CIRCULAR ECONOMY:

CYCLES, LOOPS AND CASCADES

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International Solid Waste Association

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The International Solid Waste Association (ISWA) is a global, independent and non-profit making association, working in the public interest to promote and develop sustainable waste management.

ISWA has members in more than 60 countries and is the only worldwide association promoting sustainable, comprehensive and professional waste management

ISWA's objective is the worldwide exchange of information and experience on all aspects of waste management. The association promotes the adoption of acceptable systems of professional waste management through technological development and improvement of practices for the protection of human life, health and the environment as well as the conservation of materials and energy resources.

ISWA's vision is an Earth where no waste exists. Waste should be reused and reduced to a minimum, then collected, recycled and treated properly. Residual matter should be disposed of in a safely engineered way, ensuring a clean and healthy environment. All people on Earth should have the right to enjoy an environment with clean air, earth, seas and soils. To be able to achieve this, we need to work together.

Executive summary

Recycling is a topic that has been discussed very often in recent days. There is no doubt that end-of-pipe technology is out of date and recycling is of major importance in order to move towards a circular economy. However, it must be stressed expressly that an increase of recycling rates is an achievement of enormous significance but not enough.

Recycling can help to close cycles and to feed materials back into the production process. However, cycles are never perfect and leakages are an inevitable reality. Materials will, intentionally as well as unintentionally, be mix up. Molecules will undergo a degradation and exhibit reduced intrinsic properties. To a certain extent substances will always be released into the environment in such concentrations that makes recovery impossible. Despite these limitations recycling is the only option to realize material loops. Recycling shows the further advantage of energy savings. For example, Aluminum is quite abundant but its production from virgin ores consumes 20 times more energy than recycling scrap. Furthermore the environmental impacts of mineral extraction, conversion, enrichment and production of virgin material are much higher.

However, numerous recycling processes exist and their efficiency in terms of material quality, energy consumption, environmental impact or material losses might be quite different. Even similar recycling technologies will show a quite varying efficiency depending on the properties of the input material, such as concentrations or impurities. Several evaluation tools to measure the impact of recycling activities are available of which life cycle assessment is the most widespread one. However, it is time consuming and allows a broad interpretation. As recycling is a quite complex topic its evaluation is also complex.
Recycling is in competition with other options such as re-use or incineration. In resource management the question is not whether this or that but all options have to be used at the appropriate time. In order to consider the fact that cycles are not perfect the concept of cascade utilization has been introduced. It is the sequential use of biogenic raw materials to produce materials and energy. Each material has to be used multiple times whereas the quality will decrease over time. Energy recovery is only the last step to terminate the cascade. The challenge is to define the optimal cascade in order to minimize resource and energy consumption as well as environmental impact.

There are no alternatives to a circular economy. However, also the circular economy needs virgin materials, energy and, finally, will generate waste streams. Thus the waste management sector is an essential partner but it is not the only one.

Image by Valorsul

Prepared by the ISWA task force on resource management

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Introduction

Recycling represents an important policy in waste management today. Worldwide there exist several definitions of recycling which might differ to a certain extent but it evident that our material demand cannot be met by virgin resources only. Europe[1] and the USA[2] have realized this shortage and defined a list of so called critical materials since a lack of these resources might interfere the economic development. As shown by Graedel & Cao there is a correlation between rates of metal usage and gross domestic product[3]. It is thus clear that developed countries urgently need to use materials multiple times instead of only once. Materials from end-of-life products have to be utilized again for the production process.

This report is part of the ISWA Task force on resource management (TF-RM). The scope of the TF-RM is resource and waste management, including recovery and use of secondary raw materials, fuels and energy, fertilizers and carbon matter as well as waste prevention in countries with advanced waste management systems. One issue of the TF-RM is to show what contribution the waste management sector is already making and can make in the future in the field of resource management. Furthermore it is evaluated how the transition from waste management to resource management will look like for the waste management sector. Finally it is the aim to identify the barriers and challenges that need to be overcome to support the transition from waste management to resource management.

This report has been written to provide an overview on the recycling issue. Recycling is in competition with other options. The goal is to minimize resource consumption. Cases exist in which energy recovery might be the better solution. Furthermore a certain material can be processed according to different recycling procedures such as "material recycling" or "chemical recycling". On the other hand recycling can give clear advantages over re-use. As a matter of fact the efficiency and quality of recycling processes represents an important issue since otherwise a comparison is not possible.

The document is designed to:

- show the benefits but also the limits of recycling.
- define terms in the field of recycling and, later, waste and resource management.
- discuss the role of recycling in the circular economy.
- introduce cascading as a practical approach to consider unavoidable losses (quality and quantity) over time.

Closing the loop

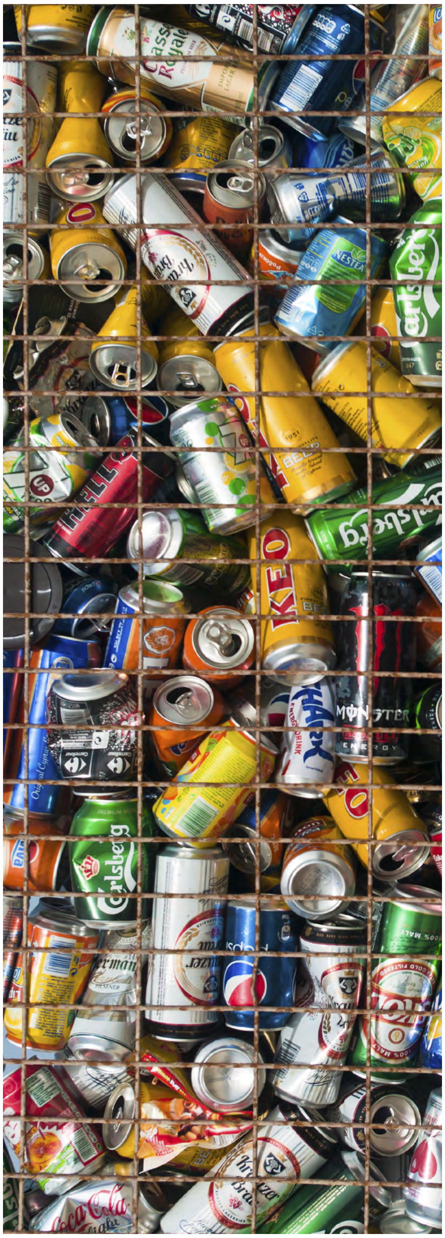


Figure 1 shows a process chain according to the end-of-pipe technology. Resources are extracted and utilized only once. A continuous feeding with virgin materials is required and at the same time material is generated that has to be disposed of. This schedule was the common practice over decades and exhibits the well-known negative effects such as excessive consumption of resources and environmental problems associated with disposal.

Our societies have realized that a shift from this end-of-pipe technology is urgently needed. As a first attempt end-of-life products are used as secondary resources to produce new raw materials as shown in Figure 2. It is, for instance, well established that iron scrap is re-fed into the steel production process.

However, the sketch (Figure 2) does not mirror the reality properly. In practice numerous side reactions, barriers and obstacles exist. In the following the advantages as well as the limitations of recycling are discussed.

Fig. 1 | Material chain according to end-of-pipe technology

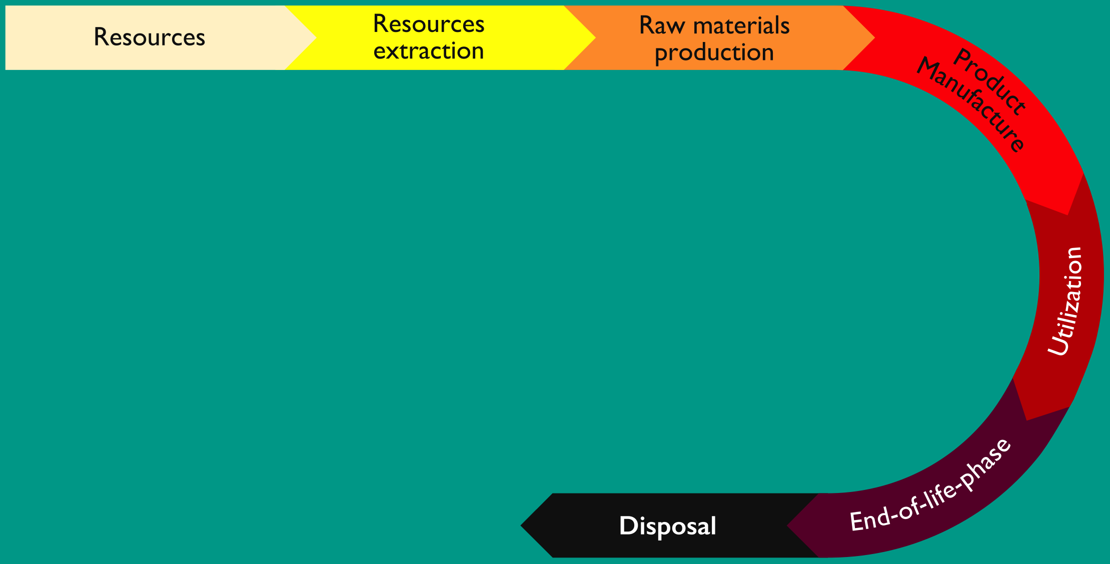
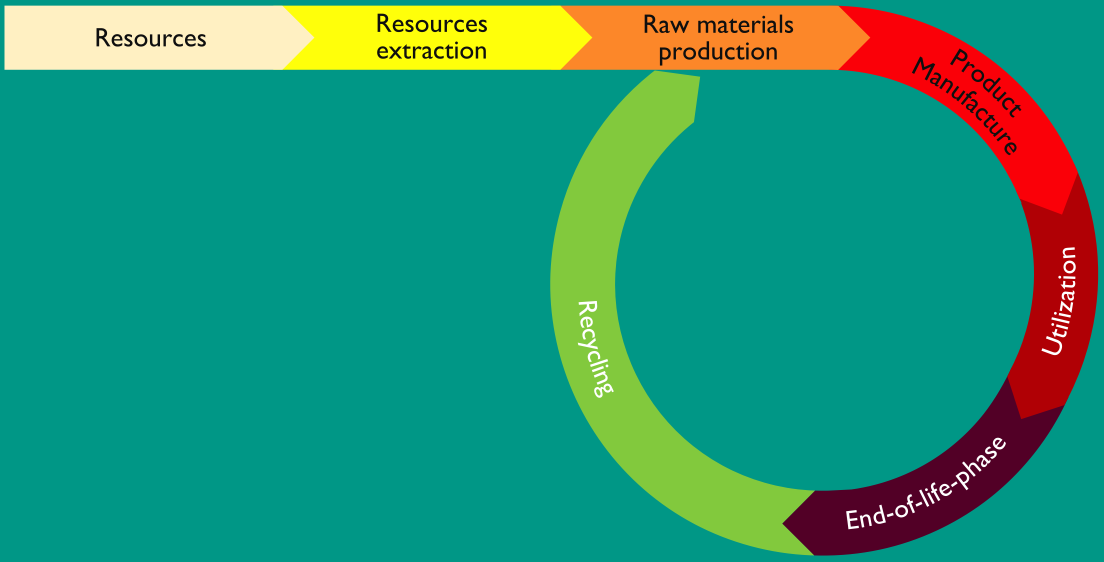


Fig. 2 | Material chain turned into a cycle by including recycling



The benefits and limits of recycling

Terms and definitions

In this documents several terms are used which might lead to some lead to uncertainties. Table 1 gives a brief description of expressions that are used hereafter in this document.

Losses and destruction

Even there is no generally applicable definition for recycling it seems clear that at least in Europe the Directive 98/2008/EG (waste framework directive – WFD) serves as a common basis.[4] According to the WFD 'recycling' means 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.

