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Moving from recycling to waste prevention: A review of barriers and enables

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Abstract

Current European waste policy does not mainly aim to treat waste streams but rather place in the foreground of interest the complete supply chain of a product. Waste prevention and re-use do have the highest priority and they take effect before the end-of-life phase of a product or a material is reached. Recycling only takes the third place whereas recovery and disposal represent the least favourable options. Recycling can help to decrease the consumption of primary resources but it does not tackle the causes but only the symptoms. In principle, recycling processes require energy and will generate side streams (i.e. waste). Furthermore, there are insuperable barriers and the practice is far from 100% recycling. The philosophy of waste prevention and re-use is completely different since they really tackle the causes. It is self-evident that a decrease of waste will also decrease the consumption of resources, energy and money to process the waste. However, even if European legislation is proceeding in the right direction, a clear decrease in waste generation did not occur up to now. Unfortunately, waste generation represents a positive factor of economic growth. Basically, waste generation is a huge business and numerous stakeholders are not interested to reduce waste. More sophisticated incentives are required to decouple economic growth from waste generation.

Keywords

Waste prevention, recycling, zero waste, thermodynamics, planned obsolescence, re-use

Introduction

Waste legislation: a brief historical review

Over the centuries waste management was a sanitary activity and it was sufficient that garbage was transported out of the cities and dumped somewhere. However, due to the significant economic growth after World War II, the amount of generated waste was increasing tremendously and environmental and health problems such as pollution of air, soil and ground water occurred. The 1960s marked the beginning of modern environmental policy making, including waste treatment, in industrialized countries such as the USA as and European countries.

In Europe, directive 75/442/EEC (Anonymous, 1975) was enacted in 1975. It was the first regulation on waste that placed the protection of the environment and human health into the foreground. The directive 75/442/EEC was revised in 1991, 1996 and 2006. Today, waste management is governed by the revised waste framework directive (WFD) which replaced all previous directives on waste (Anonymous, 2008a). Table 1 summarizes the most relevant European directives on waste.

Among other principles the WFD introduces the so-called waste hierarchy. It stipulates a priority order for waste prevention and management legislation policy and practice. It had to come into force in all EU member states in December 2010 the latest.

According to Directive 2008/98/EC (Anonymous, 2008a) waste prevention is given the highest priority and is ranked over all other policies. Waste prevention is based on a simple concept. If you create less waste, you consume fewer resources and you will have to spend less effort (e.g. money, energy) to recycle or dispose of your waste. Ultimately, a total prevention of waste to zero will result in a society with no waste at all and thus waste management would be obsolete. In practice our societies are far away from a status of no waste and it is also evident that, in theory, a complete avoidance of waste is impossible.

The second place in the waste hierarchy goes to 'preparing for re-use' (Anonymous, 2008a). Re-use shows some distinct advantages as a reduced number of new products have to be manufactured. As a consequence, less energy and raw materials are consumed and less disposal costs are necessary. However, it has to be considered that transport and cleaning, etc. will also consume energy as well as resources. New products might be more energy efficient (e.g. less electricity consumption of washing machine), cause less environmental impacts (e.g. engine which

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Table 1. Important European directives on waste.

Year	Directive	Reference	Main statement
1975	75/442/EEC	(Anonymous, 1975)	Prevention or reduction of waste production and its harmfulness
1978	78/319/EEC	(Anonymous, 1978)	Treatment of toxic and dangerous waste
1991	91/156/EEC	(Anonymous, 1991a)	Amending Directive 75/442/EEC; first priority: the prevention or reduction of waste production and its harmfulness; second priority: the recovery of waste by means of recycling, re-use or reclamation, or the use of waste as a source of energy
1991	91/689/EEC	(Anonymous, 1991b)	Treatment of hazardous waste
1996	96/350/EC	(Anonymous, 1996)	adapting Directive 75/442/EEC; definition of disposal and recovery operations
2006	2006/12/EC	(Anonymous, 2006a)	Codifies and replaces 75/442/EEC without any change in its substance
2008	2008/98/EC	(Anonymous, 2008a)	Replaces 2006/12/EC, 75/439/EEC and 91/689/EWG; Introduction of waste hierarchy

emits less toxic exhaust fumes) or show increased safety standards (e.g. vehicles with better crash performance).

Recycling

The first documented use of the term 'recycling' took place in 1924 in the field of oil-refining and similar industries (Bibra, 1924). It is an artificial word and unifies the syllable 're-' standing for back to the original place again and 'cycle' (Harper 2001–2014). However, even if the term recycling is quite new the basic principles of recycling are much older. In the nineteenth century the 'dust-yard' waste management system in London had significant similarities with informal sector recycling systems operating today in many developing countries (Velis et al., 2009).

It was not before the 1970s until the expression was used in a broader sense. Even though there has been no clear definition of recycling the phrase exhibited a positive image and it is/was extensively used for 'greenwashing' products and services. As a matter of fact there has been a tremendous increase of its use in the beginning of the 1990s. The number of annual entries in the database of SciFinder increased from 1718 (1990) to 16 451 (2013).

Since 2008 the EU directive 98/2008/EC (Anonymous, 2008a) gives a more or less clear definition of recycling. Article 3(17) defines recycling as: 'any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations.'

Recycling comprises a set of processes that can be further classified according to different aspects. On the one hand the degree of processing, that takes place, leads to the following categories (Goorhuis and Bartl, 2011):

- Product recycling: Any process in which the chemical and physical constitution of a product is maintained but the product is not used for the original purpose (e.g. using tyres or glass bottles as building material).
- Material recycling: Any process in which the physical but not the chemical constitution is destroyed (e.g. melting and reprocessing of metals, or recycling of fertilizers from food waste to the farming land by digestion or composting).
- Feedstock recycling (also raw material recycling or chemical recycling): Any process in which the physical as well as the chemical constitution of a material is reprocessed into its original constituents (e.g. de-polymerization).

On the other hand the allocation procedure for recycling distinguishes between the following two cases (ISO, 2006a):

- A *closed-loop* allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials.
- An *open-loop* allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties.

Recycling operations comprises a huge number of processes which can be more or less efficient. For recycling operations there is no comparable analogue formula to the R1 criteria (Equation 4) as it exists for recovery. It is even unclear which measures could be taken to describe the efficiency of recycling. Equally the following instruments might be used to define the efficiency of recycling (Bartl 2013a):

Material efficiency. The output stream is taken in correlation to the input stream as expressed by equation (1). The higher the value, the lower are the material losses of the process. A comparison of the material efficiency of different plants would allow a ranking to be made according to their respective efficiency. However, for each waste stream (e.g. ferrous scrap, aluminium scrap) individual values would have to be determined. However, even for the same waste streams but of different qualities (e.g. ferrous scrap of different copper content) the material efficiency will not be comparable.

$$\text{Material efficiency} = \frac{\dot{m}_{\text{out}}}{\dot{m}_{\text{in}}} \ (-) \tag{1}$$

where $\dot{m}_{\text{in}}$ is the material input to the recycling operation expressed e.g. in (t h^{-1}) or (m^3 h^{-1}) and $\dot{m}_{\text{out}}$ is the material output of recycling operation expressed e.g. in (t h^{-1}) or (m^3 h^{-1}).

Energy efficiency. The energy efficiency puts the energy consumption in correlation to the output stream of a recycling operation as calculated by equation (2). Again (as valid for material efficiency), it seems necessary to specify the quality of the processed materials and that a slight variation (e.g. content of foreign materials, dilution of the material to be recycled) might significantly influence the energy efficiency.

$$\text{Energy efficiency} = \frac{\dot{E}_{\text{in}}}{\dot{m}_{\text{out}}} \quad (\text{GJ t}^{-1}) \tag{2}$$

where $\dot{E}_{\text{in}}$ is the energy input to the recycling operation expressed in e.g. (Gt h^{-1}) and $\dot{m}_{\text{out}}$ is the material output of recycling operation expressed e.g. in (t h^{-1}).

