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Estimation of future outflows and infrastructure needed to recycle personal computer systems in California

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Abstract

The objectives of the present study are to estimate future quantities of electronic waste (e-waste) for which appropriate infrastructure needs to be established, and to the estimate the total cost for e-waste recycling in California. Estimation of the future amounts of e-waste as a function of time is critical to effective e-waste management.

To generate estimates, we use a time-series materials flow analysis model (MFAM). The model estimates future e-waste quantities by modeling the stages of production, usage, and disposal. We consider four scenarios for the estimation of future e-waste generation in order to consider the effects of exportation outside the State of California and of user preferences to store or to recycle the e-waste. These efforts were further investigated through the use of sensitivity analysis.

The results of the present research indicate that the outflow (recycling) amount of central processing units (CPUs) will increase and will reach approximately 8.5 million units per year in 2013, but the outflow (recycling) of cathode ray tube (CRT) monitors will decrease from 2004 in California because of the replacement of CRT monitors by liquid crystal display (LCD) monitors. In 2013, the cost for CPU recycling will be 1.7 times higher than that in 2005. But for CRT monitors, the cost for recycling in 2013 will be negligible. After the State of California enacted the ban on landfill disposal of e-waste, recycling became the most common end-of-life (EOL) option in California. Also, after 2005, the State of California will need more than 60 average-capacity materials recovery facilities (MRFs), to recycle the number of personal computer systems generated, which represents an investment in capital of over $16 million.

Keywords: Materials flow analysis; Infrastructure; Recycling; End-of-life

1. Introduction

Consumer electronic equipment has quickly become part of our daily life with a rapid pace of technological development. The useful lifespan of these consumer electronic devices (CEDs) is relatively short, and decreasing as a result of rapid changes in equipment features and capabilities. This creates a large waste stream of obsolete electronic equipment.

Electronic waste (e-waste) from electrical and electronic equipment is now one of the emerging waste streams in many developed countries, and management of this waste has become a major challenge. It is expected that quantities of obsolete electronics will increase rapidly in the near feature. It is expected that the amount of e-waste will increase 16–28% every year, which means a growth rate three times as fast as the average for municipal waste [1]. Also, it is estimated that approximately 70% of the heavy metals currently disposed in landfills comes from e-waste, and many heavy metals in e-waste are considered to be toxic [2,3].

Challenges faced in e-waste management are not only the consequence of the growing quantities of waste, but also of the complexity of e-waste. E-waste is one of the most complex waste streams because of the wide variety of products ranging from mechanical devices to highly integrated systems and rapidly changing product design. Electronic products are an integration of numerous modern technologies and are composed of many different materials and components [4].

Recycling and reuse of EOL electronic products provide a closed materials cycle. However, to completely close the materials flow cycle, there must be a logical connection between the use

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and the recycling of products. This connection will determine whether the economic and ecological closing of the material cycle will be successful or not [5].

The important factors for successful e-waste treatment are the laws/regulations that encourage e-waste recycling, the accurate estimation of the quantities of e-waste that will be generated both in the short term and the long term, environmentally sound treatment in qualified facilities, and the success of the after markets for materials recovered in recycling and recovery operations.

In order to develop the infrastructure for the treatment of e-waste, one of the most necessary things is an accurate estimation of future quantities of e-waste generation. Previous studies have been considered in which the potential future quantities of e-waste were estimated [6,7]. Additional studies have utilized materials flow analysis in their analysis [8–10]. Although the methods are still valid, the results of theses studies no longer provide a realistic reflection of the e-waste estimation in the State of California, because they were based on a different set of assumptions; this State now has mandates that ban landfill disposal and incineration of CRT monitors and other electronics [11].

For this study, we utilized a time-series material flow analysis model (modified from Matthews and Matthews [7]) to estimate the generation of e-waste, and technical cost modeling, as developed by Kang and Schoenung [11] to evaluate the costs associated with an e-waste material recovery facility (MRF), a detailed description of which can be found in Kang and Schoenung [4]. Furthermore, by combining these two models, we were able to estimate the cost for future e-waste recycling and the infrastructure needed in California.

We confine the regional boundary of this study to the State of California. The State of California has banned disposal of CRTs through both landfills and incineration. Therefore, all CRTs should be recycled [12]. Also, because of the universal waste law in California, all consumer electronic devices (CEDs) should also be recycled in California [13]. These facts create features within the California e-waste recycling management environment that are different than most other states in the U.S. Also, in this study, we concentrate on the treatment of personal computer equipment because most of the volume processed in electronic recycling material recovery facilities is from personal computer equipment [11,14].

2. Methodology

It is critical to know the amount of e-waste that will be generated and when it will be generated, so that appropriate infrastructure can be established.

To conduct an estimation of the future generation of e-waste, first we need to know the historical production or shipment amounts of electronic devices; second, we need to consider the rate at which these reach end-of-life. This second component for personal computer systems is more complex than for many other products such as beverage containers, which have very short useful lives, and durable goods such as major appliances, which typically have long useful lives. For personal computer systems the useful life has been rapidly decreasing [4,11]. Furthermore, at their end-of-life, they often are either stored for possible future use and/or value, or passed along to a second user. We have attempted to systematically account for these complexities in the estimation procedures, described below.

For this study, we assume that when consumers purchase a new personal computer system they buy a CPU and a CRT or LCD monitor together. Fig. 1 shows historical and projected shipments of CPUs, CRT monitors, and LCD monitors in California [15–23]. The shipments of CPUs increase continuously except for a slight decrease in year 2000 [20]. In 2010, CPU shipments will be expected to be more than 8.5 million units in California.

