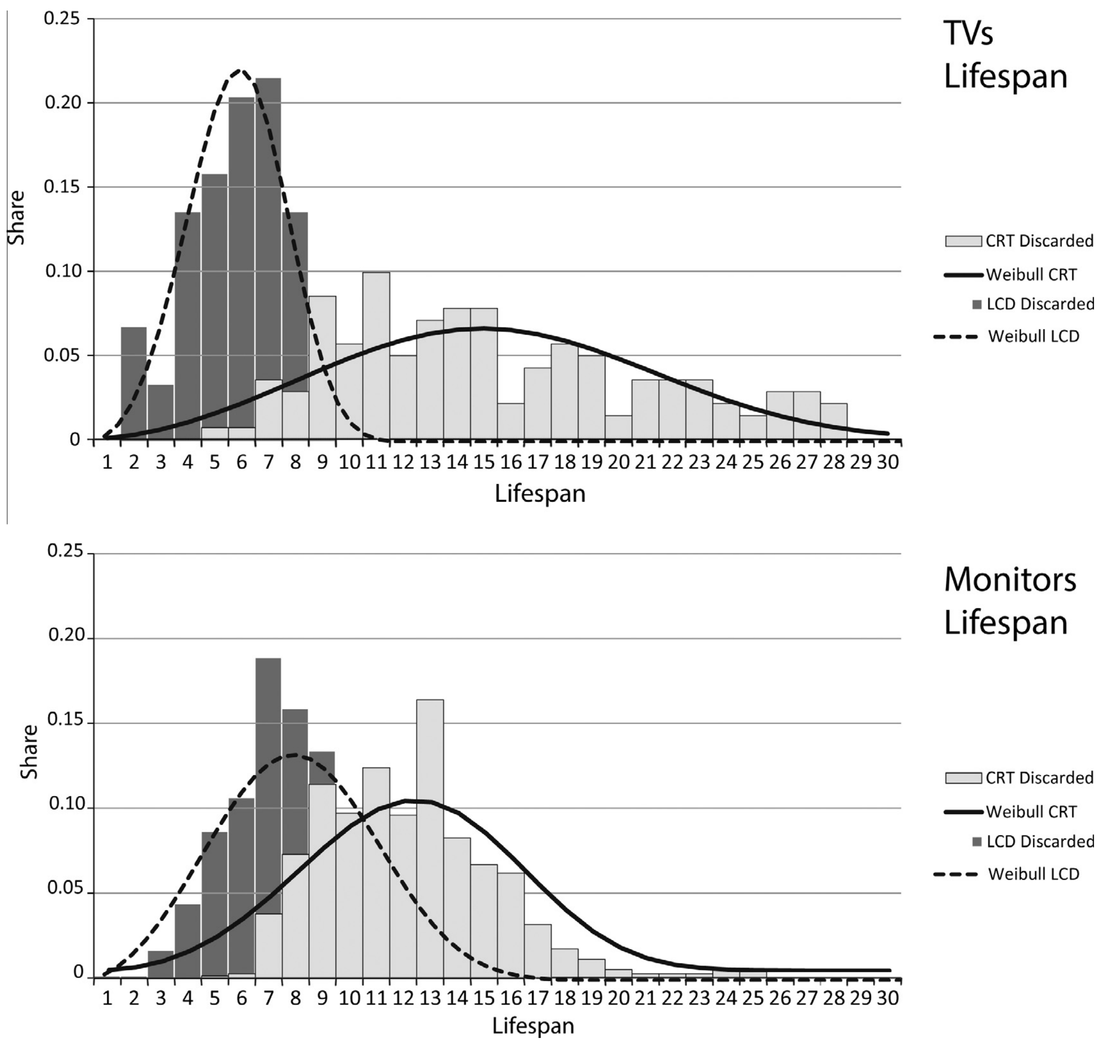

Fig. 2. Lifespans for TVs and monitors by technology type.

the following developments in peripheral technologies: new video and data storage formats (HD/Blu-ray DVD), signal transmission (TV cable, internet cable or Wi-Fi, satellite), signal coding/decoding standards. The aesthetics parameters may include the size and shape of the TV (flat screen) and display size (currently large/x-large screen sizes are the most popular, see Fig. 4). Indeed, data from the UK (MTP, 2006) indicate that falling prices and the demand for the latest TV models and features have led to lifestyle purchasing of TVs; the purchase of a new primary television is triggered by the old one being outdated rather than malfunctioning. This leads to shorter periods of product use. Lifespans reported the literature all confirm considerably shorter lifetimes for LCD products (Table 2). In general, similar lifespans for TVs and monitors have been found in different geographic areas, which means that they can be used to estimate the WEEE in other countries. In particular, the average lifespan for CRT TVs found in this study, i.e. 15 years, has also been found in Japan, USA and Viet Nam (Table 2). The variability in lifespans should be considered in the sensitivity testing of the projections to improve their accuracy. For LCD TVs a lifespan of 6–10 years would be a reasonable assumption based on published data. However, this interval should be updated frequently due to the likelihood of further decreases in lifespans for flat-screen TVs, even in those countries where replacement of the CRTs has already taken place. Further innovations in technology, introduction of new products and more development of peripheral technologies are also expected. For example, more display technologies already exist, including Organic Light Emitting Diode (OLED) or Field Emission Display (FED). Some of these offer both excellent optical properties and better energy efficiency and may well enter the market in the future.

