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Macroscopic Evidence for the Hibernating Behavior of Materials Stock

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Supporting Information

ABSTRACT: Hibernating stock is defined as material stock that is no longer used, but is not yet recovered. Although hibernating stock plays a role in materials recoverability, its contribution to the overall material cycle is not clearly understood. Therefore, an analysis of the time-series potential generation of steel scrap in Japan was performed and compared against the actual recovery, proving that the steel scrap recovered each year exceeds the annual generation potential and providing the first macroscopic evidence of hibernating stock recovery. These results indicate that hibernation behavior should be considered when evaluating materials recoverability. The particular characteristics of hibernating stock were also identified. These materials tend to be located far from scrap yards and/or have low bulk density, while also minimally obstructing new activity. In fact, hibernating materials are typically only recovered when they obstruct new activity. Hence, in order to increase steel recoverability, the recovery cost must be reduced. The end-of-life recycling rates (EoL-RRs) were also evaluated, and were found to exhibit a significant change over time. Consequently, the annual EoL-RR cannot be considered as a representative value, and a value for the EoL-RR(s) of relevant year(s) that has been evaluated over the entire period should be used instead.

1. INTRODUCTION

Although originally used to refer to a state of inactivity in animals, the term "hibernation" was first used in reference to materials by Brunner,[1] regarding materials in the anthroposphere that have reached the ends of their effective lives but are still awaiting recovery or dissipation into the environment. As an example of hibernation behavior, consider an old steel fence that no longer serves any practical purpose yet remains on site, and which will only be recovered at a time when it becomes an impediment. Thus, hibernating stock represents an important potential secondary resource that can be recovered as needed. Wallsten et al.[2] examined the hibernating infrastructure in a Swedish city and revealed that its existence was mainly spontaneously generated through inactivity, disconnection, and the abandonment of material because of decreased demand. Krook et al.[3] and Wallsten et al.[4] showed that decreasing demand for system services, such as power grids for electricity supply, has led to approximately 20% of the total stock of aluminum and copper used in the power-supply and heating infrastructures of Swedish cities being in hibernation. Since other developed countries are likely to show a similar decrease in demand, the hibernating behavior of materials (especially those used in infrastructure) will undoubtedly become the subject of considerable interest in the near future. Indeed, Milovantseva and Saphores[5] have estimated that each household in the U.S. already contains approximately 20 kg of hibernating stock in the form of waste televisions.

Previous studies of hibernating behavior have tended to rely on a bottom-up approach toward the material flow analysis (MFA)/substance flow analysis (SFA) of specific products, in order to understand the issue of hibernating stock. On the other hand, MFA/SFA studies on specific materials have also been conducted. For example, Vexler et al.[6] conducted a 1-year-cycle SFA of copper in Latin America and the Caribbean but, as they employed a bottom-up approach to estimate the waste stream, they could not differentiate between in-use and hibernating stock. Nevertheless, they were able to conclude that a significant copper stock exists, which is composed of not only in-use, but also hibernating stock in the form of disused electronic products. Meanwhile, Mueller et al.[7] and Daigo et al.[8] used a dynamic MFA (dMFA) to quantify accumulated discarded steel with an unknown destination. This was defined as obsolete stock, which consists of hibernating stock, exported end-of-life (EoL) products, and dissipative flows. Significantly, obsolete stock in this instance accounts for approximately one-quarter of the total stock in the technosphere in both the U.S. and Japan. In the case of aluminum, Chen[9] found that a quarter of the material discarded at its EoL in the U.S. has no clear destination, although this material includes not only hibernating material, but also that intended for export or material that was

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lost during collection. Although the amount of hibernating material is clearly an important consideration when evaluating the production and use of a given material, the magnitude of hibernating stock in general has never been assessed.

This paper therefore reveals macroscopic evidence for the hibernating behavior of materials, focusing on steel in Japan, by comparing time-series data for steel scrap generation against actual recovery. The particular characteristics of hibernating stock are also discussed.