Until 1999, CRT monitor shipments also increased with CPU shipments, but after 1999, CRT monitor shipments began to decrease because LCD monitors began to substitute for CRT monitors [21]. Shipments of CRT and LCD monitors were approximately the same, approximately 3 million units each, in 2003 [22]. It is projected that LCD monitors will completely replace CRT monitors by the year 2007 [23].

To estimate future quantities of e-waste, the materials flow analysis (MFA) method has been utilized. This method is based on the general physical law of mass conservation. The MFA

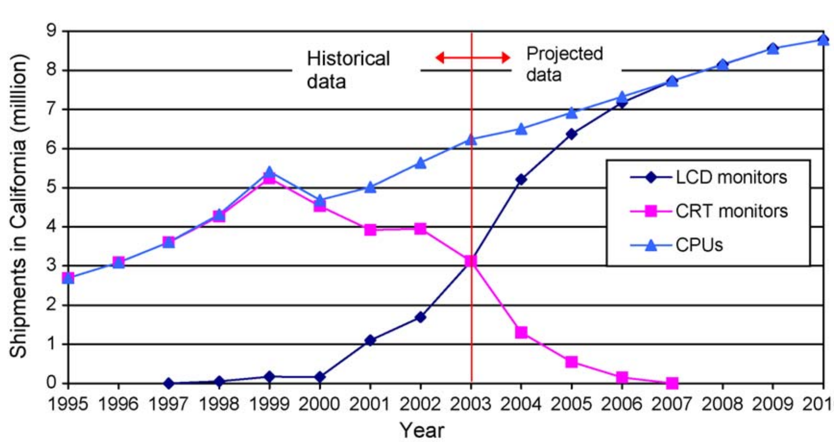

Fig. 1. Historical shipment data and estimates of future shipments of CPUs, CRT monitors, and LCD monitors in California.

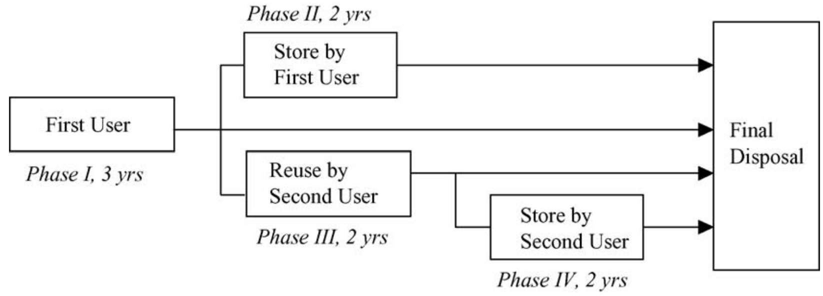

Fig. 2. The various possible lifespan and disposal options for personal computer systems.

Table 1
End-of-life options for obsolete personal computer systems for the first user, before California banned landfill disposal

End-of-life options	Approximate disposal portion, %
Store by the first user	75
Recycle	15
Landfill	7
Reuse	3

method is an appropriate analytical tool to follow materials from natural sources, to manufacturing, use, and ultimate disposal [8,10,24,25].

The EOL options for the disposition of personal computers systems, after completing a useful life with a "first" user, include: storage, recycling, landfilling, or reuse by a second user.

There are several studies on the distribution of personal computer systems among these EOL options [3,6,7], as summarized in Table 1. Table 1 shows that prior to the State of California ban on landfill disposal of CRTs, the most popular EOL option for used personal computer systems by the first user is 'Store' even though these computer systems are not in use. A considerable amount of used personal computer systems (∼75%) remain in stock to be disposed of at a later time [6,26]. The second largest EOL option (∼15%) is collection for recycling [3,6,27]. Approximately, 3% is reused immediately [6] and the remaining 7% is estimated to be landfilled. However, these disposal options have changed since California banned landfill disposal of e-waste in California, as is discussed later in this paper.

Table 2 presents the estimated average lifespan of personal computer systems in each phase [6,28]. The National Safety Council study [6] estimated that the total useful lifespan of personal computers is less than 5 years for PCs, and explained that the increasing rate of technology development is the primary reason for this shortened lifespan. This study also estimated that the lifespan of a PC would decrease to 2 years by the year 2005. But this report was published in 1999, before the economic fluctuations that can be seen from Fig. 1, so there might be a need to change the estimate of the lifespan for the year 2005. In light of the decrease in shipments observed in 2000, and the observation that most PCs taken to e-waste recycling facilities in 2004 were reported to be 5-years old [29], for the present study, the lifespan values are assumed to be those shown in Table 2. The average useful lifespan of a personal computer system by the first user, *Phase I* is estimated to be 3 years. After this, one feasible option for the first user is to 'Store' the personal computer system, *Phase II*, and it is projected to be stored for 2 years without use. Another option is to 'Reuse' the personal computer system by a second user[1], *Phase III*. In *Phase III*, the use period is estimated to be 2 years. Also, the average lifespan for *Phase IV*, 'Store by second user', is estimated to be 2 years.