Within the same technology, the lifespans of monitors, at 4–8 years, are generally shorter than those of TVs (Table 2). In this study, the median lifespans for the CRT and flat-screen monitors were found to be 8 and 12 years, respectively (Fig. 2). This is similar to empirically based lifetimes obtained for the USA in 1980–2007 (Office of Solid Waste, 2008) and for Japan (Oguchi et al., 2008). Much shorter monitor lifetimes of 4 years have been used in projections for the EU15 (Huisman et al., 2007), however, such short median lifetimes has not yet been confirmed empirically.

Table 1
Weibull equation parameters.

Electronic equipment	Technology	Shape parameter (k)	Scale parameter (λ)
Televisions	CRTs	2.89361	17.2891
	LCDs	3.75014	6.45085
Monitors	CRTs	3.54870	13.5886
	LCDs	3.06466	8.98386

3.2. EEE composition

The composition of different types of TVs and monitors, including for different generations of the devices, has been compiled from a WEEE database containing 1462 products. The typical composition and average weight for different generations can be seen in Table 3 and more detailed data, including TV models, can be found in Supplementary Table 7. The average weight of the components in Table 3 is represented as a proportion (g/kg of the total device weight), which makes it possible to reuse this data to estimate the weight of different components, as long as the generation of the device and its total weight are known. If the model and generation of the device are within those studied in this paper, the exact values for the device can be obtained from the Supplementary Table 7.

The composition by component for CRT devices did not change between 1994 and 2007, however the weight of the components altered slightly. The LCD technology is still under development, and both the types and weights of components are changing continuously. One example is the backlight used in LCD TVs, in which fluorescent lamps have recently been replaced with LED lights. Because of the continuing flat-screen TV product development, the dismantling and recycling processes for LCD TVs should be updated continuously. LCD monitors, on the other hand show no considerable changes in the composition between different generations.

3.3. MFA and WEEE projection

3.3.1. MFA and WEEE projection for Televisions

The consumption of TVs grew exponentially by on average 2.0% per year in the period 1996–2014 (Fig. 3). Also for other types of electrical and electronic devices, except the large household appliances an exponential growth has been observed in Sweden during 1996–2013 (Kalmykova et al., 2015). In the case of TVs, rapid decrease in prices of the new technology (LCD) sparked the beginning of the exponential growth (Supplementary Fig. 1). The prices of the first LCD models were far higher than the price of CRT models (Magoun, 2009). Therefore, despite the fact that LCD devices entered the market as early as in 1988, sales of flat-screen TVs were negligible until 2003 when the prices rapidly decreased. In Sweden, sales of flat-screen TVs surpassed CRT TV sales for the first time in 2006, and the market share of flat-screen TVs has stayed above 96% since 2007 (see Fig. 3). The last peak in CRT consumption was observed in 2004, as a result of the introduction of

Table 2
Television and monitors lifespans literature review.

TVs[a]		Monitors[a]		Estimation method	References	Publication date	Spatial scale
CRTs	LCDs	CRTs	LCDs				
15	6	12	8	Empirical	This study	2015	Sweden
14.3	9.7	–	–	Survey	Trana et al. (2014)	2014	Vietnam
–	9.0–9.7	–	–	Survey	Fakhredin and Huisman, 2013	2013	Netherlands
–	–	–	3–5	Assumed	Li et al. (2009)	2009	China
–	7.2	–	8.6	Survey	Oguchi et al. (2008)	2008	Japan
15.4	–	10.2	–	Empirical	Mueller et al. (2007)	2007	USA
10		4		Manufacturer estimate	Huisman et al. (2007)	2007	EU15
12	–	6.7	–	Survey	Oguchi et al. (2006)	2006	Japan
8–12		–	–	Assumed	Peralta and Fontanos (2006)	2006	Not defined

"–" no data.
[a] Average or an interval.

Table 3
Television and monitors components and their average weight.

Component	Televisions				Monitors			
	LCD (g/kg)		CRT (g/kg)		LCD (g/kg)		CRT (g/kg)	
	2004	2011	1994	2007	1998	2010	1994	2004
Connection cable	0	6	0	1	5	10	10	3
Transformer	0	0	0	9	0	0	0	0
Display (CRT or LCD)	42	115	744	730	78	81	607	707
Backlight	6	6	0	0	0	0	0	0
Printed Circuit Board (PCB)	102	77	64	41	61	65	77	72
Speakers	42	14	8	12	1	2	0	0
Miscellaneous electronics	1	0	1	1	0	0	3	1
Metals	478	390	5	2	432	454	61	50
Plastics	316	384	159	190	418	381	224	146
Internal cabling	13	9	14	14	4	6	17	20
Other combustible	0	0	1	1	0	0	0	1
Other non-combustible	5	1	4	0	1	1	1	0
Total weight (kg)	12.4	9.5	22.9	31.5	4.1	6.0	11.8	16.4