Quality efficiency. The quality efficiency puts in the correlation of the quality of the output stream to that of virgin material. A lower quality level will result in lower prices and this criterion must not be neglected. However, as demonstrated by equation (3) it is not clear how to measure the quality of a material. As in many cases a more or less pronounced quality drop has to be accepted independent of which process is used, the term 'down-cycling' is frequently used. The term 'down-cycling' does, however, not appear in the WFD.

$$\text{Quality efficiency} = \frac{\mathit{Quality}_{\text{out}}}{\mathit{Quality}_{\text{virgin}}} \quad (-) \tag{3}$$

where $\mathit{Quality}_{\text{out}}$ is the quality of output material (unclear measurement) and $\mathit{Quality}_{\text{virgin}}$ is the quality of virgin material (i.e.) material from primary resources (unclear measurement).

Other recovery

In the waste hierarchy 'other recovery' holds the last position but one. The Annex II (Anonymous, 2008a) sets out a non-exhaustive list of13 recovery operations (R1 to R13). According to the WFD (Annex II: R1) incineration facilities which are dedicated to the processing of municipal solid waste may account for recovery. It is required that an energy efficiency equal to or higher than 0.60 (installations permitted and in operation before 1 January 2009) or 0.65 (installations permitted after 31 December 2008) is ensured. The energy efficiency is calculated using the R1 formula (equation (4)).

$$\text{Energy efficiency} = \frac{(E_{\text{p}} - (E_{\text{f}} + E_{\text{i}}))}{(0.97 \cdot (E_{\text{w}} + E_{\text{i}}))} \tag{4}$$

where E_{p} is the annual energy produced as heat or electricity (It is calculated with energy in the form of electricity being multiplied by 2.6 and heat produced for commercial use multiplied by 1.1 (GJ year^{-1})); E_{f} is the annual energy input to the system from fuels contributing to the production of steam (GJ year^{-1}); E_{w} is the annual energy contained in the treated waste calculated using the net calorific value of the waste (GJ year^{-1}); E_{i} is the annual energy imported excluding E_{w} and E_{f} (GJ year^{-1}); and 0.97 is the factor accounting for energy losses due to bottom ash and radiation.

Disposal

Disposal shows the lowest priority in the waste hierarchy and should only be used as a last consequence (Anonymous, 2008a). The most well known procedure for disposal is landfill, however, Annex I of the WFD gives a non-exhaustive list of15 disposal operation (D1 to D15).

Regulations for special types of waste. Furthermore, certain products or materials have their own regulations. Table 2 shows a non-exhaustive list of special regulated wastes including the relevant European legislation and the main targets. It is striking that the focus of all these regulations is mainly on separate collection, recovery and recycling but there are no incentives for promoting re-use and waste prevention. Even if Directive 2009/125/EC (Anonymous, 2009b) demands eco-design requirements for energy-related products (EEE) there are no binding targets for reparability, availability of spare parts or durability. It is reported that in Germany only 0.5% of collected post-consumer EEE are re-used as during collection and transport potentially re-useable items are damaged (Bruening, 2013). It can be concluded that waste hierarchy (i.e. waste prevention and re-use on top) is not mirrored by the majority of directives on waste.

Limits of recycling

Moving up the waste hierarchy

Even if recycling holds the third position in the waste hierarchy, it exhibits a predominant role. The European Commission claims that the EU is moving towards a 'recycling society' (Anonymous, 2011a). Commonly in waste management only the 'classical' options, namely recycling, incineration and landfill, are taken into account. As a matter of fact statistics report the amount of waste materials that are recycled, incinerated or landfilled (Eurostat, 2013).

It is well established to compare different countries or regions according to their respective rates of recycling and recovery as sketched in Figure 1. Most of the new member countries (EU-12) have, up to now, no or only a few incineration facilities and landfilling is still the predominant waste treatment option. On average, in the EU-12 less than 3% of the waste is incinerated whereas 81% of the waste ends up in landfills. However, also some 'old' EU member countries (member before 2004; EU-15) have not yet installed incineration capacities and waste mainly ends up in landfills (e.g. Greece, 82% landfill). Even if China incinerates a considerable fraction of waste (15%) 82% of the waste is still landfilled (to a large extent on open dumps (Zhang et al., 2010)). Thus these countries are plotted at the bottom close to the left corner. Some countries have moved far away from the left bottom corner (100% landfilling) using either largely incineration (Switzerland, Sweden, Denmark, Norway, Taiwan) or recycling (Netherlands, Belgium, Germany, Austria). Even if in some

Table 2. Relevant European directives on waste.

Waste streams	Relevant European legislation / references	Main targets
Packaging and packaging waste	• Directive 94/62/EC (Anonymous, 1994) • Directive 2004/12/EC (Anonymous, 2004) • Directive 2005/20/EC (Anonymous, 2005a) • Regulation 219/2009 (Anonymous, 2009a) • Directive 2013/2/EU (Anonymous, 2013a)	Recovery ≥ 60% Recycling 55–80% Separate recycling targets for glass, paper and board, metals, plastics and wood
Waste of electrical and electronic equipment (WEEE)	• Directive 2002/95/EC (Anonymous, 2003c) • Directive 2002/96/EC (Anonymous, 2003a) • Directive 2003/108/EC (Anonymous, 2003b) • Directive 2008/34/EC (Anonymous, 2008b) • Directive 2012/19/EC (Anonymous, 2012a)	Current collection rate: ≥ 4 kg capita^{-1} annually By 2016: collection rate ≥ 45% By 2019: collection rate ≥ 65%
Batteries and accumulators	• Directive 91/157/EEC (Anonymous, 1991c) • Directive 2006/66/EC (Anonymous, 2006b) • Directive 2008/12/EC (Anonymous, 2008c) • Directive 2008/103/EC (Anonymous, 2008d) • Decision 2008/763/EC (Anonymous, 2008e) • Decision 2009/603/EC (Anonymous, 2009c) • Decision 2009/851/EC (Anonymous, 2009d) • Regulation 1103/2010 (Anonymous, 2010a) • Regulation 493/2012 (Anonymous, 2012b)	Targets for separate collection: Since 2012: ≥ 35% By 2016: ≥ 45%
End-of-life vehicles	• Directive 2000/53/EC (Anonymous, 2000) • Decision 2002/525/EC (Anonymous, 2002) • Directive 2005/64/EC (Anonymous, 2005b) • Decision 2005/63/EC (Anonymous, 2005c) • Decision 2005/437/EC (Anonymous, 2005d) • Decision 2005/438/EC (Anonymous, 2005e) • Decision 2005/673/EC (Anonymous, 2005f) • Decision 2008/763/EC (Anonymous, 2008e) • Decision 2010/115/EU (Anonymous, 2010b)	Since 2006: Re-use and recovery ≥ 85% Re-use and recycling ≥ 80% By 2015 Re-use and recovery ≥ 95% Re-use and recycling ≥ 85%

countries (Switzerland, Denmark, Netherlands, Austria, Sweden, Belgium, Denmark, Norway, Taiwan) the fraction of landfilled waste is already less than 5%, there is still a large gap to 100% recycling.