2. MATERIALS AND METHODS

2.1. Overview. Hibernating material is defined as that contained in disused products that remain in the technosphere at the end of their service lives, and which is expected to be recovered at some point in the future. As the hibernating material stage is effectively a time buffer in the recovery of EoL materials, it has been postulated that any increase in the amount of scrap recovered over the amount of scrap potentially discharged from EoL products in any given year can be attributed to hibernating behavior. The basic concept of this study is expressed more clearly in Figure 1, which schematically illustrates annual flows of EoL materials discharged from in-use material stock to recovered scrap, focusing on material hibernating behaviors in particular. Alphabetical indices, (a) to (e), are used to indicate the various flow amounts. Based on these flows, we propose a condition for when the annually recovered scrap (e) is larger than the generation of EoL materials annually discharged from in-use stock (a). Under this condition, even if the amount of EoL materials that remain unrecovered within the year (b) (some portion of which becomes hibernating stock) is zero, the amount of scrap generated from EoL products discharged in the year (c) is equal to (a), and (e) is larger than (c). The scrap generated from hibernating stock (d) contributes to the difference between (c) and (e). Although some in-/out-flows of EoL materials; such as the export/import of EoL products, have been ignored in the above description, in this study, all of the flows are taken into account when the flow of (a) is estimated. Hereafter, the flow of (a) is referred to as the "scrap generation potential".

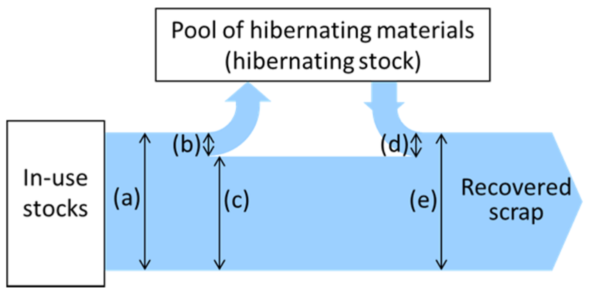

Figure 1. Schematic illustration of annual flows of EoL materials covering discharging from in-use material stock to recovered scrap. The symbols from (a) to (e) denote the following: (a) the generation of EoL materials annually discharged from in-use stock, (b) the amount of EoL materials unrecovered in the year, (c) the amount of scrap generated from EoL products discharged in the year, (d) the scrap generated from hibernating stock, and (e) the annually recovered scrap.

Time-series data on the recovered scrap and scrap generation potential were therefore estimated and compared, and the manner in which these two flows are defined is illustrated schematically in Figure 2. This figure shows both the sink, in which a material is classed as hibernating, and its reintroduction at a later point in time; although, in practice, the former does not represent a change in the material itself, but simply a change in its status from in-use to disused. Obsolete stock in this instance is regarded as inactive stock that will not be recovered in the future, but this can be a difficult distinction to make given that it relies on the estimation of future conditions.

A dMFA that has previously been used to estimate scrap generation potential was employed in this study. The methodology and data used for the dMFA of steel are described in section 2.2, while the equations used to estimate the annually recovered scrap from EoL products are given in section 2.3.

2.2. Dynamic MFA. It was necessary to estimate the scrap generation potential of steel, $G(t)$, using an analytical model, as dissipated materials that are not recovered from EoL products cannot be observed directly. Instead, historic data on steel entering into use, $I(t)$, along with lifetime distributions, $\lambda(\tau)$,

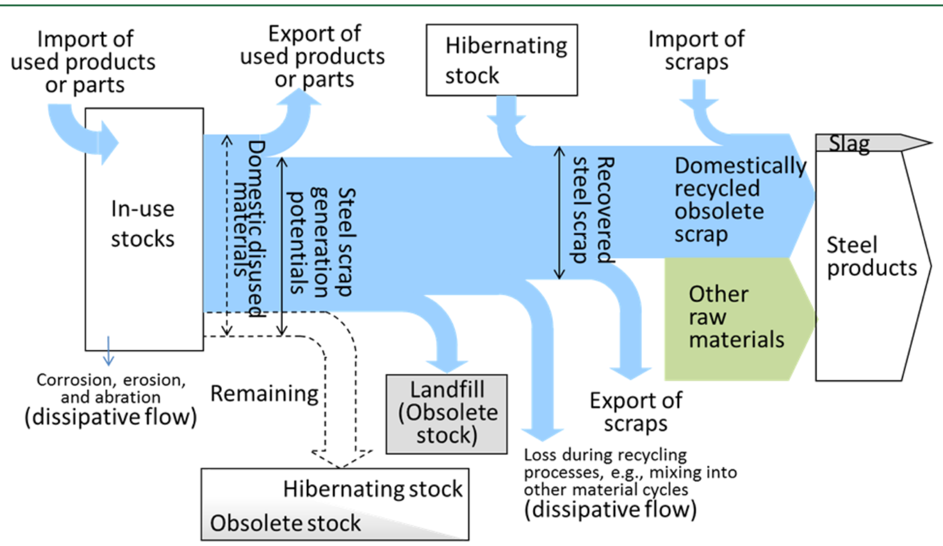

Figure 2. Schematic diagram of the steel recycling chain.

