DISSIPATIVE STRUCTURE/ STREAMS

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Abstract

Our society must deal with a finite amount of resources which may be utilized for shorter or longer periods, depending on the respective material. To tackle this issue of finiteness, various strategies have been proposed, all of which aim to transform our linear economy into a circular one. Nevertheless, these strategies are undermined by loss mechanisms that are based on dissipative structures and streams. Dissipation withdraws resources in a way that makes it economically or technically impossible to recover them. To provide a better understanding of dissipative loss mechanisms, a classification of dissipation is represented according to the research of Seelig *et al.* Thereby dissipation is divided into six categories according to which loss is due to the thermodynamic properties of the material, an unsustainable product design, the intended use of the product, corrosion, abrasion or due to poor sorting and collection systems during recycling, respectively. The loss categories are further specified in this chapter with regard to metals. Each of these loss categories shows a different potential for improvement in terms of increasing the overall efficiency of circular value creation. Nevertheless, all loss categories have to be addressed to exploit the full potential of the circular economy.

Introduction

The circular economy enables the environmentally friendly handling of raw materials as well as an increased economic independence and security of supply. However, efficient recycling is currently not existent for many raw materials, and so recycling rates for many metals are still in the single-digit range.[1] Particularly affected are the so-called high-tech metals, which also include the rare-earth elements. The primary extraction of these metals is associated with an extremely high resource and energy expenditure. In addition, given the current energy transition, it must not be forgotten that high-tech metals are increasingly being used in the production of renewable energy, such as the rare-earth element neodymium present in permanent magnets in wind turbines.[2] A more efficient recovery or recycling of these metals in the material cycle would therefore be of great benefit both from an ecological and economic point of view. In theory, metals can be recycled in endless ways, but limits are imposed due to dissipative loss mechanisms. Consequently, a considerable amount of metal is irretrievably withdrawn from the material cycle through such losses. This can occur in all lifecycle phases of a product (production, use, disposal). The reasons for this are diverse and not easy to grasp. This article presents a systematic approach characterizing dissipative losses based on the research of Seelig *et al.,* which divides dissipation into six loss categories.[3] For this purpose, the systematics of possible causes of dissipative losses are presented in figure 1. The mechanisms are explained below in more detail.

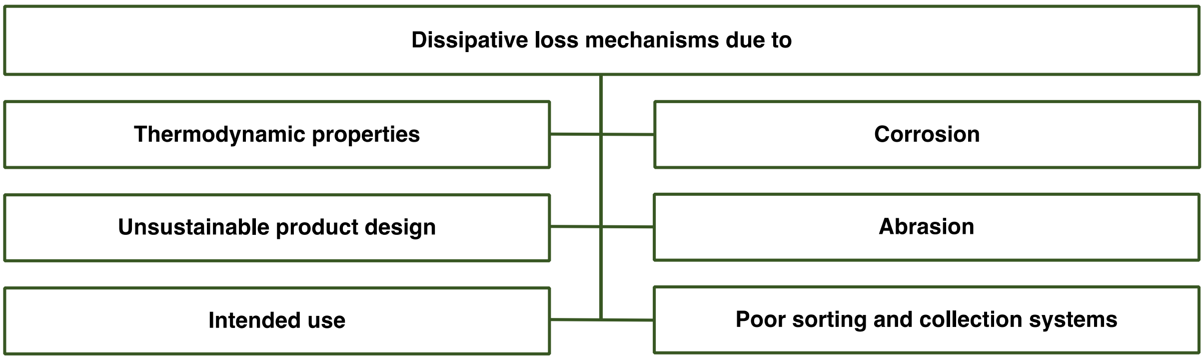

Figure 1: Overview of the mechanism of dissipative losses according to Seelig *et al.*[3]

Dissipative losses

Losses due to thermodynamic properties

Thermodynamic losses normally occur during the recycling phase, during which raw materials are recovered from a successfully returned and sorted material stream. These losses are further divided into functional and complete losses.[3]
After recycling, metals are often subjected to downcycling or cascading and therefore used in a different range of applications in comparison to their pure form. The reason is that during the recycling contaminations occur that cannot be separated owing to thermodynamic properties, leading to a lower quality and functionality of the recycled metals. This form of loss is called functional loss and can be traced back to the large number of metal alloys on the market.[3] A common example is the open-loop recycling of mixed aluminum scraps into secondary cast alloys. It is not possible to substitute a primary cast alloy in any application with the recycled material obtained, due to its inherent impurities such as iron, zinc or chromium, which would result in a lower mechanical performance.[4]
On the other hand, a complete loss permanently removes the metal from the material cycle. For example, during the processing of metals in the electric arc furnace, slags accumulate which contain various metals such as barium, lead, chromium, cobalt, copper, molybdenum, nickel, vanadium, tungsten or zinc. Because these metals cannot be recovered economically, these slags are often used as filling material in road construction.[5] To reduce metal losses in slags, new methods have already been successfully tested on a laboratory, pilot and industrial scale [6,7,8,9], which must be implemented in practice in the near future. A complete avoidance of losses cannot be realized by means of current state-of-the-art techniques.