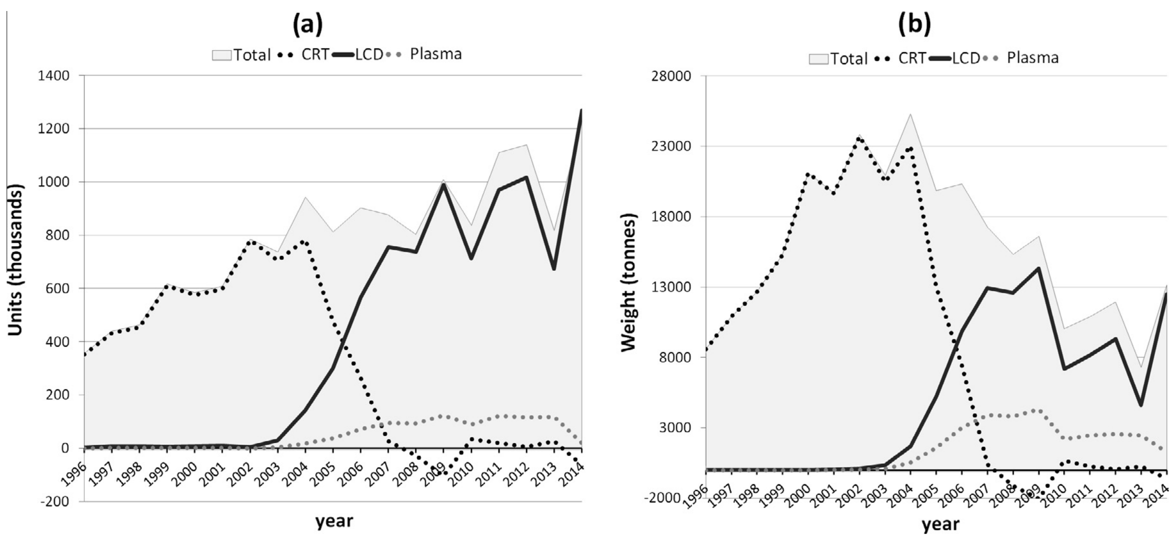

Fig. 3. TV consumption in Sweden 1996–2014: (a) by number and (b) by weight.

built-in DVD players, which flat-screen TVs did not have. However, as the data show, this feature was not important enough to prevent CRT being replaced by LCD. In 2008 and 2009, a negative consumption of CRT can be observed, explained by the high exports of devices stored from previous years (i.e. the outflow was larger than the inflow). This may be a consequence of the technology shift, from CRT to LCDs.

The TVs consumption, as accounted by the MFA method (Fig. 3), aligns well with the sales figures for TVs (Supplementary Fig. 1) and the cumulative number of TVs differ less than 7.3% between these data. The observed year-on-year differences are due to stock effects. In particular, the MFA method considers TVs to have been consumed once they have been imported into the country, however, they may not be sold until the following year. For example, the largest discrepancy in numbers is in 2012, when the TV consumption according to the MFA was lower than the sales in the previous year. This suggests that a stock of TVs had been built up in the country from imports during 2011, and then sold during 2012.

The cumulative weight of the sold TVs has decreased to levels below those in 1996, despite the exponential increase in the number of televisions sold (see Fig. 3). This is due to the dramatic decrease in the average weight of a TV (see Fig. 4) and the weight of the flat-screen TVs in particular (the average weight of an LCD TV is only half that of a CRT TV, see Supplementary Fig. 2 for trends in TV weight). Even the clear preference among consumers for ever larger screens (see Fig. 4) did not stop this weight decline, as compromises were made regarding the weight of other components included in the TVs. Yet, the weight per-capita of TVs sold in Sweden (0.105 kg in 2004) far exceeded the average for the EU (0.068 kg in 2004) (Stobbe, 2007).

According to our estimates, the number of discarded TVs will peak for all the technology types in the near future, i.e. in 2014–2020 (see Fig. 5). The flat-screen TVs have a short average lifespan of 6 years and the majority of the TVs purchased in 2006–2008 to replace CRTs are now becoming obsolete. At the same time, the CRTs purchased during the last peak of CRT sales, in 2001–2004, are approaching their normal lifespan of 9–15 years. For this reason, it is crucial to provide sufficient recycling capacity and to ensure appropriate recycling of the materials.

The WEEE from TVs was estimated using the obtained Weibull distributions and is presented in Fig. 5. The number of disposed units is likely to remain at the current high level, which suggests that a recycling capacity for flat-screen TVs is a necessary long-term investment. The total weight of the TV WEEE is also likely to stay at the current level, after a peak in 2014–2020 when large quantities of both CRT and flat-screen TVs will have to be recycled. Despite the lighter LCD TVs currently dominating the WEEE stream (Supplementary Fig. 2), the weight of the disposed TVs is not expected to decrease, due to the growing consumption. The com-

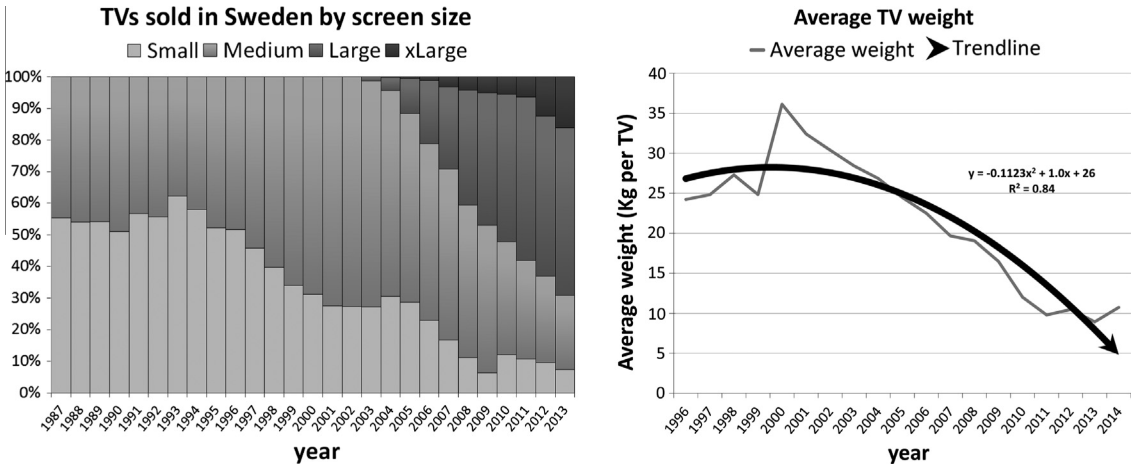

Fig. 4. Share of TVs sold in Sweden by screen size (1996–2013); average weight of TVs sold in Sweden (1996–2013).

