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AWARE

Raising public awareness on electronic waste as a source of valuable materials

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Introduction

In a modern society our lives are very much dependent on electronic devices. Typically, in a traditional linear economy, electronic devices are manufactured from natural resources, then used for a certain period of time, and eventually thrown away. When these devices are no longer needed, they become e-waste, and are regarded as a problem. However, in a circular economy, e-waste can be regarded also as a resource, instead of just waste. Most of us would not throw away expensive jewellery, but used electronics are often discarded to the bottom of the drawer or even thrown into landfills. Yet, many of the materials in e-waste are valuable and/or rare, such as gold or platinum. Thus, it makes sense to recover the valuable materials in e-waste and ensure the sufficiency of these resources for future generations.

This short introduction to e-waste and circular economy explains why it is important to recycle. The aim is to share awareness of the large variety and amount of e-waste that we produce, the valuable materials that are contained in e-waste and the benefits of recycling these devices. The life cycle of electronic devices is briefly covered. In addition, the basics of circular economy and waste hierarchy are explained in relation to e-waste.

This content is aimed at teachers at different school levels, but also for anyone interested in the materials, life cycle or sustainability of electronics. The topics introduced here may be brought into different classes including chemistry, geography and other science classes but also for example English classes. The material also contains some tasks that can be used in class or given as homework for children. Further suggestions how to implement the e-waste and circular economy topics in different lessons is included in the document AWARE – notes to teachers.

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Suggestions for learning targets for schoolchildren of different ages

Primary school (7-12 years old):

- The student understands what is electrical and electronic equipment (EEE), recognizes different types of EEE and understands when they become waste
- The student understands that e-waste consists of different materials, some of which are valuable.
- The student understands that e-waste should be recycled

Secondary school (13-15 years old):

- The student is aware of the large variety of different electrical and electronic equipment (EEE)
- Student understands the consumer's role in the generation of e-waste
- The student understands that e-waste consists of different materials (e.g. metals, plastics…), some of which are valuable and/or rare.
- The life cycle of electronics
- The student understands the benefits of e-waste recycling and knows how to recycle e-waste

Upper secondary school (16-18 years old):

- Student understands the consumer's role in the generation of e-waste
- The student understands that e-waste consists of different materials (e.g. metals, plastics…), some of which are valuable and/or rare.
- The value chain of electronics
- The student understands the benefits of e-waste recycling and knows how to recycle e-waste
- The student understands the environmental and social sustainability aspects of the production and recycling of electronics.

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List of words

Electrical and electronic equipment (EEE)

Electrical and electronic equipment include many different type of devices from large household equipment such as washing machines to small devices such as mobile phones. They all use electricity to function, and contain either a power cord or a battery.

E-waste or WEEE

When electronic devices break or are otherwise discarded by their owner, they become waste, also called WEEE (waste electrical and electronic equipment) or e-waste.

Circular economy

Circular economy is an alternative to a traditional linear economy (make, use, dispose). Circular economy is an economic system aimed at eliminating waste and the continual use of resources. Circular systems employ reuse, sharing, repair, refurbishment, remanufacturing and recycling to create a closed system, minimising the use of resource input and the creation of waste, pollution and emissions.

Conflict minerals

Conflict minerals are natural resources that are extracted in a conflict zones and their trade can be used to finance armed groups. Most common examples are tin, tungsten, tantalum and gold, which are extracted from the Democratic Republic of the Congo (DRC) and are used in everyday products such as mobile phones.

Critical raw materials (CRM)

Raw materials that are economically important for the European economy but have a high risk in their supply.

Planned obsolescence

Planned obsolescence means planning or designing a product with a limited useful life. Thus, the product is replaced with a new one after a certain time instead of being designed to last longer or to be repaired.

Printed circuit board (PCB)

Printed circuit boards are found in nearly every electronic device and their purpose is to electrically connect different components in a compact space and to act as mechanical support.

Rare earth elements (REEs)

A set of seventeen chemical elements in the periodic table, specifically the fifteen lanthanides plus scandium and yttrium. They are usually used in electronics in very small amounts, but they are vital for many high-tech applications due to their unique properties.

Urban mining

Production of raw materials from waste, spent products or buildings.

Waste hierarchy

A method that lists waste management options in an order based on what is best for the environment.

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What is WEEE or e-waste?