Table 2
Estimated average lifespan of personal computer systems in each life phase

Phase	Phase of life	Average lifespan (years)
Phase I	First user	3
Phase II	Store by the first user	2
Phase III	Reuse by the second user	2
Phase IV	Store by the second user	2

The various possible options in lifespan and disposal for a personal computer system are shown in Fig. 2. In the model, the maximum possible lifespan for a personal computer system is estimated to be 7 years: 3 years of use by the first user (*Phase I*), 2 years of 'Reuse' by the second user (*Phase III*) followed by 2 years of 'Store' (*Phase IV*). The shortest possible lifespan is only 3 years (*Phase I*), i.e., the first user disposes the system directly to final disposal. The State of California banned landfill disposal of CRT monitors in 2001 and electronic devices in 2003 [12,13]. Before the banning of landfill disposal of e-waste, the options for final disposal were landfill and recycling[2] [30]. Since the implementation of these bans, the disposal options for e-waste have changed; recycling is now the only legal final disposal option.

Fig. 3 illustrates the temporal and regional system boundary of this time-series material flow analysis model for personal computer systems in California. The temporal boundary of the system is defined as the useful life phases, such as use, reuse, and store, by the first and second users, and the regional boundary is defined as the State of California. In Fig. 3, solid lines represent the flow of material both before and after the banning of landfill disposal, and broken lines represent the flow of material only before the banning of landfill disposal in California. Only

[1] For convenience in this study, we define the 'Reuse' EOL option as the reuse only by the second user. This phase also represents reuse by the first user with a different purpose than the original usage. Also, we assume that there is no 'Reuse (*Phase III*)' after 'Store (*Phase II*)' by the first user, because the system would be obsolete.

[2] In California in the year 2000, the number of operating landfill facilities was 146 but that of incineration facilities was only 3 [29].

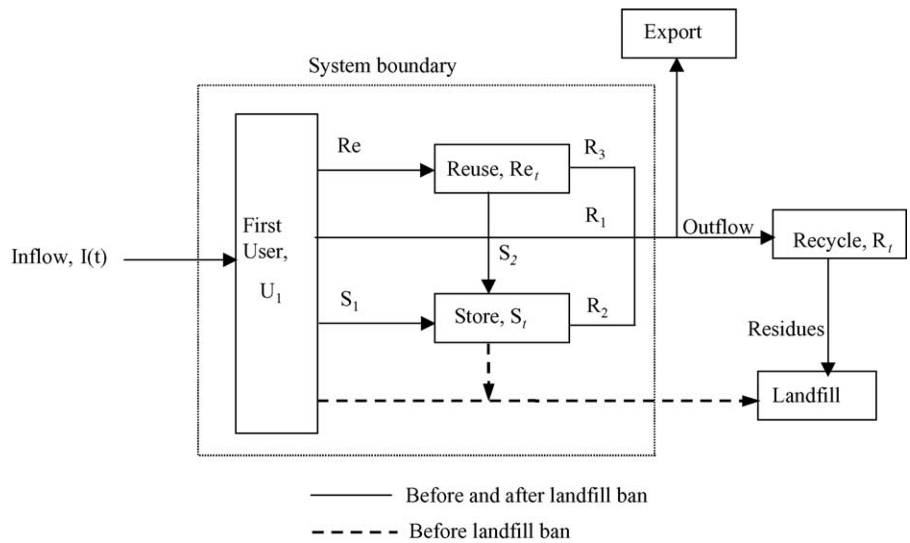

Fig. 3. System boundary of the time-series inflow-outflow model developed to evaluate e-waste generation in California. — Before and after landfill ban; - - - - before landfill ban.

residues that come from the recycling process can be disposed of in landfills after the landfill ban in California. We also take into account that a considerable amount of outflow (recycling) can occur outside of California, such as in Asia, in order to save recycling cost [3]. The variables in Fig. 3 are defined below.

In material flow analysis, the general form used to represent the outflow after the useful lifespan is a function of the inflow in the past and can be expressed by Eq. (1) [10].

$$\text{Outflow}(t) = \text{Inflow}(t - i) \quad (1)$$

where Outflow(t) and Inflow($t-i$) represent the outflow (recycling) amount and inflow (shipment) amount in the year t and in the year ($t-i$), respectively. In the model, we assume that there is no outflow before the end of the first useful average lifespan, i.e., within 3 years after shipment.

However, to apply Eq. (1) to personal computer systems, we need to modify the equation. Considerable numbers of computer systems are not going to be outflow (recycling) immediately after the first useful lifespan by the first user, *Phase I*. They can be stored by the first user for a certain period, *Phase II*, or reused by the second user, *Phase III*, and might be stored one more time by the second user, *Phase IV*. These store and reuse phases can be considered as another lifespan for the computer systems.

These factors must be considered when we estimate the outflow (recycling) (see Table 1, Figs. 2 and 3). The need to recycle instead of landfill creates a different waste management situation for PCs in California than in most other states within the U.S. After considering these factors, the modified equation is then expressed:

$$\text{Outflow}(t) = \sum_i \text{Inflow}(t - i) \quad (2)$$

In Fig. 3, the value for inflow of computer systems, $I(t)$, is the shipments for year t in California (see Fig. 1). After the ban on landfilling, there are three EOL options for the first user, i.e., recycle, reuse or store, and two options for the second user, store or recycle. Thus, the amount of outflow is the total amount to be recycled in year t, and can be expressed as R_t:

$$R_t = R_1 + R_2 + R_3 = \sum_{i=3,5,7} R'_t(t - i)_i \quad (3)$$

where $R'_t(t-i)_i$ represents the recycled amount in the year t out of the shipments amount in year ($t-i$). i has the values of 3, 5, and 7 because of the lifespan values specified in Table 2. For example, the recycled amount in 2004 ($t=2004$), is expressed as R_{2004} (see Fig. 3),

$$R_{2004} = R'_{2004}(2004 - 3)_{i=3} + R'_{2004}(2004 - 5)_{i=5} + R'_{2004}(2004 - 7)_{i=7} \quad (4)$$

