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Imperfectness in Recycling and Reprocessing and Its Effects on the Optimal Tax-Subsidy Structure on Waste

재활용 및 재처리의 불완전성이 폐기물에 대한 최적조세 및 보조금 구조에 미치는 영향

Inkee Hong*
홍인기

Abstract: This paper focuses on the fact that recycled material needs reprocessing to be substitutable for virgin material. More than one-third of household recyclables are tarnished with residues. Reprocessing consumes resources and, in the process, generates pollution. Incorporating these 'imperfect' characteristics of recycling and reprocessing into a simple general equilibrium model, I examine effects on the structure of tax-subsidy schemes when the first-best Pigouvian taxes are not available. A generalized Deposit-Refund system can achieve the optimum if illegal dumping is not taxable. Without a Pigouvian tax on illegal dumping, however, recycling is subsidized for its role in diverting illegal into proper disposal. If Pigouvian taxes on illegal disposal or waste from imperfect reprocessing are not available, a combination of output taxes on reprocessed material and subsidies for clean inputs can be used to restore the optimum. In the process, another reason to subsidize recycling emerges: recycling is a clean input for imperfect reprocessing. Therefore, recycling should be further encouraged by policymakers to achieve higher levels of resource circulation and a more sustainable economy, even if recycling is accompanied by imperfect reprocessing.
Key Words: Waste, Deposit-Refund System, Recycling and Reprocessing, Environmental Taxes and Subsidies

요약: 가계가 재활용한 물질의 3분의 1은 이물질 오염으로 재처리가 필요하다. 재처리과정에서 희소한 자원이 투입될 뿐만 아니라 또 다른 오염이 발생한다. 본 논문은 재활용 및 재처리의 이러한 불완전성으로 인해, 피구세가 가용하지 않은 경우, 폐기물에 대한 최적조세 및 보조금 체계가 어떻게 수정되는지를 일반균형모형을 이용해 도출한다. 차선의 경우를 고려하는 일반화된 예치금환불제를 이용할 때, 최적의 결과를 얻을 수 있다. 불법 투기에 대해 피구세를 부과할 수 없는 상황에서는 재활용은 불법 투기를 적절한 폐기물 처리로 바꾸는 행위이므로 보조금을 지급받아야 한다. 하지만 불법 투기가 발생하는 동시에 재처리 과정에서 발생하는 오염에 대해 피구세를 부과할 수 없는 경우에는 재처리된 물질에 대한 산출세와 청정 투입물에 대한 보조금으로 구성된 또 다른 일반화된 예치금환불제를 활용하여 최적의 결과를 달성할 수 있다. 그러므로 재활용은 단지 환경친화적 행위이기 때문에 보조금을 주어야 하는 것이 아니다. 재활용은 첫째로는 불법 투기를 줄이는 역할을 하므로, 둘째로는 불완전한 재처리과정에서 청정 투입물의 역할을 하므로 보조금을 받아야 하는 셈이다. 이는 이물질 오염에 따른 불완전성에도 불구하고 재활용에 대한 더욱 적극적인 지원이 필요함을 정책적으로 시사한다.
핵심주제어: 폐기물, 예치금 환불제, 재활용 및 재처리, 환경세 및 환경보조금

* Associate Professor, Dept. of Economics, Daegu University

I. Introduction

In recent years, the issues on waste have drawn a lot of attention in environmental and economic areas since generation and disposal of waste increasingly burdens the environment as well as economic efficiency. The World Bank estimates the amount of municipal solid waste (MSW) will rise from 1.3 billion tons per year to 2.2 billion per year by 2025. Much of the increase will come in fast growing urban areas in developing countries (World Bank, 2012). As of 2014, about 258 million tons of MSW was generated in the United States alone, which was 208 million tons in 1990. This means that each person generated an average of 2.0 kg of solid waste per person per day, which has been steadied since 1990 (US EPA, 2016). In 2016, the EU 28 member countries generated an average of 1.32 kg per person per day, which was at the peak of 1.43 kg in 2000 (Eurostat, 2018). In developing countries, each person presently generates less than 1 kg of waste per day, however, rapid urbanization along with economic development suggests that their waste generation and disposal problems will become more serious in the near future (World Bank, 1999). The situation in South Korea lies between the EU and developing countries. The annual MSW generation has been relatively stable under 400 kg per for the 1997~2016 period, recording 383 kg (1.05 kg/person/day) in 2016, which was the lowest at 353 kg (0.95 kg/person/day) in 2013 but has been steadily increasing since then (Ministry of Environment, 2017).

However, policymaker faces difficulties in achieving higher level of resource circulation due to heterogeneous agents engaging separately in recycling and reprocessing as well as imperfectness intrinsic in both activities. Previous studies have mainly focused on a single aspect of recycling: households' garbage reduction effort by recycling. Recycling is often assumed perfect in the sense that any recycled materials by households can be perfectly substitutable as an input for production (Fullerton and Kinnaman, 1995; Fullerton and Wu, 1998; Walls and Palmer, 2001).

This paper shows theoretically that the optimal tax-subsidy schemes can still be achieved, even when recycling and reprocessing are imperfect. This paper recognizes the fact that household recycling is not perfect. Household recycles usually need treatment or reprocessing to be used later for the production of consumption goods. For example, post-consumer recycling of plastics is complicated because it is often confusing to tell apart one type from another by sight or touch. Many households usually collect plastics without considering their exact types. Even a small amount of the wrong type of plastic can ruin the whole melt.

Therefore, in this paper, recycling per se is not assumed to be final in reducing waste permanently; only the proportion properly reprocessed and used in successive stages of production contributes to reduction in waste. For example, any mixed plastics and wet newspapers are useless or too expensive to salvage for reprocessing firms. Therefore, I assume that only properly reprocessed recycles can be used in production, and I explicitly take account of this point by separating reprocessing from recycling.

