



Determining advanced recycling fees and subsidies in “E-scrap” reverse supply chains

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ABSTRACT

Primarily due to environmental concerns and legislative mandates, the disposition of end-of-life (EOL) electronics products has attracted much attention. Advanced recycling fees (ARFs) and government subsidies may play important roles in encouraging or curtailing the flows of recycled items. We present a Stackelberg-type model to determine ARFs and socially optimal subsidy fees in decentralized reverse supply chains where each entity independently acts according to its own interests. The model consists of one leader (the government) and two followers (a group of manufacturers, importers, and sellers (MISs) and a group of recyclers). To maximize social welfare, the government determines the ARFs paid by MIS and the subsidy fees for recyclers when MIS sells new products and recyclers process EOL products. We find that MIS and recyclers behave at the equilibrium status by choosing optimal selling quantity in the market and optimal reward money for customers bringing EOL products to recyclers. Under this approach the two fees achieve the maximum of social welfare at the equilibrium status, while both MIS and recyclers gain the maximum of profits. For comparative purposes, we also develop a conceptual model describing the current practice by which ARFs and the subsidy fees are determined on the basis of fund balance between revenues and costs along with recycling operations. We conclude that our results outperform current practice.

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1. Introduction

The importance of recycling end-of-life (EOL) products is being recognized due to high demand in many raw material markets and greater awareness of the environmental impacts of disposal. In the past decade, much attention has focused on design, planning, and modeling for closed-loop (forward and reverse) supply chain systems (e.g. Fleischmann et al., 2000; Guide and Harrison, 2003; Hong et al., 2006; Realff et al., 2004; Wang and Yang, 2007). In general, forward supply chains include manufacturing, importing, and selling processes which convert raw materials into final products, and reverse chains involve collection, consolidation, and processing activities for reuse/recovery/recycle operations.

Electronic equipment is ubiquitous in the current era. The variety and volume of consumer products and electronic equipment pose significant reuse/recycle/disposal challenges. For the U.S.

it is estimated that 133,000 electronic devices are discarded daily, amounting to 3 million tons of e-scrap (see Hong et al., 2007a), but a recent survey suggests that the backlog is much larger than generally believed (Saphores et al., 2009). For Taiwan it is estimated that approximately 300,000 computers are discarded annually (Lee et al., 2000). Worldwide, only about 13 percent of 53 million tons of scrap electronics products, known as “e-scrap”, generated in 2009 was recycled (see *New York Times*, 2010).

Government regulation has an important role in managing and recycling e-scrap, e.g. the EU’s Waste Electrical and Electronic Equipment (WEEE) and Reduction of Hazardous Substances Directive (RoHS) (see Europa, 2007), which seeks to minimize the environmental impact of e-scrap by holding producers responsible for financing collection, processing, and recovery. The state of California’s recent legislation (IWMB, 2003; Nixon and Saphores, 2007) initially assigns an advanced recycling fee (ARF) of \$6–\$10 on all electronic products containing hazardous materials and the ARF is used to fund an electronics recycling system (Gable and Shireman, 2001) to compensate the processing costs incurred. In January 2009 the California ARF was increased to \$8–\$25 depending on screen size of the video display (SBOE, 2009). In the state of Maryland, manufacturers pay fees to the state government

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and the state reimburses recycling expenses for county and municipal recycling programs (ETBC, 2009).

Using Taiwan as an example of policy development, the Environmental Protection Administration (EPA) mandates that producers are responsible for recycling scrap personal computers as of July 1997 (Lee et al., 2000). Manufacturers, importers and sellers (MIS) of personal computers must properly recover and recycle the obsolete computers which they originally sell. The country then implemented a producer responsibility recycling program for obsolete computers on June 1, 1998 whereby consumers bring obsolete personal computers to designated collection points and receive a specified amount of reward money. In addition, when importing or selling computers, firms pay a scrap computer processing fee similar to the ARF enacted by California. A semi-official organization supervised by the Taiwan EPA collects the ARF which subsidizes the associated recyclers. Currently, the ARF and subsidy fees are determined on the basis of fund balance between revenues and costs along with recycling operations. Several examples of fees can be found in Lee et al. (2000). In addition, Canada and Japan have implemented similar programs (Hicks et al., 2005; HP, 2005; Wen, 2005).

However, government management of the e-scrap stream appears to focus more on extended producer responsibility (EPR) rather than ARF policies (ETBC, 2009). We notice that the state of California (implementing the ARF policy) contributes approximately 16.5%² e-scrap recycling in the U.S., which is a significant amount compared to the total e-scrap amount generated by other states in the U.S. In addition, some countries incorporate a fee structure into their take-back programs even while claiming adoption of EPR policies. The RN (2010) reviews the financing and infrastructure model characteristics of different countries. For example, consumers or producers pay fees similar to ARFs in Switzerland, Norway, Netherlands, Sweden, Japan, Australia (particularly for cell phones), etc. Our model is designed to conceptually capture this “pay as you buy” characteristic, and use it to determine the socially optimal fees.