This logic can also be applied to the store option, S_t, and reuse option, Re_t. Thus, the stored amount, S_t, and reused amount, Re_t, in year t can be expressed as shown in Eqs. (5) and (6), respectively.

$$S_t = S_1 + S_2 = \sum_{i=3,5} S'_t(t - i)_i \quad (5)$$

$$\text{Re}_t = \text{Re}_t{}'(t - i)_i \quad (6)$$

where $S'_t(t-i)_i$ and $\text{Re}'_t(t-i)_i$ represent the stored amount and reused amount, respectively, in the year t, out of the shipment amount in year ($t-i$).

The values on the right sides of Eqs. (3), (5), and (6), e.g., $R'_t(t-i)_i$, can be difficult to determine because they depend on external factors such as consumer behavior and legislative mandates. Several factors can affect consumer behavior relative to the disposal of electronic devices after their useful lifespan, such as price, functionality, and the design of the device. The recycling attitudes of consumers are influenced by having appropriate opportunities, facilities, and knowledge to recycle [31]. Other researchers have shown that recycling behaviors depend on age, gender, income, education, and ideology of consumers [32–34]. Research done by the US EPA shows that about 80%

of consumers are willing to pay a fee of less than $5 for the recycling of obsolete electronics [32]. Moreover, it is very difficult to quantify the behavior of consumers.

Because of the limited historical data available on the lifespan of personal computer systems, it is not possible to calculate the exact amount of outflows, or even a range of values. In this model, therefore, we have made some important assumptions so that an estimation of output could be generated. First, we assume that the average lifetime is an exact value, recognizing that in reality some individual products will have shorter or longer lifetimes than the average. Second, the residence time data used in this analysis is considered as discrete for a calendar year.

Another factor to consider is the potential export of collected e-waste into other states or from developed countries to developing countries. According to the Basal Action Network and the Silicon Valley Toxic Coalition, more than 50% of e-waste collected for recycling in California was being exported overseas to save on the costs of recycling [3,26]. In addition, the cost of recycling CRT monitors in California is more expensive than that in other states [11]. Even though California regulates e-waste as universal waste [12,13], there is still the possibility of it crossing the California border to reduce the cost of recycling. To date, there is no tracking system for collected e-waste.

After consideration of all these factors, to simplify our evaluation of consumer disposal behavior after the banning of landfill disposal in California, we consider four scenarios.

- *Scenario 1*: All e-waste that would have been landfilled before the landfill ban is diverted to recycling. All e-waste collected for recycling is actually recycled within the State of California.
- *Scenario 2*: Fifty percent of e-waste that would have been landfilled is diverted to recycling and the remaining 50% is diverted to storage. All e-waste collected for recycling is recycled in California.
- *Scenario 3*: All e-waste that would have been landfilled is diverted to recycling. Fifty percent of the e-waste collected is recycled in California and 50% is exported outside of California.
- *Scenario 4*: Fifty percent of e-waste that would have been landfilled is diverted to recycling and the remaining 50% is diverted to storage. Fifty percent of e-waste collected is recycled in California and 50% is exported outside of California.

Table 3 shows the EOL options for obsolete personal computer systems after the California ban on landfill disposal, as determined on the basis of the four scenarios outlined above and the baseline values provided in Table 1. As expected, in Scenarios 1 and 2, all collected equipment is recycled inside California, but in Scenarios 3 and 4, 50% of the collected equipment is exported outside of California.

Table 3
Distribution in the end-of-life options for obsolete personal computer systems after the California ban on landfill disposal, as determined on the basis of the four scenarios described in the text and the baseline values provided in Table 1

	Recycling		Store, %	Reuse, %
	In CA, %	Outside CA, %		
Scenario 1	22	–	75	3
Scenario 2	18.5	–	78.5	3
Scenario 3	11	11	75	3
Scenario 4	9.25	9.25	78.5	3

3. Results

3.1. Estimation of future obsolete personal computer system generation in California

Fig. 4 shows results for the outflow (recycling) for EOL options of CPUs, CRT monitors, and LCD monitors based on the four scenarios after their useful lifespan, in California. Compared to Fig. 1, the outflow pattern shows a delayed version of the inflow distribution pattern. This delayed inflow distribution shows that stock[3] acts as a time buffer, as described by Kleijn and Huele [24]. However, it can be seen that the outflow distribution is not only a delayed but also a skewed inflow distribution, which is different than a simple delayed model where the delay depends directly on the average lifespan of the system by the first user. This fact implies that to predict a more realistic outflow of personal computer systems, Eq. (2) should be used.

Fig. 4A indicates the change in recycled (outflow) amount according to the four scenarios (see Table 3). By 2002, the largest volume of CPUs in stock was in storage, S_t, but after 2003 the largest volume is being recycled. From 2003, the recycled amount of CPUs increases sharply. After 2005, Scenario 1 shows a larger amount of recycling, R_t, than Scenario 2, but Scenario 2 has a larger amount in S_t than for Scenario 1. Starting in 2003, CPU landfill disposal was banned in California, leading to the sharp increase in recycled amount. It is expected that future amounts of CPUs to be recycled will increase with increases in shipments within California.