ponents that will become available in the TV WEEE are accounted for in Fig. 8. The components with the greatest weights are: CRT Screens (31%), Metals (27%), Plastics (26%), and Printed Circuit Board (7%). However, it is the metal content, which is important from the economic and environmental perspectives. The metals with high economic value due to their relatively high concentration in electronics but also high economic value per mass are: gold, copper and palladium. Printed Circuit Board is one of the most attractive components, as they contain important amounts of precious metals (e.g. gold, palladium and silver) (Buchert et al., 2012). LCD screens contain indium, a precious metal used in electronic appliances (UNEP, 2013). Example of the flows of materials, including EU priority materials (European Comission, 2010) and valuable elements, contained in the TV and monitor WEEE are showed in Table 4 along with their estimated economic value (see Supplementary Tables 3–6 for additional elements and all the years). This information can be used as a basis for investment decisions regarding the establishment of recycling capacities, based on the cost of recycling and market for secondary materials. In addition, data on a number of toxic materials that require special treatment are also available, including mercury, antimony or lead (see Supplementary Tables 3 and 4).

3.3.2. MFA and projection of monitors WEEE

Monitors have gained widespread use since 2004 and have since reached consumption numbers on par with those for TVs (Fig. 6). The average weight of a monitor had reduced by half by 2012 (LCD monitor) compared to 1996 (CRT monitor, see Supplementary Table 2). Nonetheless, due to the fast growth in the number of consumed units, the total weight of the consumed monitors grew exponentially over the study period (see Fig. 6). There is no sales data for monitors; therefore no trends can be established in relation to the sizes of the monitors consumed.

In 2005 and 2008, the consumption of CRT monitors seems to be negative. This effect is probably caused by the increasing sales of LCD monitors, a new technology at that time. As a result, accumulated stocks of CRTs from previous years were exported to other countries. The same effect was also registered for TVs. Nevertheless, in the last few years (after 2009) an increase in the consumption of CRT monitors occurred. This increase was due to the NACE code 3210 (manufacture of electronic valves and tubes and other electronic equipment). More than 60% of the imported CRT devices belonged to this category. It can therefore be assumed that, during this period, CRT devices were mostly used by industries, probably as intermediate products.

Just like the TV WEEE, the WEEE from monitors was estimated using the obtained Weibull distributions. The results are presented in Fig. 7. A peak in the end-of-life monitor collection is expected to occur between 2016 and 2020. According to our estimations, approximately 440,000 monitors will be discarded each year of this period, which corresponds to around 5000 tonnes of WEEE. The components and materials that will become available in the monitor WEEE are accounted in Fig. 8. The components and materials with the greatest weights are: CRT Screens (37%), Plastics (26%), Metals (23%), Printed Circuit Board (8%) and LCD Screens (3%).

3.4. Applicability of the model for other countries

The consolidation of the methods used to estimate the future production of WEEE for TVs and monitors presented in this study leads to a discussion about the possibility of using this method in other countries as well. In the next few paragraphs a brief discussion on the data requirements and factors that need to be taken into account will be presented.

To account all the flows of TVs and PC monitors in a country, 2 main data sets must be compiled: International Trade Data and Industrial Production. Both sets are available in a number of countries, and the methodology for collecting them is harmonized at least for OECD countries.

Regarding the lifespan of TVs and PC monitors, as discussed, some caution should be used when selecting the appropriate value for each specific country. In any case, there are already some examples in the literature that allow for a study with sensitivity analysis for the range of possible lifespans (Table 2).

When it comes to breaking down the TVs and PC monitors into components that follow different recycling routes, Table 3 provides estimates of the proportion of the weight that should be considered for each. The same can be done using the material composition that Cucchiella and colleagues provided in their study (2015). Considerations about changes in technology have to be made, since, in the future, TVs and PC monitors may be made of different materials and have different component compositions.

Finally, the prices of raw materials on a market can be used to identify the potential economic values of the materials present in the WEEE. Cucchiella and colleagues (2015) identify 3 main relevant websites: InfoMine; London metal exchange and MetalPrices.com.

3.5. TV and monitor recycling in Sweden

According to the interviews with Elkretsen (the branch organization for WEEE in Sweden) and Stena Recycling (the dominant