Every day we use many electrical and electronic devices: they take care of our communication, entertain us, heat or keep our food cold, help us clean our houses, dishes and clothes, provide lighting, etc. Most of the devices we use often are so familiar that we rarely pay much attention to them - at least if they are working properly. When these devices break or are otherwise discarded by their owner, they become waste, also called WEEE (waste electrical and electronic equipment) or e-waste. WEEE includes a large variety of products, which can be grouped into six main categories:

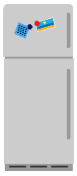
Temperature exchange equipment (cooling and freezing equipment) such as refrigerators, freezers, air conditioners and heat pumps.	
Screens such as televisions, monitors, laptops, notebooks, and tablets.	
Lamps such as fluorescent lamps, high intensity discharge lamps and LED lamps.	
Large equipment such as washing machines, clothes dryers, dishwashers, electric stoves, large printing and copying machines and solar panels.	
Small equipment such as vacuum cleaners, microwaves, toasters, electric kettles, electric toothbrushes, cameras, small electrical and electronic tools and electronic toys.	
Small IT equipment such as mobile phones, pocket calculators, printers, telephones.	

Figure 1. E-waste can be divided into many different categories.

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Facts and Figures: *The average number of electrical and electronic equipment (EEE) in EU is 44 products (plus 45 lamps and light fittings) or 248 kg per person. This includes all of the EEE that are in use or stored in households, businesses and public spaces.*

Task: *Count the number of electronic devices in your home. Are there devices that are broken or are no longer in use? Which electronic devices have you used today?*

E-waste is one the fastest growing waste streams in Europe and globally. Every year, around 45 Mt (45,000,000,000 kg) of electrical and electronic equipment end up as waste globally. This amount is equivalent to 4,500 Eiffel towers. Moreover, the generation of WEEE is predicted to grow and exceed 50 Mt by 2020. Only in Europe the amount of e-waste generated annually is around 12 Mt, an amount which equals to the mass of 1,200 Eiffel towers. This means over 16 kg of WEEE per inhabitant in Europe, while the global average is 6 kg of WEEE per inhabitant.

Facts and Figures: *45,000,000,000 kg of e-waste is generated every year, which equals to almost 4 500 Eiffel towers.*

Facts and Figures: *In Europe the amount of e-waste generated per person per year is 16 kg, whereas the global average is 6 kg per person per year.*

What materials are found in e-waste?

E-waste contains a wide variety of materials, some of which are common bulk materials whereas others are highly valuable and/or rare. These materials include

- base metals such as aluminium, copper, iron, nickel, zinc, tin
- precious metals such as gold, silver, platinum, palladium
- rare earth elements (REEs, see info box on next page)
- plastics, glass, ceramics

Typically iron, steel, aluminium, copper and plastics make up a major part of the mass in electronic devices. For example in refrigerators, steel and plastics are typically over 90 % of the total mass, and in mobile phones plastics and ceramics make up around 2/3 of the total mass.

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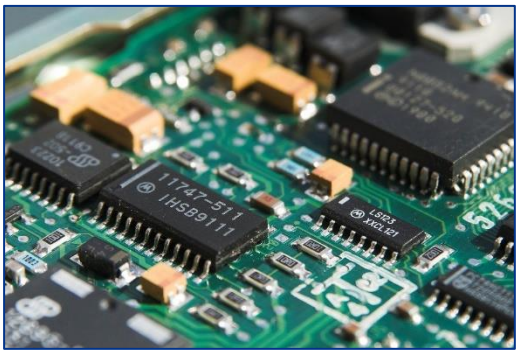

Precious metals and rare earth elements are found in small amount in electronic devices. However, they can still contain a major part of the device's material value. Precious metals are especially concentrated in **printed circuit boards (PCBs)** which contain for example gold, silver and palladium. Printed circuit boards are found in nearly every electronic device and their purpose is to electrically connect different components in a compact space and to act as mechanical support.

Rare earth elements (REEs) mean a set of seventeen chemical elements in the periodic table, specifically the fifteen lanthanides (cerium, dysprosium, erbium, europium, gadolinium, holmium, lanthanum, lutetium, neodymium, praseodymium, promethium, samarium, terbium, thulium and ytterbium) plus scandium and yttrium. They are usually used in very small amounts in electronics, but they are vital for many high-tech applications.