As can be seen from Fig. 4, Scenarios 1 and 2, and Scenarios 3 and 4 show very similar behavior, except the recycled amounts are less for Scenarios 3 and 4 because of the assumption that 50% of potentially recyclable goods are exported from the State of California.

$R'_t(t-3)_{i=3}$ in Scenario 1 is greater than that in Scenario 2, and $R'_t(t-5)_{i=5}$ in Scenario 1 is less than that in Scenario 2. These relationships are shown in Table 4. $R'_t(t-5)_{i=5}$ includes two flow paths, i.e., 'from *Phase I* to *Phase II*' and 'from *Phase I* to *Phase III*', but because the flow path 'from *Phase I* to *Phase III*' ('Reuse' by second user) is the same for both Scenarios 1 and 2, we do not need to consider the effect of this flow path (see Table 3). The main contribution to the differences in $R'_t(t-5)_{i=5}$ is the stored amount, S_1 after *Phase I* (U_1) by the first user. For $R'_t(t-3)_{i=3}$, the main contributor is the recycled amount directly from the first (see Fig. 3).

The absolute value of the difference between Scenarios 1 and 2 in $R'_t(t-3)_{i=3}$ is larger than that in $R'_t(t-5)_{i=5}$, because the

[3] In this study, stock is defined as the sum of the amount being used by the first user (U_1), the stored amount (S_t), and the amount reused by the second user (Re_t).

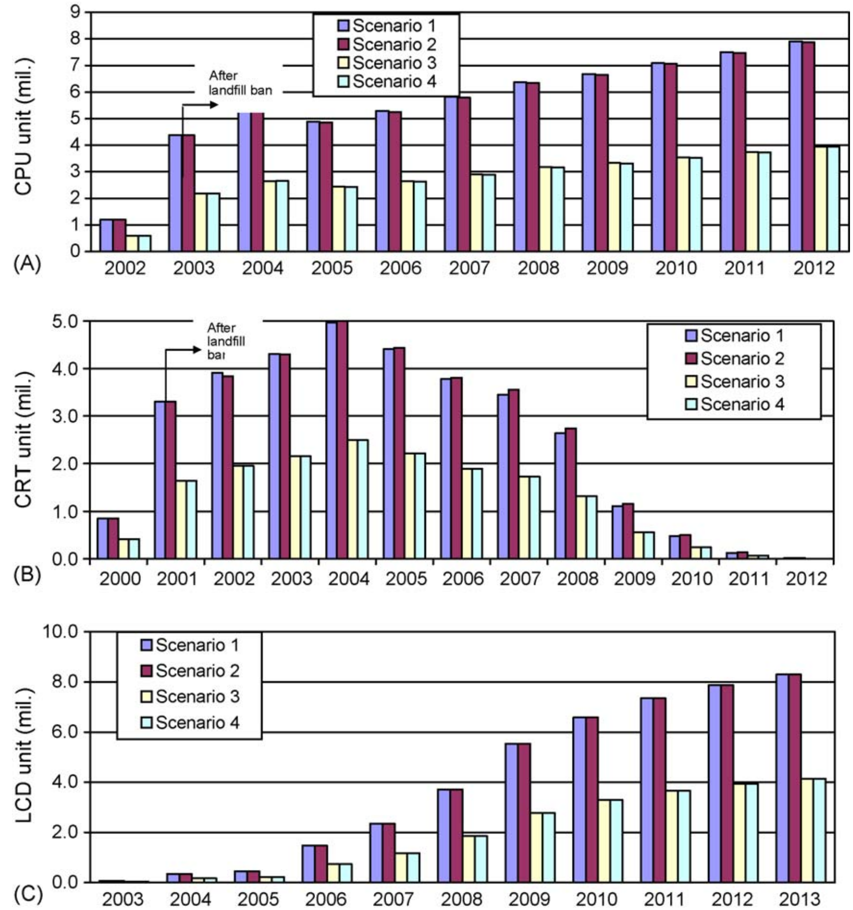

Fig. 4. Predicted recycled (outflow) amounts over time based on the four scenarios EOL options (see Table 3) after the ban on landfill disposal in California. (A) CPUs; (B) CRT monitors; (C) LCD monitors.

population for $R'_t(t-3)_{i=3}$ is the shipments in year $(t-3)$, but the population for $R'_t(t-5)_{i=5}$ is the amount stored by the first user, S_1, in Fig. 3 or $S'_t(t-3)_{i=3}$ in Eq. (5). The differences in these populations are the main sources of the differences in outflow (recycling) amount between Scenarios 1 and 2. As a consequence, R_t for Scenario 1 is greater than for Scenario 2, but the difference in the value of R_t is very small (less than 0.5%). This same effect also explains the slight difference in values calculated for Scenarios 3 and 4.

Fig. 4B shows the outflow distribution for CRT monitors in California. The largest EOL portion for CRT monitors is 'Store', S_t until 2000. But recycling becomes the largest option in 2001 for both Scenarios 1 and 2. The amount to be recycled, R_t, reaches its peak value in 2004, at the value of approximately 5 million units, and from 2005, the amount starts to decrease for both the storage and recycling options, because of the earlier decline in shipments (see Fig. 1).

It is projected that the need to deal with EOL for CRT monitors will be essentially phased out by the year 2013, which is, as assumed in our model, seven years after shipments would end. Fig. 4C shows the projected outflow distribution for LCD monitors in California, which indicates a gradual increase over time.