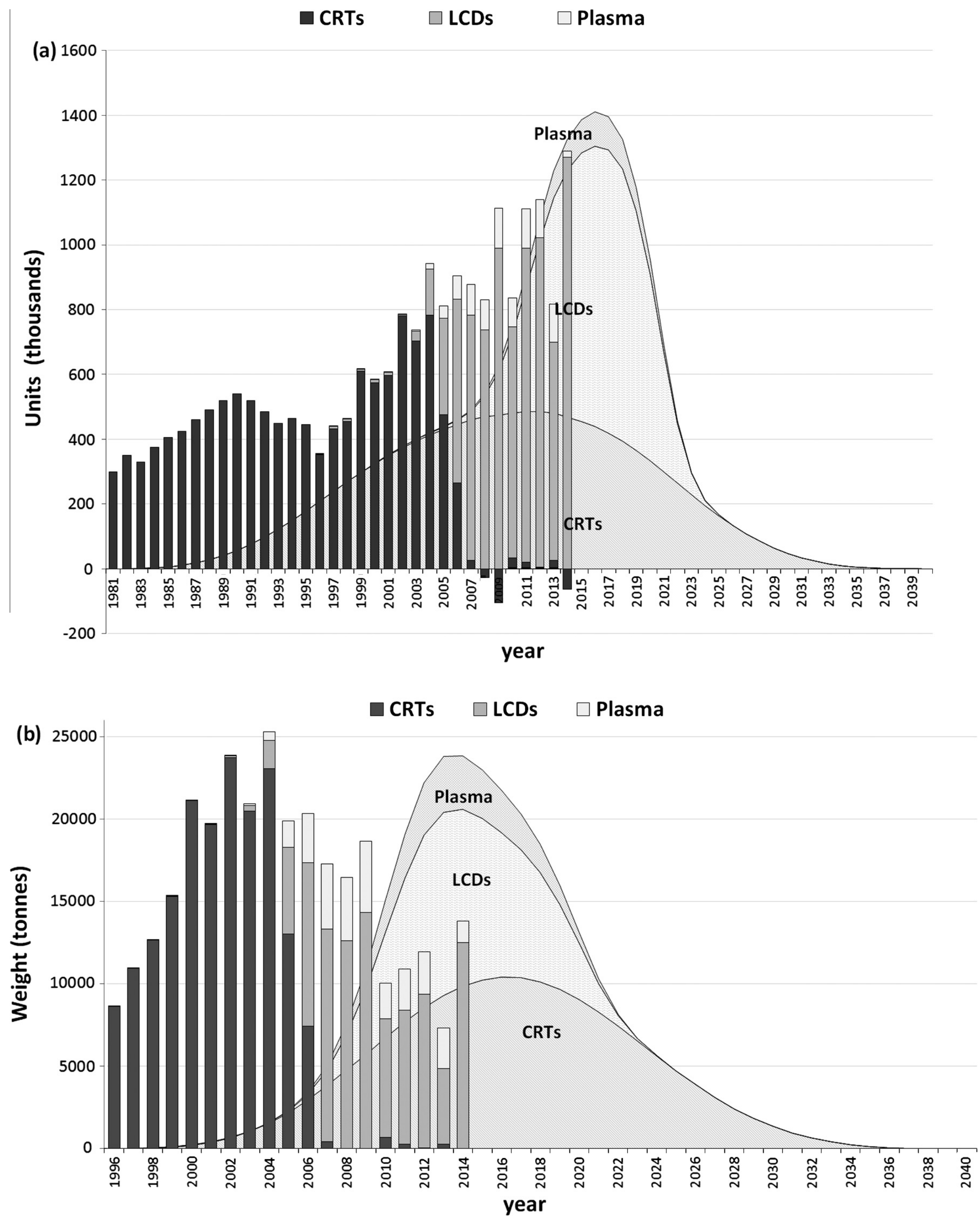

Fig. 5. Generation of TVs WEEE based on consumption during 1981–2014 and the domestic service lifespan distributions (Consumption figures for TVs from 1981 to 1995 are based on sales data.) (a) in number and (b) in weight. In bars – TV consumption, areas under the lines – forecasted WEEE generation. Note: the negative consumption of CRTs (due to stock exports) was set to 0.

CRT and LCD recycling company in Sweden) the entire flow of correctly disposed CRT and flat-screen devices is treated, within Sweden, by private companies specialized on recycling. It is estimated that 90–95% of the collected devices are recycled, reused or utilized as an energy resource.

The collected screens are manually dismantled and the parts are sorted into metals, plastics, glass, electrical (e.g. transformers) and electronic (e.g. printed circuit boards) components, etc. Metal components are further separated and treated based on a, for the market in question, appropriate content of metals, e.g. copper (see Supplementary Table 3 for the estimated metal contents of the discarded TVs and monitors in Sweden until 3032). CRT glass is crushed, then separated into different types (barium oxide and lead oxide glass) using a flotation process. The two types are then upgraded and cleaned. The treated glass can be used for production of e.g. shower cabins or, alternatively, as a construction material in the non-permeable surrounding walls of landfill sites. LCD flat screens are treated using a similar process. Plastics containing brominated flame retardants are separated from "clean" ones in a flotation process. The clean fraction enters the recycling market

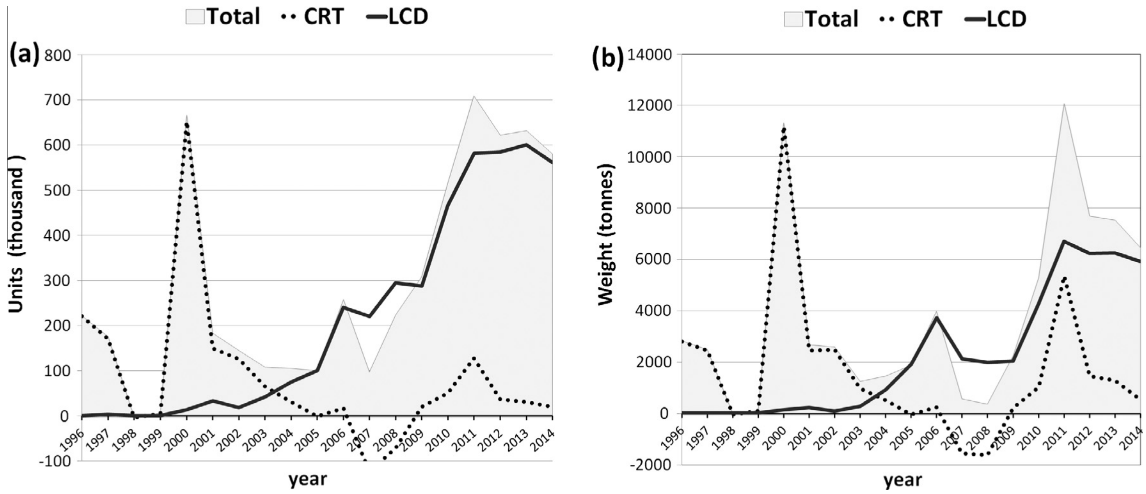

Fig. 6. Monitor consumption in Sweden 1996–2014: (a) by number and (b) by weight.