Basically recycling means that materials are led in a cycle. As chemical elements are basically stable and indestructible it seems possible to realize a closed cycle that does not need any additional material inputs. However, in practice a 100% recycling as sketched in Figure 2 is not possible to various reasons:

1. Inevitable material losses due to abrasion, corrosion, etc. (dissipation)

Kral et al.[5] use the term "tramp elements" to indicate that a certain fraction of material is released throughout the life cycle of a product. This inevitable dissipation into the environment converts substances into an unrecoverable form.

Exemplarily, it has been outlines by Ayres et al.[6] that significant amounts of copper are lost by corrosion (e.g. from roofs and water pipes) and dispersed irrecoverable into the environment. Dissipation might not only occur during the use phase but also in the course of processing. Aluminum is commonly protected against oxidation by a thin layer of aluminum oxide. However, during the recycling process the metal is melted and at elevated temperatures a certain amount of metal is oxidized. On the average about 4% of aluminum is lost by oxidation during the re-melting process[7]. Due to the high surface of foils this losses can be up to 40%.[8]

On the one hand the dissipation of elements may cause environmental and health problems. On the other hand it is evident that the lost fraction cannot be recycled and thus a recycling rate of 100% can never be reached.

2. Inevitable, frequently non-reversible, mixing with other materials

An undesired contamination of products may occur throughout the life cycle. For these substances Kral et al.[5] also use the term "tramp elements". When recycling such products these contaminations frequently cannot be removed and are transferred to the next stage.

Exemplarity, this effect can be observed in steel products that contain other metals. During the recycling process most foreign metals will be transferred into the slag. Some desirable alloying elements (Ni, Mo, Co, W) will remain in the iron metal phase as well as

Tab. 1 | Short definition of terms hereafter used in this report

TERM	DESCRIPTION
Metal	Elements are characterized by a so called metallic bonding with delocalized electrons. Metals show properties such as thermal and electrical conductivity, opacity and luster.
Alloy	An alloy is a mixture of metals or a mixture of a metal and another element. E.g. steel: alloys of iron and other elements, primarily carbon
Oxidation	In this context oxidation means that metals react with oxygen from the air forming oxides. Reduction designates the opposite reaction. E.g oxidation of aluminum to aluminum oxide: $4\ Al + 3\ O_2 \rightarrow Al_2O_3$ E.g. reduction of titanium oxide to titanium: $TiO_2 +2\ H_2 = Ti +2\ H_2O$
Molecule	A molecule is a group of two or more atoms held together by chemical bonds. Depending on the stability of the bonds, molecules can be more or less stable. E.g. very stable molecules: Al_2O_3, SiO_2
Macromolecule	A macromolecule is very large molecule commonly created by polymerization of smaller subunits. E.g. Polyethylene terephthalate (PET) produced from ethylene glycol and terephthalic acid.
Composite	Basically a composite is a material made from several different substances. Eg. concrete (rock and cement), asphalt (rock and bitumen), fiber reinforced plastics, etc.
Product	Products in this context are tangible products which are can be perceived by touch. They can be quite simple basically consisting of one material (e.g. glass bottle, PET fiber) or extremely complex consisting of numerous components (e.g. vehicle, computer).

harmful tramp elements (Cu, Sn).[9] Copper and tin cause a drop of ductility of steel at elevated temperature.[10] In particular scrap recovered from end-of-life vehicles may contain considerable amounts of copper.

Table 2 shows the distribution of elements among metal, slag and gas phase during processing of Iron, Aluminum, Magnesium and Copper. In particular for electropositive elements such as Aluminum more or less all elements will remain in the metal phase. This means that these contaminants, if possible, have to be removed before the remelting process.

Due to the contamination of materials by contraries a closed loop recycling is frequently impossible[11]. It is clear that non removable contaminants will decrease the quality of the recycled material.

3. Degradation or destruction

An atom is the smallest unit of matter. Except from a few radioactive isotopes, they are stable and cannot be destroyed or converted from one into another. It could thus be concluded that atoms can be recycled infinitely. However, due to losses (see 1.) and mixing (see 2.) in practice endless recycling is impossible.

In particular metals might be oxidized. This does not mean that the atom is destroyed but that it has to be reduced to the metal state again. As shown in Chapter 3.4 Aluminum is "lost" due to oxidation as its conversion to the metal consumes large amounts of energy.

Several molecules such as aluminum oxide or silicon oxide are very stable and the chemical bonds will not be affected during normal use or processing of these materials. Again, an infinite recycling is impossible due to the above mentioned losses.

A large number of molecules are quite sensitive and there is the danger of breaking the chemical bonds. This is in particular the case for macromolecules or polymers. These are large molecules and chemical reactions might occur. In particular heat (e.g. during melting), radiation (e.g. UV radiation during use) or mechanical impacts will lead to a pronounced degradation or destruction of the macromolecule. This will in parallel lead to a distinct decrease of material properties and in extreme cases make recycling impossible.

As an example a distinct degradation will occur in paper recycling. During each reprocessing of the cellulose fibers, an irreversible reduction in fiber length and strength takes place and hence the numbers of cycles are limited. A similar observation is made in recycling of polymers. Badia et al.[12] report that repeated extrusion induces chain scission reactions in PET and thus a dramatic decrease of mechanical properties.

It is evident that several materials, in particular polymers, are quite sensitive to mechanical, thermal or other influences. This might occur in the use phase (e.g. UV radiation, oxidation) as well as during re-processing (e.g. thermo-mechanical degradation). This means that during each cycle a more or less pronounced quality decrease has to be accepted.

Tab. 2 | Distribution of elements among metal, slag and gas phase during processing of selected metals

Gas phase	Zn Ag, Pb	Zn Cd, Hg		Hg Cd
Slag phase	Cr, Mn, V Al, Ca, Ce, La, Mg B, Nb, Si, Sr, Ta, Ti, U, Zr	Cu, Fe, Si, Mn Ag, As, Au, Bi, Ce, Co, Cr, Dy, Ga, Gd, Ge, Ho, In, Ir, La, Li, Mo, Nb, Ni, Pb, Pd, Pt, Sb, Sn, Sr, Ta, Ti, U, V, W, Y, Yb, Zn	Ag, Al, Ce, Cu, Fe, Mn, Ni, Si, Zr Bi, Ge, Hg, La, Na, Pu, Sb, Sn, Sr, Tl	Mn, Ni, Pb, Zn Al, B, Cr, Fe, Ga, Ge, In, Mg, Re, Sr, W
Metal phase	Co, Mo, Ni, W Cu, Sn	Mg Be, Ca	Y Ca, Gd, Li, Yb	Sn Ag, Au, Bi, Pd, Pt, Se, Rh, Te Sb
Element Process	**Fe** basic oxygen furnace or electric arc furnace	**Al** Remelting	**Mg** Remelting	**Cu** Converter

Source: Reck and Graedel.[9]

🟥 Recoverable element 🟦 Alloying element 🟨 Deoxidation agents

The incomplete material cycle

As discussed above the cycle as sketched in Figure 2 cannot be realized. An inevitable decrease in terms of quantity and quality has to be considered. Figure 3 gives a more realistic view of the situation. It comprises the same steps as found in Figure 2 but also includes additional streams. It has to be mentioned that the chart does neither show energy flows nor consider all possible material streams.

In the following the most important terms are describes below.

(a) Dissipation

Dissipation means that during production and utilization material losses are inevitable (see Chapter 3.1). Further material losses will also occur during all recycling processes. Material losses need to be replaced by new materials.

(b) Mixing

Mixing of materials will occur during manufacture as a product consists of a variety of components. Product design (==> c) aims to optimize recyclability by e.g. limiting the number of materials to be used. However, the opposite is actually the case, as it is a fact that products are increasingly becoming more complex and they contain more different materials.[13] Furthermore this effect might occur during the utilization phase. For instance, textiles could be contaminated with oil or other substances during use and thus subsequent recycling is prevented. It is also well known that a separate collection is essential to avoid mixing of materials and to enable recycling processes.

(c) Product design

Product design is introduced as a new chain link. Inter alia is comprises:

- design for recycling,
- long service life,
- easy to repair or
- avoidance of toxic substances.

Today it has been realized that a proper product design can help to facilitate processes that take place later in the material cycle (e.g. re-use, repair, recycling). The EU has responded to this challenge and introduced "design for recycling" in several directives (e.g., ELV-Directive[14]).

(d) (Preparation for) Re-use

Re-use in the sense of the WFD[4] comprises any operation by which products or components that are not waste are used again for the same purpose for which they were conceived. Re-use accounts for waste prevention. The epithet "preparation for" expresses that a cleaning, repairing or similar step is required in between two cycles.

In this context "product recycling" has been suggested as new category. It means that the chemical and the physical constitution of a material is maintained but the product is not used for the original purpose such as tires or glass bottles as building material.[15, 16]

(e) Material Recycling

Material recycling means that the chemical constitution of a material is maintained and only the physical constitution is changed.[15,16] This form of recycling comprises for example:

- melting and reprocessing of metals,
- composting of biogenic materials.

(f) Feedstock recycling

Feedstock recycling changes the physical as well as the chemical constitution of a material[15, 16] such as de-polymerization. Commonly the technical effort of feedstock recycling is higher than for material recycling (==> e) but its applicability is larger.

(g) Energy recovery

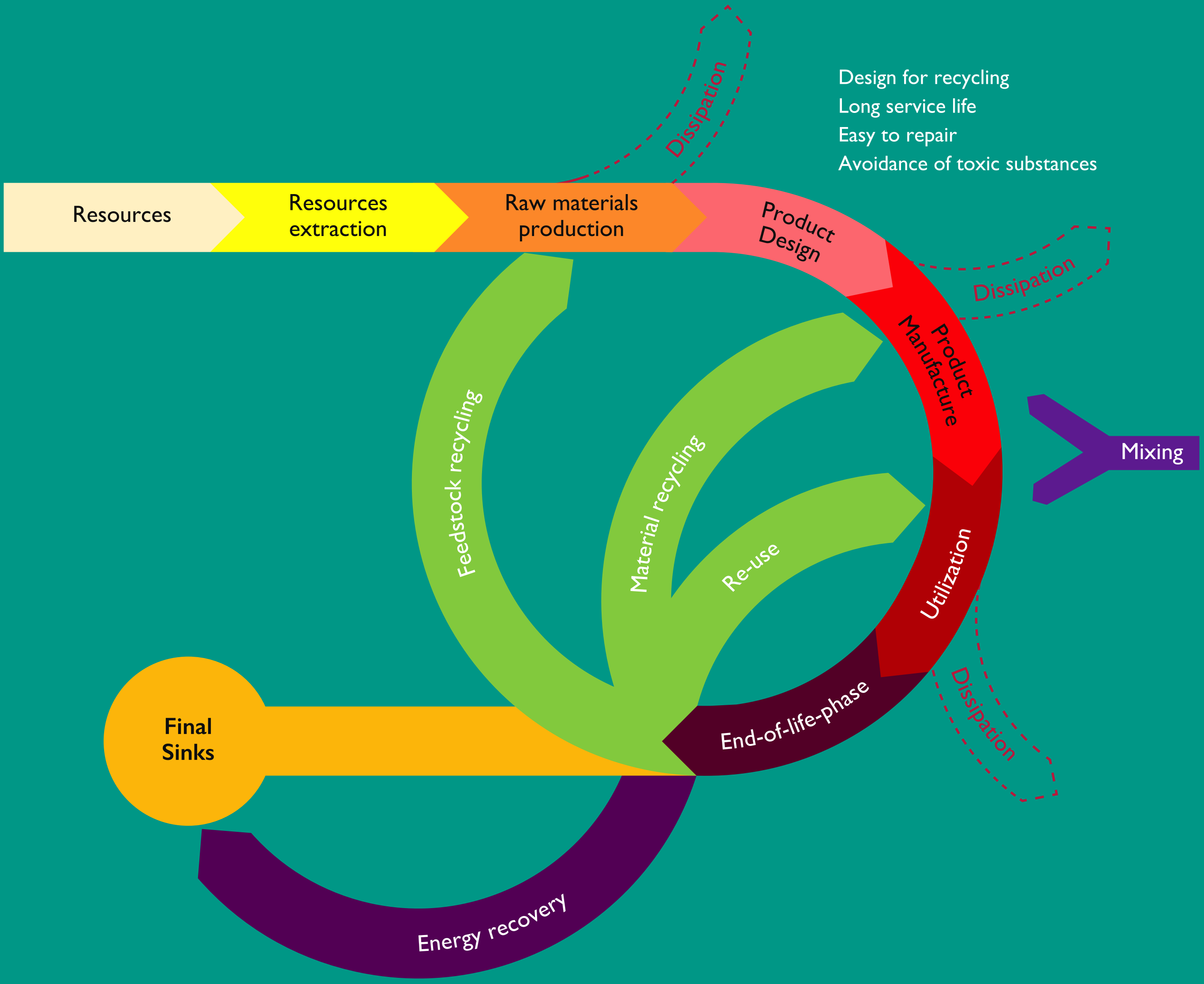
As mentioned above the inevitable loss of quality might make incineration favorable over recycling. The advantage of incineration is not only the recovery of energy but also the destruction of toxic substances. As mentioned by Brunner[17] an incinerator represents a final sink (==> h) as it destroys hazardous substances.