A comparison of outflow (recycled) and stored amounts based on Scenario 1 after the landfill ban is shown in Table 5. In the case of the CPUs, both amounts increase because shipments

Table 4
Variations in relative recycling amounts for Scenarios 1 and 2, and their differences in absolute values

Year $(t-3)$	$R'_t(t-3)_{i=3}$			$R'_t(t-5)_{i=5}$		
	Scenario 1	Scenario 2	|SC 1 − SC 2|	Scenario 1	Scenario 2	|SC 2 − SC 1|
2003	1.03	0.87	0.16	3.24	3.33	0.09
2004	1.10	0.93	0.17	4.06	4.25	0.19
2005	1.24	1.04	0.20	3.52	3.68	0.16
2006	1.37	1.15	0.22	3.77	3.94	0.17
2007	1.43	1.20	0.23	4.23	4.43	0.20

Unit: millions.

Table 5
Comparison of the recycled and stored amounts for CPUs and CRTs after the ban on landfill disposal, based on Scenario 1

Scenario 1	2001	2003	2006	2009	2012
CPU					
Recycle	–	4.38	5.26	6.66	7.88
Store	–	3.57	4.74	5.88	6.51
CRT					
Recycle	3.43	4.44	3.87	1.12	0.01
Store	3.24	3.45	2.39	0.13	–

Unit: millions.

increase in every year, but, in the case of the CRTs, both amounts decrease after the year 2003, and there is no substantial stored amount after 2009. After the ban on landfill disposal, the recycled amount for both CPUs and CRTs is larger than that of the stored amount in each year. The average ratio of the recycled amount relative to the stored amount is 1.19 and 1.28 for CPUs and CRTs, respectively. Recycling became the most common EOL option after the ban on landfill disposal in California.

The results of this modeling effort provide an example of a possible approach to identify and estimate future waste flows from societal stock. This approach used multiple lifetime spans for estimation of outflows, which is different from a single lifetime span approach. In principle, this approach can provide a more realistic analysis than a single lifetime span approach for products such as PCs. It is limited, however, by the need for additional data. This approach still derives from the most basic starting point for materials flow analysis: the requirement of mass balance. The lifespan of the products and stocks, however, determine the delay. After the first lifespan of computer systems, there are other EOL options in addition to disposal: storage by the first user and reuse by the second user, during which the systems, although not in use by the first user, are still working properly. The results of this study indicate that the major factors to influence the outflow of e-waste are the inflow amount and the decision by first user, e.g., to recycle or to store.

3.2. Sensitivity analysis with the materials flow analysis model

To test the sensitivity of the model when one or two input variables are changed, sensitivity analysis was implemented. Scenario 1 is used as the baseline for the sensitivity analysis.

Fig. 5 demonstrates the sensitivity of the model to changes in the portion of the previously landfilled, now recycled amount by the first user, $R_t'(t-3)_{i=3}$. This sensitivity analysis focuses on the time period after the landfill ban for CPUs in 2003, and shows that the amount of recycling, R_t for $t=2005$, will decrease when $R_t'(t-3)_{i=3}$ has values of 20 and 50% relative to $I(t-3)_{i=3}$. The decrease in recycling amount seen in 2005 can be explained on the basis of the decreasing shipments in 2000 compared to those in 1999. The amount that is stored in 2003, $S_t'(t-3)_{i=3}$, decreases in comparison to that in 2002 because shipments, $I(t)$, decreased in 2000 (recall the first user uses the system for 3 years and then stores it for 2 years). This phenomenon is manifest at

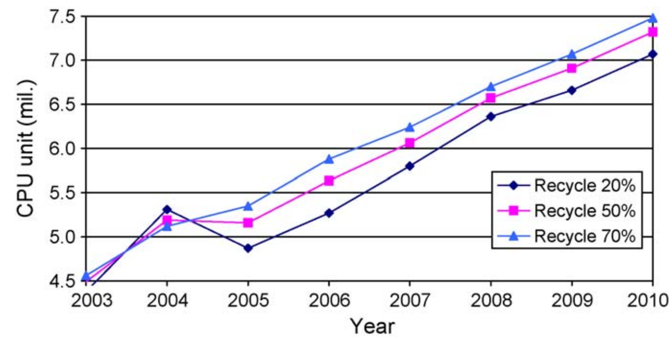

Fig. 5. Sensitivity analysis of the outflow results in CPU when the recycling amounts are changed. Scenario 1 is used as the baseline.

low recycling rates. At a level of 20% recycling by the first user, the extent of decrease in 2005 is larger than when the level of recycling by the first user is higher. Moreover, when the recycling portion by the first user is larger than the storage portion (e.g., a level of 70% recycling by the first user), there is no decrease in the total recycling amount in 2005.

Fig. 6 shows a sensitivity analysis related to the recycled amount in the CPU model when the average lifespan by the first user (*Phase I*) is changed. Scenario 1 is, again, used as the baseline. When the average lifespan by the first user (*Phase I*) is 2 years, the amount of recycled CPUs has the largest values from 2005 to 2012. In 2004, there is a decrease in the amount of recycling (R_{2004}) due to the decrease in shipments in 2000. $R_{2004}'(2000)_{i=4}$ (2 years *Phase I* + 2 years *Phase II*) and $S_{2002}'(2000)_{i=2}$ control this phenomenon. As the lifespan for the first user increases, the decrease in R_t is delayed by the extent of the increase in lifespan, i.e., when *Phase I* is 5 years, the decrease in R_t shows up in 2006, 3 years later than if *Phase I* is equal to 2 years.

From Figs. 5 and 6, we notice that the decision of the first user has the largest impact on the outflow for e-waste.