Second, previous literature also usually assumes that reprocessing is perfect. However, reprocessing costs private resources and, more often than not, generates waste. Reprocessing waste or pollution could be just any residuals unsuccessfully reprocessed from household recyclables or might be generated due to the inherent technological limits in reprocessing. For example, waste oil (used motor oil from cars) can be reused after proper reprocessing treatment, but it would generate impurities that have to be disposed after reprocessing. Waste tires, after taken off cars, can be used as fuel because they have very high BTU. However, burning waste tires generate several toxic gases.

Using a simple analytical general equilibrium, I solve for the combinations of tax-subsidy instruments that achieve the first-best social optimum. I also examine what roles household recycling have in remedying the negative externalities from various sources, and how imperfectness of recycling and reprocessing built into the model affects the characteristics of a generalized optimal D-R system adopting the two-part instrument.

If the first-best Pigouvian taxes are available, then the optimal corrective tax on each activity causing a negative externality is equal to its marginal environmental damages (MED). In this case, other output and input taxes are not necessary. And a subsidy for household recycling is also unnecessary because recycling improves (or harms) the environment only through successful reprocessing. Since the reprocessing externality is corrected by an existing Pigouvian tax, recycling is neither rewarded nor penalized.

If illegal disposal or dumping cannot be properly taxed due to monitoring and enforcement problems, that is, if a Pigouvian tax on illegal disposal is not feasible, then a combination of a presumptive output tax and the corresponding subsidies for proper garbage disposal and for household recycling is optimal (i.e., a two-part instrument). In this case, a charge on garbage disposal should be lowered by the extent that proper disposal diverts illegal dumping.

The important point is that a recycling subsidy is also needed because recycling also diverts illegal dumping to proper disposal.

In the following Chapter Ⅱ, I briefly review several previous studies. I introduce the model in Chapter Ⅲ. In Chapter Ⅳ, I derive the outcome in the social planning model and the outcome in the decentralized market. Then, I compare the decentralized outcome with the social planner's and derive the first-best optimal tax-subsidy schemes, first assuming that a Pigouvian tax on the use of reprocessed materials is available and then relaxing that assumption. Finally, Chapter Ⅴ is for conclusions and further discussion.

Ⅱ. Literature Review

Economic theory suggests that a regulator can achieve the social optimum by imposing a tax on waste-generating activity or by subsidizing its reduction (Pigou, 1932). A direct application of this approach to the MSW problem is the per-unit charge: the practice of charging waste generators for each bag or container of trash. If the per-unit charge on disposal is equal to the sum of the marginal private cost of waste collection and disposal plus any environmental externalities, and if it is perfectly enforceable, then the resulting level of MSW disposal will be optimal (Jenkins, 1993).

However, it is practically impossible to tax the polluting activity directly because the informational burden is stiff and, therefore, administrative and enforcement costs would be huge. Furthermore, these charges can make the environmental problems worse if the possibility of illegal disposal is real (US EPA, 1998). In that case, introduction of unit-pricing policy might increase illegal dumping or burning (Fullerton and Kinnaman, 1995; Sigman, 1995). The first-best optimal tax on waste cannot be achieved when household waste reduction effort is significant and possibility of illegal waste disposal exists (Choe and Fraser, 1999) Another important weakness of unit-pricing policy is that its price elasticity might be quite low (Choe and Fraser, 1998). Even after the introduction of unit-pricing, the reduction of MSW tends to be small in many cases (Yoshida, 2002).

Without an enforceable Pigouvian tax or collection charge, many studies show that a combination of output tax and recycling subsidy, also known as a deposit-refund (D-R) system, can achieve the first-best outcome. For example, using a general equilibrium model, Fullerton and Kinnaman (1995) show that the optimal D-R system consists of an output tax combined with a subsidy for recycling, and for proper garbage disposal, with each rate set on the basis of the marginal social cost of disposal. In the process, recycling has drawn great attention from many researchers due to its roles in waste management.

Other studies have also identified these aspects but examined them differently from my model. In particular, Eichner and Pethig (2001) consider the case that producers can change material mix of a final good by product design. One of these materials is recyclable, and a greater recyclable share in the output makes it easier to recover and reuse the material. They acknowledge that recycling of material is necessarily incomplete. They allow for the possibility that this ‘waste material’ is environmentally harmful after recycling, and that reprocessing is not completely substitutable. They focus their attention to the “material content” of products, which is a more limited form of product design. They do not distinguish two different kinds of imperfectness between recycling and reprocessing, either.

On the other hand, Calcott and Walls (2002) take into account the transaction costs associated with recycling markets. They model recyclability as an index that affects the cost of reprocessing household recycles. However, my model takes into account not only costly reprocessing but also externalities from reprocessing. Ino (2011) considers the possibility of firms' illegal disposal. Because it incurs a monitoring cost to prevent firms from disposing of collected residuals illegally, the optimal level of the refunds is smaller than the first-best level. However, he does not consider the imperfectness of recycling itself.

My contribution is to add another (second) reason to subsidize household recycling by considering the imperfectness in recycling as well as in reprocessing. If no Pigouvian tax is available on the waste from imperfect reprocessing, then the role of recycling becomes more important. Now recycling receives a subsidy for two different reasons: the first from the role that diverts illegal disposal as noted earlier. The second part of a recycling subsidy comes from the imperfectness in reprocessing. In the absence of a Pigouvian tax on reprocessing waste, an additional 'two-part instrument' should be implemented. In this case, it consists of a presumptive output tax on reprocessed material and the subsidies for clean inputs (e.g., labor) and for household recycling. Again, this imperfectness factor in recycling does not change the importance of a recycling subsidy: it can be handled by a charge for proper garbage disposal. But the fact that reprocessing is imperfect can only be handled by a subsidy for recycling when a first-best Pigouvian tax on waste from reprocessing is not available.