(h) Final sink

According to Kral et al.5 "sink" is defined as a process that receives anthropogenic material flows that have no positive value for present societies. Furthermore, the authors define "final sink" as a sink that either destroys a substance completely (==> g), or that holds a substance for a very long time period. Sinks can be man-made (landfill) or natural (e.g. air, water or sediment) and must be capable to store materials safely for geological time periods. It has been pointed out by Brunner[18] that final sinks are an indispensable prerequisite for realizing clean cycles.

Fig. 3

Material circle including relevant material input and output streams



Advantages of recycling

Frequently the reason for recycling is supposed to be the reduction of the consumption of primary resources. As mentioned above several materials are considered to be critical (e.g. rare earth elements) and therefore recycling could help to reduce the dependence of imports.

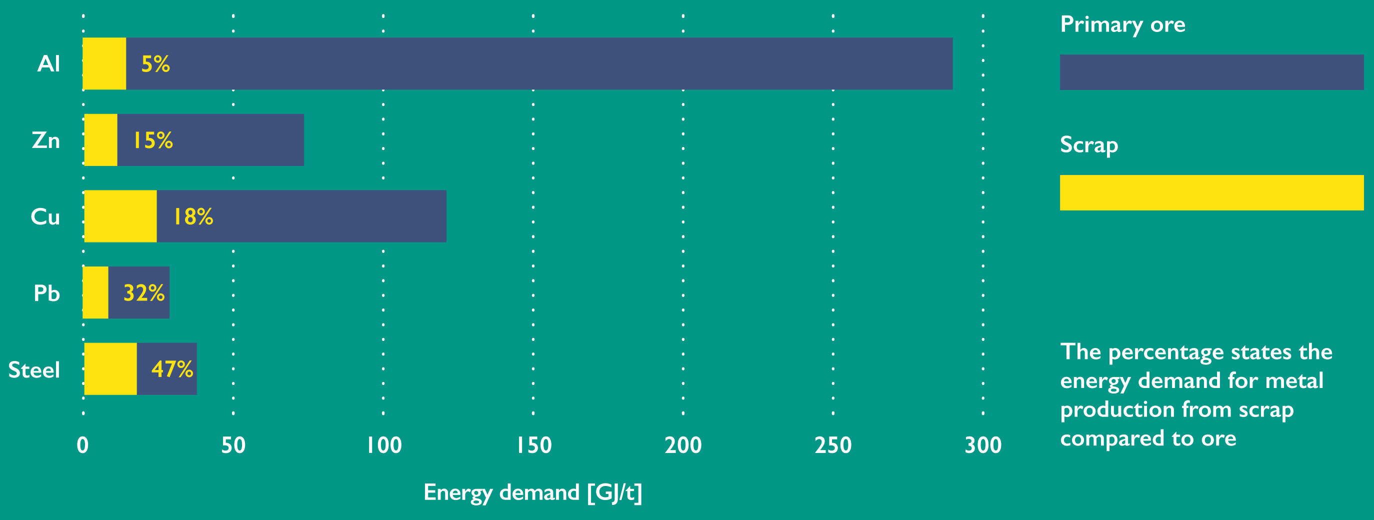
However, several materials are quite abundant and the benefit of recycling is saving of energy and subsequently money. This is in particular the case for aluminum which makes up about 9% of the surface of the earth. It is thus evident that aluminum recycling is not a question of material scarcity. The main costs for primary aluminum production is energy (i.e. approx. 165 – 295 GJ/t[19, 20, 21]) required for the electrolysis process at high temperatures. The energy demand of secondary aluminum is significantly lower and ranges at around 10 – 15 GJ/t.[19, 20, 21] It is reported that primary aluminum production is responsible for about 1% of global GHG emissions.[22] As a matter of fact the share of aluminum scrap used for aluminum production is about 50%[23]. Figure 4 demonstrates that the energetic advantage is the highest for aluminum but also for other commodity metals recycling offers a large potential for energy saving.

In many cases recycling offers economic advantages. For several (secondary) materials a market exists. The prices of recycled commodities are linked with those of virgin materials and are thus subject to wide fluctuations due to unpredictable factors. Table 3 shows prices for some selected recyclates. It is obvious that the existence of a market and a demand for (secondary) materials will create a pull factor. In the event of a demand from the market and the availability of economical recycling schedules exist recycling will need no additional incentive.

It is striking that for several materials the recycling rates are quite low or virtually zero. In 2011 UNEP has reported that the end-of-life recycling rate for all rare earth elements is below 1%.[25] Furthermore also As, B, Bi, Li, Sr, Te and Zr are recycled to less than 1%. In regard of the importance and the limited availability of some of these elements higher recycling rate could help to lower the dependency of Europe from these materials.

Finally, recycling can show distinct environmental benefits. It has been mentioned above that aluminum recycling is not a question of scarcity but an economical must. However, ores containing aluminum (bauxite) are quite abundant but the processing produces large amounts of waste. Depending on the quality of the bauxite for each t of Aluminum approximately 1.5 t of red mud are generated. As red mud contains considerable amounts of iron-III hydroxide and highly alkaline sodium hydroxide it represents a severe environmental problem. As its processing is quite expensive it is frequently deposited.

Fig. 4 Energy demand (in GJ/t) for metal production from primary ore and scrap



The percentage states the energy demand for metal production from scrap compared to ore

Source: Martens, 2011.[20]

Recycling of Aluminum is thus not only a question of energy saving but also shows clear environmental benefits as large amounts of waste can be prevented.

Finally, recycling can be based on legal framework such as binding recycling rates in Europe.

Summarizing recycling makes sense due to the following reasons:

1. Environmental protection (less consumption of resources, less waste generation, less energy consumption, etc.)

2. Economic advantages (high prices for recycled materials, saving of expensive energy, reducing dependency of imports, avoiding disposal costs, etc.)
3. Legal requirements (end-of-life vehicle directive, directive on packaging and packaging waste, etc.)

Of course point 1 and 2 are not independent of each other. As mentioned saving of energy will show economic as well as ecologic advantages. However, if all three points are aligned recycling will most probably take place. Commonly problems will occur if point 1 – 3 come to contradicting conclusions. Recycling can be a legal necessity and show environmental benefits but could be too expensive.

Tab. 3 Selection of prices for recycled materials (October 2014) for the UK

GLASS (CULETS)	€/t
Clear	39
Amber	31
Green	18
Mixed	14

PLASTICS (BOTTLES)	€/t
HDPE (natural)	537
HDPE (mixed)	185
PET (clear)	274
PET (colored)	78

METALS	€/t
Al cans	1,016
Steel cans	179
Mixed can	170
Ferrous scrap (4C grade)	164
Copper dry bright wire	5,053
Lead batteries	591

PAPER	€/t
Mixed paper & board	72

Source: WRAP, 2015.[24]

Dilution

Generally, the reasons for high costs in material production may be:

1. elements have to be derived from quite diluted ores,

4. exploitation under severe conditions (extreme depth, etc.) and/or

5. complex production process.

All three points will increase the demand of energy and in parallel the costs. Figure 5 demonstrates that there exists a strong linear relationship between the material price and the energy intensity required for its production. The energy intensity is the energy required to produce a material from its raw form, per unit mass of material produced. This relationship is valid for raw materials (e.g. metals, oxides) as well as for (simple) products (e.g. bricks). Materials that demand a large amount of energy to be produced are quite expensive such as Pt, Au or Pd. Vice versa materials will be quite cheap if the energy consumption is considerably low such as concrete or bricks. It is clear that the reported energy demand is coupled to all of the three reasons stated above.

It is obvious that dilution represents a critical parameter. As mentioned above a certain fraction of materials are "lost" due to dissipation. The materials are dispersed into the environment and the concentrations are too low. Any recovery operation is not feasible. This predominate effect of dilution is demonstrated by Figure 6 which shows the concentration of selected elements in sea water. As considerable amounts of Mg and in particular Na and Cl, are present, it is well established to derive common salt from sea water. In the 1920's the German chemist and Nobel prize winner (awarded 1919) Fritz Haber tried to extract gold from sea water but concluded that due to the low concentration it is uneconomic.[27] As the concentration of uranium is higher by the factor of thousand it has been proposed to use the sea as source. In 1983 Bernard Cohen claimed that breed reactors operated with uranium derived from sea water represent a cheap and "renewable" source for energy.[28] However, today uranium from mining is used almost entirely as fuel for nuclear power plants.

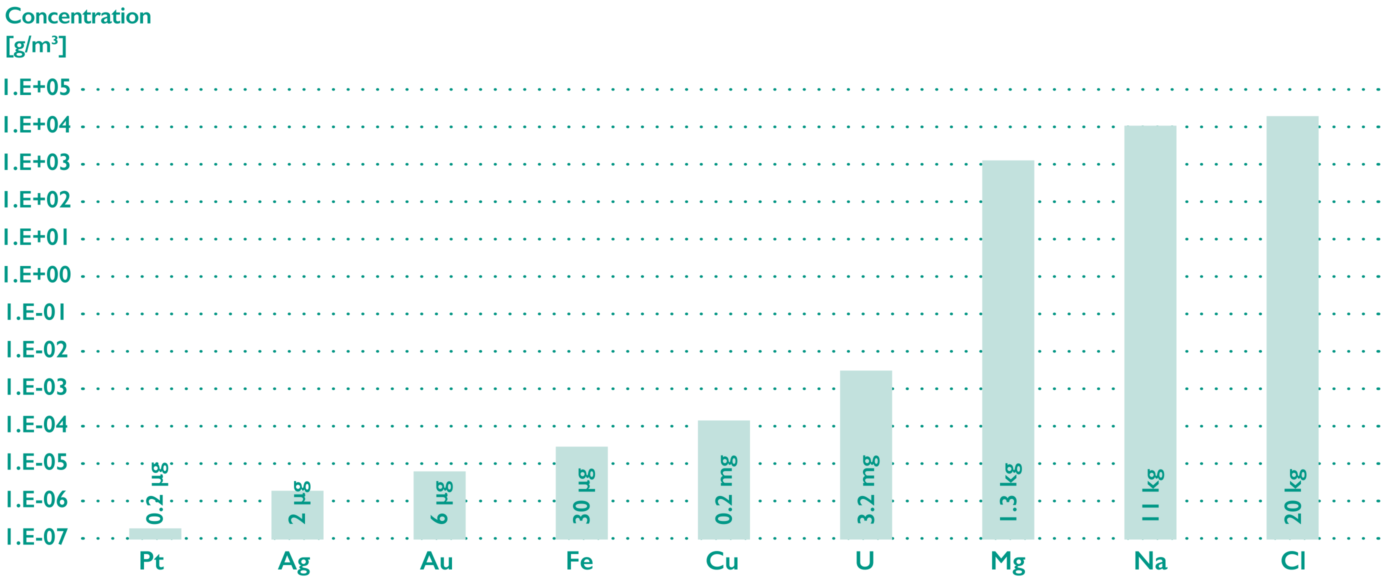
The importance of dilution is not only relevant when deriving materials from primary ores. The rules are the same for secondary resources. Metals that exhibit a low concentration in products and further downstream in waste streams show a quite low recycling rate.[30]

Fig. 5 | Material price as a function of energy intensity

(i.e. energy required to produce a material from its raw form, per unit mass of material produced).