3.3. Estimation of recycling costs in California

For the estimation of recycling costs, we use technical cost modeling, as developed by Kang and Schoenung [11]. Technical cost modeling is data intensive and requires several steps.

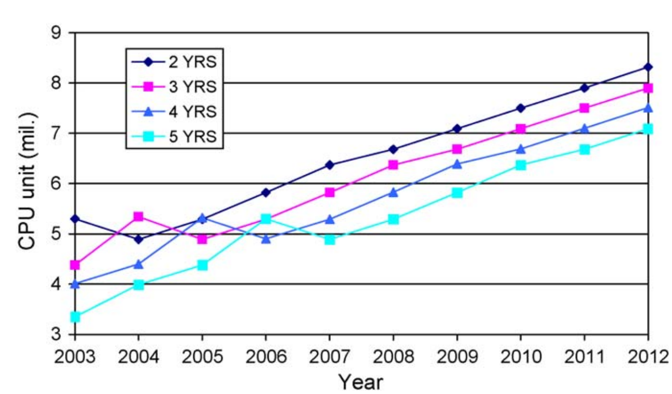

Fig. 6. Sensitivity analysis of the CPU outflows when the lifespan in *Phase I* is varied from 2 to 5 years. Scenario 1 is used as the baseline.

Table 6
Operating conditions of a materials recovery facility for CPU and CRT recycling in California [11]

Price of electricity (industry sector) ($/kWh)	N(0.10, 0.02)
Operating time (day/year)	240
Labor wage ($/h)	N(9.0, 1)
MRF equipment cost recovery life (year)	7
Treatment volume (tonnes/yr)	2500
Number of working hours (h/day)	8
Number of workers	13

$N(\mu,\sigma)$ indicates a normal distribution with mean μ and standard deviation σ.

By adding up the key process-derived costs, we can determine a cost for each unit operation. The total materials recovery facility (MRF) operating cost is calculated by summing all unit operation costs. Revenues for each unit operation and total MRF operating revenue can be estimated with the same logic as used for the cost estimation. To estimate the costs, we assume the size of the e-waste MRF to be that is typical today (∼20 employees, 1000–2500 tonnes/year treatment volume) [14,35]. The estimated or assumed general input values for the MRF cost modeling are listed in Table 6. These general input parameters are common to all of the unit operations, but are specific to the State of California [11].

The costs for CPU and CRT recycling were calculated to be $0.23/kg and $0.33/kg, respectively [11]. These recycling costs are applied to calculate total recycling costs for California.

Fig. 7 shows the change over time in the normalized recycling cost per year for both CPU and CRT monitors in California. The total recycling costs are normalized to the baseline value determined for the year 2005. The costs, which are shown in Fig. 7, are based on Scenario 1. As can be seen in Fig. 7, because of increasing shipments of computer systems, the total cost for CPU recycling will increase, and it is expected that in 2013 the cost will be 1.7 times that in 2005. Also, Fig. 7 shows the change over time in the normalized CRT monitor recycling cost per year. In the case of CRT monitors, the normalized recycling cost will decrease due to decreasing shipments, and it is expected that the total cost will decrease rapidly after 2007. After 2011 the total cost for CRT monitor recycling in the State of California is negligible.

But this cost estimation does not include the recycling cost for LCD monitors. When LCD monitor recycling cost is added, it is expected that the recycling cost for computer systems (CPU + LCD monitor) in 2013 will be more than twice that in 2005. To date there is no study about LCD monitor recycling technologies, but LCD monitor shipments are expected to increase; current shipments already exceed shipments of CRT monitors [23].

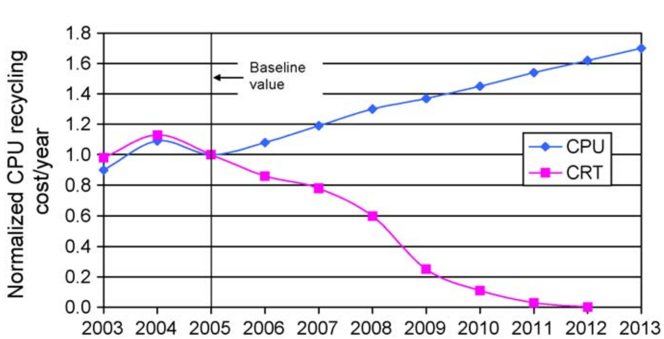

Fig. 7. Estimation of normalized recycling costs in California based on Scenario 1; LCD recycling is not accounted for.

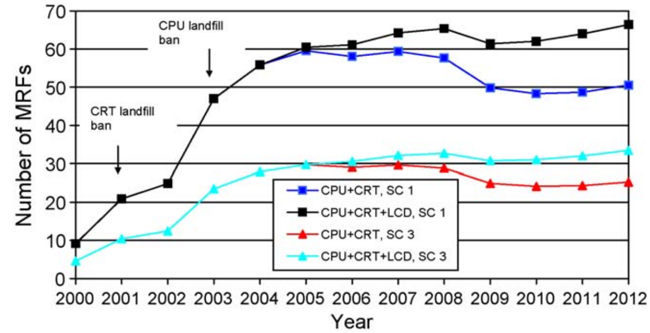

Fig. 8. The estimated numbers of average-capacity MRFs needed to recycle personal computer systems in California, based on Scenarios 1 and 3.