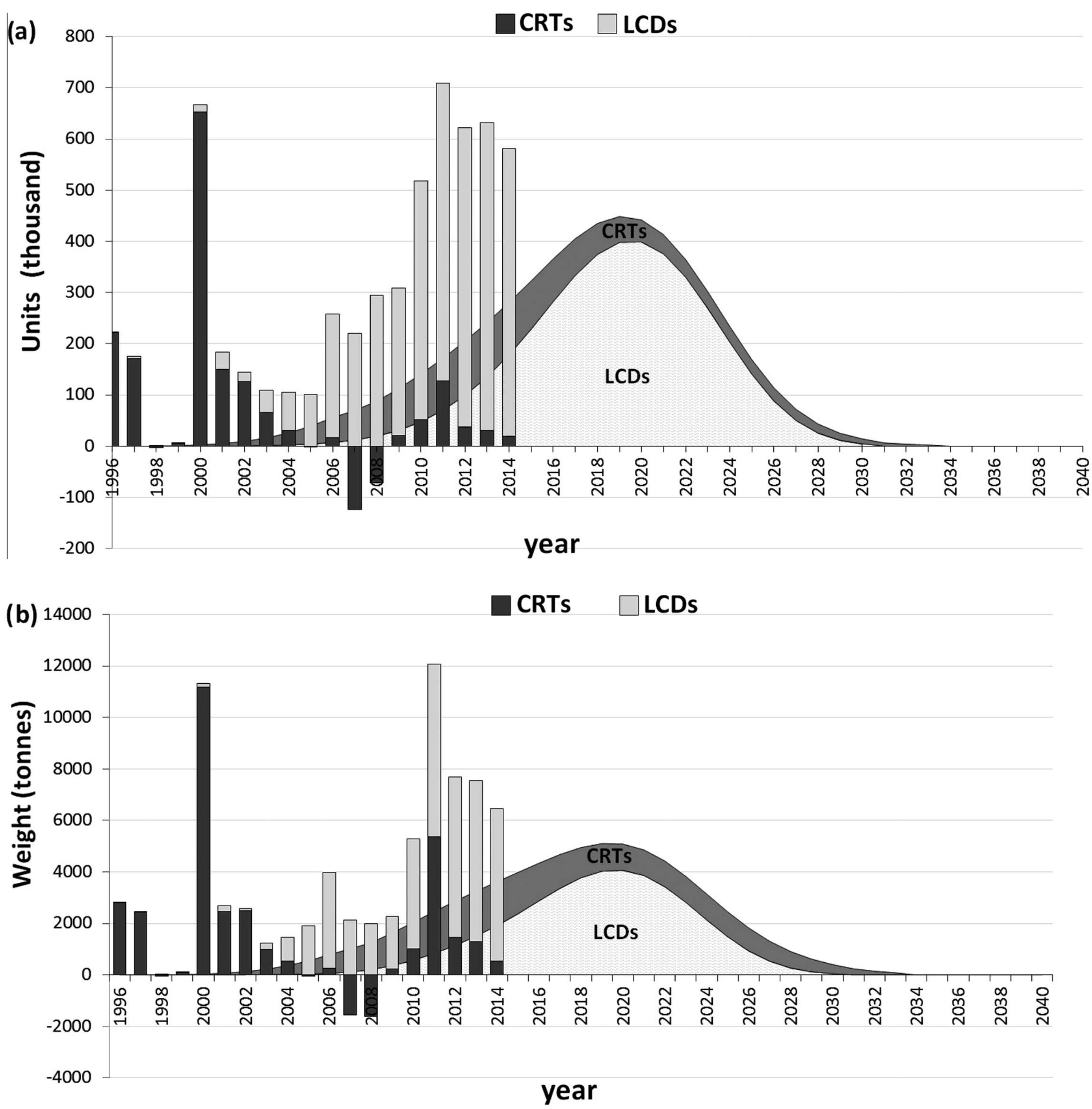

Fig. 7. Generation of monitor WEEE based on consumption in 1996–2014 and the domestic service lifespan distributions (Consumption figures for TVs from 1981 to 1995 are based on sales data.) (a) in number and (b) in weight. In bars – monitor consumption, areas under the lines – forecasted WEEE generation. Note: negative consumption of CRTs was set to 0.