Source: Mahfoud and Emadi, 2010[19] and Gutowski et al, 2013 [26]

Fig. 6 | Concentrations of selected elements in sea-water



Source: Haraguchi, 2004[29].

Indicators

In order to compare different recycling procedures indicators are required. However, there is no common sense which indicators should be used. Table 4 shows different possibilities to evaluate recycling processes. The classification represent more qualitative approach. For instance, it is not a priori clear which degree of processing is optimal. It is also unclear how to quantify the quality of a material and thus how to calculate a value for quality efficiency.

However, indicators are not only required to compare different recycling schedules but also to compare recycling with other options. Without doubt recycling exhibits several benefits but there might be good reasons to privilege energy recovery.[31]

It seems quite easy to use resource efficiency as criterion for evaluating waste management options such as recycling or incineration. However, there is also a wide variety of indicators for resource efficiency.[32] As pointed out by Allwood et al.[33] material efficiency is in competition with energy efficiency.

In order to get a better picture of the impacts of resource use and the benefits of resource efficiency is has been suggested to use four key areas of impact: material, water, land use and carbon as sketched in Figure 7.[34, 35 ,36]

It is has to be pointed out that all indicators take a life-cycle perspective.[35] Table 5 illustrates the suggested set for two exemplary levels: the product level and the national level.[35]

Lang-Koetz et al.[36] concluded that, due to the complex and complicated topic, it is hard to find quantitative estimations for resource input and resource efficiency potentials.

It is evident that the evaluation of resource consumption is not a simple task and in the literature several methods are available as summarized in Table 6.

Tab. 4 | Indicators for evaluating the efficiency of recycling

(A) CONSIDERING THE DEGREE OF PROCESSING

Product recycling	Chemical and physical constitution of a material is maintained
Material recycling	Physical but not the chemical constitution is destroyed
Feedstock recycling	Physical as well as the chemical constitution is altered

(B) CONSIDERING THE ALLOCATION PROCEDURE

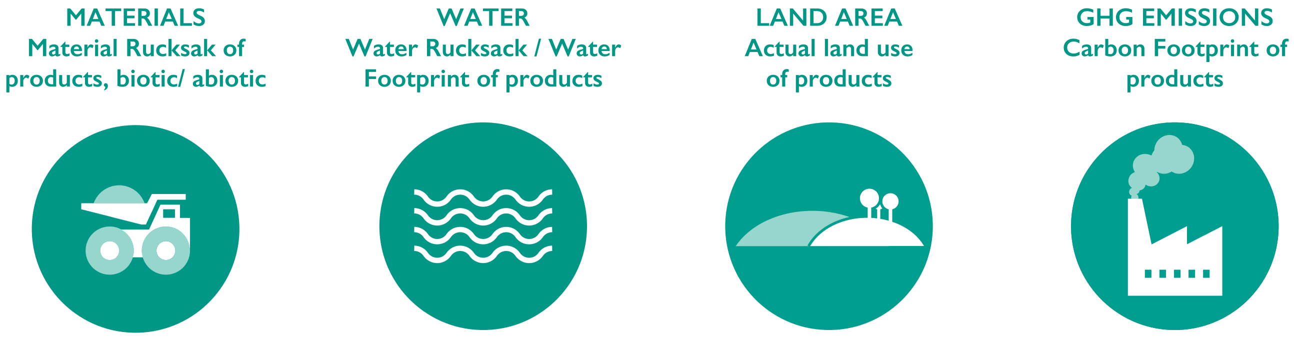
Closed-loop recycling	Recycled into the same product systems No changes occur in the inherent properties
Open-loop recycling	Recycled into other product systems Material undergoes a change to its inherent properties

(C) CALCULATION OF EFFICIENCY ACCORDING TO A FORMULA (ANALOGUE TO R1 FORMULA FOR ENERGY RECOVERY)

Material efficiency	Output stream is taken in correlation to the input stream
Energy efficiency	Puts the energy consumption in correlation to the output stream
Quality efficiency	Puts in the correlation of the quality of the output stream to that of virgin material

Source: Bartl, 2014[16]

Fig. 7 Resource indicators according to the European Environmental Bureau



Source: Beasley and Georgeson, 2014[36]

Tab. 5 The suggested system of resource use indicators on the product and the national level

RESOURCES USE CATEGORY		PRODUCT LEVEL		NATIONAL LEVEL	
Materials	Biotic	Material Rucksack of products	Biotic	Material flow-based indicators of countries (including materials embodied in imports and exports)	Biotic
	Abiotic		Abiotic		Abiotic
Water		Water Rucksack / Water Footprint of products		Water Rucksack / Water Footprint of countries (including land embodied in imports and exports)	
Land area		Actual land use of products		Actual land use of countries (including land embodied in imports and exports)	
GHG emissions		Carbon Footprint of products		National GHG emissions (including GHG emissions embodied in imports and exports)	

Source: Gilium et al, 2009.[35]

However, it is well established to use LCA which is an abbreviation for „Life Cycle Assessment“ or „Life Cycle Analysis“ but is also denominated „Cradle to Grave Analysis“. LCA is a technique to assess environmental impacts associated of a product throughout all stages of the life cycle. To conduct a LCA a series of standards have to be respected. Table 7 shows the relevant standards of the ISO 14000 series. Even if LCA is an efficient and robust tool also limits of its use are obvious as listed below.

1. The method is time intensive and costly.

2. A specialist knowledge is substantial.

3. The setting of system boundaries is to a certain extent subjective and makes comparisons difficult. Boundaries may include cradle to grave, cradle to cradle, cradle to gate or gate to gate whereas the fine adjustment of the boundaries is fuzzy.

4. LCA's will become extremely complex when evaluating the end-of-life phase and beyond. End-of-life products can contains numerous materials and contaminants. Cascading means that recycling, recovery, disposal could be applied simultaneously and repeatedly to certain components of a products.

5. There is no generally accepted impact assessment weighting method available.

6. LCA is dependent on the data. There can be uncertainties in data as well as proprietary or confidential data. Frequently there is a lack of comparable and reliable data.

7. Difficulties exist to apply LCA to new process designs.

8. LCAs do not include social impacts and acceptance, pricing, political agendas or regulations.

9. LCA's never give a clear answer, they require interpretation.

Summarizing it can be concluded that a detailed evaluation of recycling processes and its alternatives (re-use, incineration) is essential. There are different tools available. LCA is a commonly used tool showing several advantages but also exhibits distinctive drawbacks. In particular LCA's for cascading models with numerous stages of use are extremely complex. As outlined by Christensen et al.[47] the definition of system boundaries for cascading models exhibit dramatic consequences. However, in particular for the forest industry there exists a lack of specified boundaries.

As all cascades (of carbon based materials) are terminated by an energy recovery step, it has to be pointed out that any impact comparison between recycling secondary raw materials and extracting new virgin materials shall be done on the basis of cost and impacts for extraction and production only. As energy recovery will take place in any case, it should not be included into that calculation.

Tab. 6

Possible indicators for the evaluation of environmental impact of products and services

ABREVIATION	DESCRIPTION	REFERENCES
MFA or SFA	Material Flow Analysis or Substance Flow Analysis	18
CED	Cumulated Energy Demand	38
MIPS	Material Input Per Service Unit	39
SEA	Statistical Entropy Analysis	40, 41
SPI	Sustainable Process Index	42, 43
EF	Ecological Footprint	44, 45, 46

Tab. 7 | Standards of the ISO 14000 series

STANDARD	EDITION	TITLE
ISO 14001 (Technical Corrigendum 1)	11/2004 (07/2009)	Environmental management systems - Requirements with guidance for use
ISO 14004	11/2004	Environmental management systems - General guidelines on principles, systems and support techniques
ISO 14005	10/2010	Environmental management systems - Guidelines for the phased implementation of an environmental management system, including the use of environmental performance evaluation
ISO 14015	11/2001	Environmental management - Environmental assessment of sites and organizations (EASO)
ISO 14020	09/2000	Environmental labels and declarations - General principles
ISO 14021 (Amendment)	09/1999 (12/2011)	Environmental labels and declarations - Self-declared environmental claims (Type II environmental labelling)
ISO 14024	04/1999	Environmental labels and declarations - Type I environmental labelling - Principles and procedures
ISO 14025	07/2006	Environmental labels and declarations - Type III environmental declarations - Principles and procedures
ISO 14031	08/2013	Environmental management - Environmental performance evaluation - Guidelines
ISO 14040	07/2006	Environmental management - Life cycle assessment - Principles and framework
ISO 14044	07/2006	Environmental management - Life cycle assessment - Requirements and guidelines
ISO/TR 14047	06/2012	Environmental management - Life cycle assessment - Illustrative examples on how to apply ISO 14044 to impact assessment situations
ISO/TS 14048	04/2002	Environmental management - Life cycle assessment - Data documentation format
ISO/TR 14049	06/2012	Environmental management - Life cycle assessment - Illustrative examples on how to apply ISO 14044 to goal and scope definition and inventory analysis
ISO 14050	02/2009	Environmental management - Vocabulary

The cascade model

The concept of cascade utilization takes it origin in the field of biomass. According to Arnold et al. three possibilities for using renewable resources exist[48]:

1. Utilization of by-products and joint products.

2. Parallel utilization of products (energy and material).

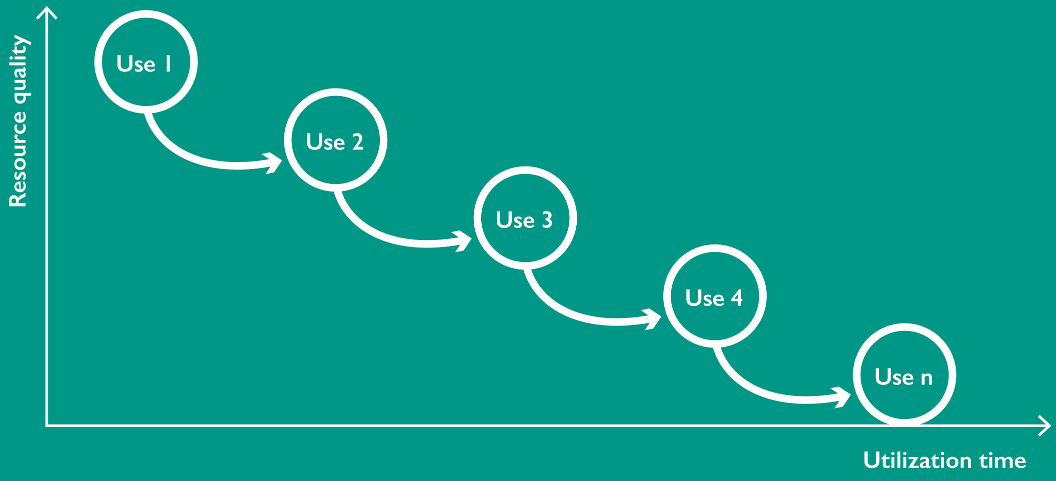
3. Cascade utilization.