Figure 2 demonstrates the large progress in waste management of EU-27 (EU-28) within the last years which is expressed by the distinct translocation in the triangle chart (i.e. moving towards the top of the triangle). The recycling rate from 1990 to 2008 was increased from 13 to 40%. However, it is also shown that the speed of improvement will dramatically decrease in the coming years and the further progress in the period from 2015 (estimated recycling rate: 47%) to 2020 (estimated recycling rate: 49%) will be fairly low.

Even if the recycling rate in Europe has been significantly increased over recent years it is can be expected that the further increase will be limited and a recycling rate of 100% will not be reached. There are several reasons for this as discussed below.

Metal recycling

Frequently it is claimed that metals are sustainable products since they consist of indestructible atoms, which can be efficiently and infinitely recycled (World Trade Organization, 2011). However, in practice, losses and contaminations are inevitable and thus certain limitations for recycling are obvious. Already during their use phase a certain fraction of material is already lost by dissipation (e.g. corrosion). Secondly, it is, of course, impossible to collect all of the material put on the market, and the amount of collected material will always be lower than the material put on the market.

In practice the situation is worse. As shown in Figure 3 (Graedel et al., 2011; Reck and Graedel, 2012) out of 60 only 18 metals (i.e. 30%) exhibit a recycling rate higher than 50%, whereas on the other side, 34 metals (i.e. 57%) are recycled by less than 1%. It is striking that all rare earth elements are within in the group below 1% recycling. It is evident that a significant improvement of recycling technologies for rare earth elements is absolutely necessary (Binnemans et al., 2013).

Iron, as the most important metal, is recycled to a large extent. Worldwide, the fraction of scrap used for steel production was for 570 million tonnes, which accounts for 36.8% compared to the total quantity (1547 million tonnes) in 2012 (Anonymous, 2013b). Figure 4 shows that the share of steel produced from secondary raw materials varies significantly between different countries. In Europe generally (56%) and particularly in Turkey (90%) the importance of steel scrap is quite high. However, in

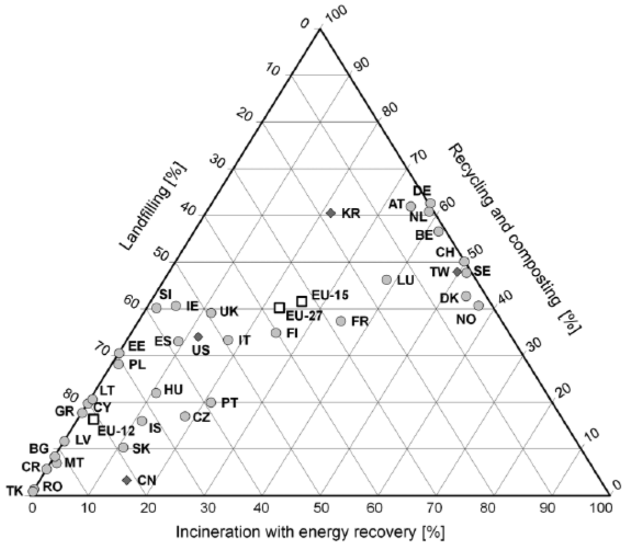

Figure 1. Proportions of recycling, incineration and landfilling in European countries (circles) in 2011 (Eurostat, 2013), European average (cubes) and non-European countries (rhombi); China in 2006 (Zhang et al., 2010); USA in 2010 (Anonymous, 2011e); Taiwan in 2010 (Chen and Chen, 2013); Republic of Korea in 2010 (Ryu and Shin 2013); codes of countries according to ISO 3166-1 (ISO, 2006b); triangle chart prepared with 'MS Excel' and 'Triplot' (Graham and Midgley, 2000).

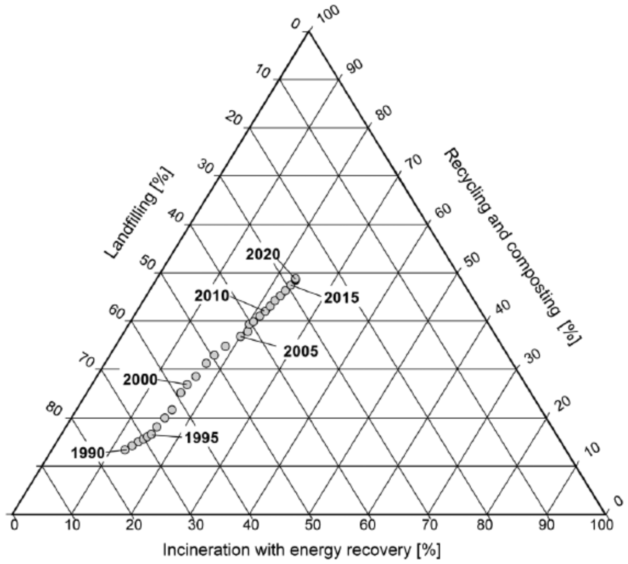

Figure 2. Waste management paths in the EU-28 (EU-27 up to 2007) from 1990 to 2020; reported data until 2008, projection from 2009 (Eurostat, 2013); triangle charts prepared with 'MS Excel' and 'Triplot' (Graham and Midgley, 2000).

China which is the most important steel producer, steel scrap only holds 11% of the total steel production.

During the recycling process of steel most foreign metals will be transferred into the slag. However, some desirable alloying elements (Ni, Mo, Co, W) will remain in the iron metal phase as well as harmful tramp elements (Cu, Sn) (Reck and Graedel, 2012). In particular copper in scrap recovered from end-of-life vehicles represents a major problem and, thus, a closed loop recycling is frequently impossible (Nakamura et al., 2012).

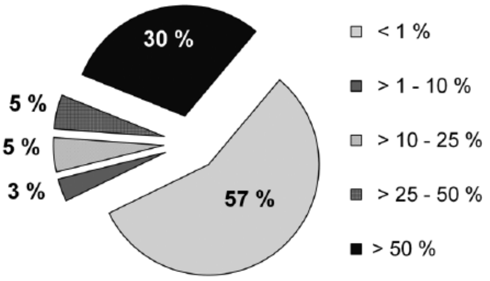

Figure 3. Global functional recycling rate of 60 metals (Graedel et al., 2011; Reck and Graedel, 2012).

Aluminium is even more sensitive in terms of removal of impurities (Nakajima et al., 2009). Due to the large deposits of aluminium (aluminium makes up about 9% of the surface of the Earth), recycling is not a question of material scarcity. The energy demand of secondary aluminium is only 2.8 kWh kg^{-1} which is only 6% of that required for primary aluminium (approximately 45 kWh kg^{-1}) (Das et al., 2010; Mahfoud and Emadi, 2010). As a matter of fact the recycling rate of aluminium is relatively high. In 2010 the production of primary aluminium was 44.6 million tonnes, whereas 46.1 million tonnes (i.e. 51%) of scrap have been used (Tsesmelis, 2013). However, the recycling process bears the risk of oxidation (i.e. loss of aluminium). Even if modern technologies can minimize the losses, in particular for foils relative high losses have to be accepted. It is reported that, depending on the technology, losses by oxidation may be up to 40% (Uchida and Ohga, 2000). On the average in the USA 4% of aluminium is lost during recycling which corresponds to 74 106 GJ of energy and 0.44 million tonnes of aluminium (Das, 2006).

Overall metal recycling is far away from a closed loop system mainly due to social behaviour, product design, recycling technologies and the thermodynamics of separation (Reck and Graedel, 2012).

Plastics recycling

The situation is even worse for plastics. They consist of macromolecular molecules (i.e. polymers) which are quite sensitive towards elevated temperatures and mechanical treatments. In practice, each recycling step means an inherent loss of properties (e.g. reduction of molecular mass) and thus recycling is limited.