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were used for the dMFA,[10−17] as shown in the following equation:

$$G(t) = \sum_{\tau>0} I(t-\tau) \times \lambda(\tau) \tag{1}$$

Data on materials entering use can be obtained by estimation using statistics for the consumption of steel from 1920 onward, $C(t)$, and the trade in finished products containing embedded steel (hereafter, indirect trade) according to end use from 1930 onward, $IT_i(t)$. Since the lifetime can vary depending on the end use, the materials entering use must be classified by end use, $I_i(t)$, and the relative share of each end use, $\theta_i(t)$, must be determined from

$$I_i(t) = C(t) \times \theta_i(t) + IT_i(t) \tag{2}$$

In terms of reliability, data regarding the consumption of steel and its end use are routinely measured and, therefore, do not require estimation, at least as regards steel consumed in Japan. The trading of finished products containing embedded steel, on the other hand, cannot be directly observed, and the flow data for this material was instead determined using an estimation approach originally proposed by the International Iron and Steel Institute.[18] This estimate is based on the weights of the traded products and incorporates a coefficient corresponding to the steel content in each specific steel product group. Recently, an alternative input/output-based approach to the estimation of the material content of products has been proposed, which is known as waste input-output material flow analysis (WIO-MFA).[19]

Since data on the lifetime distribution of products is less reliable than that on materials entering use, in general, previous dMFA studies have not considered changes to product lifetimes over time. However, in order to obtain reliable time-series results, this conventional assumption is inadequate. Consequently, in this study, time-series changes for automobile and building lifetimes were determined based on registration statistics. The time-series data for automobiles and buildings are described in more detail in the Supporting Information. We demonstrated that the steel consumption in these two end-use categories and in containers that have lifetimes of less than a year accounts for more than 70% of the total consumption of this material. The chronological change in the lifetimes of other end-use categories was subsequently considered through an uncertainty analysis, which was conducted using the Monte Carlo method with 10 000 calculations. To determine the degree of uncertainty in the lifetime distributions, the variations in the average lifetimes were determined based on the legal durable years[20] and measured lifetimes[21] of the main products included in each end-use category, as shown in Table 1. These were then used in the dMFA in order to determine the uncertainty in the scrap generation potentials.

Trade in used products containing embedded steel was also taken into account by eliminating the total amount of steel exported in used products, $U(t)$, from the dynamically estimated scrap generation potential. The dominant products in such exports are automobiles, industrial machinery, electric machinery, and home appliances; so, the amount of steel exported in each of these cases was estimated based on the methods proposed by Fuse et al.[21] The amount of steel imported in used products was expected to be negligibly small.[22] Thus, the scrap generation potential was redefined from eq 1 and estimated from

Table 1. Parametric Lifetime Distributions by End Use

end use	distribution function	parameters[a]	average lifetime[20,21]: best available	upper bound	lower bound
civil engineering	Weibull	m = 3.13, η = 48.4, δ= 8.78	34.5	30.0	45.0
industrial machinery	Weibull	m = 2.06, η = 20.3, δ= 0	18.1	22.0	5.0
electric machinery	Weibull	m = 1.75, η = 17.2, δ= 0	15.4	17.0	4.0
home appliances	Weibull	m = 1.89, η = 12.4, δ= 0	11.1	20.0	4.0
other transportation[b]	Weibull	m = 2.35, η = 39.1, δ= 0	34.6	40.0	30.0
miscellaneous products	Weibull	m = 3.5, η= 13.4, δ= 0	12.1	14.0	3.0

