Geological Survey of Finland

2021

Digitalization and natural resources

Toni Eerola (ed.), Pasi Eilu (ed.), Jyri Hanski, Susanna Horn, Jachym Judl, Marjaana Karhu, Päivi Kivikytö-Reponen, Panu Lintinen and Bo Långbacka

GTK Open File Research Report 50/2021

GEOLOGICAL SURVEY OF FINLAND

Open File Research Report 50/2021

Toni Eerola (ed.), Pasi Eilu (ed.), Jyri Hanski, Susanna Horn, Jachym Judl, Marjaana Karhu, Päivi Kivikytö-Reponen, Panu Lintinen and Bo Långbacka

Digitalization and natural resources

Unless otherwise indicated, the figures have been prepared by the author of the report.

Front cover: Documentation of a bedrock outcrop by mobile phone camera. Picture by the GTK.

Toni Eerola (GTK), Pasi Eilu (GTK), Jyri Hanski (VTT), Susanna Horn (SYKE), Jachym Judl (SYKE), Marjaana Karhu (VTT), Päivi Kivikytö-Reponen (VTT), Panu Lintinen (GTK) and Bo Långbacka (GTK)

Layout: Elvi Turtiainen Oy

Espoo 2021

Eerola, T. (ed.), Eilu, P. (ed.), Hanski, J., Horn, S., Judl, J., Karhu, M., Kivikytö-Reponen, P., Lintinen, P. & Långbacka, B. 2021. Digitalization and natural resources. *Geological Survey of Finland, Open File Research Report 50/2021,* 92 pages, 16 figures, 17 tables and 1 appendix.

The report focuses on the mineral natural resources needed for digitalization. The use of digital applications and digital devices continues to grow and increasing amounts of information are being converted into a digital format. Prior research on digitalization in the context of sustainability has focused mainly on energy consumption and emissions. However, with the increasing demand for ICT hardware in numerous applications in modern society, the raw materials requirement of digital devices has become a crucial sustainability issue. Therefore, this report delves deeper into the topic of the raw materials consumption of digitalization. We focus on the following challenges and topics:

- Sources, production, availability and sustainability of digitalization raw materials
- ICT sector's raw materials consumption, with a specific focus on selected key end-user devices: smartphones and smart TVs
- Key aspects of the ICT value chain
- Key ICT consumer and end-user aspects
- Possible solutions to support the sustainability of digital devices throughout their life cycle
- Key policy aspects and recommendations

Keywords: digitalisation, raw materials, metals, minerals, mining, sustainability, sustainable development, corporate social responsibility, environmental impacts, ICT, mobile phones, smart TVs, recycling, circular economy, refurbishing

Toni Eerola
Geological Survey of Finland
P.O. Box 96
FI-02151 Espoo, Finland

E-mail: toni.eerola@gtk.fi

Pasi Eilu
Geological Survey of Finland
P.O. Box 96
FI-02151 Espoo, Finland

E-mail: pasi.eilu@gtk.fi

The project has been funded by Finnish Innovation Fund Sitra. The project is a part of Sitra's future-oriented work that aims at strengthening biodiversity and accelerating ecological reconstruction.

CONTENTS

EXECUTIVE SUMMARY

Digitalization is a **transformational trend** that uses digital technologies to create value from data. It has and is expected to further reshape the labour market, empower individuals and enable the creation of ecologically sound economic and societal systems that match the planetary carrying capacity. Furthermore, it is a **valuable economic sector**. The value of digital transformation to society and industry is predicted to exceed €80 trillion by 2025. In the EU, the information and communication technology (ICT) sector employed 5.4 million people in 2017. However, in the digital economy, value is mostly produced in only a few economies.

Digitalisation is also a significant **source of emissions and a large consumer of energy**. The estimated global greenhouse gas emissions of the digital economy range from 2.6% to 5% of global emissions. Estimates of total electricity use for different European countries range from 0.5% to 6.4% of their GDP, and the energy consumption of the digital economy is estimated to range from 5.4% to 8% of total energy consumption.

Digitalization is **one of the consumers of critical raw materials, competing for the same minerals with sectors such as renewable energy and e-mobility**. A great variety of commodities are used in the manufacture of an expanding diversity of devices by the digital industry for numerous purposes. Moreover, ICT infrastructure requires these same critical raw materials. Most of the ICT metals and minerals are produced in China or Africa and transported over long distances. **ICT, entertainment and media sectors consume about 0.5% of total raw materials (measured in weight)**. However, for some raw materials, such as indium, gallium and germanium, the digital economy represents 80–90% of the total consumption. This might pose a problem in the near future for some of the ICT commodities, as these materials will probably also be required in the green energy transition (e.g., in solar panels and wind turbines). Unless steered by regulations, it will ultimately be a matter of economics and prices, i.e., which sector will be able to pay the highest price in the competition for these minerals.