In practice, a so-called bottle-to-bottle (B2B) process is a viable solution for PET. B2B means that PET, mainly from beverage bottles, is recovered and used for the production of new PET bottles. However, during the conventional process a small amount of contaminants (typically in the lower ppm range) remains in the polymer which requires that for food grade applications the recycled PET is covered by a layer of virgin PET (Welle, 2011). By an improved process higher purities can be obtained which are

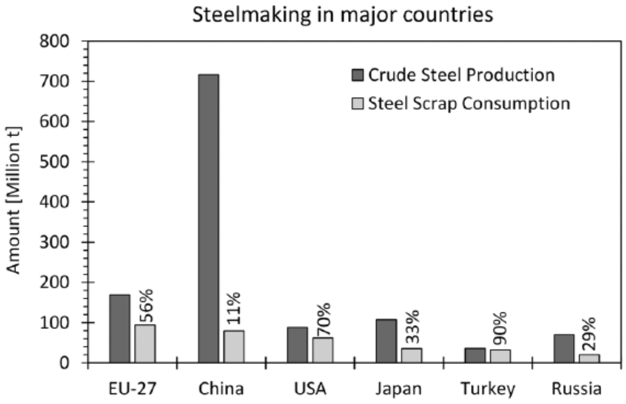

Figure 4. Crude steel production and steel scrap consumption of major countries (Anonymous, 2013b).

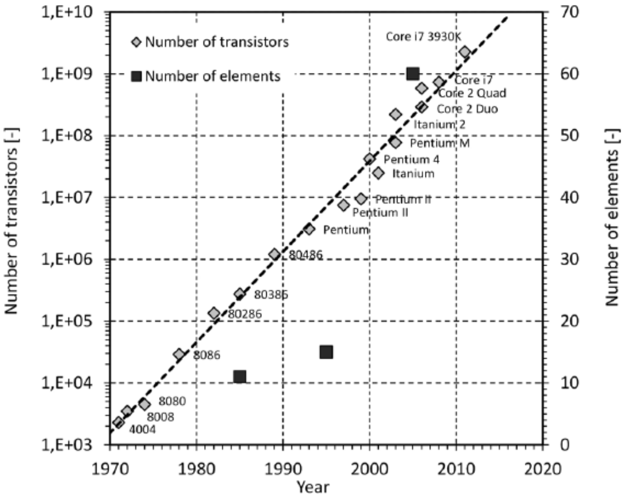

Figure 5. The Moore's Law: number of transistors per Intel CPU (Anonymous, 2013e) and number of elements used for Intel chips (Greenfield and Graedel, 2013).

feasible for food grade applications. PET flakes have to undergo a so called 'super-clean recycling technology' (Welle, 2011) which will consume more energy. Partially these processes are based on a depolymerization which does not account for material but for feedstock recycling. However, material recycling represents the best option for plastics (Michaud et al., 2010).

Alternatively recycled PET from beverage bottles can be used for other purposes than bottles. In practice, a significant fraction of recycled PET goes to the so called bottle to fibre (B2F) process (Bhatt, 2008; Gurudatt et al., 2003). The fibre industry accounts for about 73% of the recycled PET consumption (Silva, 2012). This practice represents an open-loop process but still shows distinct environmental advantages (Shen et al., 2010). Recycled polyester shows reduced material properties such as molecular weight. It can, however, be blended with virgin material resulting in comparable fibre qualities (Elamri et al., 2007). Fibres from recycled PET show, in particular, a reduced tensile strength and a lower elongation at break (Lee et al., 2013).

Recycling of PET from beverage bottles is a rather easy task as compared to many other plastics waste streams. End-of-life PET bottles represent a relatively homogenous and clean material. In practice plastics waste streams are not well defined and contain a mixture of ten or even more different polymers, various types of fillers, reinforcing materials, colorants, plasticizers, stabilizers, coatings and flame retardants. Thus, in many cases incineration with energy recovery represents the better solution than recycling. Only recently it has been demonstrated by life-cycle analysis that recycling is only the preferred option if a minimum of 70–80% of virgin plastics can be replaced whereas otherwise thermal recovery is favourable (Rajendran et al., 2013).

Products become more complex

The well-known empirical Moore's Law (1965) states that number of transistors per chip doubles every 18 months (McManus, 2001). This prediction is proved in Figure 5 which plots the number of transistors per central processor unit (CPU) of Intel chips over time. The number of transistors increased dramatically from 2300 (Intel 4004 processor) in 1971 to 2.27 billion (Intel Core i7 3930K) in 2011 (Anonymous, 2013e). The higher performance and more electronic features of semiconductors made it necessary to shrink the feature size on a chip. As the chip shrinks, the distance between transistors decreases. In order to achieve this miniaturization the number of chemical elements used for a CPU has dramatically increased (Figure 5). Whereas in the 1980s 11 elements have been used this number has been tremendously increased to 60 elements in the 2000s (McManus, 2006).

It is also reported that General Electric (GE), a huge international industrial group, uses 70 of the first 83 elements listed in the periodic table of elements. Rare earth elements are in particular necessary for healthcare, lighting, energy, motors, and transportation products (Duclos, 2010).

It is evident that that a larger number of chemical elements will make recycling of products much more difficult. The more elements one can find in a given volume the lower the concentrations will be and the more interactions between individual elements might occur. In the literature there is an ongoing discussion on the reasons for wastes to be recycled or not. Frequently the so-called 'Sherwood plot' is used to describe the recycling potential of a certain material waste stream. The term 'Sherwood plot' goes back to Thomas K. Sherwood, who published a figure in 1959 that indicated a relationship between the price of a material and its dilution. Later a similar chart was used for predicting the metal price as function of the ore grade (Phillips and Edwards, 1976). Resources which are present at very low concentrations require an elaborate extraction and refining process resulting in high prices. The function between price and dilution is called the Sherwood line.

In 1994, Allen and Behmanesh examined whether the 'Sherwood plot' could be used to indicate the recycling potential of material waste streams (Allen and Behmansh, 1994). The authors determined the concentration distribution of metals in waste streams and the respective recycling rates. For each metal

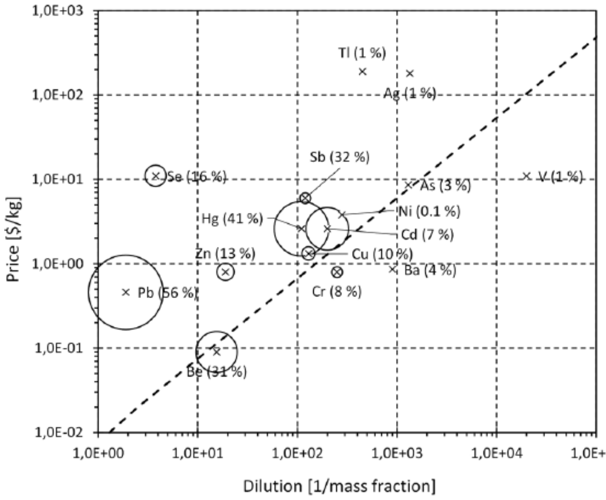

Figure 6. Relationship between dilution and market price; the dashed line is for virgin materials (Sherwood plot); the spheres show the lower bound for recycling according to Allen and Behmansh (1994); the sizes of the spheres indicate the actual recycling rate.