Most research on reverse supply chain design takes a *centralized* view; the key assumption is that one planner with the requisite information about all of the participating entities will seek the optimal solution for the entire system (see Ammons et al., 2001; Shih, 2001; Barros et al., 1998). However, many emerging reverse supply chain systems are *decentralized*, consisting of independent entities with their own profit functions and which may be unwilling to reveal private information to one another, regulators and the public. Additionally, in most ARF-financed programs, a governmental entity assigns fees and rates based on the concept of fund balance, where fees and rates are simply determined by the idea that the total amount of fee collection is equal to the total expenditure on subsidies. Our literature survey, therefore, raises the following questions:

- Is the concept of fund balance ideal for determining rates and fees?
- What are the socially optimal ARFs and subsidy fees?
- How might the associated players behave in a decentralized system?
- What are the potential benefits if a governmental entity establishes socially optimal fees instead of fund balance fees?

² California generated more than 135 million pounds of covered electronic devices (CEDs), including electronic devices with a screen greater than four inches (CAW, 2010). In 2007, approximately 410,000 tons of selected consumer electronics were recovered for recycling (EPA, 2008). It is estimated that the amount of e-scrap in California contributes approximately 16.5% e-scrap recycling in the U.S. (135 million pounds/410,000 tons \approx 16.5%).

In this paper we make two assumptions: government establishes the associated fees to maximize social welfare and considers them public information; and all players select best responses to the government-determined rates. Hence, we develop a Stackelberg-type model whereby government is the leader in determining ARFs and subsidy fees, and MIS, recyclers and similar parties are the followers responding via their own optimal decisions. To compare the current practice of fee determination on the basis of fund balance, we develop a conceptual fund balance model where the total amount of fee collection is equal to the total expenditure on subsidies.

The remainder of this paper is organized as follows. In Section 2, we review the relevant literature. We present the model and its equilibrium outcomes followed by the fund balance model for comparative purposes in Section 3. The detailed derivations of the models and the proofs of propositions are available in the [Online Supplemental materials](#). In Section 4, we conduct a case study analysis and present comparative statics that examine the difference in the performance measures between our proposed social welfare maximized model and the current practice model. We conclude the paper in Section 5.

2. Literature review

A literature review reveals some examples of policies concerning recycled material flows in common use throughout the world. A deposit-refund system requires consumers to pay a deposit that is subsequently refunded when they return the reusable part of the product (Kulshreshtha and Sarangi, 2001). Lavee et al. (2009) investigate the effect of price uncertainty on waste management decisions by municipalities on whether or not to switch from landfill to recycling. Other policy options are various take-back requirements (Fullerton and Wu, 1998; Huhtala, 1999; Eichner and Runkel, 2005; Hong et al., 2007b).

The literature proposes various environmental instruments. Chen and Sheu (2009) demonstrate that a proper design of environmental-regulation pricing strategies can promote EPR for the firms in supply chains. Discussion on general tax-subsidy schemes applied to reverse supply chains can be found in Bansal and Gangopadhyay (2003), Conrad (1999), Cremer and Thisse (1999), Fullerton and Wolverton (1997), Palmer and Walls (1997). Our focus is on the analysis of fee determination of ARFs and subsidies specifically for e-scrap reverse supply chains, where several states or countries have implemented such policies, because a literature survey reveals scant research on how ARFs and subsidies are determined. In the near future, fee structures that support e-scrap policies will likely become increasingly prevalent, and this paper's insights about the impacts of fiscal schemes are relevant for global and regional regulators.

3. Model analysis

An e-scrap reverse supply chain is a logistics and production network that includes collection, sorting, remanufacturing, and refurbishing processes for EOL products. This section presents a Stackelberg-type model structuring a reverse supply chain as a system consisting of government, MIS, and recyclers, where the government as leader determines ARFs and subsidy fees, and the MIS and recyclers as followers seek to optimize their own objectives according to the government's transparent data.

3.1. E-scrap reverse supply chain

There are three key elements describing supply chains: material, information, and cash flows (Swaminathan et al., 1998). In this

paper, we assume that a supply chain consists of three groups: MIS, customers, and recyclers. In general, MIS may act as manufacturers, importers, or sellers selling electronics products to customers. After usage, customers may bring obsolete products to recyclers which remanufacture or recycle EOL products and convert them into recovery materials as well as some accompanying trash.

