ECONOMICS OF RECYCLING

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This article deals with recycling as one of the answers to the problem of the scarcity of natural resources. It consists of three sections. The first section contains the technical aspect of the recycling process, a second deals with the 'recycling multiplier', and the third deals with the necessary adjustment of the Hotelling rule when a recyclable exhaustible natural resource is involved.

1. The recycling process

Recycling is more important than most economists think. There are also remarkably few publications on the economic aspects of recycling, although a number of interesting articles were collected by Pearce and Walter (1977). By then, the editors realized that no standard reference work existed on the economic dimension of materials recycling policy. This is still true today. Indeed, the conclusion of the editors that there cannot be such a thing as "the" economics of recycling is largely correct. Detailed studies of individual secondary commodities are the core of 'recycling economics'. Still, a number of interesting general remarks on the phenomenon of recycling can be made.

In view of the present and future scarcity of resources, recycling and re-use are becoming economically more and more important. Almost all resources can be recycled in an economic sense. Take, for instance, a technically spoken non-recyclable resource like oil. In an economic sense this resource can be recycled. If, for example, one buys a second hand spare part for one's car, it is not only the material within the spare part which is recycled, but also the energy which has helped produce it. If, in this specific case, the energy source is oil, then the oil used in the production process of the spare part would have been recycled by buying a second hand spare part (Robinson, 1989).

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This article does not go into this complex type of recycling, but concentrates upon exhaustible (non-renewable) resources which are recyclable in a technical sense with a fixed recycling factor.

The recycling process for exhaustible resources with a fixed recycling factor, for example metals like copper and iron, can be modelled with q_t for the quantity of virgin material supplied to the market in period t, r for the recycling factor and Q_t for the total quantity of the material supplied to the market in period t. Of course, this total quantity consists of virgin material plus recycled material. The recycling process with a fixed recycling factor r is represented in Table 1.

0	1	2	...	t
q_0	rq_0	r^2q_0		r^tq_0
	q_1	rq_1		$r^{t-1}q_1$
		q_2		$r^{t-2}q_2$
				.
				.
				.
				rq_{t-1}
				q_t
$Q_0 = q_0$	$Q_1 = rq_0 + q_1$	$Q_2 = r^2q_0 + rq_1 + q_2$	...	$Q_t = \sum_{\tau=0}^{t} r^{t-\tau} q_\tau$

Table 1: The recycling process.

2. Recycling multiplier

In 1974, Solow remarked:

> ... the size of an exisiting stock [of an exhaustible natural resource] can never increase through time. It can only decrease (or, if none is mined for a while, stay the same). This is true even of recyclable materials; the laws of thermodynamics and life guarantee that we will never recover a whole pound of secondary copper from a pound of primary copper in use, or a whole pound of tertiary copper from a pound of secondary copper in use. There is a leakage at every round; and a formula just like the ordinary multiplier formula tells us how much copper use can be built on the world's initial endowment of copper, in terms of the recycling or recovery ratio. There is always less ultimate copper use left than there was last year, less by the amount dissipated beyond recovery during the year. So copper remains an exhaustible resource, despite the possibility of partial recycling. (Solow, 1974, p. 2).

Although this is an adequate description of the recycling process, the conclusion does not seem completely correct. If an exhaustible resource is a resource of which the stocks can be exhausted completely, then a recyclable resource with a fixed recycling factor is not an exhaustible resource, since there will always be a stock of such a resource in the final products made or partly made from such a material, which can be re-used.

The aim of this section is to calculate Solow's recycling multiplier. Suppose there is a stock of ore S. During each period t, this stock is depleted by S_t. S_t is a fraction o_t of the initial stock of ore S, so that:

$$S_t = o_t S$$

and:

$$\sum_{t=1}^{\omega} S_t = S,$$

in which ω denotes the number of periods during which the initial stock of ore is exhausted. From these two equations it follows:

$$\sum_{t=1}^{\omega} o_t = 1 .$$

Now suppose that M represents the total generation of the material (for instance copper or iron) out of the initial stock of ore S, and that M_t represents the generation of raw material out of one year's extraction of ore.

Further, suppose that π represents the raw material-ore ratio (for instance the copper grade of the ore) and $1 - r$ the fractional loss of material when it is recycled. Then:

$$M_t = \pi o_t S\{1 + r + r^2 + ...\}$$

$$M_t = \frac{1}{(1-r)} \pi o_t S.$$

Further it is known that:

$$M = \sum_{t=1}^{\omega} M_t.$$

The last three equations give:

$$M = \frac{\pi}{1-r} S.$$

So, the recycling multiplier equals $\pi/(1-r)$ (see also Heijman, 1991). Besides, we can be certain that materials with a fixed recycling factor r will never be exhausted completely. This has an important consequence for the efficient pricing of such kinds of resources as I show in the next section.