Losses due to unsustainable product design

The reduction of dissipative losses can already be realized by industry in the design of products. Here, two aspects are in focus. On the one hand, the lifetime of the products has a decisive influence on the quantity of the material losses. On the other hand, the quantities of material used and the complexity of the product design are both crucial.[3]
The lifespan of a product can greatly affect the cycle time a raw material takes to go through the use phase. Consumer goods can achieve a much longer service life by the use of a well thought out product design. Not only is the robustness of a product relevant, but also the application of a timeless design, which prevents a premature removal of functional products from the use phase.[3]
In addition to the design aspects mentioned, product design also plays a key role in terms of expandability and disassembly. Expandability can be realized, for example, by a modular design

construction.[10] By exchanging individual modules of a device, on the one hand, the existence (for example by increasing the computing power of a mobile phone) can be extended. On the other hand, potentially unused modules can be omitted from the outset (for example the camera in mobile phones).[3] Furthermore, a study from Reuter *et al.* has revealed that modular design has clear recycling as well as environmental advantages.[10] Nevertheless, the ecological meaningfulness of such a strategy must be examined on an individual basis as a modular structure often goes hand in hand with increased material use.[3]

Losses due to the intended use

Some metals are withdrawn from material circulation because the product structure requires a dissipative distribution of these materials. Examples are metals that are used as part of fertilizers or pesticides in agriculture and are thus actively distributed in nature, but also included are cosmetics and pharmaceuticals as well as paints and coatings. After use, pharmaceutical and cosmetic products enter the sewage systems. Ideally, in the various stages of a wastewater treatment plant, the dissolved metals can be removed from the water and accumulate in the sewage sludge. Metal residues that are still in the water after treatment are fed into the natural water cycle and lost for further use.[3] As heavy metals are found in sewage sludge in addition to the elements that tend to promote growth, their use as agricultural manures is subject to regulation by EU legislation.[11] As a result, a large proportion of the sewage sludge is currently being thermally exploited. There are a number of different approaches using the metal-rich ashes obtained, which, however, all result in the loss of the metals contained. Metal recovery from sewage sludge is currently not state-of-the-art but is beginning to gain entry into research. So far, sewage sludge recycling aims at recovering phosphorus as a fertilizer.[12]

Losses due to corrosion

Material losses due to corrosion are the best-known example of dissipative loss mechanisms. The cause of metal corrosion is that metals in their reduced form are in an unstable und high-energy state. In contrast, according to the laws of entropy, everything in nature strives for a stable, low-energy state. This state can be reached through oxidative processes. As a consequence, corrosion destroys machines, buildings and important elements of the infrastructure. Examples are motor vehicles, ships, bridges, metal buildings, railway networks, etc. Against this background, it quickly becomes apparent that corrosion represents an enormous economic factor.[3] According to a study by NACE International, the global impact of corrosion is estimated to be US$ 2.5 trillion, which is equivalent to 3.4% of the global GDP in the year 2013.[13]

Losses due to abrasion

Abrasion refers to the loss of material due to the influence of friction forces and the associated scratches and micro-cutting of material surfaces.[3] Examples of this type of dissipative loss are grinding dust and abrasive wear in the transport sector.[14] In the case of abrasive loss, metal particles enter the environment in the form of fine dusts that accumulate along traffic routes and are distributed by weather conditions. In addition to the problem of material loss, particulate emissions also cause health problems for humans.[15, 16]

Losses due to poor sorting and collection systems

The sorting and collection systems for the recovery of residual and waste materials still require a great deal of improvement. With regard to the recycling of metals, the most important consumer product categories are batteries, beverage containers, food cans, electrical and electronic equipment as well as vehicles. Strategic metals in the categories mentioned are increasingly found in products of information and communication technology (ICT). Losses can be traced back to different causes associated with the sorting and collection systems.[3] The problems range from the simple absence of collection systems to the unfavorable positioning of collection points and ineffective mechanical sorting.[17] A major problem of existing recycling systems is that they cannot compete with the increasing complexity of the technology on the market. This applies both to the structure and to the sheer number of elements used.[3] An example from the modern era are smartphones, which contain more than 40 elements from the periodic table.[18] In emerging economies, ICT products are widely used as a result of expanding economic activity, while appropriate collection systems still have to be established. Accordingly, the rate of return often tends to be zero.[3] In Germany, the return and disposal of mobile phones has improved since the introduction of the Electrical and Electronic Equipment Act (ElektroG) in the year 2005, leading to a return rate of up to 45 %. It should be noted that the taking back of waste equipment by commercial shops has been prescribed by law since the change of the ElektroG in 2015.[19]

Conclusion

Recycling enables the environmentally friendly handling of raw materials as well as increased economic independence and security of supply. Highly efficient recycling systems already exist for individual materials. Metals, in particular, can be recycled indefinitely in theory, but in practice there are high losses of a dissipative nature. The avoidance of such losses would bring great economic benefits. This becomes particularly clear with regard to the high-tech metals. For the future development of recommendations for avoidance, a classification of dissipative losses is necessary. One suggestion is the subdivision into the six loss categories proposed by Seelig *et al.*, as shown in figure 1.[3] These loss categories show various degrees of potential for improvement, a preliminary step to increasing the overall efficiency of the circular economy. Avoidance strategies for material losses over the life cycle of industrial products are conceivable at many points of the usage chain, which are partly based on each other. A fundamental step towards avoiding material losses for the sake of a sustainable circular economy is to improve the willingness of consumers to comply with separate waste streams and thus to increase the return rates. To this end, raising awareness through education about transparent waste management would be useful.[3] The introduction of deposit systems, which demonstrably increases return rates[20], is also conceivable for relevant product categories. Closing the material cycle is an elementary step on the way to the raw material shift, which together with the transformation of the energy system represents the foundation for a sustainable industrial society.[3]

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