Before presenting the model in Chapter Ⅲ, it would be helpful to clarify two terminologies: imperfect recycling and imperfect reprocessing. By ‘imperfect recycling,’ I mean that the recycling activities by households are partial. It could be so because households do not always know how to correctly recycle many different materials. By ‘imperfect reprocessing,’ I mean that the reprocessing technology is not perfect.

Ⅲ. The Model

My model is a simple general equilibrium model. It is also a first-best model, since it does not incorporate any other distorting taxes on labor supply or capital. I use lower case letters to denote values per household and upper case letters for aggregates. I consider a single jurisdiction with identical households. Each buys a single composite consumption good (c), and each disposes of solid waste in three forms: proper garbage collection (g), potentially recyclable materials (r), or illicit burning or dumping (b). These alternatives are substitutes in the technology of household of disposal options.

$$c = d(g,\ r,\ b) \tag{1}$$

where $d(\bullet)$ is continuous and quasi-concave, with first derivatives $d_g > 0$, $d_r > 0$, and $d_b > 0$. That is, all three kinds of disposal by households can increase the quantity of consumption (c). This relationship also depicts how the household is able to shift among disposal methods. With a given amount of consumption, the household may be able to reduce g and/or increase r by engaging in various activities such as collecting plastic and newspapers and/or increase b by burning garbage in her backyard or dumping them in public places at night. Therefore, the above equation (1) relates all the different combinations of g, r, and b that are consistent with any given level of consumption (like an isoquant).

The household has a fixed total of resources k (which can be labor, capital, or both). Though illegal activities by household do not incur any costs in terms of market price, they are assumed to use private resources $k_b = \beta(b)$. The marginal costs of burning are assumed positive $(\beta_b > 0)$ and rising $(\beta_{bb} > 0)$.

In the household garbage collection industry, firms use resources k_g, as the only input with a linear production technology:

$$g = \gamma k_g. \tag{2}$$

Firms extracting virgin materials produce v, use resources k_v, and generate pollution with a constant returns to scale technology:

$$v = v\left(k_v,\ \ w_v\right) \tag{3}$$

with both first derivatives v_{kv} and v_{wv} positive. Thus, firms have to use more input materials and/or allow more pollution to produce more virgin materials.

Reprocessing firms collect potentially recyclable materials r from households, reprocess it into reprocessed material m, and supply to the producers of the consumption good. In doing so, they use resources k_m and generate reprocessing waste w_m:

$$m = m(k_m,\ r,\ w_m), \tag{4}$$

with all the first derivatives m_{km}, m_r and m_{wm} positive. Note that, like firms in extracting virgin materials, reprocessing firms can increase output if they increase pollution from reprocessing (w_m) or any other input. Previous literature usually assumes that household recycling is complete and final, so that any recycled materials can be used as inputs for production without further waste. However, recycled materials by households usually require treatment or reprocessing to be used later for the production of consumption goods. For example, recycling newspaper involves de-inking process of wet papers and generates residues, which have to be landfilled.

The consumption good is produced using a constant returns to scale production function

$$c = f(k_c,\ v,\ m) \tag{5}$$

with input of resources k_c, virgin materials v, and reprocessed materials m.[1] Since all production functions are constant returns to scale, the scale of the firm is irrelevant. Thus, I can assume that each symbol above represents an amount per capita.

1) Note that the above production function (5) is general with respect to the relation between v and m. For example, this production function includes a special case where virgin and reprocessed and/or recycled materials are homogeneous in quality and, therefore, can be used as a perfect substitute for each other: $c = f(k_g,\ v+m)$.

Utility of each individual depends positively on the amount of consumption good purchased in the market (c) and leisure use of time and resources $(l = k_l)$. It depends negatively on the total amount of garbage generated by households $(G \equiv ng)$, the total amount of pollution generated in the production of virgin material $(W_v \equiv nw_v)$, and the aggregate pollution generated in the production of reprocessed material $(W_m \equiv nw_m)$.2) Utility also depends on the aggregate pollution generated by illegal burning or dumping $(B \equiv nb)$. These four negative externalities could require four Pigouvian taxes. If any one such Pigouvian tax is not available, it can be replaced by a two-part instrument. Some of those two-part instruments might imply a subsidy to recycling, and some might not.

The utility function is

$$u = u(c,\ l,\ G,\ B,\ W_v,\ W_m), \tag{6}$$

where the first derivatives are $u_c > 0$, $u_l > 0$, $u_G < 0$, $u_B < 0$, $u_{Wv} < 0$ and $u_{Wm} < 0$. I also assume that the MED from illegal disposal or dumping exceeds that from proper disposal $(u_G > u_B)$.3) This assumption seems innocuous: for example, the contamination of the water supply polluted by waste dumped in unsafe pits and the air pollution caused by illegal burning aggravate the social health and clean-up problems, more-so than proper disposal of garbage in a landfill (Ferrara, 2003).

2) Extraction of virgin materials may reduce the utility of others. For example, cutting timber may reduce the enjoyment of natural areas and possibly aggravate global warming (Fullerton and Kinnaman, 1995).

3) For example, the Economist (1993) reports that the costs incurred by illegal burning or dumping are significantly greater than the costs of proper landfilling.

Note that the utility function has four different types of waste that all affect utility differently. Hence, our model is more general than having only one waste externality in utility. This feature is useful to show what happens in the special cases where all add to the same externality. Also, the different types of externalities from waste help clarify what happens in my results with optimal taxes and subsidies. This point will be discussed with the analytical results later.