3.4. Infrastructure needed to treat personal computer systems in California

Based on the modeling results and assuming Scenarios 1 and 3, we calculated the number of MRFs needed for treatment of EOL personal computer systems in California. Fig. 8 shows this result: the State of California will need more than 60 average-capacity MRFs after the year 2005 to properly recycle personal computer systems, based on Scenario 1, i.e., assuming all systems collected are recycled in California. Assuming Scenario 3, the State of California will need more than 30 such MRFs after the year 2005. The number of MRFs needed increased in 2001 and 2003 because of the ban on landfill disposal for CRTs and CPUs, respectively. To date, there are no published accurate data about the actual amount of e-waste generated in California, the percent of the equipment collected that is sent outside of California for recycling, or the total treatment capacity of current California e-waste recyclers. However, the results from Fig. 8 provide some guidance on the magnitude of the need for e-waste recycling capability within the State of California.

As can be seen from Fig. 8, the number of MRFs needed increased sharply in 2003 and gradually increases until 2008. In 2009, it shows a decrease and then another increase. The decrease in the number of MRFs needed in 2009 is explained by the sharp decrease in the CRT recycled amount (see Fig. 4B).

Based on the modeling results, from 2008 to 2009, the decrease in the amount of CRT recycling is 24,480 tonnes but the amount of increase in CPU and LCD combined is 15,460 tonnes. The increase in the CPU and LCD amount cannot compensate for the decrease in the amount of CRTs, thus the number of MRFs needed is decreased. However, from 2010 on, the increases in CPU and LCD outflows exceed the decrease in CRT amount, so the number of MRFs needed increases again, as shown in Fig. 8. This phenomenon is applicable to both the (CPU + CRT) and the (CPU + CRT + LCD) models, although the (CPU + CRT) model shows a somewhat different pattern from the (CPU + CRT + LCD) model.

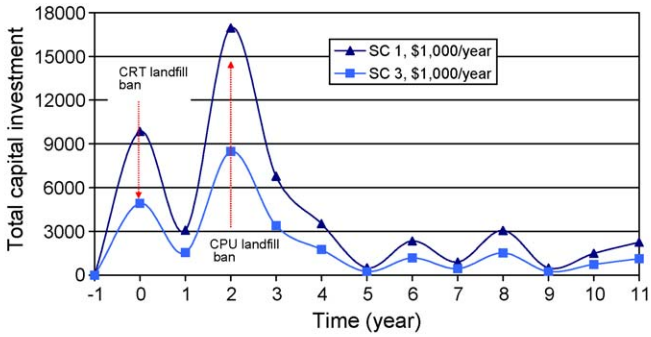

Fig. 9. Estimated total capital investment needed to set up new MRFs for the recycling of personal computer systems after the bans on landfill disposal in California, based on Scenarios 1 and 3.

Fig. 9 shows the estimated total capital investment needed each year to develop the additional MRFs needed to recycle personal computer systems in California after the bans on landfill disposal, based on Scenarios 1 and 3. For Scenario 1, the State of California needs to invest more than $9 million and $16 million, respectively, to provide the capital in MRFs needed to handle the additional recycling needs that result from the ban on landfill disposal of CRT monitors and CPUs. Fig. 9 also shows that more total capital investment was needed to cope with the CPU recycling needs than for the CRT monitors. Assuming this level of capacity had actually been achieved in the years immediately following the bans, subsequent investment needs would decrease sharply. After the second ban, on CPU landfill disposal, little additional capital investment would be needed each year, as can be seen in Fig. 9.

4. Conclusions

To estimate the infrastructure needed for future recycling of CPUs and CRT monitors in California, we used technical cost modeling combined with projections of future outflow amounts generated by utilizing materials flow analysis modeling. E-waste is a major waste stream of concern in many developed countries because of its growing amount and adverse effects to human health and potential toxicity to the environment. The State of California has banned landfill disposal of consumer electronics so that all e-waste must be recycled properly. Thus, it is critical to know ‘When?’ and ‘How much?’ e-waste will be generated so that appropriate infrastructure can be developed.

The results of this case study lead to several conclusions. Although the inflow pattern and amount are factors affecting the outflow pattern and amount for computer systems, the pattern of outflow and amount does not simply depend on the inflow because consumers have multiple options and because of changes in legislation. For instance, the outflow amount (recycling) increased sharply after the ban on landfill disposal in California. The behavior of the first user is a critical factor in determining the outflow amount. The first user’s choice of EOL option, to recycle or to store (and for how long) is also critical to determining the pattern and amount of outflow.

The costs for CPU recycling will increase as shipments continue to increase, and in 2013 the total cost will be 1.7 times that in 2005. But in case of CRT monitors, the total cost for recycling will decrease, and after 2011 it will be negligible because shipments of CRT monitors are projected to be completely replaced by shipments of LCD monitors starting in 2007. After banning landfill disposal of CRT monitors and CPUs, the State of California had a need for more than 60 MRFs to recycle the CPUs, CRTs and LCDs in California, which represents an estimated $16 million total capital investment initially, and additional incremental investment for subsequent years.

It should be noted, however, that these results are only for personal computer systems recycling. There are other electronic products that should be recycled such as TVs, audio systems, VCRs, and cell phones. If these items are also considered, the number of MRFs and capital investment needed for California e-waste management will be even greater. These needs have the potential to provide a new employment base within the State of California.

It is important to realize that the results summarized about were derived on the assumptions that available data are accurate and that average values, especially for lifespan, are reasonable representatives of the entire data set. It would be preferred if sufficient data were available for statistical and uncertainty analysis. The development of such a data set through future work is strongly encouraged.

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