Examples of metals and their use in electronic devices:

- **Copper (Cu)** is used for wiring and printed circuit boards in the electronic devices because of its high electric conductivity.
- **Gold (Au), silver (Ag), platinum (Pt), palladium (Pd)** are used in printed circuit boards (PCBs).
- **Neodymium (Nd) and praseodymium (Pr)** are used in magnets in hard disk drives. Neodymium magnets are the strongest permanent magnets known.
- **Cobalt (Co)** is used in lithium ion batteries which are used as power sources in mobile phones, tablets, laptops and other portable electronic devices.
- **Indium (In)** is used in liquid crystal displays (LCD panels) found in many applications which have screens (for example LCD televisions, computer monitors and mobile phones).

Facts and Figures: *In complex electronics, such as mobile phones, up to 60 elements from the periodic table can be found.*

Facts and Figures: *The value of precious metals and plastics contained in one mobile phone (with an average weight of 90 g) is approximately 2 €. However, when we consider the total amount of mobile phone waste generated globally in one year the value adds up to 9.4 billion €!*

Task: *How many discarded mobile phones are there in your home? Based on this, estimate the amount of gold in discarded mobile phones in your country and its value. (Hint: one mobile phone contains approximately 0.03-0.04 g of gold, and the price for gold is approximately 45,000 €/kg (in January 2020, for current price check LME.com)).*

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Examples of critical raw materials used in electronics		
antimony beryllium cobalt gallium germanium	indium palladium platinum REEs (rare earth elements)	scandium tantalum tungsten vanadium

Many elements that are classified **as critical raw materials (CRM)** are used in different electronic devices. CRMs are raw materials that are economically important for the European economy but have a high risk in their supply. An example of CRMs **are rare earth elements (REE)**, which are used in many electronic applications. Because of their unique properties, these elements are crucial in many high tech applications and are difficult to substitute with other materials. REEs are mainly produced in China (95 % of world production in 2010-2014). Despite of their name, rare earth elements are not especially rare, but are typically not found in rich deposits and are thus laborious to extract from the earth.

In addition to valuable and rare materials, e-waste can also contain substances harmful to people and the environment. Thus, recycling WEEE through an official recycling system is important for both recovering the valuable materials but also for preventing hazardous substances from entering the environment. Improper management of e-waste also poses a risk for the people working with waste management.

Examples of hazardous substances found in e-waste:

- **Brominated flame retardants** such as polybrominated biphenyls (PBB) and polybrominated diphenyl ethers (PBDE). Flame retardants are used e.g. in plastics to reduce their flammability and improve product safety.
- **Chlorofluorocarbons** (CFCs). CFCs have been widely used as refrigerants. Some of the CFC compounds are detrimental to the ozone layer and thus their use has been prohibited.
- **Heavy metals** are used for various purposes in electronic devices. Many of the heavy metals (such as cadmium, lead and mercury) are toxic even in low concentrations and tend to accumulate in living organisms.

Life cycle of electronics: from mining to recycling

Many of the electrical and electronic devices are complicated products that contain numerous materials and components. As a result, their life cycle involves numerous steps, starting from the mining of the raw materials, and refining and using these materials for the manufacturing of components for electronics. The manufactured products are then packaged and transported to retailers before finally being used. Ultimately the discarded products are collected and recycled. These steps are presented in the Figure 2 and, as an example, the life cycle of cobalt used in electronics is described more in detail.

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Figure 2. Life cycle of an electronic device (or any other product manufactured using natural resources) in a circular economy. (Picture: EIT Raw Materials)

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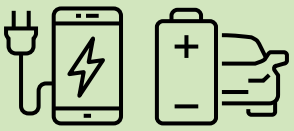
Example: Cobalt (Co) in a lithium ion battery

Cobalt is a metal that is used for example in lithium ion batteries for consumer electronics and electric cars. The demand of cobalt is predicted to increase rapidly in the future due to the increasing number of electric cars and portable electronics. The life cycle of cobalt from ore to the consumer product such as a mobile phone includes numerous phases, and it has been estimated that the cobalt in your mobile phone battery might have traveled close to 30,000 km before being purchased in Europe!