Finally, the model is closed by the overall resource constraint:

$$k = k_c + k_l + k_g + k_b + k_m + k_v. \tag{7}$$

1. Outcome in the Social Planner's Problem

The social planner maximizes the utility of the representative household in (6) subject to the social planner's constraint (5) that is reformularized with the resource constraint and production functions (1) and (7). The resource and production constraints can be substituted directly, to maximize the appropriate Lagrangian:

$$\begin{aligned} L = u\,[\,d(\gamma k_g,\ r,\ b),\ k_l,\ n\gamma k_g,\ nb,\ nw_m,\ nw_v\,] \\ + \delta\left[f\!\begin{pmatrix} k - k_l - k_g - k_m - k_v - \beta(b), \\ v(k_v,\ w_v),\ m(k_m,\ r,\ w_m) \end{pmatrix} - d(\gamma k_g,\ r,\ b) \right] \end{aligned} \tag{8}$$

with respect to r, b, k_g, k_l, k_v, k_m, w_v and w_m. I assume that a unique and internal solution exists. The first-order conditions are as follows:

$$u_c d_g + u_G n = \delta\left(\frac{f_{kc}}{\gamma} + d_g\right), \tag{8a}$$

$$u_c d_r = \delta\left(d_r - f_m m_r\right), \tag{8b}$$

$$u_c d_b + u_B n = \delta\left(f_{kc} \beta_b + d_b\right), \tag{8c}$$

$$u_l = \delta f_{kc}, \tag{8d}$$

$$u_{Wm} n = -\delta f_m m_{wm}, \tag{8e}$$

$$u_{Wv} = -\delta f_v v_{wv}, \tag{8f}$$

$$f_{kc} = f_m m_{km}, \tag{8g}$$

$$\text{and } f_{kc} = f_v w_{kv}, \tag{8h}$$

where δ denotes the social marginal utility of income, f_{kc} is the marginal product of capital used in the production of consumption good (c), f_m is the marginal product of reprocessed materials (m), f_v indicates the marginal products of virgin materials (v), and m_{km} is the marginal product of resources used in reprocessing (k_m).

The equations from (8a) to (8h) state that each input should be employed up to the point where its marginal social benefit equals its marginal social cost. In (8a), for instance, the monetary value of utility from consumption made possible by a unit of garbage $(u_c d_g / \delta)$ is reduced by the utility cost of the garbage externality $(u_G n / \delta)$ before comparison with the production cost of garbage.

2. Outcome in the Decentralized Model

For the case of private markets, individuals maximize utility in (6) subject to a budget constraint that may be affected by a tax or subsidy on each good,

$$p_k\left(k - k_l - \beta(b)\right) + \left(p_r - t_r\right) r = \left(1 + t_c\right) d(g, r, b) + \left(p_g + t_g\right) g + t_b b \tag{9}$$

where p_k is the price earned on resources, the price of consumption good equals one $(p_c = 1)$ since c is numeraire, t_c is the tax per unit of consumption, p_g is the price paid by households for proper garbage collection, t_g is the tax per unit of garbage, p_r is the price for recyclables paid by the reprocessing firms to the households (which could be positive or negative), t_r is the tax on (or subsidy for) the household per unit of potentially recyclable materials collected by the household, and t_b is an ideal Pigouvian tax on illegal disposal.[4] Note that the private cost of illegal disposal $p_k\beta(b)$ is included in the budget constraint.

Consumption goods producers receive a price $(p_c = 1)$ for selling c and pay for inputs k_c, v and m. Their profits are expressed as follows:

$$\pi^c = f(k_c,\ v,\ m) - (p_k + t_{kc})k_c - (p_v + t_v)v - (p_m + t_m)m, \tag{10}$$

where t_{kc} is the tax on the resources used in production of consumption good (k_c), p_v is the price paid for virgin materials, t_c is the tax per unit of virgin materials, p_m is the price of reprocessed materials, and t_m is the tax per unit of household recycling. Under perfect competition with constant returns to scale, maximization of π^c gives the following first-order conditions:

$$f_{kc} = p_k + t_{kc}, \tag{10a}$$

$$f_v = p_v + t_v, \tag{10b}$$

4) A tax on illegal disposal (t_b) is included in (9) for the standard case of the first-best Pigouvian taxes. It can be set to zero for more realistic cases.

and $f_m = p_m + t_m$. (10c)

Producers of household garbage collection services similarly maximize their profits $\pi^g = p_g \gamma k_g - p_k k_g$ and the first-order condition is $\gamma p_g = p_k$. Substituting (10a):

$$p_g = \frac{f_{kc} - t_{kc}}{\gamma}. \tag{11}$$

For reprocessing firms, the following profit function is maximized:

$$\pi^m = p_m m(k_r, m, w_m) - (p_k + t_{km}) k_m - p_r r - t_{wm} w_m. \tag{12}$$

Using (10a) and (10c), the first-order conditions can be simplified as follows:

$$(f_m - t_m) m_{km} = f_{kc} - t_{kc} + t_{km}, \tag{12a}$$

$$(f_m - t_m) m_r = p_r, \tag{12b}$$

and $(f_m - t_m) m_{wm} = t_{wm}$. (12c)

Finally, virgin materials producers maximize the following profit function:

$$\pi^v = p_v v(k_v, w_v) - (p_k + t_{kv}) k_v - t_{wv} w_v. \tag{13}$$

Using (10a) and (10b) to simplify the first-order conditions:

$$(f_v - t_v) v_{kv} = f_{kc} - t_{kc} + t_{kv} \tag{13a}$$

and $\left(f_v - t_v\right)v_{wv} = t_{wv}$. (13b)

In this decentralized economy, the consumer chooses g, r, b and l to maximize utility in (6) subject to the budget constraint in (9). The resulting four first-order conditions involve prices (p_k, p_g and p_r), but I replace those with marginal products from (10a), (11), and (12b) to get the following equations (14a)~(14d). The consumer's Lagrangian multiplier μ denotes the private marginal utility of income. Four other conditions for the decentralized equilibrium (14e)~(14h) come from various profit maximizations.