We use a hypothetical EPA as the governmental entity which determines the ARFs and subsidy fees. The MIS pays ARFs to the EPA when manufacturing, importing, or selling electronics products in support of the implementation of e-scrap recycling. The ARFs subsidize certified recyclers for their operational and recycling costs. The recyclers may choose to compensate consumers who bring their e-scrap products with a specified amount of reward money to encourage recycling behavior. An illustration of the cash flow in an e-scrap reverse supply chain is shown by the solid line in Fig. 1.

We assume that the EPA has the requisite regulatory power over its followers to act as the Stackelberg leader in the determination of the ARFs and subsidy fees. MIS and recyclers therefore behave at the equilibrium status by choosing the optimal quantity and the rate of reward money for collection. In practice, the EPA can obtain MIS quantitative information, i.e. the quantities that MIS manufactures, imports, and sells. We also assume the recycling quantity handled by recyclers is affected by the rate of reward money offered and that the recyclers must update and report quantitative data to the EPA for auditing purposes. The information flow is represented in dashed lines in Fig. 1.

3.2. Models of the EPA, MIS, and recyclers

We let MIS be the group of manufacturers, importers, and sellers which represent the associated entities involved in forward supply chains. Recyclers include several collection, consolidation, or processing sites in reverse chains. As mentioned, the EPA acts as a leader to determine the fees, and the MIS and recyclers make their corresponding decisions on the basis of the announced ARF and subsidy fee. The following sections present our model for the players and the synthesis of computation for the corresponding decisions in the e-scrap reverse supply chain.

3.2.1. Model of MIS

We first construct the MIS model to determine the quantity of electronics products manufactured, imported, and sold in the market given the ARF fee announced by the EPA. We let Q_x be the quantity supplied to the market, and P_x denote the selling price. Assume that the demand for the (single) final product is characterized by a commonly-used linear demand function, $P_x = a - bQ_x$, where a and

b are parameters, $a, b > 0$, a can be interpreted as the choke-off price (the lowest price at which there is no demand), and b is the sensitivity of price with respect to the quantity demanded, i.e. the decrease in price per unit of an extra unit of quantity demanded. This may also be viewed as a linear approximation of the actual demand function, enabling us to develop analytical results of the fee determination. A linear form of the inverse demand function helps to obtain qualitative insights without much analytical complexity. Suppose that MIS has infinite production capacity and chooses the quantity Q_x . We assume that the unit production cost is C_v . In addition, MIS pays the ARF, denoted by t per unit, in support of the recycling program. The MIS then maximizes its profits:

$$\Pi_{MIS} = (P_x - C_v - t)Q_x. \tag{1}$$

It is straightforward to show that at equilibrium, the MIS chooses

$$Q_x^* = \frac{a - C_v - t}{2b} \tag{2}$$

and obtains

$$P_x^* = \frac{a + C_v + t}{2}. \tag{3}$$

We note that (2) specifies the MIS's optimal selling quantity after it observes the level of the ARF, t , announced by the EPA. Obviously, (2) and (3) can be interpreted as the MIS's best responses to the EPA's decision of the ARF, t .

3.2.2. Model of recyclers

Now consider the model of recyclers. Learning the subsidy fee, recyclers determine the optimal reward money compensating consumers who return their EOL e-scrap for recycling. We let Q_c be the quantity collected by recyclers, and P_w denote the rate of reward money. Assume that there is a dynamic e-scrap market where the collected quantity depends on the reward money. We denote the relationship between the collected quantity and reward money as the source supply function, which is characterized by a linear function, $Q_c = c + dP_w$, where c and d are parameters, $c, d > 0$, c is the base collected quantity of zero reward money, and d is the sensitivity of the collected quantity with respect to the reward money, i.e. the increase in collected quantity per unit of reward money added. We assume that the value or cost of a single type of e-scrap products is uniform since the quality of e-scrap items typically cannot be differentiated due to volume-based or weight-based collection programs. For the sake of analytical tractability, a linear function allows us to easily capture the qualitative market behavior of increased flow with an increased rate of reward money. We let r be the net cost for recycling one unit of e-scrap products. In addition, recyclers receive a subsidy fee per unit, s , for recycling e-scrap products. The recyclers maximize their profits:

$$\Pi_{proc} = (s - P_w - r)Q_c. \tag{4}$$

It is straightforward to show that at equilibrium, the recyclers choose

$$P_w^* = \frac{s - r}{2} - \frac{c}{2d}. \tag{5}$$

and obtain

$$Q_c^* = \frac{c + d(s - r)}{2}. \tag{6}$$

We also note that (5) specifies the recyclers' optimal reward money after they learn the level of the subsidy fee, s , announced by the EPA. Again, (5) and (6) are the recyclers' best responses to the