In this context cascade utilization defined as the sequential use of biogenic raw materials to produce materials and energy[48]. The concept of resource cascading can be compared to a river flowing over a sequence of falls as shown in Figure 8. The water falls from one level to another until it reaches the lowest level in the cascade.

Transferring the cascade concept of a water fall to use of a resource is sketched in Figure 9. A repeated use of the resource over time takes place. It is obvious that the quality is decreasing over time and for

Image by Valorsul

Fig. 8 | Concept of cascading by repeated using of a resource at decreasing quality



Source: Sirkin and Houten, 1994.[49]

Fig. 9 | Cascade on its path towards equilibrium

Image by Skoeber

each additional utilization a quality drop has to be accepted. However, as the resource is passing through several phases, the overall use of resources is significantly reduced. It is also sketched that different possibilities for cascades are possible.

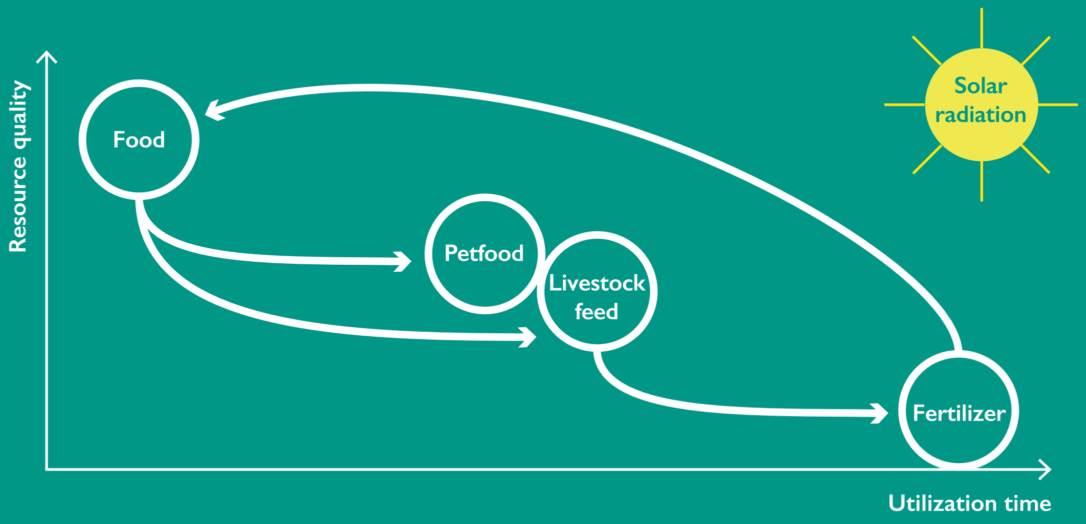
In 1992 Janicki et al. used "Material Cascade" for reprocessing rejected plastics parts (Polystyrene, Polycarbonate) during injection molding by defining a cascade method for utilizing regrinds.[50]

Biogenic materials as well as plastics are basically composed of carbon and thus as last step (i.e. if the quality level is not acceptable any more) energy recovery and/or composting ideally terminates the cascade.

The simple resource cascade as sketched in Figure 9 just knows one way. Resource economy is achieved by the stepwise utilization of resources beginning at the highest possible level until the resource is fully exhausted (frequently thermally utilized). However, in contrast to the example of the water falls a resource cascade must not necessarily be a one-way street. Figure 10 sketches a cascade of biomass as it is realized in rural areas for centuries. Food is grown on the fields and in a first step it is used for the preparation of meals. The best quality kitchen waste gets fed to domestic pets first. Food that cannot be consumed by the pets, is fed to other animals such as pigs or chickens. Finally chicken and pig manure is used thereafter as fertilizer. However, the fertilizer is not lost. With the help of solar energy it is recirulated back into a new food cascade. Thus cascading becomes a cycle process.

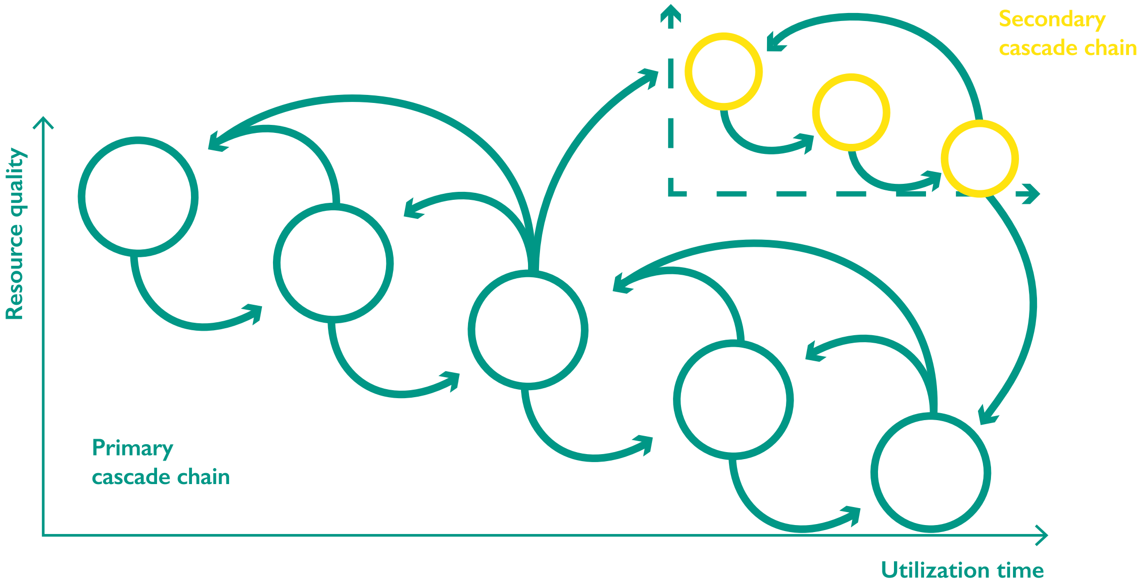
Sirkin and Houten[49] introduced the term resource resource salvageability. The authors assume that resource economy can also be obtained through salvaging and recirculating resource quality back to higher levels of the cascade (similar as solar radiation will help to recirulate fertilizer into the food cascade). Salvageability concerns the degree to which the resource qualities of a substance, material or product can be recirculated. Again, the cascade concept becomes a cycle process. Sirkin and Houten[49] suggested the term cascade chain to express the cyclical behavior. Furthermore, the authors point out that salvation of resource quality is not restricted to the boundaries of the primary cascade chain, but it may be commute to secondary (and even more) cascade chains as illustrated in Fig. 11.

Fig. 10 | The cascade of nutritional quality



Source: Sirkin and Houten, 1994.[49]

Fig. 11 | The cascade chain operates through salvageability



The degree to which a resource quality can be recirculated, regenerated or reprocessed[49]

Source: Sirkin and Houten, 1994.[49]

Recycling efficiency: three model cases

Introduction

The following three types of materials have been evaluated in detail:

- Wood/cellulose
- Iron and steel
- Polyethylene/Polypropylene

These materials are traded in large volumes, represent large commercial values, are handled by the general waste management sector and are already exhibit relatively high recycling rates. Figure 12 compares the annual production of the selected materials (blue columns) with important commodities (in t and m³).

Wood/Cellulose

Annually about 5.7 · 10^{24} J of solar energy is irradiated to the earth. Plants and other photosynthetic organisms (bacteria) utilize about 3 · 1021 J (i.e. 0.05% of total available solar energy) to convert CO_2 into biomass.[56] The basic process of plants to produce carbohydrates is photosynthesis according to Equation 1 and subsequently cellulose is the final product.

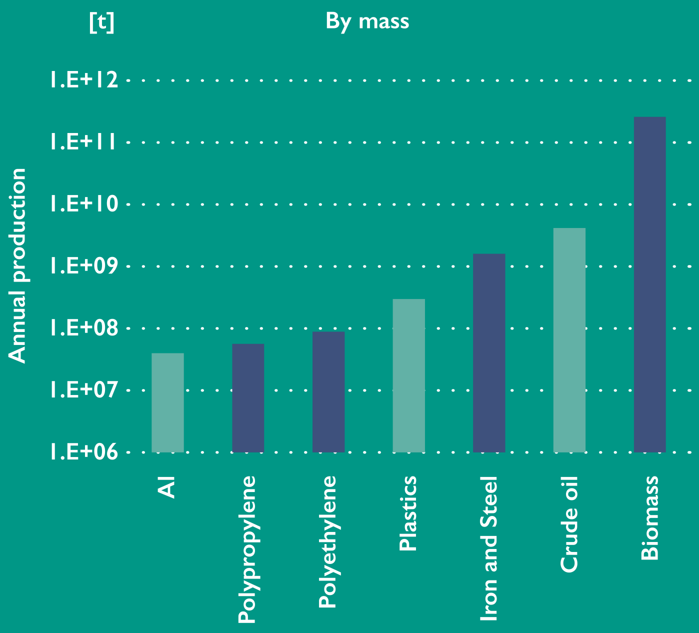
Even if the efficiency of photosynthesis is rather low the global net primary production (NPP) is estimated to be 105 · 109 t of carbon annually.[55] Considering the formation of carbohydrates (Equation 1) a total of about 260 · 109 t of biomass is produced each year. This is several orders of magnitude higher than compared to iron and steel (1.6 · 109 t) or aluminum (40 · 106 t) Further assuming a caloric value of 15 GJ/t the total available energy from biomass is about 2.5 · 1021 J. However, only around 10% of the biomass is potentially available for technical processes which limits the potential for energy utilization to about 0.^{25} · 1021 J. Thus, the utilization of all available biomass could theoretically (efficiency of 100%) cover only about 50% of the annual global energy demand (0.5 · 1021 J in 2010).[57] It is obvious that biomass is a scare product and it should be primarily used as material and only secondly as energy source.

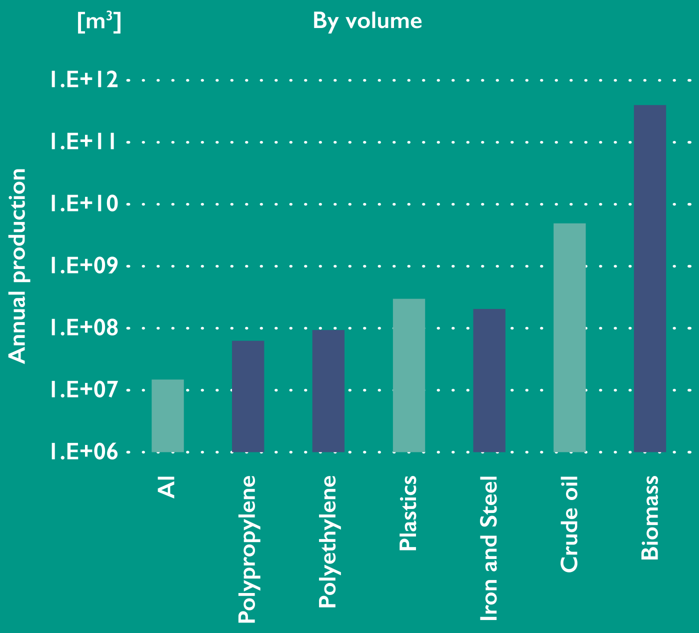
Equation 1

$$CO_2 + H_2O \xrightarrow[\text{plant}]{\text{sunlight}} \underset{\text{carbohydrate}}{[CH_2O] + O_2}$$

Fig. 12

Annual production rates of selected materials





Al by 2013[51]; PE, PP and plastics (including PE and PP) by 2013[52]; iron and steel by 2013[53]; crude oil by 2014[54]; biomass average 1982 to 1990[55]; for calculating the volumes the following densities have been used: Al: 2,700 Kg/m^3; Polypropylene: 900 Kg/m^3; Polyethylene: 9,500 kg/m^3; Plastics: 1,000 Kg/m^3; Iron & steel: 7,800 Kg/m^3; Crude oil: 850 Kg/m^3; Biomass: 650 Kg/m^3.