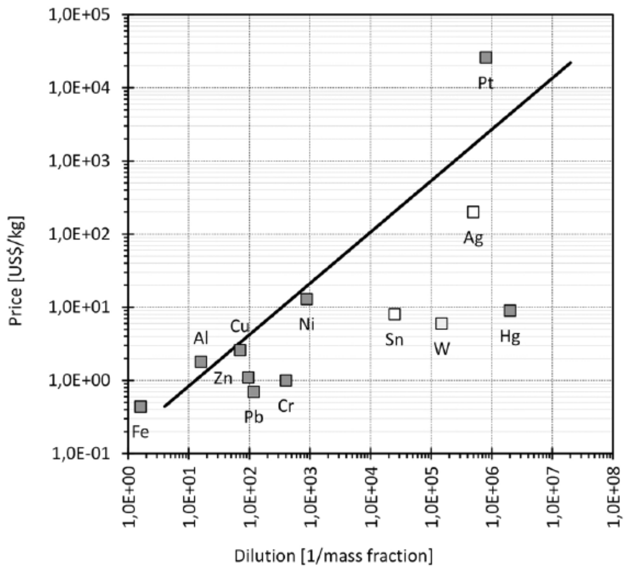

Figure 7. Metals concentrations in relation to price for automobile waste (Johnson et al., 2007); the dark-shadowed cubes indicate metals that are recycled to a high extent.

the concentration below which only 10% of the metal recycling took place was identified. This lower bound has been plotted versus the market price in 1986 and is shown in Figure 6. The metals Cr (8%), Ba (4%) and V (1%) are below the Sherwood line and are, in accordance to the Sherwood plot, recycled to a quite low extent. However, there are some metals above the Sherwood line but which are not or hardly recycled. In particular the recycling rates of Tl (1%), Ag (1%) and Ni (0.1%) are very low. The authors concluded that commonly the concentrations of resources in waste streams have to be higher than for virgin materials. They further assume that significant disincentives to make use of waste exist (Allen and Behmansh, 1994).

More recently, Johnson et al. (2007) used the same approach to product recycling for a variety of waste streams, namely: printed wiring boards, mobile phones, personal computers, waste electrical and electronic equipment (WEEE), municipal solid waste, automobiles and construction and demolition debris. The results showed that there is a quite good correlation between the dilution of metals in waste streams and the ability of recycling. Most materials are currently recycled if they fall above the Sherwood line.

An exception seems to be waste of end-of-life vehicles as demonstrated in Figure 7 (Johnson et al., 2007). More or less all metals are below the Sherwood line and should thus not be recycled. However, end-of-life vehicles are commonly disassembled before they are crushed in a shredder. The concentration of metals in components is significantly higher than in a vehicle. Thus lead (from batteries), platinum (from catalytic converter), copper (from wiring) or iron, chromium and nickel (from exhaust system) are recycled even if their dilution in a vehicle falls below the Sherwood line. It can be concluded that the concentration of a metal in a waste stream represents a parameter of major importance and that a disassembly process can significantly increase the recycling ability of wastes.

A more sophisticated concept has been developed by Dahmus and Gutowski (2007). The authors introduce a measure for complexity of a product and do not solely calculate the dilution of a material. It is called the material mixing and considers the number of the components as well as the concentrations of the components in a product. The material mixing is expressed by the factor H which is calculated according to equation (5). It can be interpreted as the average number of binary separation steps needed to obtain any material from the mixture (i.e. product). For a simple product consisting of a single material only (glass bottle) H would be zero. The more complex a product is composed the higher will the value H be.

$$H = -\sum_{i=1}^{M} c_i \cdot \log_2 c_i \tag{5}$$

where H is the material mixing (–); M is the number of materials (–); and c_i is the concentration of material i (kg kg^{-1}).

Similar to the Sherwood plot Dahmus and Gutowski (2007) set into relation the material mixing H and the market price of the materials derived from an end-of-life product as shown in Figure 8. The respective recycling rates in the USA are indicated by the size of the spheres. Products with high recycling rates are situated in the upper left corner and, vice-versa, the products with the low recycling rates in the lower right corner. Thus the authors suggested a line, labelled ‘apparent recycling boundary’ which separates the region where recycling takes place and where recycling does not take place.

Dahmus and Gutowski (2007) also investigated the material mix over time for three products, automobiles, refrigerators and computers. For all categories the material mixing is significantly increasing over time. This means that products are becoming

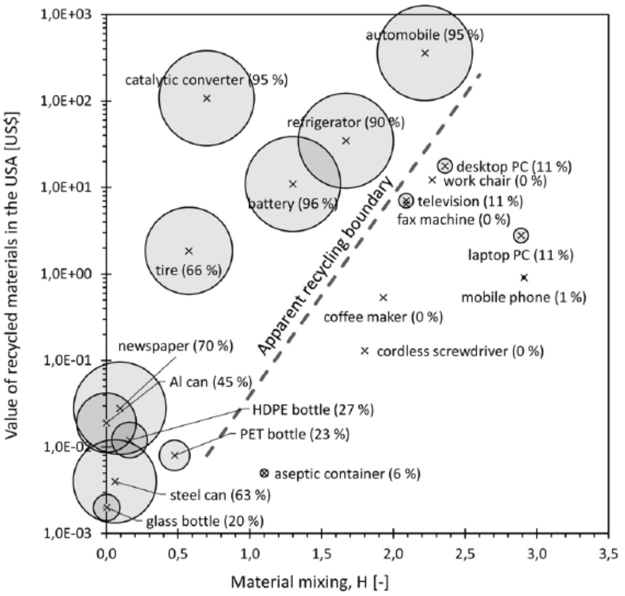

Figure 8. Single product recycled material values, material mixing (*H*) and recycling rates (indicated by the size of the spheres) for 20 products in the USA (Dahmus and Gutowski, 2007).

more complex. This effect is sketched in Figure 9. Both refrigerators and automobiles show a more or less constant material value over decades while at the same time the material mixing *H* showed a distinct increase. This means that the costs for recycling these products have been increasing because a more complex product requires more sophisticated and more expensive recycling processes. On the other hand the reward for the reclaimed materials and thus the income for financing the processing costs stagnated. An ironic exception are sports utility vehicles (SUV) which decreased in material mixing *H* compared to conventional passenger cars based on an increase of the mass (steel) and as a consequence the value of materials. This trend to more complex products is even worse for computers. Today desktop computers ($H \approx 2.3$) are more and more replaced by laptops computers ($H \approx 2.8$). The recycling process is thus more expensive but significant lower material values can be obtained.

Is 'zero waste' the goal of recycling?

'Zero waste' is a term which is inflated and abused almost constantly in waste management today. A short search in scientific and technological databases revealed that over the last 20 years an exponential increase of entries of zero waste occurred (Bartl, 2013b). However, it is evident that there exists no unambiguous definition of the term.

There is no clear evidence of the origin of the term zero waste but it is documented that in 1973 Paul Palmer founded the Zero Waste Systems Inc. (ZWS) in Oakland, California. The first attempt of the ZWS was to use excess chemicals from the nascent electronics industry instead of disposing of them. Later on Palmer founded the Zero Waste Institute which extended its activities to a broader scale. Palmer defines zero waste as 'a practical theory of how to wring maximum efficiency from the use of resources' (Palmer, 2009).

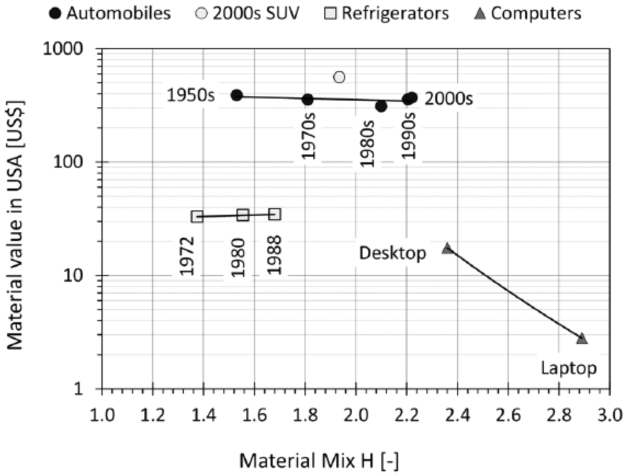

Figure 9. Complexity of products (computers, refrigerators and automobiles) expressed by *H* (material mix) and the material value of a single product over time according to Dahmus and Gutowski (2007).