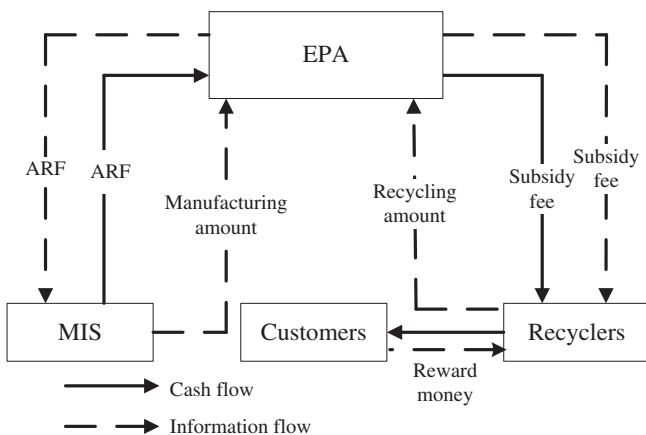


Fig. 1. The cash and information flows in an e-scrap reverse supply chain.

EPA's decision of the subsidy fee, s . With the MIS's best responses to the ARF announced by the EPA, we can develop the EPA's model in the next subsection.

3.2.3. Model of the EPA

The EPA's objective is to maximize social welfare, which is the sum of the producer surplus, consumer surplus, tax/subsidy revenue, and the environmental externality cost (Bansal and Gangopadhyay, 2003). There are two markets in our proposed model: one for new electronics and one for e-scrap products. The consumer surplus is the difference between the price consumers are willing to pay and the actual market price. In other words, the consumer surplus is the triangular area above the market price level and below the demand curve. It is easy to show that the consumer surplus in the market for new products is $1/2bQ_x^2$ when the (inverse) demand behaves in a linear downward function, $P_x = a - bQ_x$. We can extend the concept of the consumer surplus to the recycling market, defining it as the difference between the announced rate of reward money and the fee level that consumers are willing to pay to bring their EOL products to recyclers. In other words, consumers are willing to recycle EOL products when the announced reward money is higher than the value they expect. Hence, the consumer surplus of the recycling market is $P_wQ_c - 12dP_w^2$ when the source supply function is $Q_c = c + dP_w$ in this market. The detailed derivations of the consumer surplus in the market for new products and the recycling market for EOL products can be found in the Online Supplemental material.

The producer surplus is the sum of the profit of the MIS, $(P_x - C_v - t)Q_x$, and the profit of recyclers, $(s - P_w - r)Q_c$, and the EPA's total tax revenue and subsidy expenditure which are tQ_x and sQ_c respectively. The environmental externality cost is the sum of the pollution cost caused by uncollected e-scrap products and the indirect pollution cost resulting from manufacturing/importing/selling electronics products. In practice, if the amount of EOL products may not be available to decision-makers, or is difficult to estimate, the amount of current generation of new electronics is relatively traceable and probably can be obtained from other agencies, i.e. the department of commerce. We characterize the return rate of EOL products by τ , $\tau \geq 0$, the rate of current generation of new products that are expected to return to recyclers after usage. A similar model appears in Savaskan et al. (2004) and Savaskan and Van Wassenhove (2006). Hence, one can think of τ as an EPA pre-defined desirable level of returned rate of EOL products from customers based on the quantity supplied to the market. Parameter τ is allowed to be greater than one since the expected returned quantity may include the quantity sold in previous planning epochs. The proposed model allows the decision-maker to tailor the proposed model to its individual concerns of the return rate and to avoid data unavailability of the amount of EOL products.

We let E be the unit indirect pollution cost of uncollected e-scrap products and e be the unit indirect pollution cost incurred in manufacturing/importing/selling new products. The total environmental externality cost can then be described as $E(\tau Q_x - Q_c) + eQ_x$, where $(1 - \tau)Q_x$ implies the amount of products that are not expected to return to recyclers in the planning time epoch, for example, the products still being used by customers. Those $(1 - \tau)Q_x$ may return to recyclers in the following time epochs and will be estimated based on τ at the planning time epoch. Hence, the EPA optimizes the total social welfare as shown in (7).

$$\begin{aligned} \text{Max}_{t,s \geq 0} \Pi_{\text{gov}} = & [(P_x - C_v - t)Q_x] + [(s - P_w - r)Q_c] + \frac{1}{2}bQ_x^2 \\ & + \left(P_wQ_c - \frac{1}{2}dP_w^2 \right) + (tQ_x - sQ_c) - [E(\tau Q_x - Q_c) + eQ_x] \quad (7) \end{aligned}$$

Assuming it behaves rationally, the EPA anticipates that the MIS and recyclers choose their best response to the announced fees. This allows us to characterize the Nash equilibrium solution of the MIS and recyclers' problems, which depend on the EPA's decisions of the ARF, t , and subsidy fee, s . We then solve for the EPA's decisions; the EPA's problem is to maximize the total social welfare. The Nash equilibrium solution of the ARF and subsidy fee is

$$t^* = -a + C_v + 2e + 2E\tau \quad \text{and} \quad s^* = 2E - r + \frac{c}{d} \quad (8)$$

We then find the resulting selling quantity in the MIS and collected quantity in recyclers, as well as the selling price and the reward money, by substitution of t^* and s^* . The results are summarized in Table 1.