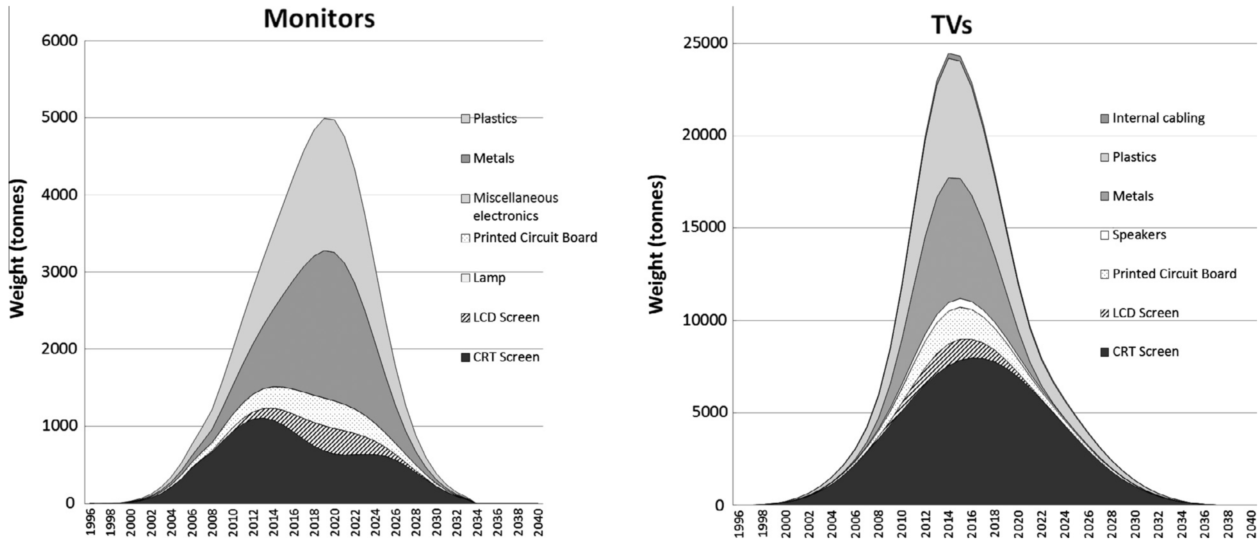

Fig. 8. Forecast of material flows in WEEE due to disposal of TVs and monitors consumed from 1996 to 2014.

Table 4
Quantities and economic value of valuable and priority materials in disposed TVs and monitors, year 2016.

	Gold	Plastics	Palladium	Copper	Tin	Steel/iron	Lead	Silver
Tonnes	0.645	8,888.1	0.123	330.6	87.348	8,860.621	572.417	1.721
Million €	21.984	10.666	2.855	1.719	1.485	1.063	0.973	0.885
	Aluminum	Glass	Nickel	Tungsten	Indium	Barium	Molybdenum	Antimony
Tonnes	447.647	8,192.824	19.415	1.947	0.243	0.098	1.947	5.073
Million €	0.671	0.410	0.272	0.138	0.134	0.054	0.041	0.039
	Titanium	Yttrium	Ferrite	Zinc	Europium	Terbium	Vanadium	Gallium
Tonnes	1.947	0.147	47.122	3.116	0.003	0.003	0.098	0.009
Million €	0.021	0.007	0.006	0.005	0.002	0.002	0.002	0.002
	Praseodymium	Gadolinium	Mercury	Cadmium	Cerium	Lanthanum	Chromium	
Tonnes	0.003	0.003	0.003	0.072	0.003	0.003	0.011	
Million €	0.000	0.000	0.000	0.000	0.000	0.000	0.000	

and the brominated fraction is used as an energy source in cement kilns.

While the main part of the flow is recycled as glass, plastics and metals, a small amount is recycled as components. There is an interest in more substantial recycling of components, but there are at least two obstacles: (1) many components are old, and it is not always known how long they will last; (2) no law regulating the responsibilities of the producer in relation to the reuse of a component has been implemented. Is the primary producer, the recycler or the company reusing the component responsible for its end of life management?

The recovered and upgraded materials are sold on the global market, often on a spot market. This means that the deposition can change fast and that there is a lack of stability in the circulation of material. Elkretsen has suggested that TVs and monitors WEEE will still be treated in Sweden in the future. They anticipate that an overcapacity for CRT recycling may follow and believe it is possible to adapt the capacity for flat-screen recycling to the changing flows. In general, they regard studies like the one described in this article as being of high importance for planning the recycling capacity.

3.6. Implications of the transition in TV and monitor technology

Among the most profound consequences of the technology shift in TVs and monitors is the change in consumption patterns. On the one hand, the latest TV models are being purchased to replace existing TVs, despite the fact that these are still functional. As shown in Section 3.1 the "new technology" – LCD TVs – are discarded while they are probably still functioning; 40% are being discarded within 5 years of purchase. This results in a three-fold shorter lifespan for LCD TVs than for CRT TVs. In addition, multiple TVs are being installed in households (this fact has been well-documented in the USA with 2.8 working TVs per household in 2005, see US EPA 2006). These consumption trends has led to a looming peak in the number of discarded TVs, when both the "old" CRT TVs and the "new" flat-screen TVs are discarded simultaneously. The implication for the recycling industry is a need for research and development of the best possible resource management for the discarded materials, and a rapid increase in the capacity to recycle flat-screen technology. The fast turnover of TVs in households is expected to continue, alongside further development of new TV technologies, features and designs. For this reason, the number of discarded flat-screen TVs is likely to remain high in the short and medium term. However, the WEEE from TVs could decrease if the price of TVs increased substantially due to, for example, taxes on electronic equipment or on the materials used in the manufacture of such equipment.

