RESOURCE REUSE AND RECYCLING: LIMITATIONS AND POTENTIAL OPPORTUNITIES

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A typical display of fireworks. The brilliant colors are produced by compounds of copper, barium, calcium, magnesium, strontium, and others

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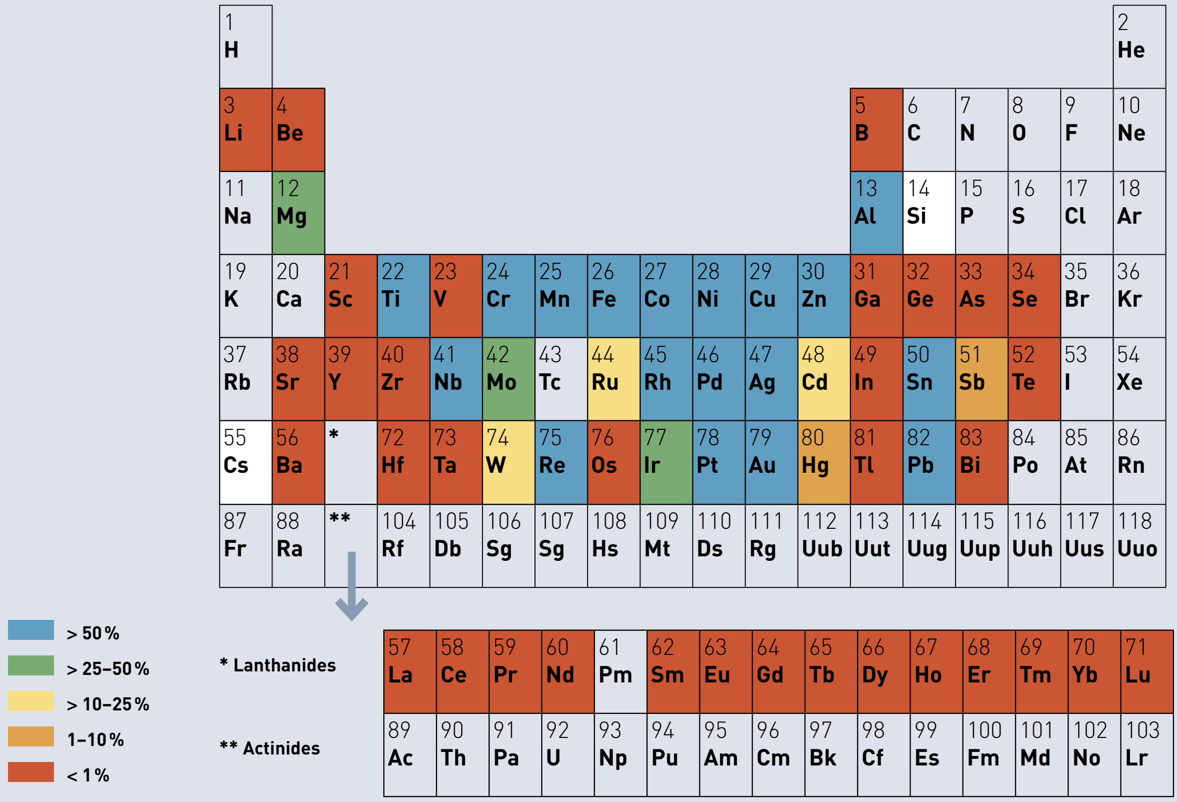
Materials today are often discarded after their first use. This is especially true of those materials in uses that are inherently dissipative, in complex assemblages where elements in low but vital concentrations are often lost in recycling, and for useful but toxic materials. The status of reuse and recycling as well as five opportunities for improvement are presented: (1) eliminate dissipative uses of materials; (2) develop advanced technologies for reuse and recycling; (3) create suitable repositories for materials unsuitable for a circular economy; (4) Design new products for circularity at end of life; (5) create and support international collaborative shipping and recycling chains.