To maximize social welfare, the EPA must determine the rate of ARF, t , and subsidy fee, s , as noted in (8). After observing the ARF and the subsidy, MIS and recyclers behave at the equilibrium status by choosing the optimal selling quantity in the market and optimal rate of reward money for individuals who bring EOL products to recyclers. Hence, the ARF and subsidy fee determined by our approach achieve the maximum of the social welfare at the equilibrium status, while both MIS and recyclers gain their maximums of self-profits. For notational simplicity, we refer to the model proposed in Section 3.2 as the social welfare model. After characterizing the equilibrium decisions of the leaders and followers, we make three propositions which lead to practical policy implications. We summarize the results of the derived analytical propositions in Table 2. The detailed proof of the propositions addressed below can be found in the Online Supplemental materials.

Proposition 1. If the EPA charges MIS the ARF for production, the following situations exist: (a) the selling quantity decreases, (b) the selling price increases, (c) the selling quantity is reduced by $1/2b$ and the selling price is increased by $1/2$ when the ARF increases by one unit.

Proposition 2. If recyclers are subsidized by the EPA, the following situations exist: (a) the rate of reward money increases, (b) the collected quantity increases, (c) the rate of reward money is increased by $1/2$ when the subsidy fee increases by one unit.

It is intuitive that the ARF paid by the MIS is transferred to the consumers who purchased products so that the ARF leads to an increase in selling prices and a reduction in consumption quantities. It is more interesting to examine the magnitude of changes both in selling quantity and price following the imposition of an ARF. Proposition 1 shows that a unit increase in the ARF gives only a half-unit increase in the selling price. This implies that the ARF program probably has little impact on selling prices even though the MIS transfers the ARF cost to consumers. In addition, the rate of the reduction in the selling quantity due to the ARF program can be affected by the slope term of the demand function in the new products market. Proposition 2 also indicates that an increase in the subsidy fee results in an increase in the reward money and, therefore, an increase in the collected quantity of EOL products.

Table 1
Decisions of MIS and recyclers.

MIS		Recyclers	
The selling quantity	The selling price	The collected quantity	The reward money
$Q_x^* = 1/b(a - C_v - e - E\tau)$	$P_x^* = C_v + e + E\tau$	$Q_c^* = c + d(E - r)$	$P^* = E - r$

Table 2
Summary of sensitivity analysis.

	The EPA charges MIS the ARF for production	Recyclers are subsidized by the EPA	The pollution costs are increased	
Change	One unit of increase in the ARF, t	One unit of increase in the subsidy fee, s	One unit of increase in the indirect pollution cost, e , incurred in manufacturing, importing, or selling new products	One unit of increase in the pollution cost, E , of uncollected e-scrap products
Impact	The selling quantity, Q_x , is reduced by $1/2b$ and the selling price, P_x , is increased by $1/2$	The rate of reward money, P_w , is increased by $1/2$	The ARF, t , is increased by two units	The subsidy fee, s , is increased by two units

Proposition 3. The ARF is increased by two units due to a unit increase in the indirect pollution cost incurred in manufacturing/importing/selling new products. The subsidy fee is increased by two units due to a unit increase in the pollution cost of uncollected e-scrap products.

Proposition 3 shows that both the increments of the pollution costs in new products and in e-scrap products double the increment of the ARF and subsidy fee. In other words, reducing the pollution costs by one unit saves two units on the expenditure of the ARF and subsidy fee if the demand market for new products and recycling markets exist within one area. This result furthermore provides a useful policy implication: *government has greater incentives to encourage MIS to improve their production processes to reduce the pollution cost or to import and sell a product containing fewer pollutants so that uncollected e-scrap products do not result in a high pollution cost.* Thus, it is more effective to reduce the *ex-ante* pollution cost compared to the expense of *ex-post* cost for pollution recovery.