$$u_c d_g = \mu\left[\left(1+t_c\right)d_g + \frac{f_{kc} - t_{kc}}{\gamma} + t_g\right], \tag{14a}$$

$$u_c d_r = \mu\left[\left(1+t_c\right)d_r + t_r - \left(f_m - t_m\right)m_r\right], \tag{14b}$$

$$u_c d_b = \mu\left[\left(1+t_c\right)d_b + \left(f_{kc} - t_{kc}\right)\beta_b + t_b\right], \tag{14c}$$

$$u_l = \mu\left(f_{kc} - t_{kc}\right), \tag{14d}$$

$$t_{wm} = \left(f_v - t_m\right)m_{wm}, \tag{14e}$$

$$t_{wv} = \left(f_v - t_v\right)v_{wv}, \tag{14f}$$

$$f_{kc} - t_{kc} + t_{km} = \left(f_m - t_m\right)m_{km}, \tag{14g}$$

$$\text{and } f_{kc} - t_{kc} + t_{kv} = \left(f_v - t_v\right)v_{kv}. \tag{14h}$$

Now I can find the optimal tax and subsidy rates in equations (14) that make those market conditions in (14) match up perfectly with the social planner's conditions in (8).

Ⅳ. Derivation of the Optimal Tax-Subsidy Policies

1. When the First-Best Pigouvian Taxes are Available

If the market does achieve the optimum, then $\delta = \mu$ from (8d) and (14d). By comparison of (8) and (14), if $t_c^* = t_m^* = t_v^* = t_r^* = t_{kc}^* = t_{km}^* = t_{kv}^* = 0$, then:

$$t_g^* = -\frac{u_G n}{\mu}, \tag{15a}$$

$$t_b^* = -\frac{u_B n}{\mu}, \tag{15b}$$

$$t_{wm}^* = -\frac{u_{Wm} n}{\mu}, \tag{15c}$$

and $$t_{wv}^* = -\frac{u_{Wv} n}{\mu}. \tag{15d}$$

This is the standard result from the general principle of Pigou (1932): the optimal corrective tax on an activity causing a negative externality is equal to its MED. Therefore, any output or input taxes become unnecessary if the first-best Pigouvian taxes are available. Note that the tax on household recycling is zero $(t_r^* = 0)$. Household recycling itself has no external effect. It improves (or harms) the environment only through reprocessing. Since any waste generated by reprocessing firms is already taxed according to its damage to the environment $(t_{wm}^* > 0)$, household recycling should is neither rewarded nor penalized.

Note that the first-best optimal taxes on virgin waste (W_v) and on reprocessing waste (W_m) can be collapsed into a single optimal tax on waste (t_w), if there is no difference between household recycling and reprocessing.

Can the environmental authority estimate the necessary quantity restrictions from these results and implement the command and control policies such as mandatory recycling for households and/or minimum recycled-content standards on producers in order to achieve socially efficient outcomes? At least in theory, it appears to be possible. As Palmer and Walls (1997) show, however, such standards by themselves can achieve the social optimum only when combined with additional taxes on both the final product and other inputs. Furthermore, the information burden required to achieve those efficient outcomes would be huge, and so this information is not likely to be available to policymakers.

It is not certain if illegal disposal increases after introducing a tax on garbage pickup services. On one hand, some studies (Reschovsky and Stone, 1994; Fullerton and Kinnaman, 1996) report that this was indeed the case, especially in the densely populated urban areas of the city. On the other hand, there exist other studies that report the contrary (Miranda and LaPalme, 1997; Nestor and Podolsky, 1998). Even if illegal disposal was initially caused by the imposition of a price on garbage, it might not long remain a serious problem (OECD, 2004).

2. When Illegal Disposal Cannot be Taxed

The first-best Pigouvian taxes on disposal derived in the previous section is generally considered to be impractical. In particular, a simple

Pigouvian tax on illegal burning or dumping (t_b^*) is difficult, if not impossible, to implement due to monitoring and enforcement problems. If t_b^* is not available, then the social optimum can still be achieved by using a combination of a presumptive tax on consumption and a subsidy for proper disposal activities as follows. If $t_b^{**} = t_m^{**} = t_v^{**} = t_{kc}^{**} = t_{km}^{**} = t_{kv}^{**} = 0$, then:

$$t_c^{**} = -\frac{n\,u_B}{\mu\,c_b}, \tag{16a}$$

$$t_g^{**} = -\frac{n\,u_G\,d_g}{\mu\,c_b} + \frac{n\,u_B\,d_g}{\mu\,d_b}, \tag{16b}$$

$$t_r^{**} = \frac{n\,u_B\,d_r}{\mu\,d_b}, \tag{16c}$$

$$t_{wm}^{**} = -\frac{n\,u_{Wm}}{\mu}, \tag{16d}$$

$$\text{and } t_{wv}^{**} = -\frac{n\,u_{Wv}}{\mu}. \tag{16e}$$

Since $u_B < 0$, the presumptive consumption tax is positive $\left(t_c^{**} > 0\right)$ and it reflects the MED from illegal disposal $(-nu_B/\mu c_b)$ from (16a). The first part of the right-hand side of (16b) means that garbage is taxed for its detrimental effects on the environment $(-n\,u_G\,d_g/\mu d_b > 0)$. But the second part of (16b) means that proper garbage disposal is subsidized to avert illegal disposal $(n\,u_B\,d_g/\mu d_b < 0)$. This result clearly shows that if the corresponding first-best Pigouvian tax on illegal disposal (t_b^*) is not available due to various difficulties, a combination of proper "two-part instruments" can be used instead (Fullerton and Wolverton, 1999).