[a]The scale parameters given in this column are valid for the best available average lifetime. For the other average lifetimes, the scale parameters are adjusted to fit. The shape and location parameters given in this column are valid for all of the average lifetimes. [b]The "other transportation" category includes ships, trains, airplanes, and bicycles.

$$\mathrm{G}(t) = \sum_i \sum_{\tau>0} I_i(t-\tau) \times \lambda_i(\tau) - \mathrm{U}(t) \tag{3}$$

2.3. Estimating Recovered Scrap from EoL Products. The total amount of domestically recovered scrap, $T(t)$, can be measured by gathering statistics on the domestic consumption of steel scrap, $D(t)$, and the trade in steel scrap, $ST(t)$. Here, the trade in scrap was considered to be the net export or, in other words, the imported amount was eliminated from the exported amount. Then:

$$T(t) = D(t) + ST(t) \tag{4}$$

However, as the collected scrap is indivisible, it includes not only scrap recovered from EoL products (i.e., obsolete scrap), but also scrap recovered from manufacturers and fabricators (i.e., processing scrap). Prompt scrap (or home scrap) generated by steelmakers, on the other hand, can at least be readily distinguished from other scrap. In this study, obsolete scrap, $R(t)$, was explicitly distinguished, as it represents the value of recovered scrap relative to the generation potential. The amount of processing scrap, $PR(t)$, was then estimated using the steel manufacturers' and fabricators' scrap generation rates, which are published every few years by The Japan Ferrous Raw Materials Association.[24] These generation rates give the end-use category, $g_i(t)$; therefore, the amount of domestically generated processing scrap can be estimated by multiplying the rate and steel consumption for each end-use category. Thus:

$$PR(t) = \sum_i g_i(t) \times C(t) \times \theta_i(t) \tag{5}$$

Finally, the obsolete scrap recovered each year can be calculated from

$$R(t) = T(t) - PR(t) \tag{6}$$

3. RESULTS AND DISCUSSION

3.1. Evidence for Hibernating Stock. In the comparison of the amount of recovered obsolete steel scrap and the generation potential of obsolete steel scrap over time (Figure 3), the inclusion of different product lifetimes for each year in the dMFA of the latter can be seen to produce a zigzag pattern

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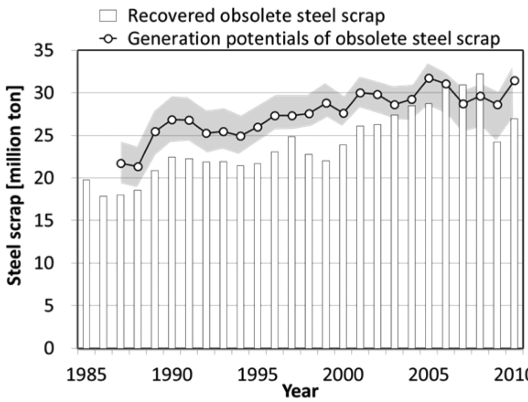

Figure 3. Comparison of steel scrap generation potential and recovered steel scrap.

that differs from the smooth curves previously obtained for aluminum,[10] television sets,[11] lead,[12] housing,[13] copper,[14] stainless steel,[15] steel,[16] zinc,[17] and other materials.[25] The gray area represents the range of uncertainty of the various end-use lifetimes, as shown in Table 1. Note also that the best value is not always centered between the upper and lower bounds, because the entry uses of steel have changed from preceding years. Nevertheless, we can see that the amount of recovered scrap increased more or less in accordance with the scrap generation potential during the 1990s but, after that decade, the recovered scrap increased by a significantly larger amount. This increase led to the amount of recovered scrap actually exceeding the scrap generation potential for the years 2007 and 2008; indeed, this number even exceeded the upper bound of the scrap generation potential. This phenomenon can be explained by viewing these years as exceptions in terms of a dramatic global increase in resource prices.

In this analysis, different lifetimes are applied for each year for two of the major end-use categories, that is, automobiles and buildings, as higher/lower building demolition rates and faster/slower automobile replacement were recorded each year. These fluctuating lifetimes may reflect short-term economic conditions, which are not captured by conventional dMFA. In other end-use categories, the range of uncertainty in the product lifetime values was considered in order to account for the overall uncertainty. Therefore, the upper bound of the range of uncertainty in a given year indicates the corresponding maximum potential steel scrap generated from EoL products discarded in that year, based on the highest scrap rates. At least some of the scrap that exceeded the generation potential in 2007 and 2008 must have come from EoL products that were discarded in the past, which can be thus be regarded as hibernating stock. In our approach, we need not consider the time point when the hibernated materials are discarded, although examination of the exact period of hibernation may be of interest as a means of understanding hibernation behavior more thoroughly. In this analysis, however, we were not in a position to analyze the hibernating periods of the recovered materials.