$$P_w^* = \frac{s' - r}{2} - \frac{c}{2d} \tag{11}$$

$$Q_c^* = \frac{c + d(s' - r)}{2}. \tag{12}$$

Under current practice, the EPA determines the rates on the basis of fund balance. Thus, the total tax revenue is equal to the total subsidy expenditure

$$t' \cdot Q_x^* = s' \cdot Q_c^*. \tag{13}$$

To have a fair basis for comparison, we let the EPA collect the identical total tax revenue under the two different policies. Thus,

$$t' \cdot Q_x^* = t^* \cdot Q_x^*. \tag{14}$$

Combining (13) and (14) gives us two equations for two unknowns and allows us to analytically obtain the corresponding ARF, t' , and subsidy fee, s' , under the policy of fund balance as follows:

$$t' = -a + C_v + 2e + 2E\tau \quad \text{and} \quad s' = \frac{1}{d} \left[\left(\frac{dr - c}{2} \right) + \sqrt{\left(\frac{dr - c}{2} \right)^2 + \frac{2d}{b} (-a + C_v + 2e + 2E\tau)(a - C_v - e - E\tau)} \right]. \tag{15}$$

3.3. The fund balance model: current practice

The Taiwan and California e-scrap recycling systems determine the ARF and subsidy fee on the basis of the fund balance between revenues and costs along with recycling operations (Lee et al., 2000; IWMB, 2003). This motivates us to construct a model where the total revenue the EPA collects equals the EPA's total expenditure for use as a baseline to compare with the social welfare model described in Section 3.2.

Let t' denote the ARF charged by the EPA and s' be the EPA subsidy fee under the policy of fund balance. The MIS and recyclers face the same decision problem as proposed in Section 3.2 after observing the rates of the ARF and subsidy fee announced by the EPA. Hence, the best response of the selling price, $P_x^{t'}$, and quantity, $Q_x^{t'}$, to announced t' are

$$P_x^{t'} = \frac{a + C_v + t'}{2} \tag{9}$$

$$Q_x^{t'} = \frac{a - C_v - t'}{2b}. \tag{10}$$

Similar to the model in Section 3.2.2, the best response of the rate of reward money, $P_w^{t'}$, and the collected quantity, $Q_c^{t'}$, to announced s' can be stated as

Thus, we then find the resulting selling quantity in the MIS and collected quantity in recyclers, as well as the selling price and the reward money, by substitution of t' and s' . The results are summarized in the [Online Supplemental materials](#). The following section illustrates computational results for our proposed social welfare model and fund balance model using a case study that addresses several key questions regarding how different ideas for determination of associated fees would affect the total value of social welfare.

4. The comparison: a case study

4.1. Case study overview and input data

This section provides a set of numerical experiments to illustrate the use of the proposed model to determine the ARF and subsidy fees in an e-scrap reverse supply chain in Taiwan and the behavior of the ARF and subsidy with different objectives. Our case study is based upon representative data for a particular product in the geographical region and time period of our study. We note that the data only apply to our case study and will differ for different geographical regions, products, and/or times.

We consider the market of laptop computers and use the estimated data of the inverse demand function in the market for new

laptop computers in Taiwan as $P_x = 33,000 - .01Q_x$ and the source supply function for recycling market as $Q_c = 5600 + 80P_w$, where all currency is in New Taiwan Dollars (NTDs) (Hong et al., 2007b). We observe a relatively low margin in an electronics consumer products market, especially for laptop computers, due to fierce price competition and rapid product update. This leads us to assume a relatively high production cost of 29,000 NTD per unit of new laptop computers where the unit production cost is approaching the average selling price.

It is not straightforward to estimate the unit indirect pollution cost, e , incurred in production processes of new products and the unit pollution cost of uncollected e-scrap products, E . According to Li (2005), production costs have increased by around 5–10% due to the launch of WEEE and RoHS. Therefore, we estimate e as the average of the increase in production costs due to WEEE and RoHS ($e = 2175$). In Wen (2006), the total cost of recycling one unit of laptop computers is approximately estimated as 135 NTD, which we assume to be the unit pollution of uncollected e-scrap products, E . The ballpark figure of the value of recovered components of laptop computers is approximately estimated as 83 NTD (Wen, 2006). Therefore, the net cost for recycling one unit of laptop computers is approximated to 50 NTD. The rate of current generation of new products that are expected to be returned to recyclers after usage is estimated as $\tau = .97\%$ (Wen, 2006), which is a conservative estimation. We note that the return rate in this case study is relatively lower than our initial conjecture, most likely since consumers tend to retain obsolete laptops because of their relatively high price and small volume compared to desktop computers.

4.2. Case study results

Based on the above estimated data, the computed ARF for both models is 352 NTD, and the subsidy fees in the fund balance model and the social welfare model are 1258 NTD and 290 NTD, respectively. Our results show that social welfare improves by approximately 6% if the EPA chooses a social welfare maximization model instead of the fund balance model in the laptop computer recycling market.