It is obvious that the disposal fee is less than the Pigouvian charge derived in the previous section $(t_g^{**} < t_g^{*})$ because of the negative second term $(n u_B d_g / \mu d_b)$. It is not easy to determine, however, how much t_g^{**} would be lower than t_g^{*}. If the MED from illegal disposal is large enough, then the optimal charge for garbage pickup might approach zero or, in extreme case, turns out negative. The ultimate level and/or sign of t_g^{**} also depends on the relative easiness of illegal burning to proper garbage collection (d_b and d_g).[5] If proper garbage pickup systems are not readily available (i.e., high d_g) or unsafe garbage disposal is wide-spread (i.e., low d_b) as in many developing countries, free garbage pickup services may be more effective in improving environmental welfare.[6] UN Habitat (2011) shows how surprisingly basic infrastructure such as convenient design of garbage containers, use of suitable and reliable vehicles, and ability to provide full coverage are important to establish well-functioning proper garbage disposal system.

This result implies that the gradual increase of the price of per unit garbage disposal bag proposed by the First National Framework Plan for Resource Circulation (FNFPRC) by the Korean Government in 2018 might not be desirable. A substantial portion of households lives in various residences such as detached dwellings and multi-family houses in Korea. And they are well-known for lower rates of source separation and recycling efforts because of lack of proper garbage disposal services, compared to those living in apartment complexes. It

5) Consider the 'material balance' case: $d = g + r + b$. Since $d_r = d_b = 1$, in this case, the optimal tax and subsidy rates show that garbage receives a net subsidy (because it is assumed that $u_B < u_G$).

6) This case would be also relevant in some developed countries that have vast and less-populated areas like Australia (Choe and Fraser, 1998).

means that higher price of garbage bag is likely to increase illegal burning or dumping. Hence, it would be more beneficial to maintain the price of garbage bag lower than the level of the first-best case. Or if a pay-as-you-throw waste charge is enforced, intensive materials separation services should be provided, too (Palatnik et al., 2014).

Note that the tax on household recycling $\left(t_r^{**}\right)$ is negative (i.e., a subsidy). Recall that the first-best optimal subsidy for recycling was zero in the previous section $\left(t_r^{**}=0\right)$, since recycling was not held responsible for being either detrimental or beneficial to the environment and the environmental authority could remedy the four externalities with the four corresponding Pigouvian taxes (t_g^*, t_b^*, t_{wm}^* and t_{wv}^*). In the absence of any t_b, however, household recycling contributes to proper waste disposal by diverting illegal burning or dumping. Therefore, household recycling is subsidized to the extent of its contribution.

Also note that the optimal tax on waste from extracting virgin material $\left(t_{wv}^{**}\right)$ is exactly equal to the MED caused by this activity: it is not used to encourage recycling or to discourage the generation of waste. Therefore, the environmental authority should not attempt to use this upstream tax to solve the externalities from downstream activity. This confirms the results from Fullerton and Kinnaman (1995) and Walls and Palmer (2001).

My model shows that the same logic can be applied to the case of a Pigouvian tax on reprocessing waste. The optimal tax on waste or pollution generated from reprocessing $\left(t_{wm}^{**}\right)$ is also exactly equal to the MED caused by reprocessing: it is not used to remedy the imperfectness of household recycling or to discourage illegal dumping. This result implies that the environmental authority should not be confused between two different kinds of imperfectness between household recycling and reprocessing. Household recycling should be subsidized exactly to the extent that it diverts potential illegal dumping. It should not be penalized based on any presumptive mistakes that households might cause such as placing recyclables into garbage containers. Any household recyclables sent to landfill sites due to incomplete recycling can be charged with t_g^{**}.

3. When Pigouvian Taxes are Unavailable

In practical viewpoint, it is not much easier to implement the first-best Pigouvian taxes on both reprocessing waste (t_{wm}) and virgin material extraction externality (t_{wv}) than a tax on illegal dumping or burning (t_b). It would be difficult to monitor pollutants accurately and to enforce the optimal charges. Although this paper primarily focuses on the optimal MSW policies, any efforts to reduce MSW are intrinsically related to other forms of pollutants such as air borne particles and sewage. These factors dramatically increase the difficulties in gathering any necessary information to calculate the optimal rates of Pigouvian taxes and in enforcing them.

Even if no Pigouvian taxes are available, however, the environmental authority still can find the appropriate first-best tax-subsidy scheme to achieve the optimum, as follows. If $t_b^{***} = t_{wm}^{***} = t_{wv}^{***} = t_{kc}^{***} = 0$, then the social planner's first-best FOC can still be satisfied if:

$$t_c^{***} = -\frac{n\,u_B}{\mu\,d_b} > 0, \tag{17a}$$

$$t_g^{***} = -\frac{n\,u_G\,d_g}{\mu\,d_b} + \frac{n\,u_B\,d_g}{\mu\,d_b} \begin{matrix} > \\ = \\ < \end{matrix} 0, \tag{17b}$$

$$t_r^{***} = \frac{n\,u_B\,d_r}{\mu\,d_b} + \frac{n\,u_{Wm}\,m_r}{\mu\,m_{wm}} < 0, \tag{17c}$$

$$t_m^{***} = -\frac{n\,u_{Wm}}{\mu\,m_{wm}} > 0, \tag{17d}$$

$$t_{km}^{***} = -\frac{n\,u_{Wm}\,m_{km}}{\mu\,m_{wm}} < 0, \tag{17e}$$

$$\text{and } t_{kv}^{***} = -\frac{n\,u_{Wv}\,v_{kv}}{\mu\,v_{wv}} < 0. \tag{17f}$$

The different waste externalities that I use in my model (i.e., G, B, V, W_v and W_m) help clarify what happens in the above results. For example, every term with u_B can be grouped conceptually, because they all are used in combination to correct for the fact that government cannot tax illegal burning or dumping. Similarly, every term with u_G can be grouped conceptually because they all are used in combination to correct for the case that government cannot tax proper disposal of household garbage. For example, the three tax rates in (17c), (17d) and (17e) have a term with u_{Wm} for waste in materials reprocessing. The production function is $m = m(k_m, r, W_m)$. If government cannot tax W_m, then the equivalent is to tax output m, and subsidize both other inputs k_m and r.