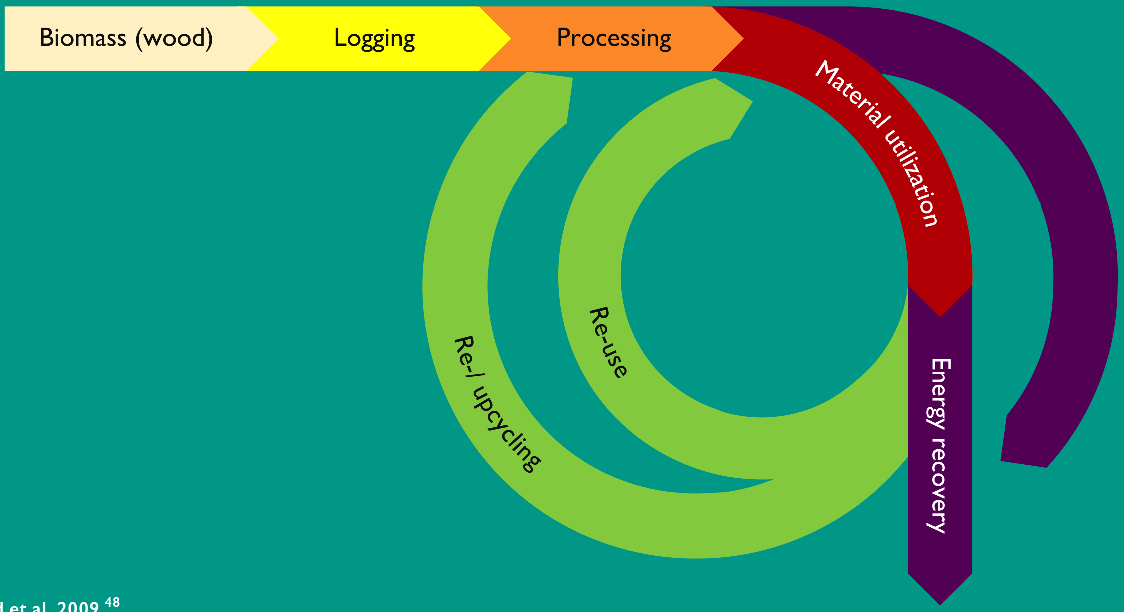
A product of major importance is wood which is a hard, fibrous structural tissue found in the stems and roots of trees and other woody plants. Basically it consists of cellulose (40 – 50%), hemicellulose (15 – 25%) and lignin (15 – 30%). It has been used for thousands of years for both fuel and as a construction material. As sketched in Figure 13 wood should be preferably used in a cascade.

Table 8 shows the utilization of raw wood in Germany. Material utilization contributed to about 70% (64.4 Million m^3]. In particular wood of low quality (e.g. waste wood) is rather used for energy generation.

The data of Table 8 do not give any indication of cascading. However, without doubt cascading of wood shows large environmental benefits. According to Sirkin and Houten[49] and Fraanje[58] cascading of pine wood substantially prolongs carbon sequestration to mitigate climate change. Figure 14 shows a possible cascade for pine wood which is realized in practice in the Netherlands. The total cascade of pine wood covers 7 utilization steps which could can be expanded to more than 350 years[58]. Only recently it has been demonstrated that =] cascading led to savings of up to 14% of the annual primary wood supply[59].

Cascading of wood is already widely used. As it shows considerable advantages it should be applied whenever possible. The cascades can be quite complex, in particular when implementing secondary cascade chains (e.g. production of cellulose fiber). As the final product after the last cascade (i.e. incineration) is CO_2 which is the raw material for photosynthesis, wood cascading is not a one way route but a cycle process.

Fig. 13 | Multiple utilization of biomass (wood) by cascading



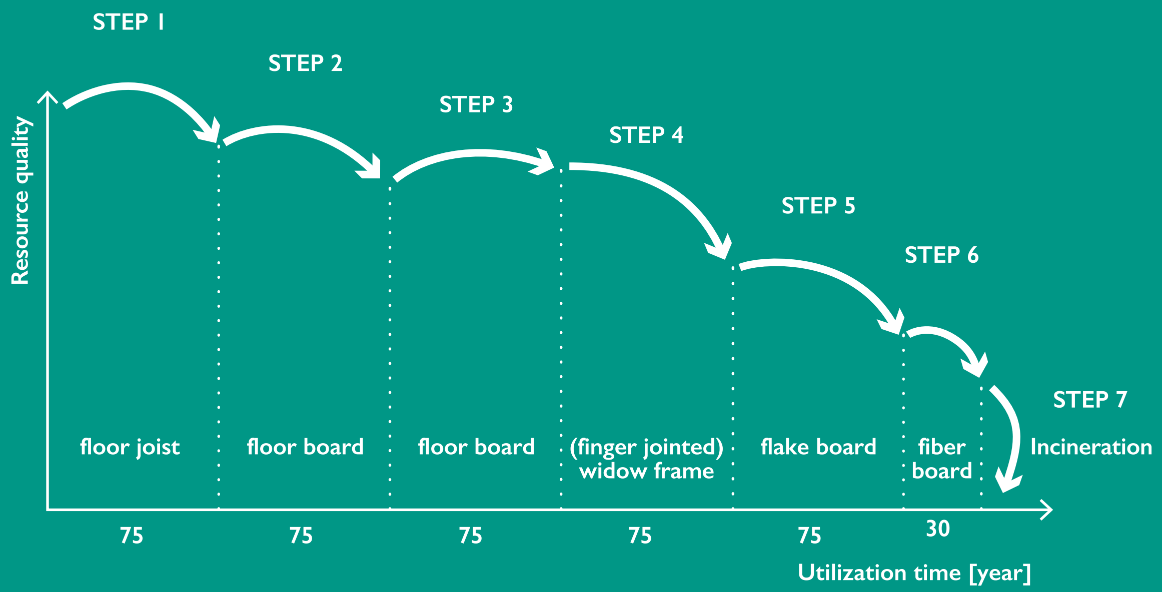
Source: Arnold et al, 2009.[48]

Tab. 8 | Utilization of raw wood in Germany by 2004 in [Million m³]

		MATERIAL UTILIZATION				ENERGETIC UTILIZATION		
ASSORTMENT OF TIMER RAW MATERIAL	VOLUMES OF RAW MATERIAL	PRIMARY LIGNIN	ENGINEERED WOOD	SAWMILL INDUSTRY	OTHER MATERIAL UTILIZATION	FACILITIES (> 1 MW)	FACILITIES (< 1 MW)	DOMESTIC FUEL
Log wood	33.6	-	-	33.3	0.3	-	-	-
Industrial wood	21.0	5.2	10.0	0.1	0.2	0.2	-	5.4
Forest timber remains/ smallwood	7.1	-	-	-	-	-	1.2	5.4
Sawmill by-products	11.8	3.3	5.9	0.2	0.3	1.3	0.4	0.4
Bark	2.4	-	-	-	1.6	0.5	0.3	-
Other industrial waste wood	4.1	-	0.9	-	0.1	2.8	0.4	-
Waste wood	11.0	-	2.6	-	0.3	5.8	1.2	1.2
Landscape conservation wood	0.3	-	-	-	-	0.2	0.1	-
Sum	-	8.5	19.4	33.6	2.7	11.3	3.6	12.3
Total	91.4	64.2				27.2		

Source: Arnold et al, 1994 2009.[48]

Fig. 14 | Possible cascade for thatch reed



Source: Fraanje, 1997.[58]

Low density polyethylene

Plastics play an important role today -they are so common that they are now taken for granted. Basically, plastics are produced from crude oil and thus they are not sustainable. However, the share of plastics compared with total crude oil production is quite low as shown in Figure 15. In 2013 the worldwide production of petroleum was 4.[54] billion t which was mainly used for energy purposes such as heating or transportation.

Polyethylene is a thermoplastic polymer of the Polyolefin group. The polymer was developed by the British company ICI and patented in the 1930s[60] based on a polymerization at high pressure (> 1500 bar) and high temperature (150 – 250°C) which lead to branched polymer chains and a relatively low density (LDPE). Later an alternative route for was developed by the German chemist K. Ziegler[61] at moderate temperature (80 – 90°C) and pressure (1 – 10 bar). The polymerization, for which a catalyst is essential, leads to linear polymer chains and thus to a polymer of high density (HDPE). The same process can be used by adding a certain fraction of another monomer (e.g. butylene, pentene, etc.) leading to well defined side chains, the so called linear low density Polyethylene (LLPDE).[62]

Fig. 15 | Plastics production (in Million t) compared with total crude oil production for 2013

Source: Plastics Europe, 2015.[52] and Fenton, 2015.[54]

Polypropylene

Polypropylene is also a thermoplastic polymer of the Polyolefin group. The patent of Ziegler[61] did mention Polyethylene only but no other polyolefin. During this period Ziegler had a cooperation with the team around G. Natta who was supported by the Italian company Montecatini. Due to this cooperation Natta received the detailed data of the catalysts used by Ziegler and used them for the synthesis of polypropylene which was registered for patent approvals in Italy.[63, 64] As a result decades of legal disputes occurred and great uncertainties about license fees existed. It was not until 1978 when Ziegler was granted the US Patent for Polyethylene.[65]

As the propene molecule is asymmetric, polypropylene can occur in different stereochemical configurations whereas the most important ones are shown in Table 9. The most common type of polypropylene is isotactic configuration (iPP) showing a relatively high crystallinity (60 to 70%). Thus iPP exhibits the highest strength and E-modulus of all types of PP. Thy crystallinity of syntactic PP is significantly lower (30 to 40%) and therefore shows highly transparent and flexible properties. The fully amorphous atactic PP is a waxy, slightly tacky solid.

Polyethylene and Polypropylene are polymerized from the monomer Ethylene or Propylene which is usually a petroleum based raw material. However, Ethylene can also be derived from ethanol by fermentation of the renewable material sugar. The bio-based process is known since the 1940ies but was never used on an industrial scale. Petroleum and bio based Polyethylene are indistinguishable and not biodegradable.[67] Table 10 shows the energy consumption and the solid waste generation for the production of Polyethylene (HDPE and LDPE). Roughly it can be estimated that for 1 t of PE about 2 t of oil are required, whereas one half is used for feedstock the other half for energy.

Polyethylene is the most frequently produced polymer and contributes about 40% to the demand of thermoplastic material and about 30% of overall plastic material[62]. Polypropylene ranks the second most widely spread polymer. By 2013 its market is 56 Million t (i.e. 19% of total polymer market) only surpassed by Polyethylene (76 Million t or 30% of total polymer market).