Another implication with a potentially large impact on the recycling industry is the negligible share of the modern television market made up by CRT TVs. No significant sales of CRT TVs have occurred since 2006 and the disposal of CRT TVs will decrease gradually until the last sets enter the waste stream around 2034. The recycling of CRT TVs would be more effective if considerable numbers were recycled together. To accelerate collection of the last CRT TVs, a concerted collection campaign should be considered. As suggested by the lifespan distribution, over 60% of the

CRT TVs were discarded 15 years after their production date, and another 20% within 20 years of the production date (Fig. 2). This suggests that CRT TVs that are 15–20 old, may no longer be in use, but stored and available to be turned in upon request. As a result of such a campaign, the recycling line capacity can be used more effectively while the line can be discontinued as early in 2020–2025, when no more CRT TVs are expected.

Lifecycle assessment studies have shown that the environmental impact of flat-screen TVs is up to three time lower than for CRT TVs of the same screen size (Socolof et al., 2005; Bhakar, 2015; Kim & Kara, 2014). However, the expected decrease in environmental impact did not materialize, as has been shown using market data for USA in 2005 (Kim & Kara, 2014). This is due to the much larger screen sizes of the used flat-screen TVs. This and other comparative LCA studies of CRT and LCD displays have concluded that contrary to common belief, the newer technology is not necessarily better (Kim & Kara, 2014; Aoe et al., 2003; Socolof et al., 2005). Our results show that lifestyle purchases of TVs will increase their accumulated environmental impact through: consumer preference for ever larger screens, multiple TVs in households, and fast turnover of TVs, as a result of still functioning sets being replaced.

The environmental impact of TVs and monitors could be reduced in the manufacturing, usage and disposal phases. In the manufacturing phase, a reduction in the use of SF6 and natural gas has been advocated, as has reducing the electricity consumption in the usage phase (Sokolof et al.). The useful lifespan of TVs and monitors could be extended by promoting the second-hand market and repairs of existing sets, and taxes on materials can be considered as a means to curb over-consumption. In the disposal phase, as many materials and elements as possible should be separated and reused instead of being landfilled or used for waste-to-energy recycling (Felix et al., 2012). However, the complexity of the TVs' electronic hardware and system integration continues to increase, which prohibits separation of the materials both mechanically and by metallurgical techniques. Moreover, new materials are constantly emerging or being mixed in new ways, making dismantling more difficult. In addition, new display technologies such as Organic Light Emitting Diode (OLED), Field Emission Display (FED) or Quantum dot display (QD-LED) may enter the market and rapidly saturate it, in a similar way to what happened during the LCD/LED technology advance, thereby changing the recycling conditions once again. All this could also influence the environmental impact of new products, as a result of changes in material composition and the number of advanced electronic components. Eco-design, where both the life-cycle impact and metallurgical knowledge are taken into account when new products are designed, is one of the potential approaches to make future WEEE recycling successful (UNEP, 2013). Cooperation between the producers and the recycling industry is highly required. The legislators must set standards and codes of conduct and give incentives for resource-recovery oriented product design and materials recovery. For example: in the EU the European Eco-Label voluntary agreement has been implemented to promote products and services that have a reduced environmental impact throughout their lifecycle (European Commission, 2014). For TVs, several types of criteria are used, such as, for manufacturing – Total amount of mercury in fluorescent lamps, per screen; for end of life – Easy disassembly of the system unit, with fixtures that are easily accessible using commonly available tools.

4. Conclusion

Consumption trends for TVs and monitors of different technologies have been investigated quantitatively for Sweden for the period between 1996 and 2014 (Objective 2). During this period, a technology transition has taken place, with flat-screen TVs dominating the market since 2007 and CRT TVs holding only 4% of the market. This phenomenon can readily be observed in the figures along with several other important unfolding trends, such as the considerably shorter lifespans of TVs and monitors; the drastically decreasing weight of devices, and consumer preferences for ever larger screens, as well as lifestyle purchases of TVs. The fact that the lifespans of flat-screen TVs are three times shorter than the lifespans of CRT TVs is likely to be a contributing factor to the lifestyle purchases of TVs. In particular, 40% of the flat-screen TVs are discarded within five years of purchase, when they are most probably still functional. Such short lifespans are expected to persist or even decrease further, as a result of the observed recent trend of preference for x-large screens, along with further developments in peripheral technologies, and the availability of new display technologies. The consumption of large screens, together with the installation of multiple TV units in many households will further aggravate the environmental impact caused by the consumption of TVs.

The amounts of discarded TVs and monitors by technology type, and the available secondary resources, by quantity, type and economic value generation have been investigated (Objectives 2 and 4). As a result of the recent exponential growth in flat-screen TVs, in combination with their short lifespans, a peak in the disposal of these devices is forecasted in 2014–2020 and will require an adequate response (for example adjustment of recycling capacities) from the WEEE collectors and recycling facilities. Since 2007, the consumption of CRT TVs has made up less than 4% of the Swedish TV market. As a result, the last wave of disposed CRT products is projected to occur around 2020 (Objective 3). As low volumes of these products will be discarded over an extended period of time, a concerted campaign to collect all CRT products would be one way to make recycling more effective (Objective 5). In addition, as the development of flat-screen TVs is still on-going, the dismantling and recycling processes for LCD TVs should be updated continuously.

This study contributes to the consolidation of the available methods for forecasting the amounts of discarded TVs and monitors by technology type, as well as the available secondary resources, by quantity, type and economic value (Objective 1). Both the data requirements and the methods are described in detail, including data sources in different countries and reasonable assumptions made based on findings of this and other published studies. In particular, typical lifespans, weights of products and components, material compositions, and economic values are provided for different technologies and generations of devices. Weibull distributions of lifespans, together with size and weight distributions of consumed TVs may inform WEEE estimations under conditions of data scarcity, when for example only the number of sold units is known.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.wasman.2015.08.034.

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