The optimal level of a presumptive consumption tax (t_c^{***}) does not change from the one obtained in the previous section 2 (t_c^{**}). It is positive and reflects the MED from illegal disposal. Garbage is again taxed for its detrimental effects on the environment but this proper disposal is subsidized to avert illegal disposal. However, an output tax on reprocessed material $\left(t_m^{***} > 0\right)$ is needed to handle the externality from reprocessing waste $\left(w_m\right)$. In this case, t_m^{***} should be combined with a subsidy for the clean input $\left(t_{km}^{***} < 0\right)$ to undertake the same role of the first-best Pigouvian tax on reprocessing waste $\left(t_{wm}^{***}\right)$ in the previous section 2. This is exactly the same logic of the 'two-part instrument' that replaces the Pigouvian tax on illegal burning $\left(t_b^{***}\right)$ with a combination of the presumptive consumption tax and a recycling subsidy. Reprocessing firms are assumed to be polluting and therefore pay tax t_m^{***} in advance, but this effectively means that all inputs employed in the reprocessing industry also have to pay taxes even though not all of these inputs are polluting. Hence, in this case, the clean input k_m receives a subsidy $\left(t_{km}^{***} < 0\right)$. The same logic also applies to the case of virgin material. Producers of virgin material pay a presumptive output tax $\left(t_v^{***} > 0\right)$, but a part of this output tax is returned to the clean input as a subsidy $\left(t_{kv}^{***} < 0\right)$. These two parts together make up for the absence of a Pigouvian tax on waste from reprocessing (t_{wr}).

Also, note that the absence of t_{wm} can be replaced by the combination of a tax on reprocessed material $\left(t_m^{***} > 0\right)$ and subsidy to clean inputs ($t_r^{***} < 0$ and $t_{km}^{***} < 0$). Now the subsidy for household recycling has an additional term $n\, u_{Wm}\, m_r \,/\, \mu m_{wm}$ unlike the previous t_r^{*} and t_r^{**}. This additional term shows how the characteristics of reprocessing affect the subsidy structure for household recycling. The first role is that recycling can divert illegal dumping, as already shown in the previous section. The second and new role is that recycling serves as a clean input for the reprocessing industry and therefore should receive a portion of the presumptive output tax on reprocessed material as an other clean input k_m does.

Since marginal products of both reprocessing waste and recycling (m_{wm} and m_r) are positive, the second term of t_r^{***} is negative ($n\, u_{Wm}\, m_r / \mu\, m_{wm} < 0$). Therefore, $t_r^{***} < t_r^{**} < 0$. This means that a subsidy for recycling when reprocessing is imperfect should be bigger than the subsidy for recycling when reprocessing is perfect and generates no waste. Therefore, the roles of the recycling subsidy are strengthened when the first-best Pigouvian taxes cannot be used.

These results implies that the government's support for household recycling should be strengthened even with its imperfectness. It is true that households' recycling activities like separating and sorting potential recyclables are not always perfect: dirt on papers or cigarettes inside glass bottles. But these kinds of imperfectness should not hinder households' recycling activities. It is rather better to subsidize pickup, sorting, and reprocessing firms in forms of financial and technical supports, particularly targeting clean inputs.

Ⅴ. Conclusions and Further Discussion

In recent years, environmental concerns about generation and disposal of municipal solid waste have greatly increased in both developed and developing countries. Economic theory suggests that the social optimum can be achieved by imposing a tax on waste-generating activity or by subsidizing its reduction.

The per-unit charge on household garbage has been proposed to implement this approach and accepted by many municipalities and countries, even though the informational burden is heavy and often the actual rates of the per-unit charge are believed to deviate from the optimal ones. Furthermore, these charges can make the environmental problems worse if the possibility of illegal disposal is present. Therefore, a Depost-Refund (D-R) system has recently been in the center of discussion. In general, a presumptive output tax combined with subsidies for recycling and proper garbage disposal can achieve the social optimum in the presence of illegal disposal.

Previous studies, however, have assumed that recycling is perfect in the sense that any recycled materials by households can be substitutable for virgin material without reprocessing. Furthermore, reprocessing is also usually assumed perfect in the sense that no reprocessing waste or pollution is generated during the process.

Neither recycling nor reprocessing was assumed perfect in my model. Using a simple general equilibrium model, I examined how the tax-subsidy structure should change as the first-best Pigouvian taxes cannot be adopted by policy-makers.

If illegal disposal or dumping cannot be properly taxed, a positive output tax combined with the corresponding subsidies for proper garbage disposal and household recycling can achieve the social optimum. When no other Pigouvian taxes are available either, then the optimal tax rates on consumption and garbage disposal are not different from those derived earlier. New presumptive taxes on reprocessed and virgin materials should be introduced and any clean inputs are subsidized. The subsidy for recycling now consists of two parts. The first part corresponds to the role of recycling that diverts illegal disposal. On the other hand, the second part rewards the role of household recycling as a clean input for reprocessing. In the context of previous literature, these results confirm that a generalized D-R system proves effective in remedying various externalities without depending on the use of Pigouvian taxes. This suggests that the roles of household recycling are crucial in solving the externality problems even in the case that the environmental authority cannot freely choose all policy instruments. The authority can achieve the social optimum by increasing the magnitude of a recycling subsidy accordingly as the possibility of using the Pigouvian taxes become lower.