According to Robin Murray zero waste is an extension of the Japanese-based ideas of total quality management (TQM) into the environmental field (Murray, 2002). The original aim was to reduce failures and reject rates in the car industry towards zero in order to increase the economic efficiency. Consequently this approach also aims to avoid all unintended by-products, thus, reaching 'zero waste'.

Unfortunately the term zero waste is interpreted more or less literally. According to Palmer zero waste does not mean that waste is only diverted from landfill. It represents the third stage of development in the production and usage of goods as sketched in Table 3. Incineration and recycling definitely have to be avoided by using intelligent design and re-use (Palmer, 2009).

Frequently the term zero waste is interpreted less strictly. According to GRRN (the grass roots recycling network) zero waste is a philosophy and a design principle for the twenty-first century. It includes recycling but goes beyond recycling (Liss, 1997). There are, however, no binding figures. The Zero Waste International Alliance states that, 'over 90% diversion of waste from landfills and incinerators are considered to be successful in achieving zero waste, or darn close' (Zero Waste International Alliance, 2012).

Several regions or cities have started zero waste initiatives which show totally different targets. A detailed study by Robert Krausz takes a closer look at various zero waste initiatives. According to Krausz four categories can be defined according the level of apparent ambition (Krausz, 2012).

- Zero waste as an aspirational target
- Zero waste with relatively modest targets
- Zero waste with relatively ambitious targets
- Zero waste to landfill target

Table 3. Development how humanity has dealt with the excess goods it generated according to Palmer (2009).

Generation	Time scale	Policies
First	Immediate satisfaction	Discard and dump = Garbage
Second	Short term	Post-discard re-use = Recycling
Third	Long term	Explicit design for re-use = Zero waste

Table 4. Suggestions for a precise wording in the field of zero waste (Bartl, 2013b).

Suggested term	Definition
Zero landfill	Total or almost total diversion of waste from disposal (e.g. landfill); Feasible options include other recovery (i.e. incineration) as well as recycling.
Zero Incineration	Total or almost total diversion of waste from disposal as well as other recovery (e.g. incineration); All waste that is generated needs to be recycled.
Zero waste	Total or almost total avoidance of waste by excessive waste prevention and re-use; landfill, incineration as well as recycling must not take place.

It can be concluded that the term zero waste stands for numerous policies which show totally different goals. The importance of clear definitions in the field of green chemistry, cleaner production and pollution prevention has been pointed out by Glavic and Lukman (2007). At the moment the term zero waste has no a precise definition, thus, it is an empty statement. It would be legitimate to distinguish between a pure avoidance of landfill, an avoidance of landfill as well as incineration and finally to avoid waste as outlined in Table 4.

According to the definition given in Table 4 zero waste would definitely mean that no waste at all is generated. It is to be discussed whether a complete avoidance of waste will ever be possible. However, even if the final goal (i.e. no waste) cannot be reached, an attempt can be made to move as close as possible. In practice it means that as little waste as possible should be generated. This very strict definition of zero waste means that traditional waste management is obsolete and resource management plays a fundamental role.

Recycling and thermodynamics

There are no generally applicable rules if a product or a material is (or should be) recycled. On the one hand economy is a powerful driver and it can be concluded that recycling will take place if it is a profitable process. On the other hand recycling is a legal issue and should take place if legislation has set quotas or other incentives. Last not least recycling is an ecological issue since it might help so save energy and resources. However, often the three do not agree. In practice, a recycling process can be economically feasible and a legal must but might not be economically feasible. In order to have an objective evaluation tool for recycling systems it has been suggested to use thermodynamics (Gutowski, 2008).

Repetitive recycling can be thought to be a material loop with additional input of energy. This requirement for energy is explained by the first law of thermodynamics. Basically, if any energy that is released when for example a bond is created must be added to take it apart again (Craig, 2001). From a physical point of view energy can be transformed from one form to another, but cannot be created or destroyed. From a technical point of view the statement that energy cannot be lost is unsatisfactory as in practice only a certain portion of energy can be used whereas the other fraction is 'lost' by dissipation. In order to describe the part of the energy that can perform mechanical work the artificial word 'exergy' was introduced by Rant in 1956 (Rant, 1956). Exergy analysis is performed in the field of industrial ecology (Valero et al., 2010) and can be also applied to evaluate recycling processes (Ignatenko et al., 2007).

As a matter of fact a recycling cycle can never run autonomously but will need additional energy as energy 'losses' are inevitable. It can be further concluded that the amount of energy to propel the recycling cycle must be smaller than the energy that is contained in the processed materials. In particular for (mixed) plastics, which are basically based on petroleum, a thermal recovery might be the better option than recycling if the recycling process consumes more energy that is necessary for producing new materials (Rajendran et al., 2013).

The first law of thermodynamics only considers the energy conservation but does not state whether a processes is really viable or not. In practice it is evident that processes are not necessarily reversible but that processes have a preferred direction of progress. Exemplarily, heat always flows spontaneously from hotter to colder bodies but never the reverse. In order to comply with that reality the second law of thermodynamics introduces a new physical quantity, the entropy. The second law of thermodynamics postulates that during all natural processes the entropy in a closed system is never decreasing. The extreme value applies to (hypothetical) processes if a closed system is in the equilibrium state and thus entropy remains constant.

Practically, according to the second law of thermodynamics each time that energy is used, some of its usefulness is lost. It is always transformed from a more concentrated form to a more dispersed. It was in 1972 when Georgescu-Roegen postulated that the second law of thermodynamics is not only relevant for energy but also for materials ('material entropy'). In practice during each utilization of a product or a material a more or less pronounced deterioration, wear and tear, pollution or co-mingling will take place which is a fact of the increase of entropy. Georgescu-Roegen called this effect the fourth law of thermodynamics (Georgescu-Roegen, 1971) claiming that 'complete recycling is impossible'. Thus limitations for recycling are very obvious for plastics as they will degrade (e.g. reduction of chain length) and lose quality over time. However, metals, which are 'indestructible' atoms, also increase their entropy over time as they are partially lost by abrasion, oxidation or dilution. It has been shown by Gutowski (2008) that the extraction of a certain element (e.g. from a waste fraction) means that entropy has to be decreased, thus vice-versa, a high amount of energy is necessary as expressed in equation (6). The equation is monotonically increasing as the concentration gets lower. In the borderline case as the concentration goes towards zero, the work goes to infinity.

$$w_{\min,n} = T_0 \cdot R \cdot \left(\ln \frac{1}{x_n} \right) \tag{6}$$

where $w_{\min,n}$ is the minimum work to extract one mole of the material n from a mixture ($\mathrm{J\,mol^{-1}}$); T_0 is the temperature (K); R is the general gas constant ($8.314\,\mathrm{J\,mol^{-1}\,K^{-1}}$); and x_n is the mole fraction of component n.

Basically Georgescu-Roegen was an economist and he supposed the laws of thermodynamics to be valid in economic systems. Later on a controversial discussion took place by various authors on that topic (Ayres, 1997a, 1998, 1999; Ayres and Nair, 1984; Valero et al., 2010). Beyond the theoretical or academic issue of this topic it is obvious that a recycling rate of 100% is, at least in practice, impossible.