3. Recycling and the Hotelling rule

To show the consequences of the possibility of recycling of exhaustible resources with a fixed recycling factor for the efficient pricing of this resource, I deal first with a simple case of two periods. The model is then

$$\text{Max} \quad \sum_{j=0}^{1} \frac{U(Q_j)}{(1+i)^j} = U(Q_0) + \frac{U(Q_1)}{1+i}$$

$$= U(q_0) + \frac{U(q_1 + rq_0)}{1+i}$$

with U for total utility, Q for the total amount of resource supplied to the market, q for the amount of primary resource supplied to the market, r for the recycling factor and i for the discount factor. Further we know that

$$q_1 + q_0 = M$$

$$U(Q) = \int_0^Q p(\xi)d\xi$$

$$U'(Q) = p(Q)$$

with M for the total amount of primary resource which is available and p for the rent of the resource.[1] The solution to this dynamic programming problem is:

$$\text{Max} \quad f(q_0) = U(q_0) + \frac{U(M - q_0 + rq_0)}{1+i}$$

$$= U(q_0) + \frac{U((r-1)q_0 + M)}{1+i}$$

$$0 = f'(q_0) = U'(q_0) + \frac{U'((r-1)q_0 + M)}{1+i}(r-1)$$

$$p(q_0) + \frac{p((r-1)q_0 + M)}{1+i}(r-1) = 0$$

$$p(Q_0) + \frac{p(Q_1)}{1+i}(r-1) = 0$$

$$p(Q_1) = \frac{1+i}{1-r}p(Q_0).$$

Note that if $r = 0$ the original Hotelling rule emerges (Hotelling, 1931). Because $1 - r < 1$, rent rises faster with recycling than without. The solution for N periods is given in the appendix. Of course, this does not say anything about the absolute level of the recyclable resource price. If there are two

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1 By *rent* or *royalty* of an amount of primary material is meant the market price minus the extraction costs. The rent of recycled materials equals the rent of an equivalent amount of *in situ* primary material.

resources between which the only difference is that one is recyclable and the other is not, then the absolute price level of the recyclable resource will always be lower than the absolute price level of the non-recyclable resource.

Appendix

$$\text{Max} \quad \sum_{j=0}^{N} \frac{U(Q_j)}{(1+i)^j}$$

subject to

$$q_0 + q_1 + \ldots + q_N = M$$

where

$$Q_t = \sum_{\tau=0}^{t} r^{t-\tau} q_\tau$$

and

$$U(Q) = \int_0^Q p(\xi) d\xi .$$

To solve this problem I define

$$W_j(q_0, q_1, \ldots, q_j) = U(Q_j) = U\left(\sum_{\tau=0}^{j} r^{j-\tau} q_\tau \right)$$

and form the Lagrange function

$$L = \sum_{j=0}^{N} \frac{W_j(q_0, q_1, \ldots, q_j)}{(1+i)^j} + \lambda \{ M - (q_0 + q_1 + \ldots + q_N) \} .$$

The first order condition is

$$\sum_{j=k}^{N} \frac{\partial W_j / \partial q_k}{(1+i)^j} = \lambda \qquad (0 \le k \le N).$$

Because, with $p_k = p(Q_k)$

$$\frac{\partial W_j}{\partial q_k} = U' r^{j-k} = p_k r^{j-k},$$

we have

$$\lambda = \sum_{t=k}^{N} \frac{p_k r^{t-k}}{(1+i)^t} \qquad (0 \le k \le N).$$

Thus, for $0 \le k \le N-1$:

$$\sum_{t=k}^{N} \frac{p_k r^{t-k}}{(1+i)^t} = \sum_{t=k+1}^{N} \frac{p_{k+1} r^{t-(k+1)}}{(1+i)^t}$$

$$p_k \sum_{t=0}^{N-k} \frac{r^t}{(1+i)^{t+k}} = p_{k+1} \sum_{t=0}^{N-k-1} \frac{r^t}{(1+i)^{t+k+1}}$$

$$\frac{p_k}{(1+i)^k} \sum_{t=0}^{N-k} \left(\frac{r}{1+i}\right)^t = \frac{p_{k+1}}{(1+i)^{k+1}} \sum_{t=0}^{N-k-1} \left(\frac{r}{1+i}\right)^t$$

$$\frac{p_k}{(1+i)^k} \frac{1-\left(\frac{r}{1+i}\right)^{N-k+1}}{1-\frac{r}{1+i}} = \frac{p_{k+1}}{(1+i)^{k+1}} \frac{1-\left(\frac{r}{1+i}\right)^{N-k}}{1-\frac{r}{(1+i)}},$$

which means that

$$p_{k+1} = (1+i) p_k \left\{ \frac{1-\left(\frac{r}{1+i}\right)^{N-k+1}}{1-\left(\frac{r}{1+i}\right)^{N-k}} \right\} \qquad (0 \le k \le N-1).$$

Note that if $r = 0$, the original Hotelling rule occurs (Hotelling, 1931). If $0 < r < 1$, we have $0 < \frac{r}{1+i} < 1$, which implies that

$$\frac{1-\left(\frac{r}{1+i}\right)^{N-k+1}}{1-\left(\frac{r}{1+i}\right)^{N-k}} > 1 .$$

This means that the rent of the resource rises faster with recycling than without recycling.

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