In 2013 the plastics demand in Europe was 46.3 Million t of which LDPE/LLDPE was 8.1 million t (i.e. 17%), HDPE 5.6 million t (i.e. 12%) for PP 8.7 million t (i.e. 19%). Thus they cover almost 50% of the European market.[52]

Tab. 9.1 | Types of Polypropylene

TYPE OF POLYPROPYLENE	DESCRIPTION
Isotactic (iPP)	All methyl groups are located on the same side of the polymer chain
Syntactic (sPP)	The methyl groups are located on alternating sides of the polymer chain
Atactic (aPP)	The methyl groups are arranged randomly along the polymer chain

Tab. 9.2 | Basic properties of Polyethylene (LDPE and LDPE)

POLYMER GRADE	HPDE	LDPE	LLDPE	iPP
Density [kg/m³]	961.0	924.3	922.0	910
Crystallinity [%]	67	40	40	65
Max. temperature of fusion [°C]	131	110	122	-
Vicat softening point [°C]	127	93	101	-
Short branche	1.2	23	26	-
Tensile yield strength [MPa]	26.5	12.4	10.3	33
Tensile rupture strength MPa]	21.1	12.0	25.3	-
Elongation at rupture [%]	906	653	811	800
Modulus of elasticity [MPa]	885	240	199	1,300

Source: HUG Industritechnik und Arbeitssicherheit, 2015.[66]

Tab. 10 | Total energy and feedstock input and solid waste generation per 1 kg of product

	ENERGY	HAZARDOUS SOLID WASTE	NON-HAZARDOUS SOLID WASTE
HDPE	80.2 MJ	0.93 g	1.28 g
LDPE	82.9 MJ	3.06 g	2.38 g
LLDPE	79.2 MJ	0.56 g	0.84 g
iPP	77.9 MJ	2.28 g	1.84 g

Source: Shen et al, 2009.[67]

To a large extent PE is used for packaging, whereas this trend is even more pronounced for LDPE (75%) than HDPE (60%) as shown in Figure 16. The share of packaging of PP is significantly lower but still of major importance (39%). As packaging usually represents short-lived products it can be assumed that a large fraction of PE and PP put on the market will reach its end-of-life state quite soon and the fraction on stock (e.g. used for building and construction) is rather low.

In 2012 25.2 million t of post-consumer plastics waste ended up in the waste upstream. A total of 62% was recovered through recycling (26%) and energy recovery (36%). Overall 38% still went to landfill.[52] In countries that have set in action a landfill ban the amount of landfilled plastics virtually goes to zero.

As PP and PE are thermoplastics they can be melted and reprocess. However, in practice several barriers exist as the molecular weight is reduced or oxidation might occur. The degree of degradation depends on processing temperature and mechanical stress.[68] During and after recycling the thermo-oxidative degradation of Polypropylene can be controlled by incorporation of proper stabilizers.[69]

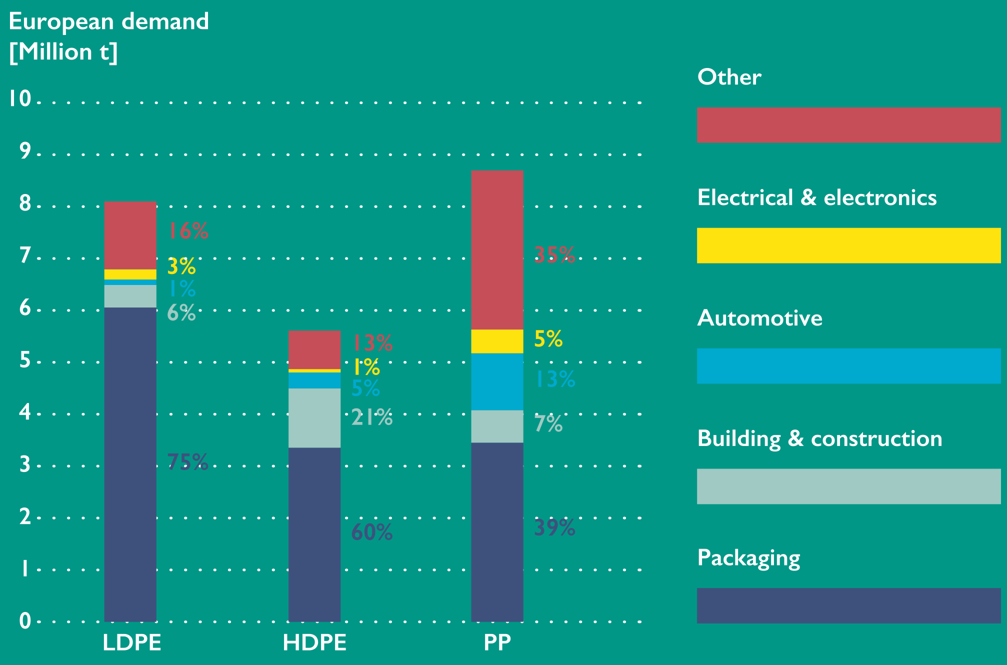
The other limiting problem in recycling of PP and PE is the contamination with other material, plastics as well as non-plastics. There exists a large number of technologies to separate and sort plastics such as:[70]

- Induction sorting
- Eddy current separator
- Drum separator/screen
- Sink-float separation
- X-ray technology
- Near infrared sensor

It is in particular difficult to separate PP and PE as the densities are quite the same. For PET is has been demonstrated that multiple-recycling can reduce the environmental impact of the recycling system.[71] Even comparable studies of PE and PP do not exist a multiple usage of these plastics is highly recommended (i.e. cascading). Figure 17 shows a cascade for PE and/or PP. As today the recovered plastics are frequently "down-cycled" the cascade is quite short. As pointed out by Shen and Worrell[70] it is needed to improve monitoring and track the actual recycling rates to allow optimization and "quality cascading". It should be the aim to generate the highest economic and environmental gain.

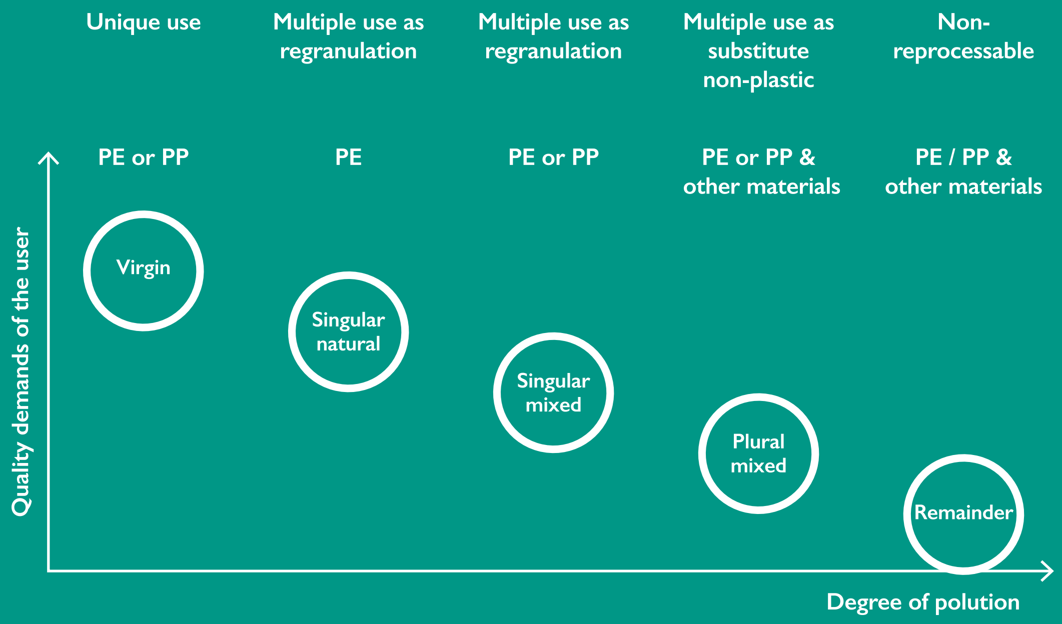
Cascading of plastics is possible and must be terminated by an incineration step (as late as possible). In contrast to bio-based materials such as wood the concept of cascading is not yet well developed for PP and PE.

Fig. 16 European (EU27+NO+CH) markets for Polyethylene and Polypropylene in Europe (in Million t and percentage) by 2013



Source: Plastics Europe, 2015.[52]

Fig. 17 | Re-use of PE and PP



Source: Sirkin and Houten, 1994.[49]

Iron and steel

Iron is the least expensive and most widely used metal today. It was first discovered in the form of the native element, which occurs only rarely as tellurian iron of volcanic origin, and mainly as meteoric iron. The oldest known examples of worked meteoric iron are beads from Gerzeh dated 3,500 B.C.[72]. It is not known when or how iron was first produced from ores, it is estimated that iron was first smelted in eastern Asia Minor and northern Mesopotamia around 2,000 – 1,500 B.C.[72]

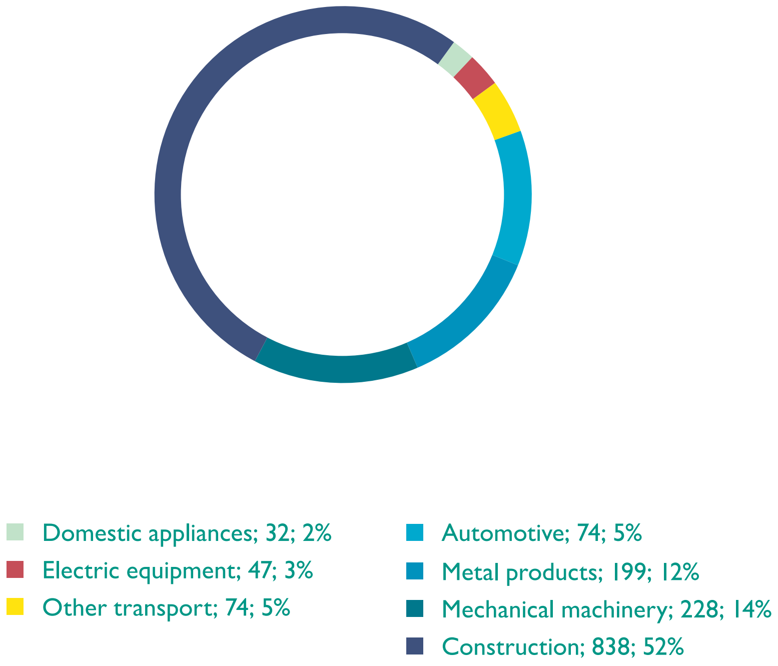
Steel is a general term for materials in which the iron content is higher than that of any other element, and in which the carbon content is normally below 2%.[73] In 2013 the world production of raw steel was 1.[62] Billion t.[53] Steel is thus the most important metal well before Aluminum with 47.6 million t.[51] The major portion of steel is used for constructions such as houses, car-parks, schools or skyscrapers but also on roofs and as cladding for exterior walls.[74] Figure 18 shows the portions of the most important sector. It is obvious that steel is predominantly used for long (e.g. buildings) and medium (e.g. vehicles) lasting goods as demonstrated in Table 11.

Recycling of steel is a very old practice and over centuries a system of scrap collectors and processors have been developed. In 2012 the fraction of scrap for iron & steel production was reported to be around 56%.[76] Figure 19 shows that the importance of crap is quite different for various regions. It is the highest in Turkey (90% scrap use) and the lowest in China (11% scrap use).