Using the same data and case study we further investigate the impact of these parameters on the value of social welfare. It is obvious that the social welfare model outperforms the current practice model for the value of social welfare in all occasions of the case study. We first study how the characteristics of the new product and recycling markets affect the value of social welfare, where the new product market characteristics can be interpreted as the parameters, a and b , in the inverse demand function, and the recycling market characteristics can be viewed as the parameters, c and d , in the source supply function. The results are given in Fig. 2. The major observations for policy-makers are as follows:

- (i) An increase in a (choke-off price), c (base collected quantity of zero reward money), or d (sensitivity of the collected quantity with respect to the reward money) results in an increase in the value of social welfare for both models. This indicates a positive relationship between social welfare and a , c , and d . However, both models show that social welfare decreases as the value of b (sensitivity of price with respect to the quantity demanded) increases, which implies a negative relation. The results show that an increase in a , c , or d favors the value of social welfare, but an increase in b hurts it.
- (ii) The difference in the value of social welfare between the models decreases as the value of c or d increases. This shows that policy-makers may pay more attention to the characteristics of the recycling market (c and d) to determine the associated fees when the value of either c or d is at a relatively low level, since the current practice model may give a poor performance at the low level of the value of c or d .

We next study how cost parameters, i.e. the unit indirect pollution cost incurred in the operations of manufacturing, importing, or selling new products (e), the unit pollution cost of uncollected e-scrap products (E), the unit production cost (C_v), and the net cost for recycling one unit of e-scrap products (r) would affect the value of social welfare. The results are given in Fig. 3. We summarize the major observations as follows:

- (i) The value of social welfare decreases in both models as the cost terms of e , C_v , or r increase. While it is surprising that

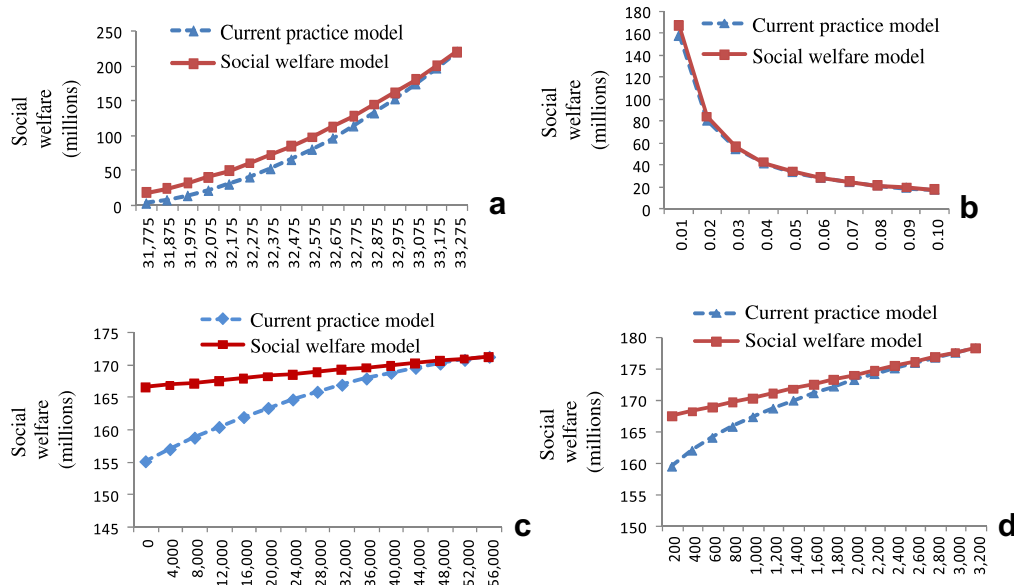


Fig. 2. Impact of a (choke-off price), b (sensitivity of price with respect to the quantity demanded), c (base collected quantity of zero reward money), and d (sensitivity of the collected quantity with respect to the reward money) on the value of social welfare.