Since the estimated scrap generation potential includes unknown outflows and products that are semipermanently used, it tends to be an overestimation. For instance, although the main source of unknown outflow (i.e., the exporting of used products) has been taken into account, steel discharged as waste into landfills has not been quantified. Steel in semipermanent usage is generally found in civil engineering applications such as slit dams and ground anchors, but these are assumed to have the same lifetimes as other applications in civil engineering. This overestimation, however, only serves to further the case for recovery from hibernating stocks, so, we can conclude that the contribution made by scrap that may have hibernated for many years certainly is not negligible.

3.2. Triggers for the Recovery of Hibernating Stock.

Chen[9] has confirmed that the recovery of aluminum in the U.S. has increased as a result of the high price of scrap, providing an incentive for recycling. Thus, the relation between the recovery of steel scrap and its price is certainly worth considering. In this section, we first calculate the end-of-life recycling rate (EoL-RR). Its relation to the price of steel scrap is shown in the next section.

Past scrap generation potentials were estimated using dMFA, in order to determine if the recovery of steel scrap was affected at any point in the past by changes in the amount of material entering into use. In other words, the analysis of the recovery of steel scrap took into account the fact that an increase in the amount of recovered scrap could be caused by past trends in the material entering use and/or its recovery from additional scrap sources. To negate the former factor, it is useful to express this value in terms of EoL-RR, which is the ratio of recovered scrap to the scrap generation potential, as defined by Graedel et al.[26] However, even though the dMFA was conducted on the basis of end use, EoL-RRs could not be calculated for each specific end-use category, owing to the fact that recovered steel scrap is classified by shape rather than end-use source. Figure 4, therefore, shows the historical evolution of the EoL-RR of steel in Japan, which provides evidence of hibernating behavior in that it can exceed one hundred percent.

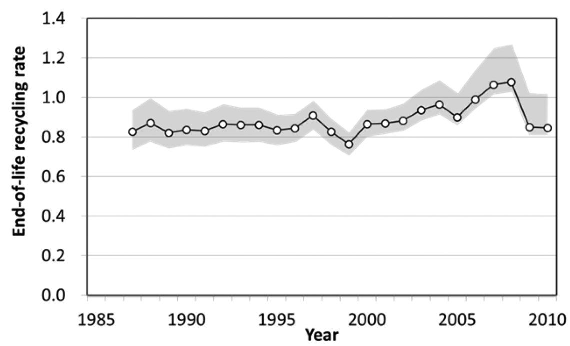

Figure 4. End-of-life recycling rate for steel in Japan, 1987−2010.

Figure 5 shows the relation between the historical EoL-RR of steel and the price of steel scrap between 1987 and 2010. The simple linear regression line obtained here indicates that a positive correlation between the price of steel scrap and the EoL-RR exists, which would suggest that an increase in price does indeed provide an incentive for additional recovery. In other words, hibernating material can be generated through the abandonment of EoL steel when prices are low, which is subsequently recovered when prices are high. However, the data shows that the correlation between price and recovery was not positive in some years, which may be the result of other factors such as the rate of steel production and ore prices. Even if a regression analysis for data from 1987 to 2006 is conducted, meaning that exceptional data are eliminated, the correlation coefficient is 0.56 and the significant level is more than 99%.

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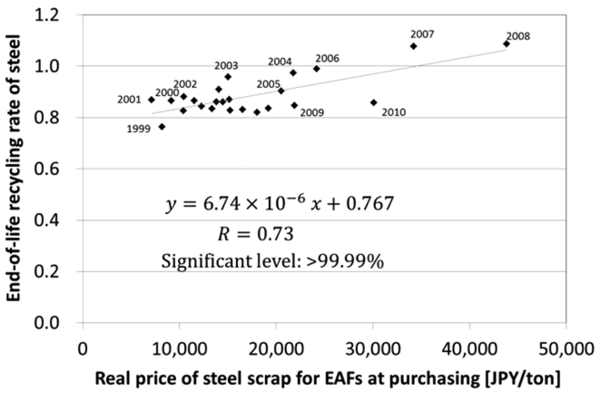

Figure 5. Relation between the end-of-life recycling rate of steel and the price of steel scrap in Japan, 1987−2010.