INTRODUCTION

The basic idea of the circular economy is to transform our material society from the traditional material use approach ("dig it up, use it, dispose of it") to one in which materials retained in the inner circles of the "generic" circular economy diagram by the Ellen MacArthur Foundation require less energy and fewer or no new resources to reuse them than would be needed for similar actions in the outer circles. The idea is inherently attractive; the challenge is to determine the degree to which such a transition from the present approach is possible and desirable from technological, economic, social, and political perspectives. Several major issues involving product design, recycling technology, material toxicity, and spatial impediments to effective reuse pose significant challenges to achieving a fully circular economy.

End of life functional recycling rates of sixty elements, with the individual elements categorized into one of five ranges



(International Resource Panel, Recycling Rates of Metals, ISBN 978-92-807-3161-3, United Nations Environment Programme, Nairobi, Kenya, 2011).

Figure 1

RECYCLING STATISTICS

Before deciding where the world is going so far as recycling is concerned, one should assess how the world is doing at present. Unfortunately, the situation, with a few notable exceptions, is not very encouraging. Almost a decade ago a committee of the United Nations International Resource Panel assigned the "best-estimate" end-of-life functional recycling rate of the elements of the periodic table to one of five percentage ranges, as shown in Figure 1. It is easy to see that only fifteen to twenty elements have rates above 50% (and the committee states that few appear to be above 75%). Perhaps more dramatic are the more than thirty elements with essentially no functional recycling at all. Only a few elements were assigned values in between 0% and 50%. Thus, a majority of the elements employed in technology were used once and then lost to technology forever, a sad fate given the energy and effort expended to acquire them in the first place.

Recycling statistics have never been very good, as no regulations require them to be collected. As a consequence, the best current estimates of EOL-RR (end-of-life recycling rates) values remain those of the International Resource Panel of 2011 (see Figure 1). This would seem to call for a more structured data-driven approach to routinely quantifying recycling rates. It would be hoped that such an approach could be put in place in the future; at present all end-of-life recycling rates must be considered "informed estimates based on minimal data".

HOW MATERIALS ARE USED

Why can't materials that are incorporated in products of various kinds be reused when the use of those products is finished? This seemingly obvious inquiry can be addressed, at least to some extent, by realizing that the forms of use of resources can be divided into four categories: "in-use dissipated", "currently unrecyclable", "potentially recyclable", and "unspecified" (generally small-scale uses whose low volumes do not justify tracking them). The "in-use dissipated" category includes uses that may seem beneficial (vehicle brake pads, fireworks, etc.) but offer little or no prospects for material recovery and reuse. Some other applications, such as the use of rare earth elements in polishing powders, could be recyclable if a technological approach had been developed, but often no suitable

The delaying effect of material in product stocks in use

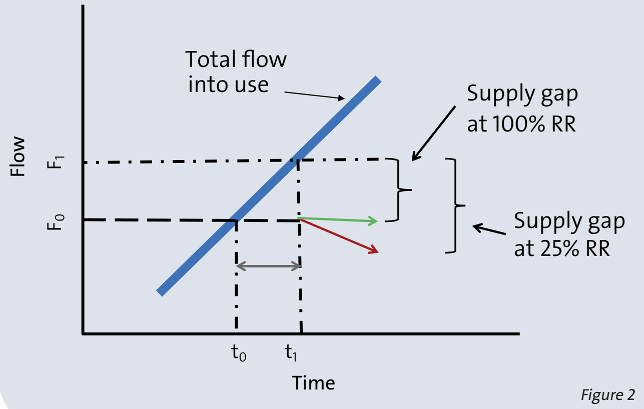


Figure 2

technologies exist at present. In the "potentially recyclable" category, recycling methods are known to exist although they are sometimes not employed for reasons of cost, inconvenience, or lack of sufficient incentives.

In the ideal world, material available through recycling would satisfy the demand for the same material and no new resource extraction would be needed. However, materials enter service and remain there for extended periods, often decades, while all the while demand is increasing. This situation is termed the "delaying effect of stocks", a consequence of which is that in a world of increasing demand even perfect recycling is not enough to meet supply (Figure 2). Even then, some materials may not immediately undergo reprocessing and reuse. Personal electronics are famous for being retained in a bedroom drawer for as long as a decade – these are sometimes termed "hibernating stocks". A related category is "comatose stocks" – material that is stored in such a way that it may never be recovered. For example, power distribution cables that have been disconnected from service but left in place because the benefits of recovery do not offset the effort and expense involved provide an example. Finally, there are stocks that are designed never to be recovered and reused, such as the foundation pilings under tall buildings and harbor structures; these might be termed "abandoned stocks".