Limits for waste prevention

Conflicts of interest

European waste management is substantially driven by the WFD (Anonymous, 2008a). One of the key elements is the waste hierarchy which defines waste prevention and re-use as the highest objectives. This policy gives constant cause for conflicts. Waste management deals with collection, sorting, recycling, recovery and landfill of waste.

Waste management has become a major business in Europe and other industrialized countries. Without doubt the activities of the waste management sector such as incineration (with effective exhaust cleaning), proper recycling or sanitary landfill exhibit a positive impact on environmental protection. Basically the activities of the waste management sector comprise collection, recycling, incineration and landfill. Re-use seems not to be within the core business of waste management. In general, re-use requires checking, cleaning or repairing operations between two cycles of use. Usually for these operations specially equipped workplaces, trained employees or detailed knowledge about the products are necessary. It is preferable that these processes take place at producers, retailers or special service centres than in the waste management sector.

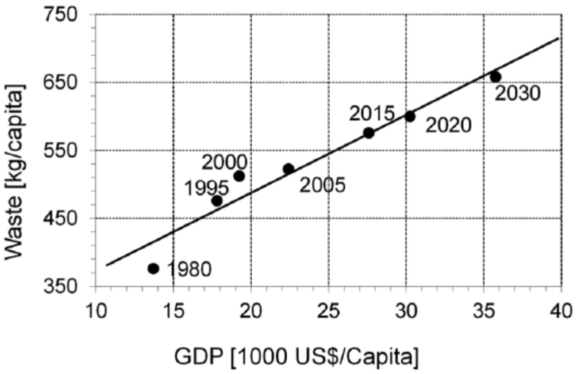

Figure 10. Waste versus GDP of OECD countries; 1980–2005: historic data; 2015–2030: perspectives (Anonymous, 2007).

Basically, waste prevention means a decrease of consumption and, in further consequence, a decrease in manufacture, extraction and processing and use of primary resources. These goals are also not within the activities of the waste management sector. Even worse, as waste prevention reduces the quantity of waste, it reduces the amount of materials that have to be processed. Any successful waste prevention will decrease the turnaround and profit of waste collectors, recyclers, incinerators and landfill operators. Ultimately, the hypothetical case of a complete waste prevention (i.e. no waste generation at all) would mean that most companies in the waste management sector will be obsolete.

Decoupling of waste generation from economic growth?

The gross domestic product (GDP, usually measured in US$ per year) is the market value of all officially recognized goods and services produced within a country. It is quite common that the GDP per capita (US$ $\mathrm{capita^{-1}}$) is considered an indicator of the standard of living. It was in 1955 when Kuznets assumed the hypothesis that as a country develops (low GDP), market forces will at first increase inequality of incomes and then, after a certain average income is attained (reaching a relative high GDP), inequality of incomes will decrease (Kuznets, 1955). Subsequently this inverted-U-shaped function was called 'Kuznets curve'.

A similar relationship was postulated by Grossman and Krueger (1991) between pollutants and the gross domestic product (GPD). According to the theory, concentrations of toxic matters increase with per capita GDP at low levels of national income, but decrease with GDP growth at higher levels of income. This function has become widely known as environmental Kuznets curve (EKC) whereby waste or certain waste streams are seen as pollutants (Ayres, 1997b).

Numerous studies on a decoupling of waste generation from economic growth have been published over recent years. Figure 10 plots the GDP versus waste generation of OECD countries. At least up to 2030 the perspectives point out an increase of waste within

OECD countries (Anonymous, 2007). In contrast, Khajuria et al. claim a function according to an EKC for municipal solid waste in India whereas the turning point already occurred in 1997 (Khajuria et al., 2012). The evidence of an EKC has also been found for hazardous waste in the USA (Berrens et al., 1997). However, results of different studies might be controversial and interpreted in various ways (Bohara et al., 2001). An elaborate study on the EKC theory reveals that there is no agreement in the literature (Dinda, 2004). More recently Nicolli et al. showed that in Europe there is no clear evidence for a delinking of waste generation even if for some regions the current policies seem to have an influence on landfill diversion (Nicolli et al., 2012).

How to measure waste prevention?

Despite this focus on waste prevention, its measurement is quite unclear. In general, statistics report the amount of waste but will hardly report about waste prevention. Any decrease of waste could be a result of waste prevention policy but could equally be a result of an economic crisis or just happen accidentally. The key question is how to measure something that is not there.

In the literature different approaches to monitor and evaluate waste prevention are described (e.g. Gentil et al. (2011); Gottberg et al. (2010); Sharp et al. (2010); Zorpas and Lasaridi (2013)). The calculation of a zero waste index (ZWI) suggests an easy and quick tool to measure waste prevention (Zaman and Lehmann, 2013). On closer inspection, it is evident that the ZWI does not show any relationship to waste prevention. It considers the treatment (e.g. recycling) of waste streams and the resulting savings of resources. In conclusion it can be assumed that waste prevention is a complex topic and a 'basket of measures' is required for a satisfactory description of prevention policies and their influence on waste generation (Cox et al., 2010).

Durable products?

European legislation demands ecodesign and durability (Anonymous, 2009b). However, even if the potential life span of a mobile phone is approximately 10 years most consumers use their device only for 12–24 months (Paiano et al., 2013). This trend counteracts the WFD which defines waste prevention as most desirable goal. It has to be concluded that the aim to extend the life span of products has not been achieved and that there exists a huge potential to save energy and resources.

Current legislation does not result in a distinct reduction of waste. One of the main reasons that the amount of waste is not significantly decreasing is that there exists a conflict of interests. It is in the interest of producers and retailers to increase production and sales. The stakeholders of these branches wish to maximize their revenues by selling more and more products and are not interested in durable goods or items that are easy to repair. Commonly this policy is called planned obsolescence. The reasons for a quick replacement of products by new products are listed here.

- The items are considered to be used a single time only (i.e. disposables).
- The items are replaced due to fashion or style (even if fully functional).
- The items contain components which show a limited, predetermined lifetime; the design does not allow an economic replacement of spare part.

The term 'planned obsolescence' goes back at least as far as 1932 when London published a pamphlet entitled *Ending the Depression Through Planned Obsolescence* (London, 1932). London proposed to decrease the useful life of products in order to increase production. Commonly the term stands for a policy of planning or designing products with a limited useful life. The products will become unfashionable or be no longer functional after a certain period of time and thus the consumer is forced to buy a new product. The policy of planned obsolescence is a topic of intensive investigations for economists (e.g. Bulow (1986); Grout and Park (2005); Singh and Sandborn (2006)). Recently it has been demonstrated that enterprises, that follow planned obsolescence as business model, are more successful in the market on a long term (Desmarchelier et al., 2011).

Planned obsolescence exhibits benefits for producers and retailers because the consumer is under pressure to purchase again. It is not within the interests of producers and retailers to decrease consumption and sales. This policy counteracts the efforts of waste prevention and reuse. The effect of incentives such as extended producer responsibility (EPR) does not seem to be a proper tool. Usually producers would rather pay a fee for a separate collection and recycling than actually reducing waste generation. For instance, the useful lifetime of electronic devices is becoming increasingly shorter. However, there are just a few academic works written on the subject but numerous theories of conspiracy. Recently an elaborate study on planned obsolescence focused on electronics (Keeble, 2013).