3.3. Characteristics of Hibernating Stock. Having established how hibernating stock is created, an obvious question exists in relation to identification of its characteristics, including common site locations, geometric profiles, and end-use sources. Answers to this question were explored through statistical analysis by comparing the change in the EoL-RR of 13 different categories of steel scrap on the market over time, as shown in Table 2. Note that, although some of these groupings were taken directly from the ISRI guidelines for ferrous scrap,[27] some have been translated from Japanese because of differences in categories between markets. The category-based distribution of steel scrap on the market could be obtained from a different source,[28] namely, from statistics used for calculating the total scrap generation. Therefore, the total of 13 categories given here is less than the total shown previously in Figure 3.

Table 2. Correlation between EoL-RR and Recovery for Different Types of Steel Scrap

	coefficient of correlation
H2 (≑ HMS2)	0.82
turnings	0.76
H1 (≑ HMS1)	0.67
other heavy melt scrap (lower-grade than HMS2)	0.67
A-press (generated mainly from automobiles and machinery)	0.57
miscellaneous others	0.49
HS (higher grade than HMS1)	0.49
C-shredded (generated mainly from containers)	0.32
industrial bundles	0.35
A-shredded (generated mainly from automobiles and machinery)	0.19
industrial heavy plate	−0.00
cast iron	−0.01
C-press (generated mainly from containers)	−0.48

The correlation coefficients for the EoL-RRs and the amount of steel scrap purchased annually for each category were calculated for the period between 1999 and 2010, as 1999 was the earliest year for which statistical data on steel scrap could be obtained. Recall that EoL materials that are recovered and unrecovered during high and low EoL-RR periods, respectively, are expected to contribute to hibernating stock. We can expect that dominant scrap types have high correlations with the EoL-RR values, because the EoL-RR numerator is composed of these factors. In the case of the Japanese steel scrap market, industrial bundles, HS, H1, H2, and other heavy melt scrap account for more than 10% of the total scrap, none of which corresponds to more than 20% of the market. The results of the calculation are shown in Table 2, with those scrap types showing strong correlation with the EoL-RR (e.g., H2, other heavy melt scrap, and H1), being more likely to be sources of hibernating material. Hibernation would therefore seem to be associated with relatively low-grade scrap that is mainly generated from disused buildings, construction, and products made predominantly of thin or small-diameter steel. Products composed of thick or large-diameter steel are typically dismantled, downsized, and traded as HS; however, if they are also composed of other materials, they are more likely to be roughly dismantled and shredded. Turnings could also be a source of hibernating material, which is likely due to their being regarded as being of relatively lower grade by steelmakers. This is on account of the fact that they are typically composed of a mix of different alloy steel types combined with various cutting oils. Industrial scraps do not correspond well with the EoL-RR and do not seem to contribute to hibernating stock. Industrial scraps tend to be largely free of contaminants, consistent in composition, and are generated in large amounts, which contributes to reduced collection cost and makes them well suited for use in steelmaking. No correlation is seen with iron scrap, but this relation is a result of cast iron recycling being independent of that of steel. A comparison of the change in steel scrap recovery over time for each category is provided in the Supporting Information.

From the positive correlations in Table 2, we can conclude that it is the lower grades of heavy scrap that provide the most substantial buffer to the EoL-RR. Unfortunately, there is insufficient data to differentiate between scrap recovered from hibernating stock and that recovered directly from in-use stock, but interviews with recyclers and scrap dealers have tended to support these results. For example, it has been found that a greater recovery of specific steel products, such as disused agricultural machinery and outdoor items (e.g., fences), occurred during 2007 and 2008. As these products tend to be made of relatively thin steel, they are recovered as H2 or other heavy melt scrap, which conforms well with the results of the statistical analysis. It was also mentioned that these scraps were recovered mainly from rural areas, meaning that they were transported over larger distances than usual. Since larger transport distances and the low bulk density of thin-steel sheet scrap (which is not a commonly known fact) invariably increase the cost of transport, it makes sense that these would only be recovered during a time at which the scrap price is high.