In a world of increasing demand even perfect recycling is not enough to meet supply.

Imagine, however, that a decision has been made to discard a product containing potentially recyclable material. Many steps may be involved in actually carrying out technologically appropriate recycling, as discussed below in some detail.

Reuse and recycling sound as if they are sensible approaches to deal with the accumulation of discarded products, and in general they are. However, there are instances where routine reuse and recycling may not be the ideal approach. One of the most obvious is where a discarded product contains a material that would not now be desired in the economy, particularly materials or assemblages not regarded as hazardous when first employed but now of significant concern: toxic metals such as cadmium in aircraft landing gear, lead in paint, or carcinogenic materials such as polychlorinated biphenyls in transformers. Ulrich Kral and colleagues from the Technical University of Vienna suggest that new product designs need to avoid such constituents, and that older products leaving service or hazardous material dissipated during use should eventually reach a "final sink": a repository that either destroys an unwanted substance completely or retains it for a long time period so that it can be considered in the future. The process is suggested schematically by Figure 3.

In a world of increasing demand even perfect recycling is not enough to meet supply

Examples of the establishment of final sinks are the deep repositories set up by some countries to responsibly contain waste material from nuclear power reactors. Because those materials are potentially hazardous such repositories tend to be controversial, especially to those living nearby.

Material flows based on a clean cycle strategy

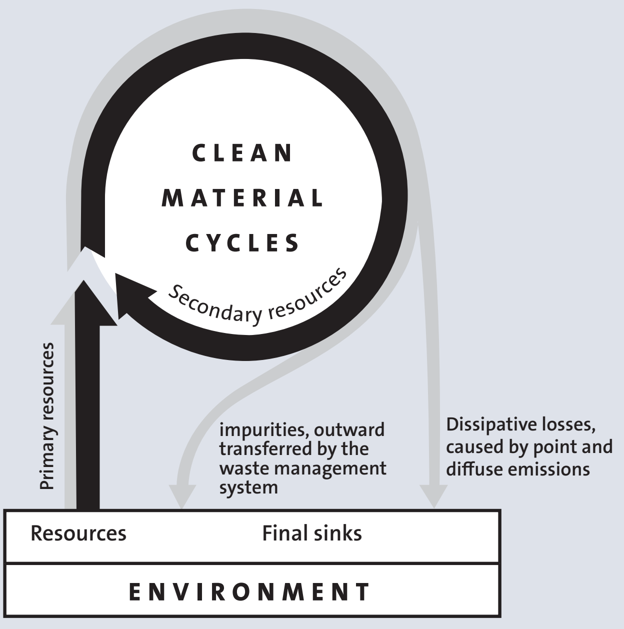


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Figure 3

Despite the societal challenges, however, it is clearly inappropriate to utilize materials known or suspected of toxicity and then to provide no way to deal with them when they are no longer desired. If these materials are deemed so beneficial to modern technology that society wishes to use them, the challenges to doing so need to be recognized, and provision made for approaches that do not follow a circular economy approach.

THE CHALLENGES OF PRODUCTS COMPLEXITY

It is worth considering the scope of what a truly circular economy would demand of the medical device industry. As an example, the diversity of elements used by manufacturers of medical devices is thought to include at least seventy different elements for purposes of imaging, robotic surgery, artificial joints, and many more. This incredible elemental diversity is similar to that of modern electronics.

Each element's use in medical devices or for electronics has a purpose, of course: better imaging of body organs, faster storage and retrieval of information, etc. A device maker adhering dogmatically to the circular economy vision would thus have to not only deal with contamination and sterilization issues, but also with the reprocessing of essentially the entire suite of the elements. This would be a major commitment for designers, product manufacturers, and executives, and suggests that dogmatism regarding advanced devices of all kinds so far as the circular economy is concerned is perhaps an unrealistic goal.