- **Raw materials:** Cobalt is mainly extracted as a by-product of nickel or copper. 65 % of the total production of cobalt is from mining and 35 % from secondary sources such as spent batteries. The major part of the global cobalt production originates from the Democratic Republic of the Congo (DRC), Zambia or the Central African Republic. It has been estimated that 10 % of the cobalt mined in DRC originates from small-scale mining, often in dangerous working conditions. Also child labour is reported in this informal sector.
- **Processing:** Co-containing ores are processed into different chemicals (sulphates, oxides) which are further processed to materials used in lithium ion batteries (for example lithium cobalt oxide ($LiCoO_2$)).
- **Manufacturing:** Lithium ion batteries are manufactured from various chemicals and components. In addition to lithium cobalt oxide, graphite, aluminium, copper, plastics etc. are needed. Lithium ion battery is then used in portable consumer electronics such as mobile phones or tablets. These devices are manufactured in a separate factory, typically in China and India which are the two largest mobile phone manufacturers in the world.
- **Use:** The typical lifetime of a smartphone (including the battery) is 2-3 years before being replaced with a new device.
- **Recycling:** When the mobile phone is no longer used by its owner, it should be delivered to recycling where valuable materials can be recovered and hazardous components removed. Cobalt, copper, and nickel can be extracted from the used batteries and processed to chemicals which can be used again for example to manufacture new devices.

Cobalt is a metal that is used for example in batteries of electric cars and smartphones.



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Mining of raw materials

Raw materials for electronics (metals and minerals, oil) are natural resources extracted from the earth and further processed into chemicals and components used in manufacturing electronics. Mining and processing of the materials use large amounts of energy and natural resources and produce greenhouse gas emissions, pollution and mining waste. Using recycled materials for the manufacturing of an electronic device reduces the need for virgin materials obtained by mining and thus potentially reduces the environmental and social impacts of the device.

For example, a mobile phone contains 50-60 different elements from the periodic table. These materials originate from all over the globe. Figure 3 presents the origins of several critical raw materials, many of which are also crucial elements in smart phones and other consumer electronics.

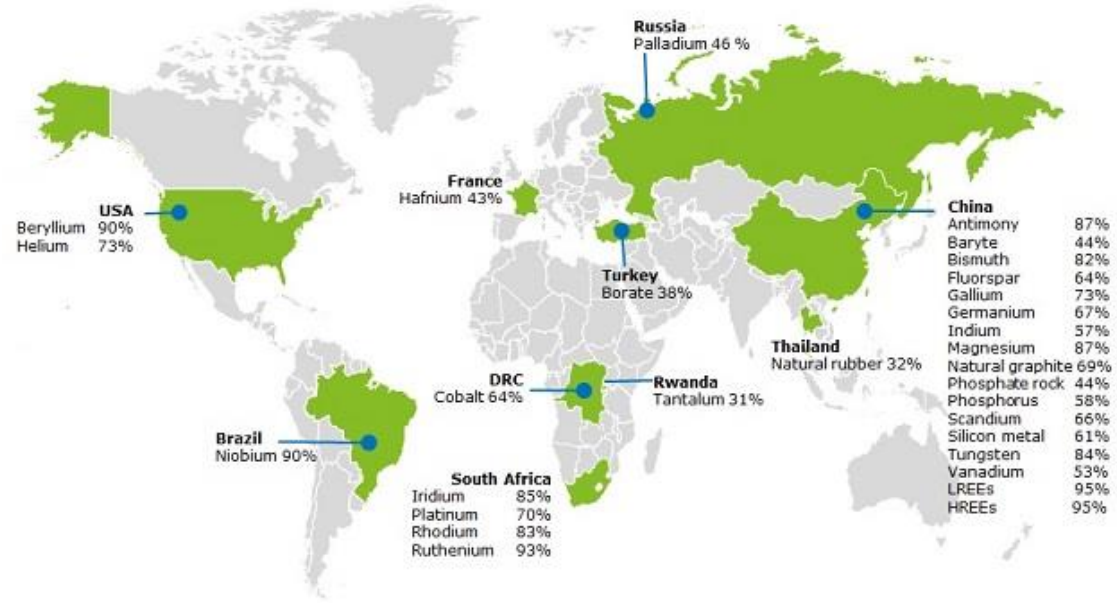

Figure 3. Countries accounting for largest share of global supply of CRMs. (Figure from https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en)

Many of the elements that are used in electronics are scarce and this might lead to shortage of some crucial materials in the future. Figure 4 presents the availability of different elements of the periodic table.