Another characteristic of disused products in hibernation is that they can often pose an obstruction to new activity on a given site, thus rendering their recovery and recycling beneficial even if the cost of this process exceeds the scrap value. In many cases, however, disused agricultural machinery and other outdoor products do not cause significant obstruction, even if they are not removed at the ends of their lives. Thus, the common characteristics of hibernating stock can be defined as (1) being located a long distance from scrap yards and/or having a low bulk density; (2) minimally obstructing new activity. However, if one of these factors should remove any advantage in recovering a particular disused product, this material can instead be regarded as obsolete stock.

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ASSOCIATED CONTENT

Supporting Information

Lifetime distribution of automobiles, buildings, and containers, and the amount of recovered steel scrap by category, relative to EoL-RR. The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b01164.

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Author Contributions

The manuscript was written with contributions from all authors. All authors have approved the final version of the manuscript.

Notes

The authors declare no competing financial interest.

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REFERENCES

(1) Brunner, P. H. In search of the final sink. *Environ. Sci. Pollut. Res.* **1999**, *6* (1), 1 DOI: 10.1007/BF02987111.

(2) Wallsten, B.; Johansson, N.; Krook, J. A cable laid is a cable played: On the hibernation logic behind urban infrastructure mines. *J. Urban Technol.* **2013**, *20* (3), 85−103, DOI: 10.1080/10630732.2013.809222.

(3) Krook, J.; Carlsson, A.; Eklund, M.; Frändegårda, P.; Svenssona, N. Urban mining: Hibernating copper stocks in local power grids. *J. Cleaner Prod.* **2011**, *19* (9−10), 1052−1056, DOI: 10.1016/j.jclepro.2011.01.015.

(4) Wallsten, B.; Carlsson, A.; Frändegård, P.; Krook, J.; Svanström, S. To prospect an urban mine—Assessing the metal recovery potential of infrastructure "cold spots" in Norrköping, Sweden. *J. Cleaner Prod.* **2013**, *55*, 103−111, DOI: 10.1016/j.jclepro.2012.05.041.

(5) Milovantseva, N.; Saphores, J.-D. Time bomb or hidden treasure? Characteristics of junk TVs and of the U.S. households who store them. *Waste Manage* **2013**, *33*, 519−529, DOI: 10.1016/j.wasman.2012.07.020.

(6) Vexler, D.; Bertram, M.; Kapur, A.; Spatari, S.; Graedel, T. E. The contemporary Latin American and Caribbean copper cycle: 1 year stocks and flows. *Resour. Conserv. Recycl* **2004**, *41* (1), 23−46, DOI: 10.1016/j.resconrec.2003.08.002.

(7) Mueller, D. B.; Wang, T.; Duval, B.; Graedel, T. E. Exploring the engine of anthropogenic iron cycles. *Proc. Natl. Acad. Sci. U.S.A.* **2006**, *103* (44), 16111−16116, DOI: 10.1073/pnas.0603375103.

(8) Daigo, I.; Igarashi, Y.; Matsuno, Y.; Adachi, Y. Accounting for steel stock in Japan. *J. Iron Steel Inst. Jpn.* **2007**, *93* (1), 66−70, DOI: 10.2355/isijinternational.47.1065.

(9) Chen, W.-Q. Recycling rates of aluminum in the United States. *J. Ind. Ecol.* **2013**, *17* (6), 926−938, DOI: 10.1111/jiec.12070.

(10) Melo, M. T. Statistical analysis of metal scrap generation: The case of aluminium in Germany. *Resour. Conserv. Recycl.* **1999**, *26*, 91−113, DOI: 10.1016/S0921-3449(98)00077-9.

(11) Tasaki, T.; Takasuga, T.; Osako, M.; Sakai, S. Substance flow analysis of brominated flame retardants and related compounds in waste TV sets in Japan. *Waste Manage.* **2004**, *24* (6), 571−580, DOI: 10.1016/j.wasman.2004.02.008.