Assume, however, that a material (contained in a product) is not subject to any of the constraints to recycling and reuse discussed above and that the material has been discarded. A stepwise sequence is then involved in successful disassembly and recycling of a product, as shown in Figure 4, but incomplete disassembly or the failure to capture components once disassembly is complete occurs all along the recovery and recycling sequence.

Given the estimated current probabilities for successful processing at each stage, the efficiency of the overall total product recycling process turns out to be quite low. Improving this situation requires efforts at all stages of the recycling process, but also in the original product design process. Some of the main points are summarized below:

- If possible, capture a product before discard and seek to use it elsewhere (this is termed 'relocation');
- If relocation is not feasible, seek to remanufacture the product so as to return it to its original condition and capabilities or, better yet, upgrade it to the most recent capabilities of similar products (this is termed 'remanufacture');

A four-node separation sequence for disassembly of a generic product

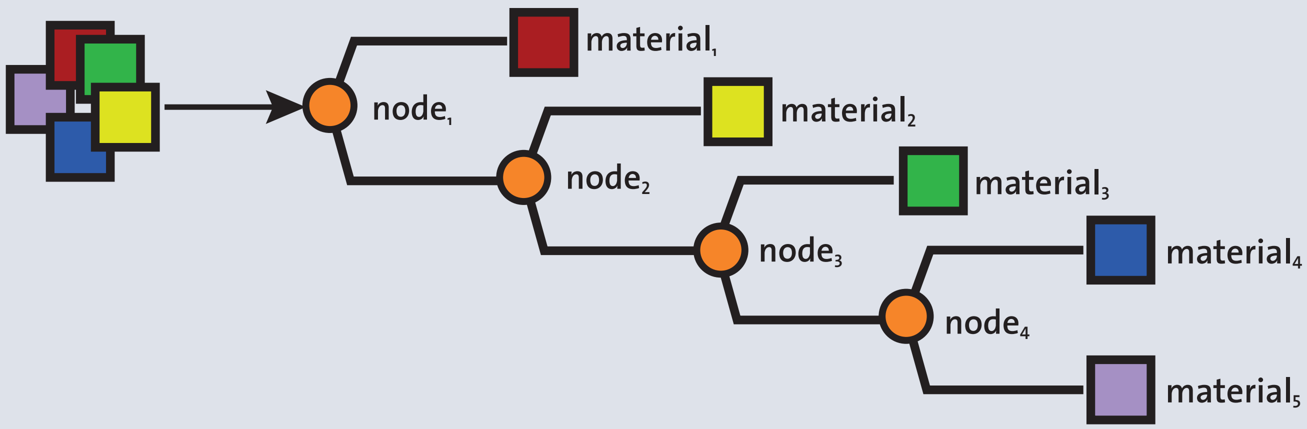

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Figure 4

- If remanufacturing is not practical, disassemble the product and reuse the components. This step will be enabled by efficiently identifying the components and researching opportunities for their redeployment. Disassembly is best addressed at the product design stage by minimizing the steps needed for disassembly.
- Components and assemblages that cannot readily be disassembled, or where doing so is not economically or practically feasible, may or may not be shredded, but in any case are sent on to sorting facilities, followed by treatment in chemical or metallurgical reactors.