Is it possible to implement any other tax-subsidy schemes without relying on the use of a recycling subsidy? The answer would depend on whether the environmental authority has any other policy instruments to use following this simple logic of the 'two-part instrument.' For example, assuming substitutability between household recycling and virgin material as well as no externalities from reprocessing, the authority can still achieve optimum by subsidizing another clean input if a subsidy for recycling is not available as shown in Fullerton and Kinnaman (1995). However, if recycling is imperfect and reprocessing generates waste as modeled here, then a subsidy for recycling becomes an indispensable instrument since the household recycling enters into both the household's consumption function and into reprocessing firms' production function.

These results imply that recycling still has important roles to achieve to achieve higher levels of resource circulation and a more sustainable economy. Major industrial countries recognize it, too. For example, the EU's 2008 Waste Framework Directive introduced a new 50 percent recycling target for MSW by 2020 (EEA, 2013). The overall rate of recycling (material recycling, composting, and digestion) for the EU increased from 31 percnet in 2004 to 45 percent in 2015. This improvement is evaluated as a result from a combination of a reduction in the amount of municipal waste generated and an increase in the total quantity undergoing material recycling, composting, and digestion. Around two thirds of the progress in enhanced recycling rates between 2004 and 2015 was primarily because of more material recycling. Increased composting and digestion was responsible for the remaining third (EEA, 2017a, 2017b). Despite substantial increases in recycling of MSW, however, the majority of the 32 European countries will still need to make an extraordinary effort in order to achieve the target of 50 percent recycling by 2020.

Meanwhile, the situations surrounding waste management policies in Korea has recently taken a course for the worse. The annual MSW generation, which was relatively stable under 400 kg per for the 1997~2016 period, has been steadily increasing since then (Ministry of Environment, 2017). Landfilling ceased to be a favored disposal option due to shortage of landfill sites and leachate problems. Conflicts surrounding unequal waste transportation among municipalities aggravated the difficulties in securing landfill sites (Yoon and Baek, 2014). As a result, the government of South Korea established the *Framework Act on Resource Circulation* in 2016, which has been enacted since January 2018.

More recently, the waste pickup services in Korea observed a sudden disruption in major metropolitan areas in April 2018. On the surface, China's prohibition of waste import was spotted as the main factor. In the process, however, the weaknesses of waste management system in Korea has been exposed. Households are required to source separate various recyclables such as plastics, paper, and glass bottles from waste. But the pickup service refused to collect them claiming that a substantial portion of recyclables were mixed and contaminated with dirt, which were hard to reprocess. To solve these problems, the Korean Government announced the *First National Framework Plan for Resource Circulation (2018~2027)* (hereafter, FNFPRC) in September 2018 with the goals of reducing waste generation by 20 percent and increasing recycling rate from 70 to 82 percent in 10 years (Government of Korea, 2018). In particular, the Plan emphasizes the extended producer responsibility (EPR) to achieve more comprehensive resource circulation and aims to establish performance management governance in national, regional, sectoral levels.

Unfortunately, the policy propositions for consumers and households included in the Plan appears quite weak and focuses mainly on suppressing the use of discard after use (DAU) products and increasing the price of standard plastic garbage bags. Nowhere to be found the use of economic incentives for the market to efficiently allocate resources in the chain of production, consumption, recycling, and disposal. Of course, social norms and mandatory recycling laws can be effective in encouraging recycling activities (Ashenmiller, 2010, Viscusi et al., 2013). However, economic incentives can have stronger effects as Homonoff (2018) accurately points out.

The results from this paper implies that policies proposed in the FNFPRC might not be effective to achieve the planned goals. The FNFPRC emphasizes greatly on the EPR, mandating producers to source reduction efforts with compulsory guidelines and evaluations and providing strategic consulting services. With households and consumers proposed are the minimal increase in price of per unit garbage bags and promotion of eco-friendly consumption behaviors.

However, it is rather better to support more for household recycling as well as the clean inputs for reprocessing. Furthermore, presumptive taxes on outputs produced either from virgin or reprocessed materials should be charged at the level equal to marginal environmental damages and be used to finance public waste policies. A generalized D-R system can be devised to channel these financial compensation to reach the agents or firms who specializes sorting, separating, and reprocessing. And it could be quite significant income source as Ashenmiller (2009) points out.

One might question the robustness of the theoretical results derived in this paper in various respects. Ferrara (2003) shows that a combination of presumptive consumption taxes and legal disposal and recycling subsidies is still needed to achieve social optimum even when both the waste stock externality and the households' heterogeneous preferences for garbage pickup frequencies are considered. In addition to a uniform consumption tax and a uniform recycling subsidy, in this case, varying pickup frequencies and differential legal disposal subsidies are also required to achieve social optimum. Considering the 'transaction costs' problem associated with any large-scale recycling programs, Shinkuma (2003) finds that a D-R system is one of the three promising alternative policy schemes. The other two policies include the per-unit charge with an advance disposal fee and a producer take-back requirement system. Similarly, Calcott and Walls (2002) find that the most encouraging policy is a modest disposal fee which is less than the Pigouvian tax combined with a D-R system applied to all products. Therefore, the results in this paper appear to be quite robust with respect to various model specifications and market conditions.

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홍인기: The University of Texas at Austin 경제학과에서 재정학과 환경경제학 전공으로 경제학 박사학위를 취득하였다. 국회예산정책처 경제분석실 세제분석팀 경제분석관을 거쳐 현재 대구대학교 경제학과 부교수로 재직 중이다. 재정학 및 환경경제학 관련 논문을 다수 발표하였고, 최적조세이론을 적용하여 다양한 환경 문제를 해결하는 연구에 주된 관심을 두고 있다(ihong@daegu.ac.kr).

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