A huge amount of steel is on stock and not available for recycling (see the product lifespan shown in Table 11). In industrialized countries the amount of iron stored in applications is between 6 and 16 t/Capita.[77] However, it has been reported that the saturation level for steel on stock is around 13 ± 2 t/Capita.[77] As soon as the saturation level is reached the use of scrap will further increase. It is estimated that by 2050 the share of scrap could reach 80%.[75]

Basically steel is produced via two main routes, the blast furnace-basic oxygen furnace (BF-BOF) route and the electric arc furnace (EAF) route. The BF-BOF is predominately based on ore as raw material, however, scrap is used as cooling agent to avoid too high temperatures during blowing in oxygen. Table 12 compares the main characteristics of both processes.

Fig. 18 | Steel use (in Million t and percentage) by sector in 2013



Source: World Steel Association, 2014.[74]

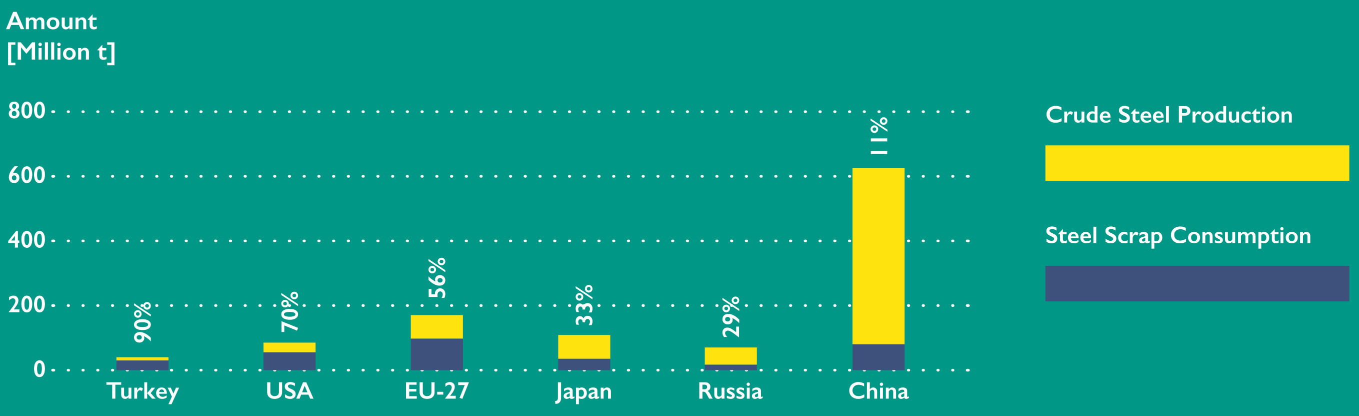
Tab. 11 | Typical steel product lifespan

PRODUCT	TYPICAL PRODUCT LIFESPAN [YEARS]
Buildings	20 – 60
Major industrial	40
Heavy industrial machinery	30
Rails	25
Consumer durables	7 - 15
Vehicles	5 – 15
Steel cans	< 1

Source: Bjoerkman and Samuelsson, 2014.[75]

Fig. 19

Crude steel production and scrap consumption of major countries



The percentage specifies the part of scrap in relation to total steel production of the region.

Source: Bureau of International Recycling, 2013.[76]

Tab. 12

Basic characteristics of the blast furnace-basic oxygen furnace (BF-BOF) and the electric arc furnace (EAF)

	BF-BOF	EAF
Raw materials	predominantly iron ore, coal and steel scrap	steel scrap and electricity
Share of total steel production	70 %	29 %
Share of scrap	15 %	100 %
Emissions	2.1 – 2.5 CO_2/t	0.4 - 0.7 CO_2/t
Energy consumption	21 - 25 GJ/t	8 – 11 GJ/t
Virgin material consumption	2.8 – 3.0 t/t	0.2 - 0.3 t/t

Source: Bjoerkman and Samuelsson, 2014.[75] and Laplace Conseil, 2013.[78]

The data demonstrate impressively that recycling of steel is a good thing. It helps to save energy and resources and significantly decrease emissions of greenhouse gasses. Even if it can be concluded that the production via the EAF route is less energy intensive (and less CO_2 insensitive) it is, however, specifically pointed out that due to the different products and qualities the processes and are therefore not totally interchangeable.

Cascading of steel is only an auxiliary construction. On the one hand iron as a metal will show no degradation as observed for cellulose of polyethylene. Steel produced from secondary resources can exhibit the same properties as steel produced from virgin ores. However, it has been shown above that a recovery rate of 100% is impossible as a certain portion will be lost due to dissipation and incomplete collection. On the other hand the commonly used last step of cascading, incineration, is not a feasible solution for steel. The major limitation in steel recycling are tramp elements which can concentrate in the iron and decrease the properties.

Cascading in the field of iron and steel thus means that (secondary) resources that contain high amounts of impurity elements can only be used for lower qualities of steel. Table 13 compares typical level of impurities of some (secondary) raw materials with the specifications of some steel grades. It is obvious that scrap that shows a high content of impurities is only feasible for low quality. It is reported that steel scrap from WEEE typically contains Copper at a concentration of 2.3%. However, different types of scrap or scrap and virgin ore can be mixed in order to achieve the required specifications.

As mixing of different grades of raw materials makes it possible to obtain a virtually closed cycle without a drop of quality. However, it has to be pointed out that all tramp elements are irreversibly fed to the iron cycle. As global recycling rates will further increase (up to 80%[75]) the issue of tramp elements will become more important in the future. The minimization of the detrimental carryover of tramp elements is thus of great importance. The actions as summarized in Table 14 seem to be feasible to reduce the problem.[75]

Steel recycling is a highly attractive policy to reduce the consumption of energy and resources. Cascading in this context means to consider possible but un-removable contaminants in the iron cycle which commonly means that a lower product quality has to be accepted. However, as there is no danger of destroying chemical bindings the major limit of recycling are unavoidable losses.

Tab. 13 Typical content of impurity elements (Cu, Sn, Ni, Cr, Mo) in different types of raw materials and requirements for production of different steel grades

RAW MATERIALS	TOTAL IMPURITY* CONTENT [MASS %]	STEEL GRADE	MAXIMUM IMPURITY* CONTENT [MASS %]
Direct reduced iron	0.02	Tin plate for draw and cans	0.12
Pig iron	0.06	Extra deep drawing quality sheet	0.14
No. 1 factory bundles	0.13	Drawing quality and enameling steels	0.16
Bushelling	0.13	Commercial quality sheet	0.22
No. 1 heavy melting	0.20	Fine wire grades	0.25
Shredded auto scrap	0.51	Special bar quality	0.35
No. 2 heavy melting	0.73	Merchant bar quality	0.50

Source: Bjoerkman and Samuelsson, 2014.[75]

Tab. 14 Possible actions to minimize the pickup of tramp elements to the iron

ACTION	DESCRIPTION
Design for recycling	Proper choice of materials placed together. Easy separation of crucial parts. Still large room for further improvements.
Improve sorting at the shredder plant	Tramp elements have been much in the focus in the 1980ies and 1990ies as that time sorting technologies have not yet been well developed. Shape-sensitive magnetic separator can generate fraction high and low in contaminants[79]. Sensor sorting. Better knowledge of composition of scrap.
Improve processing at the steel plant	Keep scrap with high Cu content in separate loop Processes that allow higher tolerances for impurity processes (e.g. direct casting)
Live with impurities	Development of new alloys that can accept higher levels of impurities. Precipitating nanoscale copper sulfides.
Dilute	Mix scrap with other ore-based iron units. Direct reduced Iron (DRI). Hot briquetted Iron (HBI).
Understanding of steel flow	Improve the understanding of steel flow in the society. Model the accumulation of impurity elements. Material Flow analysis (MFA). Substance Flow analysis (SFA).

Discussion, analysis and conclusions

Efficiency

Due to unavoidable losses (dissipation) and mixing of materials (intentionally or unintentionally) a recycling rate of 100% is in practice impossible. Furthermore all recycling procedures require energy. Commonly recycling schedules are quite intricate and show large deviations in terms of input materials (e.g. concentrations, contaminations), output materials (e.g. purity) and process details (e.g. energy consumption, emissions). A comparable criterion to incineration (i.e. R1 formula according to WFD) would be urgently needed as it moved the sector towards higher efficiency. Velis and Brunner[80] conclude that, so far, there is no adequate measure available.

Quality

A more or less pronounced drop of quality has to be accepted during utilization as well as during processing of materials or products. For some recycling schedules the quality drop is negligible (e.g. metal recycling) but for others the quality drop is very high (e.g. recycling of mix plastics). Frequently in case of a distinct loss of quality the recycling process is regarded as "down-cycling". However, the quality drop can hardy be quantified. Again there is neither a simple criterion or formula to compare recycling processes amongst themselves nor with other options (e.g. incineration). The need for quality has been outlined by Velis and Brunner.[80]

Measuring quality and efficiency

There exists a number of procedures to evaluate the environmental impact of products or services. It is therefore reasonable to apply such indicators for different options in waste management. LCA is one of the most common quantitative methodologies for assessing the sustainability of human activities. It is exactly defined in a series of international standards which guarantee that different studies will receive comparable results. However, it is possible that different input conditions exist (e.g. local electricity mix) or different system boundaries are defined. The result of an LCA is therefore not a single number but a set of impacts that have to be weighted and can be interpreted more or less randomly.

Can recycling close the loop?

European legislation is currently promoting a so called circular economy. It is based on high recycling rates (e.g. 90 for metal) in order to decrease the demand (and import) of raw materials. Even if recycling is an excellent policy to save resources and energy, one has to consider its limitations. Each cycle has leakages. As recycling scheme differ a lot in terms of quality and efficiency (see above) and evaluation of complete product chains (including cascades) is required. However, an evaluation of cascade chains is an elaborate task but offers much better results than a pure determination of recycling rates.

Cascading

Cascading takes into account the inherent loss of quality over time. It took its origin in the field of biomass utilization. However, it seems possible to extend the concept to other materials. Basically a resource is sequentially used over time with decreasing quality. Incineration should take place as last step only if material use is completely impossible.

The concept is widely used for bio-based materials such as wood. As the generation of cellulose picks up CO_2 from the atmosphere, cascading represents a cycle process. In the last step the biomass can be used as fertilizer or fuel. In both cases the carbon is fed back.

As plastics are based on fossil carbon sources (petroleum) a plastics cascade cannot be a closed loop. Today cascading of plastics is not far developed and a large room for further improvements is obvious. Iron as a metal might undergo a cascade utilization with some restrictions. The material will not degrade itself but due to contaminations. As several contamination will decrease the properties the material can be used within the cascade at lower quality. However, the cascade is not terminated by incineration. It can be, theoretically, infinite but in practice unavoidable losses requires additional input of virgin materials.

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Acknowledgments

Reference Group and Contributors: We would like to express our gratitude towards the Reference Group of the Task Force on Resource Management who were continuously consulted and who provided inputs and guidance to the Reports. The Members of the Reference Group were: Elisa Tonda (UNEP DTIE), Heijo Scharf (Avfalzorg), Jean-Paul Leglise (ISWA), John Skinner (SWANA), Liazzat Rabbiosi (UNEP DTIE), Patrick Dorvil (EIB), Peter Börkey (OECD), Sarah Sanders Hewett (ERM), Tore Hulgaard (Rambøll). Furthermore, we would like to thank the ISWA Board Members and the Scientific and Technical Committee Members for their contributions to the Task Force outputs through suggestions, written and in person comments and participation at the Task Force related sessions and workshops organized in September 2014 in Sao Paulo (ISWA World Congress 2014), and in June 2015 in Paris (Task Force on Resource Management workshop). Finally, we would like to thank the various experts and consultees who advanced the report quality through their valuable insights.

Layout and Design: Ana Loureiro and Deslink Design

Photographs and graphics: Photographs and graphics were provided and developed by Deslink Design using existing graphics with the permission of the credited authors.

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