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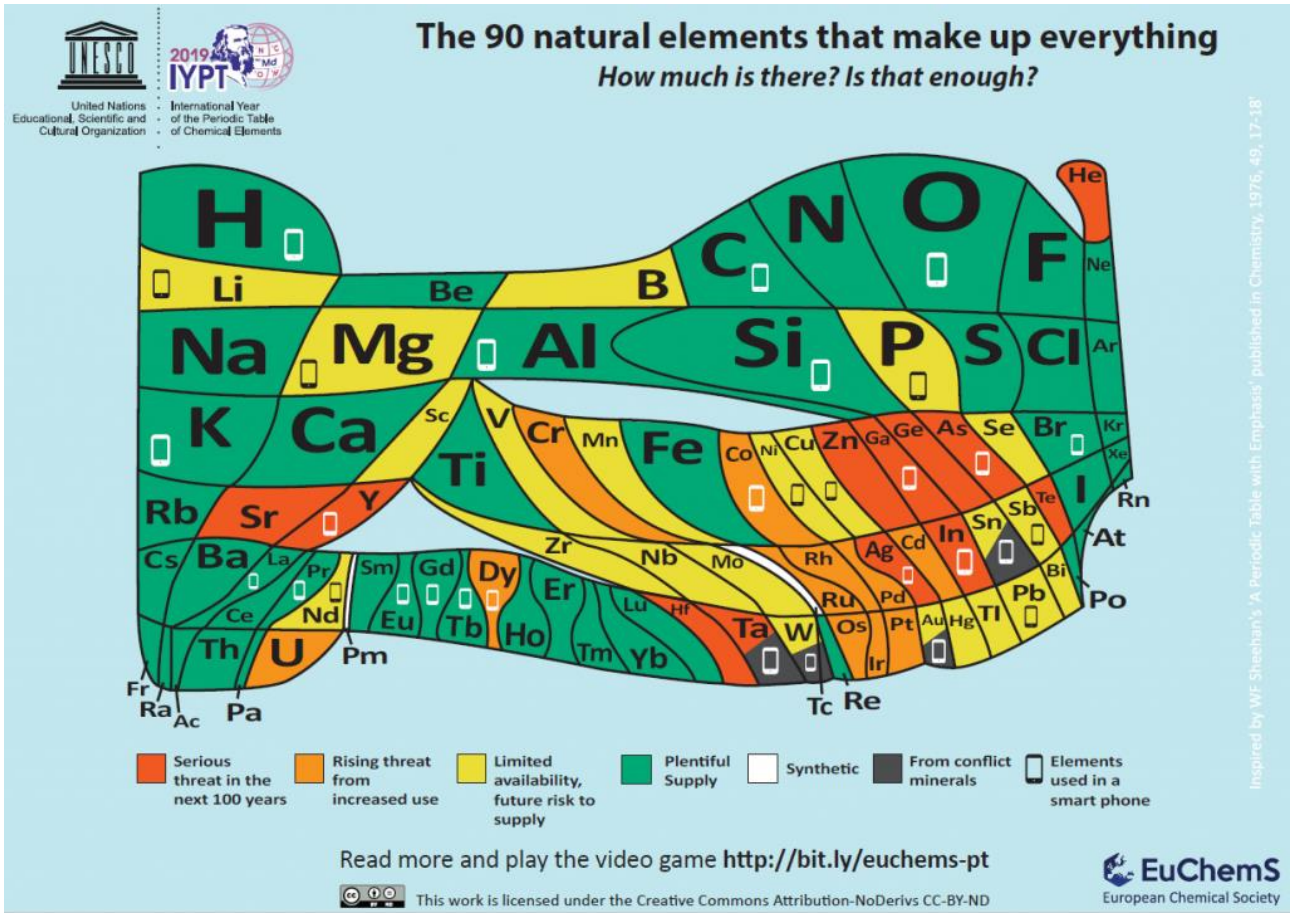

Figure 4. Are there enough materials for smart phones and other electronic devices in the future? (https://www.euchems.eu/euchems-periodic-table/)

Conflict minerals

Conflict minerals are natural resources that are extracted in a conflict zones and their trade can be used to finance armed groups. Most common examples are tin, tungsten, tantalum and gold, which are extracted from the Democratic Republic of the Congo (DRC) and are used in manufacturing everyday products such as mobile phones

Manufacturing of electronic devices

Electronic devices are typically composed of a large number of components which are manufactured in different locations. The production of many of these components requires a lot of materials and energy. For example the manufacturing of semiconductors and microchips requires a clean environment and is very energy consuming.

In smart phones, the key components are printed circuit boards, battery and the screen. Other components include for example antenna, microphone, speaker and casings. Over the years, the components in many devices have become smaller and their number and the amount of elements they contain has increased. This means new fancy functionalities but in the same time the reparability and recycling of the devices has become more difficult.

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Figure 5. Smart phone dissembled into components.