Despite the negative impacts of digitalisation, it plays a crucial role in **reducing environmental impacts in other sectors**. It enables more efficient energy and raw material usage and environmental performance in other sectors. However, there is a distinct research gap in identifying whether the total environmental benefits of ICT use outweigh the environmental impacts of the ICT sector.

Digital devices, such as smartphones and smart TVs, usually have **short lifespans** and frequently they may even be designed for planned obsolescence, i.e., to have an intentionally short life cycle. Moreover, if a device breaks, it might not be possible to repair, or the repair costs might equal the price of a new device. Thus, a new device will need to be purchased and the old one may be left at home or discarded by the consumer, which means that valuable raw materials may be lost after the short use of such devices. Even if the devices are brought for recycling, not all the metals can currently be recovered due to the lack of technology, high cost and high energy consumption.

Mineral raw materials have formed through a diversity of processes and under suitable conditions **during millions or even billions of years** of the Earth's history. Substantial erosion has been needed to expose mineral deposits for their exploration and exploitation. Mineral exploration takes time and few of the deposits that are found end up being mined. This is dependent on many factors, including the content, volume and location of the deposits, the infrastructure, market prices, demand and acceptance of mining. If a mine is planned, considerable time, work and investment is needed to set it up. When the geological processes and time involved in their generation are compared with the short use and loss of natural resources, it sounds inherently unsustainable, especially when considering the durability of these materials and their potentially endless recyclability.

Mineral raw materials needed by society are **produced by mining and refining processes and to a smaller extent by recycling**. The primary raw materials (from mining) are further processed into materials and components and are manufactured into devices. Moreover, materials are processed with a diversity of processes, which are constantly improving their energy and material efficiency, e.g., through intelligent technologies. Materials are further manufactured into components and devices. However, if not properly and responsibly managed, the mining and refining of the materials can produce considerable negative impacts on the environment and local communities. Mining may also compete with other forms of land use and livelihoods, which often generates conflicts. Therefore, the responsibility of mineral exploration and mining should be improved, especially if a green energy transition and higher level of self-sufficiency are targeted in the EU regarding raw materials production.

In line with the principles of the circular economy, **the devices and components should be repairable and recyclable.** Recycled materials should be used as far as possible, and the life cycle of devices should be extended. Fortunately, metals have an excellent variety of properties, as they are durable and mostly repairable, as well as recoverable and recyclable, for instance through pyro- or hydrometallurgical processes. Metals can be considered as permanent materials due to potentially endless recycling without losing their properties and performance. However, regarding ICT devices, there are serious challenges in achieving this endless cycle. As **many commodities are used in small amounts and in complex metallic alloys,** the recovery and recycling of many of these metals is expensive, energy and resource consuming or even impossible. Therefore, the collection, recovery and recycling processes for devices need to be developed. Moreover, huge amounts of e-waste are transported to developing countries, where there is no assurance about the conditions under which they are processed. In a true circular economy, sustainability needs to be considered during the whole life cycle of the devices, from exploration for raw materials and production to reuse and recycling as a joint effort. This requires changes by each actor along the value chain, targeting the sustainability of the entire life cycle instead of actor-specific sub-optimization.

The circularity and sustainability of these devices can be improved by already considering these aspects at the very beginning of the life cycle and **in particular, during the design and material development phases**. In fact, 80% of the life cycle impacts are determined in the design phase. The need for an increased upstream volume and number of raw materials can be influenced by design choices. Furthermore, through design choices, the downstream lifetime extension and closing of the material loops can be supported. Starting from the so-called material design hotspots, such as replacing current composite materials and alloys that are not easily recycled or are toxic, re-thinking the materials, joints and components to increase repairability, as well as considering the use of recycled materials, all these actions are important to support sustainability throughout the life cycle of ICT devices. Through design, it is also possible to develop and maintain **digital passports** to follow products through their life cycle. These passports could support and strengthen the pre-material recycling options and the design-for-X approaches, i.e., utilizing opportunities to reuse or repair the devices or components before materials recycling. Substitution of materials and compounds can be seen as a design solution to reduce the demand for critical raw materials, as well as the supply risk of raw materials. However, these aspects would need a system-level assessment to understand the wider impacts of design choices along the product life cycle and across other value chains.