(12) Elshkaki, A.; Van der Voet, E.; Van Holderbeke, M.; Timmermans, B. The environmental and economic consequences of the developments of lead stocks in the Dutch economic system. *Resour. Conserv. Recycl.* **2004**, *42*, 133−154, DOI: 10.1016/j.resconrec.2004.02.008.

(13) Spatari, S.; Bertram, M.; Gordon, R. B.; Henderson, K.; Graedel, T. E. Twentieth century copper stocks and flows in North America: A dynamic analysis. *Ecol. Econ.* **2005**, *54* (1), 37−51, DOI: 10.1016/j.ecolecon.2004.11.018.

(14) Mueller, D. B. Stock dynamics for forecasting material flows—Case study for housing in The Netherlands. *Ecol. Econ.* **2006**, *59*, 142−156, DOI: 10.1016/j.ecolecon.2005.09.025.

(15) Daigo, I.; Matsuno, Y.; Adachi, Y. Substance flow analysis of chromium and nickel in the material flow of stainless steel in Japan. *Resour. Conserv. Recycl.* **2010**, *54*, 851−863, DOI: 10.1016/j.resconrec.2010.01.004.

(16) Hatayama, H.; Daigo, I.; Matsuno, Y.; Adachi, Y. Outlook of the world steel cycle based on the stock and flow dynamics. *Environ. Sci. Technol.* **2010**, *44* (16), 6457−6463, DOI: 10.1021/es100044n.

(17) Daigo, I.; Osako, S.; Adachi, Y.; Matsuno, Y. Time-series analysis of global zinc demand associated with steel. *Resour. Conserv. Recycl.* **2014**, *82*, 35−40, DOI: 10.1016/j.resconrec.2013.10.013.

(18) International Iron and Steel Institute, Committee on Economic Studies. *Indirect Trade in Steel— 1989−1993*; International Iron and Steel Institute, Brussels, 1996.

(19) Nakamura, S.; Nakajima, K. Waste input-output material flow analysis of metals in the Japanese economy. *Mater. Trans.* **2005**, *46*, 2550−2553, DOI: 10.2320/matertrans.46.2550.

(20) National Tax Agency, Japan. Taiyo Nensu Hyo (in Japanese). https://www.keisan.nta.go.jp/survey/publish/34255/faq/34311/faq_34353.php.

(21) Nomura, K.; Momose F., 2008. *Measurement of depreciation rates based on disposal asset data in Japan.* Working Party on National Accounts of OECD, OECD STD/CSTAT/WPNA, 9.

(22) Fuse, M.; Nakajima, K.; Yagita, H. Outflow of resources from Japan focusing on end-of-life vehicles. *Mater. Trans.* **2007**, *48* (9), 2436−2444, DOI: 10.2320/jinstmet.72.557.

(23) Nakajima, K.; Nansai, K.; Matsubae, K.; Kondo, Y.; Kagawa, S.; Inaba, R.; Nakamura, S.; Nagasaka, T. Identifying the substance flow of metals embedded in japanese international trade by use of waste input-output material flow analysis (WIO-MFA) model. *ISIJ Int.* **2011**, *51*, 1934−1939, DOI: 10.2355/isijinternational.51.1934.

(24) The Japan Ferrous Raw Materials Association. *Quarterly Ferrous Raw Material Statistics/ Monthly Ferrous Raw Material Statistics*, (1985, 1990, 1995, 2004).

(25) Mueller, E.; Hilty, L. M.; Widmer, R.; Schluep, M.; Faulstich, M. Modeling metal stocks and flows: A review of dynamic material flow analysis methods. *Environ. Sci. Technol.* **2014**, *48*, 2102−2113, DOI: 10.1021/es403506a.

(26) Graedel, T. E.; Allwood, J.; Birat, J.-P.; Buchert, M.; Hagelűken, C.; Reck, B. K.; Sibley, S. F.; Sonnemann, G. What do we know about metal recycling rates? *J. Ind. Ecol.* **2011**, *15* (3), 355−366, DOI: 10.1111/j.1530-9290.2011.00342.x.

(27) Institute of Scrap Recycling Industries. Scrap Specifications Circular 2014. http://www.isri.org/docs/default-source/commodities/specsupdatesept2013.pdf?sfvrsn=2.

(28) The Japan Ferrous Raw Materials Association. *Quarterly Tetsugen*, Vol. 1−49, (1999−2011).