Use

Using habits and lifetimes of electronic devices depend strongly on the device type. For example typical lifetimes are longer for large household machines (such as 11 years for washing machines and 5-8 years for vacuum cleaners) whereas smartphones are products that are typically replaced within 2-3 years of their purchase. For many electronic products, the major environmental impact is caused in the raw material extraction and product manufacturing phase. For example for smart phones only a small part of their total greenhouse gas emissions are caused in the use phase, whereas in case of washing machines the major part of their total greenhouse gas emissions are caused when they are used.

Facts and Figures: *If we could get one more year of use out of all smartphones, laptops, vacuum cleaners and washing machines, we could reduce carbon dioxide emissions by an amount that corresponds to removing 2 million cars from our roads.*

Task: *If you buy a new smart phone every two years and live to be 85, how many phones will you have eventually bought during your lifetime? What if you only bought a new phone every three years instead?*

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Collection of WEEE

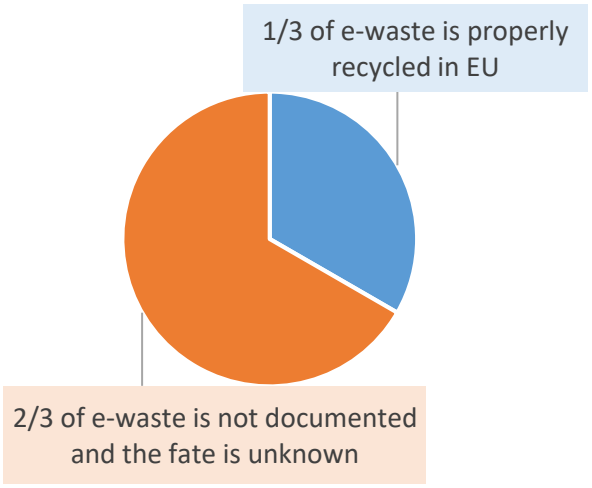
After an electronic product is no longer usable or is otherwise discarded, it becomes waste. Appropriate recycling of WEEE is important for protecting the environment and ensuring the sustainable use of resources. To achieve this we need both

1. a high collection rate of the discarded devices
2. an efficient and safe recycling processes.

Why should we recycle WEEE?

- **Economy:** Recovery of valuable and scarce materials. Additional jobs created in the recycling industry.
- **Environment:** Keep hazardous waste out of landfills. Using recycled materials reduces the demand for virgin materials which can reduce GHG emissions, energy consumption and pollution of water and air.
- **Health and safety:** WEEE contains various hazardous materials, which can damage the health of people if not properly managed.

Globally, only 20% of WEEE is separately collected and appropriately recycled. In the EU, the situation is better but still only 1/3 of WEEE is recycled through an official recycling system. This means a huge amount of valuable resources are lost, as up to 6.5 Mt of WEEE does not reach an official recycling network each year. This amount of WEEE has been estimated to contain 23 tons of gold, 118 tons of silver and 5 tons of palladium.



Part of the WEEE ends up in municipal waste and metal recycling instead of dedicated WEEE recycling. Especially small IT devices such as mobile phones are known to stockpile in people's homes instead of being brought to WEEE collection points. For example, a Norwegian study estimated that up to 10 million discarded mobile phones are being kept in households in Norway. Stockpiling of mobile phones and other devices happens due to various reasons: people tend to keep old mobile phones as spare devices, are not aware of the collection points or collection network is inconvenient, and mobile phones contain personal information and the data security is of concern.

Task: *Do you have mobile phones at home that are not in use anymore? Why have you stored them?*

Task: *Find out where WEEE should be taken in your residential area.*

Facts and Figures: *By recycling 1 million smart phones, it would be possible to obtain as much as 24 kg of gold, 250 kg of silver and 9,000 kg of copper.*

WEEE collected from Europe can also end up in developing countries through unofficial or illegal channels, because the labour costs associated with material recovery are not as high there. This also means that the

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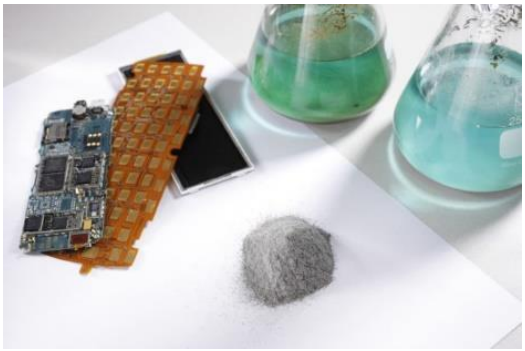
workers in developing countries might not be adequately protected and could work in dangerous conditions. Guiyu in China and Agbogbloshie in Ghana are some of the largest e-waste disposal sites in the world which have received attention and concern in the recent years.