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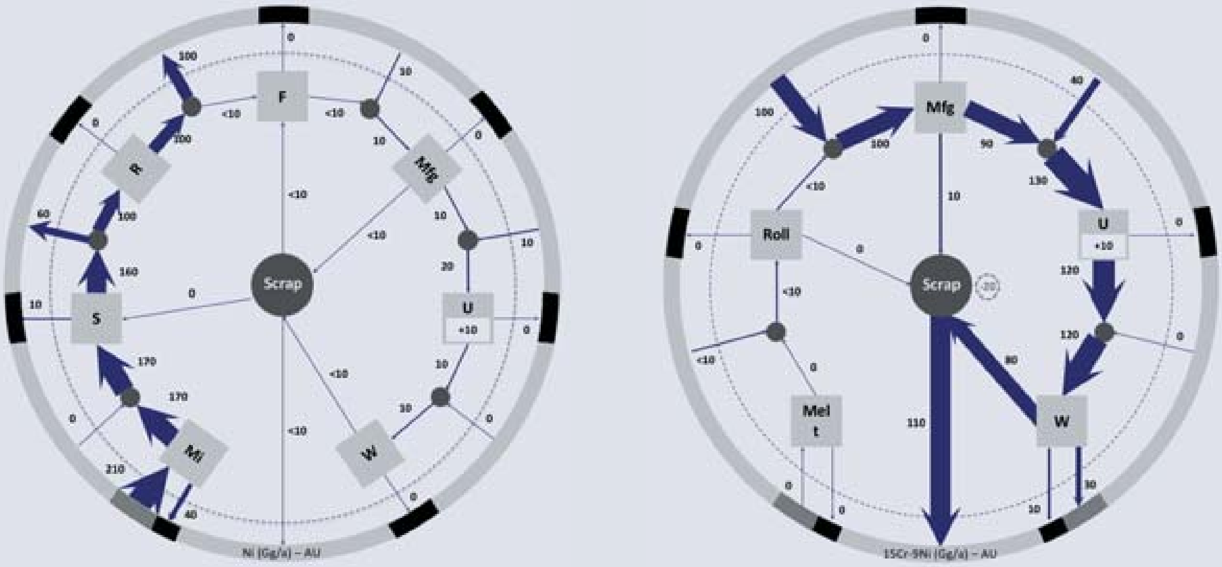
SPATIAL LOGISTICS

One issue not commonly discussed by circular economy advocates is where the reuse, remanufacturing, and recycling should or can happen. In a technological world where diverse and complex products are often manufactured in a small number of specialized facilities, sold to users around the world, perhaps later resold or re-leased, and eventually discarded, product complexity and recycling technology cannot be assumed to exist everywhere in order to enable local remanufacturing and reuse. Ideally, one would capture the end-of-life products once they are obsolete but before they become degraded and disassembled and then ensure that

The Australian cycles of (left) nickel and (right) stainless steel in 2010



The units are Gigagrams (thousand metric tons) of metallic equivalent per year (Graedel, T.E., B.K. Reck, L. Ciacci, and F. Passarini, On the spatial dimension of the circular economy, Resources, 8, 32 doi:10.3390/resources8010032, 2019).

Figure 5

they are transported to a facility fully capable of their remanufacture or recycling. For more complex products there will likely be few such facilities in the world, and the challenges of identification, transportation, and economics quickly become daunting.

The locational issues can be illustrated by a simple example, that of nickel in Australia, whose nickel material cycle is shown in Figure 5 (left). Australia has very large metal deposits and a vigorous mining industry. As a result, nickel extraction and ore processing is substantial, but the resulting refined metal is largely exported. Much of this nickel goes to be utilized in stainless steel production elsewhere (Australia does not produce stainless steel, an alloy of nickel with about 74 parts iron, 15 parts chromium, and 9 parts nickel), so does not have the technology in place to reprocess it – that has to happen elsewhere if at all. Thus, stainless steel imports to Australia must themselves be exported if they are to be reused (Figure 5, right). The message here is that in a global economy it is very unlikely that the facilities to enable a circular economy will be available everywhere and for every product, no matter how complex; rather, extensive ocean shipping and international political and scientific coordination would almost certainly be required.

CONCLUSION

The challenges discussed in this article simultaneously suggest five opportunities for improvement. They are as follows:

- Decrease or eliminate dissipative uses of materials;
- Invent and develop reuse and recycling technologies that are currently inadequate or do not now exist for many materials and products;
- Develop national and regional repositories for materials unsuitable for retention in a circular economy because of toxicity, radioactivity, or other undesirable property;
- Design new products for circularity at end of life, not disposal;
- Optimize the collection of components and products that are difficult to remanufacture or recycle and develop an international system to transport such objects to facilities capable of rendering them fit for reuse in one form or another.

None of these improvement opportunities will be easy to accomplish. Indeed, some are likely to be quite challenging. However, the same could have been said about the activities and technological approaches that made them necessary in the first place. Some of the opportunities will require new thinking in product design, materials processing, and recycling. Others will require collaborative actions by governments. Making even modest steps in these directions will generate significant improvement in circularity, however. A moral judgement would seem appropriate: A technological society whose activities have caused these challenges to exist should feel responsible for responding to them.