The market-based economy of the consumption society is based on unlimited economic growth. This is a critical issue; the industry is constantly developing new models and properties, producing a great variety and quantity of devices for numerous purposes, which are not necessarily required as such by society. New needs are created to increase the revenues and profitability of digital companies, which have expanded and gained considerable power. Although sustainability issues are increasingly being discussed by different societal actors, this has still not enabled a sufficient impact that is in line with global requirements. A similar disconnection is visible on the consumer side. Even though consumers are increasingly aware and acknowledge the urgency of sustainability challenges, it is difficult to operationalize these issues into real actions. In effect, the actions by businesses are still lagging. According to the interviews conducted as part of this study, the factors impacting on purchasing decisions are primarily brand, performance and price. In some cases, however, the longevity as well as the repairability and updateability of devices impacts on the purchase decision, issues which may have a positive impact on circularity, sustainability and raw material use. The awareness of sustainability issues is seen to be increasing, and the use of various labels conveying this information is seen as a potential tool to strengthen the ability of consumers to make sustainable choices.

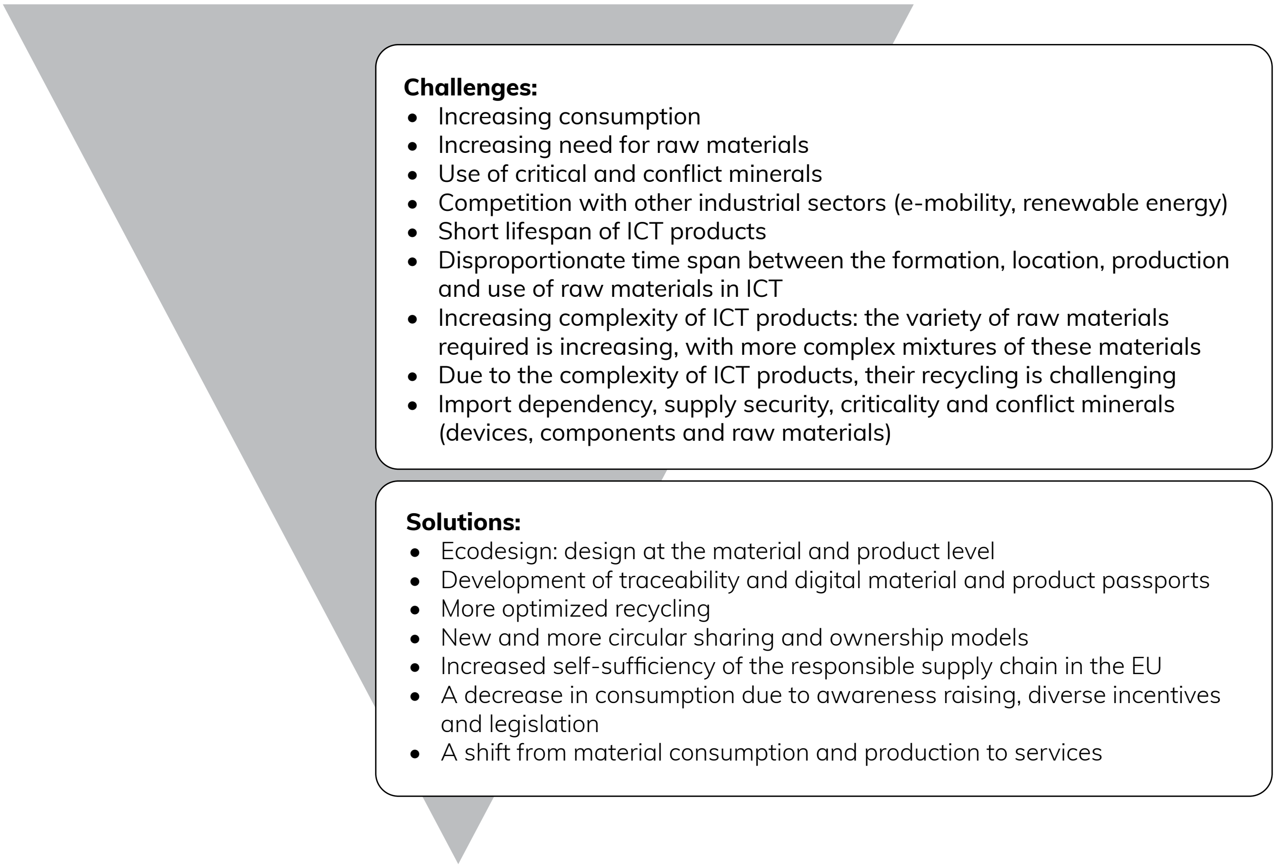
In summary, consumers, policy makers, states and the industry have a strong role to play in making the production of digital raw materials and the design of digital products more responsible. The extension of product and raw material life cycles towards a circular economy is the key recommendation of this report. The key question for policy making is: “How can we utilise the opportunities provided by digitalisation in an environmentally, socially and economically sustainable way?”