E-waste recycling

After the collection, WEEE is sent to dedicated recycling facilities. Because WEEE consists of a wide variety of materials, recycling typically takes place in several different steps including various different types of treatments. The purpose of these treatments is to get the different materials and elements separated from each other so that the materials can be used again.

- **Pre-processing** includes **dismantling, shredding and mechanical separation** of different material fractions. In the dismantling, both valuable components and hazardous materials are removed from the waste stream before shredding. Shredding processes are used to reduce the size of WEEE and then different type of material fractions are mechanically separated from each other. For example ferrous materials such as iron and steel can be sorted out based on their magnetic properties. Typically several material fractions are obtained from the pre-processing such as ferrous metals, non-ferrous metals, and plastic and other non-metallic fractions.
- **In the end-processing**, different metallic fractions from the pre-processing are further refined which typically includes different types of treatments. For example ferrous fractions are processed in steel smelters to recover iron. **Pyrometallurgical treatment** involves melting of the metals in a high temperature furnace whereas in **hydrometallurgical treatment** metals are leached from the concentrate using strong acids.



What can be recycled then? Base metals such as ferrous metals, aluminium and copper are recycled to a large extent, as well as precious metals (gold, silver, platinum and palladium), but not all metals can be effectively recovered from WEEE. Especially elements that are present in small quantities are difficult to recover. For example the recycling rates of rare earth elements are less than 1 %.

Metals have high economical value and in principle can be recycled endlessly. For plastics, the situation is more difficult as the mechanical properties tend to degrade when processed repeatedly and plastics in e-waste also contain harmful additives such as brominated flame retardants which might prevent their reuse. Thus plastics are often incinerated for energy use. However, it is possible to recycle some types of plastics from e-waste and use them in manufacturing of new electronics for example.

Facts and Figures: *Approximately 1 kg of CO_2 equivalent is saved by the responsible recycling of a single mobile phone handset.*

Facts and Figures: *Using recycled aluminium can save 95 % of energy when compared to using virginal materials. This is because the production of aluminium from primary sources is very energy consuming.*

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Circular economy and WEEE

Today there is a lot of talk about circular economy. So what is circular economy and how is it related to e-waste? Circular economy can be seen as the opposite of today's linear economy. In linear economy products are designed to be manufactured, used and then discarded as waste. In circular economy, products and materials are kept in use, and in the end of product's life, the materials are recycled back to use in new products. Thus, depending on the viewpoint, E-waste can be seen either as a **resource or waste**. The idea is to minimize both the use of raw materials as well as the production of waste. Essentially this resembles the way nature works.

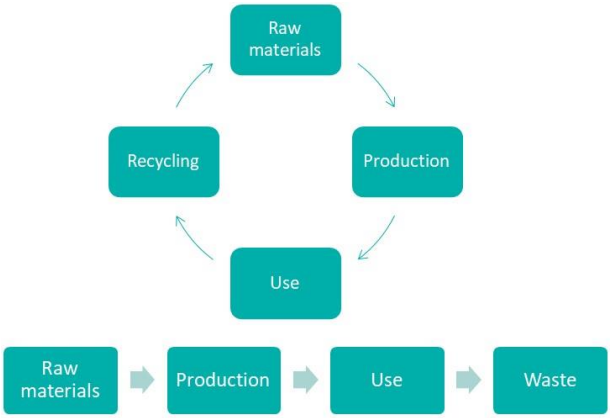

Figure 6. Circular economy (above) vs linear economy (below)

Switching from linear economy to circular economy requires sustainable design of the products. This means products need to be designed as durable, reparable and eventually easily recyclable. An example of a sustainable design is Fairphone, a company which designs and sells modular phones. This enables longer lifetimes as consumers can replace broken components themselves.

Planned obsolescence

Planned obsolescence means planning or designing a product with a limited useful life. For example, if the components in a device are glued together, it is difficult to replace broken components. As a result, the product is replaced with a new one instead of being repaired.

Task: *Watch a video 'Why things don't last':* https://www.youtube.com/watch?v=toIFN8eR0ro

Waste hierarchy is another concept related to waste management and circular economy. Waste hierarchy is a method that lists waste management options in an order based on what is best for the environment.