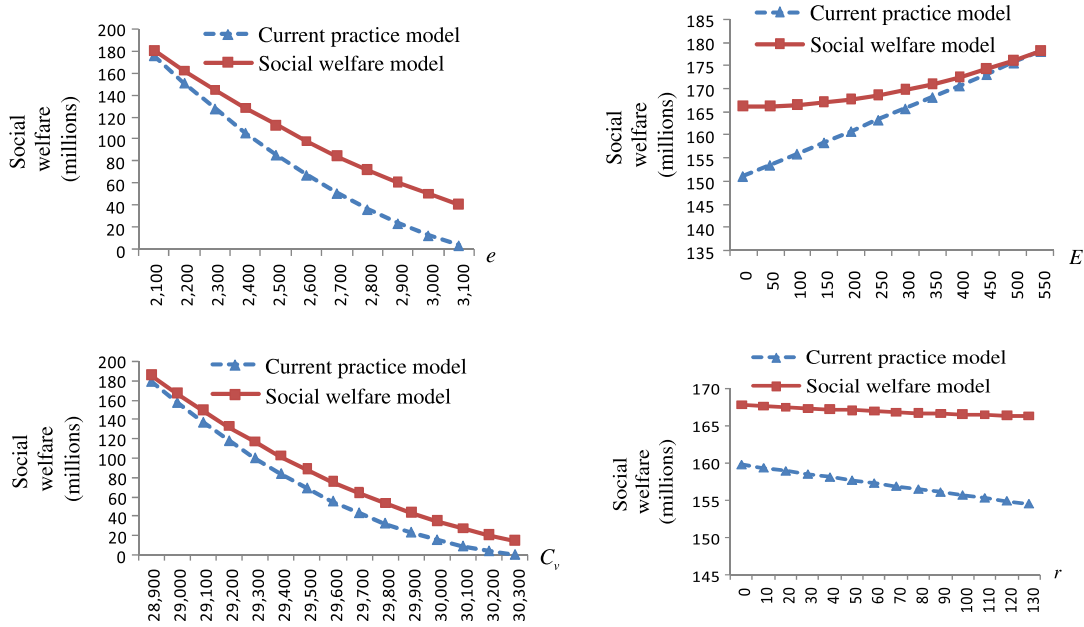


Fig. 3. Impact of e (unit indirect pollution cost incurred in the operations of manufacturing, importing, or selling new products), E (unit pollution cost of uncollected e-scrap products), C_v (unit production cost), and r (net cost for recycling one unit of e-scrap products) on the value of social welfare.

social welfare increases as the unit pollution cost of uncollected e-scrap products (E) increases, one possible explanation is that if the EPA raises the subsidy fee to attract a higher volume of e-scrap products to recycling streams, the increase benefits the consumer surplus in the recycling market. The conjecture can be analytically proved in the social welfare model and numerically verified in the fund balance model respectively.

- (ii) As the unit indirect pollution cost incurred in the operations of manufacturing, importing, or selling new products (e) increases, it is reasonable to imagine that the EPA would raise the ARF to restrain production of new products. At a relatively high level of the value of e , the proposed social welfare model performs better considering social welfare value.
- (iii) The results demonstrate a significant difference in the value of social welfare between two models when the value of E is at a relatively low level. This shows that policy-makers may pay more attention to the system objective (the value of social welfare) when the value of E is located in a relatively low level since the current practice model may perform poorly when E is low.

5. Conclusions

Society increasingly recognizes that recycling EOL products is as an important task due to high demands in many raw material markets and growing concern about the environmental impacts of disposal. Proper management and recycling of e-scrap products are challenging tasks for all players and government regulation is important for success. An ARF-financed system is typically implemented whereby the ARF is used to fund compensation of the processing costs incurred in recycling processes.

This paper describes a social welfare maximization model examining the impacts of ARFs and exogenous subsidies on recycled material flows in a decentralized system where the EPA acts as a leader and MIS and recyclers are followers. The EPA determines the ARF paid by the MIS when they sell new products to customers. The EPA also decides the level of fees which subsidize recyclers when they process EOL electronics products. After observing the

rates of ARF and subsidy fees announced by the EPA, MIS and recyclers choose the optimal selling quantity in the new products market and the optimal reward money for customers who return EOL products to recyclers.

Currently, the associated ARF and subsidy fees are determined on the basis of the fund balance between revenues and costs along with recycling operations. For comparative purposes, we also develop a fund balance model. Our results demonstrate that the proposed social welfare model outperforms the current practice model considering the value of social welfare. Although it is an intuitive observation, the proposed social welfare model may generate a significant improvement in the value of social welfare in some numerical examples studied in this paper. The results can provide policy-makers with another social welfare perspective when considering an appropriate fee determination mechanism. In addition, our analytical results show that government has greater incentives to encourage MIS to improve their production processes to reduce the pollution cost or to import and sell a product containing fewer pollutants so that uncollected e-scrap products do not result in a high pollution cost. This is also evidence that it is more effective to reduce the *ex-ante* pollution cost compared to the expense of *ex-post* cost for pollution recovery.

We suggest that extending our modeling framework is worth investigation, since, in reality, the two followers (MIS and recyclers) typically consist of several independently owned firms or organizations. It would be useful to develop a model wherein each entity seeks to optimize its own interests considering profits, revenues and collection quantities. In this scenario, recyclers would compete for EOL electronics products returned from customers, MIS entities would compete for market share, and the competition effect overall would affect ARFs and subsidies. An empirical study on how an ARF-financed program shapes behaviors throughout the recycling industry would be of benefit to policy-makers. Exporting e-scrap products opens up the issue of policy-making across countries. Recognizing that many reverse supply chains involve more than one type of e-scrap products to be collected and recycled, the extension to the multiple e-scrap products with interactions requires further refinement of our proposed model.

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Appendix. Supplementary material

Supplementary data related to this article can be found online at doi:10.1016/j.jenvman.2010.12.004.

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