Basically customers buy goods and products in order to fulfil their needs. In recent years producers realized that providing just the products is insufficient in terms of remaining competitive. As a result companies began not only to offer a product but also the service related to the product. These solutions are widely known as product-service system (PSS) (Mont, 2002). The prime goal of PPS is to increase competitiveness and profitability of the enterprises. PPS is a system in which the ownership of a product is replaced or complemented by the utilization of a service. The service fulfils the need of the consumer who does not necessarily own the product. Basically, different definitions of PPS can be found in the literature as outlined in detail by Beuren et al. (2013).

As a side effect, PPS offers the potential to reduce the amount of waste. As the consumer pays for the service it is no longer the sole interest of the producer to increase sales. Conventionally, producers intend the customer to buy the product again and again which is a strong driver for waste generation. As a matter of fact PPS systems can align the interests of all stakeholders (enterprise, consumer and environment). For three showcases it has been demonstrated that PPS can significantly lower the environmental impact (up to a factor of 10) and increase the economic benefit (Lindahl et al., 2014) as compared to a conventional purchase system.

The European Union has already realized that PPS offers the opportunity for business to increase competitiveness in an environmentally friendly way. Numerous incentives exist to promote waste prevention by PPS (Fischer et al., 2012). However, more effort has to be undertaken to introduce such actions that have to be undertaken and there seems to be a large amount of room for further improvements.

Is re-use the solution?

Re-use offers a large potential for waste prevention. According to the WFD (Anonymous, 2008a) it means that products can be used again for the same purpose for which they were conceived. Consequently, any re-use of a product makes it unnecessary to produce a new product.

The re-use of end-of-life apparel is a well-established practice for many years. Since clothing represents a basic human need most people exhibit ethical concerns about apparel disposal and many people in the industrialized countries support the idea of second-hand textiles. In Germany the coverage is one of the highest in the world. In 2007 about 750·million tonnes of post-consumer clothes have been collected separately which corresponds to 60% of the amount put on the market (Anonymous, 2011b). In the UK in 2008 a total of 523 million tonnes of clothes have been collected for resale and recycling which corresponds to 24% of the total consumption (Morley et al., 2009). The collection rate in the USA is significantly lower and ranges around 15% (total amount: 11.3 million tonnes including shoes) (Anonymous, 2011c). The total energy demand for apparel collection comprising transport, sorting, packing, etc. ranges at about 6 GJ t^{-1} (Woolridge et al., 2006) and is thus two magnitudes below the energy for the production of new items (Allwood et al., 2006; Steinberger et al., 2009).

About 70–80 % of the collected end-of-life apparel is suitable for second-hand clothing. The total share of second-hand clothing counts less than 0.5% compared to virgin clothing (considering the value). As a large fraction of second-hand clothing is exported to poorer countries the importance might be high for certain regions. In the sub-Saharan region the share held by second-hand clothing is close to 30% and can even reach more than 90% in the Central African Republic (Baden and Barber, 2005). In contrast to the export of WEEE or end-of-life vehicles second-hand clothing shows beneficial effects in the receiving countries (Abimbola, 2011).

In terms of the high collection rate, clothing seems to be a unique product. It has been mentioned above that in Germany only 0.5% of collected post-consumer EEE are re-used (Bruening, 2013). Another difference is the fact that apparel is frequently changed due to fashion even if the items are fully functional. Frequently items have to be processed in order to be used once again. The WFD mentions checking, cleaning or repairing recovery operations (Anonymous, 2008a). King et al (2006) distinguish between repairing, reconditioning and remanufacturing as outlined in Table 5.

Table 5. Actions for promoting re-use of products (King et al., 2006).

Process	Description
Repairing	Correct of specified faults of a product Quality of repaired products is inferior Limited or no warranty
Reconditioning	Rebuilding of major components Reconditioned product is clearly not new Lower performance specification Lower warranty
Remanufacturing	Products are brought to original equipment manufacturer Quality equal to that of a new equivalent Equal warranty Only 20–25% of the energy

The current economic system is not feasible to realize a high rate of re-use. Producers are not interested in promoting repair because the production of a new item will generate a higher profit. However, the economic frame conditions could also be changed to promote repairing. As mentioned by Cooper (2011) lower taxes for labour and higher taxes for energy and raw materials could help to promote re-use. However, the latter one needs to be introduced on a global scale.

Waste exports

The waste hierarchy as introduced by the WFD (Anonymous, 2008a) comprises five options. On the one hand it has been demonstrated previously that waste prevention is not easy to measure. Moreover, for an engineer all input and output streams of a system have to be considered. When taking Europe into account it is evident that waste imports and exports must not be neglected.

On the one hand waste is transferred from Europe to third-world countries. For instance, a major portion of WEEE (52%) is not treated in Europe but, legally as well as illegally, exported (Anonymous, 2011d). Overall about 70% of the global WEEE ends up in China (Anonymous, 2012c) largely on open dumps. Major amounts of WEEE goes to recycling facilities, which do not even show basic standards and represent a significant danger for the environment and the health of residents. The situation for end-of-life vehicles is comparable. In 2005 the fraction of vehicles with unclear whereabouts (i.e. export) in Europe ranged between 1% (Estonia and Latvia) and 93% (Greece) (Scherhaufer and Beigl, 2008).

On the other hand also a so called ‘indirect’ waste export occurs. This means that production of products is increasingly shifted into countries outside of Europe. Currently China holds 80% of the global mobile phone production (Anonymous, 2012c). The fraction of polyester fibres produced in China increased from 33% in 2001 to 67% in 2008 (CIRFS, 2009). It is evident that all waste that is generated during the production of these products is not evaluated in the European statistics. The weight of a mobile phone is about 150 g but the total amount of waste to produce the item is 44.42 kg (Welfens et al., 2013).

It seems to be self-deception if a waste reduction is reported for Europe. Consequently the amount of directly exported waste as well as the waste backpack of each imported item should be evaluated in the European waste statistics. Typically, exported waste ends up on open dumps or recycling facilities, which do not even show basic standards. It would have been reasonable to rank any treatment of waste outside of Europe lower than any other option taking place in Europe. Thus, it has already been suggested to extend the waste hierarchy by a sixth, least favourable option: waste trafficking (Bartl, 2013b).

Conclusions

Waste is regulated by numerous laws and regulations. In Europe the revised waste framework directive (Anonymous, 2008a) plays an important role and introduces the waste hierarchy. Waste prevention is on top of the hierarchy and favourable over all other options. In the EU several other directives put effect of special types of waste (e.g. WEEE, packaging). However, the current legislation has introduced quotas for recycling and recovery but hardly for waste prevention.

Over recent years, in several countries the recycling rate has been tremendously increased. It is, however, evident that there are certain limits for recycling. Often recycling is a question of money. The ‘goodies’ are already recycled but for other waste streams recycling is not competitive with recovery, disposal or, in particular, export. The limits of recycling can also be explained with thermodynamics. Even if recycling frequently shows ecological advantages, it consumes energy and resources and does not tackle waste generation itself.

Without doubt, waste prevention and re-use are very effective policies to reduce the consumption of resources and the environmental impact since the amount of waste is decreased. Unfortunately, up to now economic growth will generate more waste. Basically, waste prevention is difficult to measure and counteracts the economic interests of various stakeholders. Producers and retailers are interested to increase sales and turnaround, which are both drivers for waste generation. Even the waste management sector, collectors, landfill operators, incinerators and recyclers, will have less revenue, if less waste is generated. New and more sophisticated drivers are necessary to align the interests.

Waste trafficking is a major issue and causes severe environmental and health problems. On the one hand, waste from industrialized countries is exported into third-world countries. On the other hand, a transfer of production and the associated waste generation is transferred into third-world countries (‘indirect’ trafficking). Both forms of waste export show distinct environmental and social disadvantages.

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