1. According to waste hierarchy, **reduction of waste** is considered as the best option in the first place. In the context of electronic products, this can mean for example changes in consumer behaviour so that less is consumed, but also designing products so that they last longer.
2. Second option is the **reuse** of the product, for example buying second hand products or repairing used devices.
3. If reusing the product or its components is not possible, then **recycling** of materials is the next favoured option. Recycling the materials into new products reduces the need of virgin raw materials.
4. The least favoured options in waste hierarchy are the **energy recovery** of the material by incineration
5. and **landfill** of the waste.

Task: *Watch a video on circular economy concept explained in 1 minute: https://multimedia.europarl.europa.eu/en/repair-reuse-and-recycle_V007-0034_ev*

or a video Re-thinking Progress: The Circular Economy by Ellen MacArthur Foundation https://www.youtube.com/watch?v=zCRKvDyyHmI

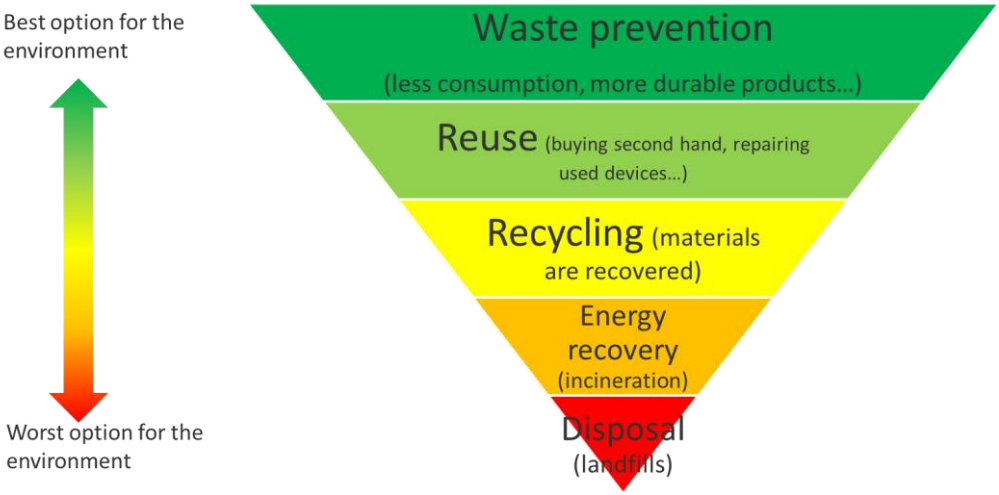

Figure 7. Waste hierarchy principle.

Using e-waste as a source for raw materials makes also sense because the concentrations of precious materials in e-waste can be multifold when compared to concentrations in ores. This is also called **urban mining** and it means production of raw materials from waste, spent products or buildings. For example, 1 ton of old mobile phones can contain up to 300-400 grams of gold, whereas the highest grade gold mines in the world have 44 g of gold in 1 ton of ore and in lower grade ores the concentrations are only 1-4 g/t. Thus the concentration of gold in old mobile phones is multifold when compared to gold mines!

Facts and Figures: *The gold, silver and bronze medals of the 2020 Tokyo Olympics are to be made from the country's urban mines -- made up of millions of discarded smartphones and other consumer electronics.*[1]

Facts and Figures: *Up to 7% of the world's gold may currently be contained in e-waste.*

Conclusions: what could consumers do?

Consumption of electronics in general has grown rapidly in recent years, and the consumption and thus generation of e-waste is predicted to continue growing. The environmental impact of these devices is quite significant and thus it is important for also consumers to consider how to improve the situation. Although there is plenty of room for improvements in collection and recycling of e-waste, e-waste is also a huge opportunity for recovering valuable materials.

When the product is discarded, it is important to deliver it to an official recycling center, so that the materials can be recovered and put into use again, but also to prevent harmful substances from entering the environment. Although it is important to recycle, it is equally important to try to avoid generating waste in the first place. Manufacturing a device, even using just recycled material, still consumes energy and resources. If possible, repairing and otherwise prolonging the lifespan of a device decreases its environmental impacts.

[1] https://asia.nikkei.com/Business/Japanese-companies-digging-for-gold-in-urban-waste

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Selected references and further reading

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About AWARE

This content has been created as a part of AWARE project. The purpose of the AWARE project is to spread information on e-waste and circular economy among schoolchildren of different ages and teachers. For more information, please visit

https://aware-eit.eu/

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