In summary, the main challenges in connection with ICT raw materials are:

- Increasing consumption due, for example, to marketing, increasing wealth and product development
- The increasing need for raw materials, with impacts resulting from their exploitation
- The use of critical and conflict minerals
- Competition with other industrial sectors (e-mobility, renewable energy)
- The short lifespan of ICT products
- The disproportionate time span between the formation, finding, production and use of raw materials in ICT
- The increasing complexity of ICT products: the variety of raw materials required is increasing, with more complex mixtures of these materials
- Due to the complexity of ICT products, their recycling is challenging
- Import dependency and supply security (devices, components and raw materials)

The potential solutions:

- Ecodesign: design at the material and product level
- The development of traceability and digital material and product passports
- More optimized recycling
- New and more circular sharing and ownership models
- Increased self-sufficiency of the responsible supply chain in the EU
- A decrease in consumption due to awareness raising, diverse incentives and legislation
- A shift from material consumption and production to services



Prior research on digitalization in the context of sustainability has focused on energy consumption and emissions. However, with the increasing demand for ICT hardware in numerous applications in modern society, the raw materials requirement of digital devices has become a crucial sustainability issue. Therefore, this report delves deeper into the topic of the raw materials consumption of digitalization. We focus on the following challenges and topics:

- The sources, production, availability and sustainability of digitalization raw materials
- The ICT sector's raw materials consumption, with a specific focus on selected key end user-devices: smartphones and smart TVs
- Key aspects of the ICT value chain
- Key ICT consumer and end-user aspects
- The possible solutions to support the sustainability of digital devices throughout their life cycle
- Key policy aspects and recommendations

GLOSSARY WITH ABBREVIATIONS

Battery metals = Metals or minerals commonly used in batteries, especially in lithium-ion batteries, which are crucial parts of portable two-way communications devices and computing devices. These essentially include lithium, cobalt, nickel, manganese, aluminium as the battery cathode and predominantly graphite as the anode. Lithium is also to some extent used in the electrolyte. To a large extent, the same metals and minerals are also important in the batteries of electric vehicles. However, the battery configuration differs, since the available space is less restricted in vehicles and an extended battery life is of higher importance (Buchman 2021).

Carbon footprint = Total amount of greenhouse gases emitted during the life cycle of a product or service.

CRT = Cathode Ray Tube. A technology used in televisions screens before the rise of flat screen panels.

CRM (Critical raw material) = A raw material of high importance to the economy and whose supply is associated with high risk (Blengini et al. 2020). The EU has listed these and updates the list periodically. The first release, a list of 14 CRMs, was published in 2011, the second, revised list of 20 CRMs in 2014, the third list of 27 CRMs in 2017, and the fourth list of 30 CRMs was published in 2020 (83 individual raw materials were assessed for the 2020 list; European Commission 2020c).

CSR (Corporate social responsibility) = A concept whereby companies integrate social and environmental concerns in their business operations and in their interaction with their stakeholders on a voluntary basis (European Commission 2011).

Digitalization = Digitalization refers to the use of digital technologies to change a business model and provide new revenue and value-producing opportunities. It should not be mistaken with the similar term "digitization", which refers to the change from an analogue process into a digital form without any changes to the process itself. (Gartner 2021)

Digital transformation = Digital transformation is interpreted in various ways, from IT modernization (for example, cloud computing) to digital optimization, to the invention of new digital business models. It is widely used in public-sector organizations, with initiatives such as putting services online or legacy modernization. In this context, the term is more like "digitization" than "digital business transformation". (Gartner 2021). Digital transformation covers both the integration of digital technologies by companies and the impact on society of new technologies (European Parliamentary Research Service 2019).

Digital disruption = An effect that changes the fundamental expectations and behaviours in a culture, market, industry or process that is caused by, or expressed through, digital capabilities, channels or assets (Gartner 2021).

Digital economy = A digital economy consists of three layers: the information and communication technology (ICT) sector, digital economy and digitalized economy (Bukht & Heeks 2018).

Digital technologies = Electronic tools, systems, devices and resources that generate, store or process data. These include, for instance, the Internet of Things (IoT), cloud computing, artificial intelligence, advanced robotics, innovative digital platforms and blockchain technologies (European Parliamentary Research Service 2019).

EcoCAD = A computer-aided design tool integrating environmental criteria in the design phase.

Ecodesign = Design and management method that integrates environmental issues into product development, and thus proactively reduces, avoids or eliminates adverse environmental impacts that occur at different stages of the life cycle.

EEE (Electrical and Electronic Equipment) = Equipment that is dependent on electric currents or electromagnetic fields to work properly and equipment for the generation, transfer and measurement of such currents and fields. EEE consists of products with circuitry or electrical components with a power or battery supply (Forti et al. 2020, STEP 2014).

EIP = European Innovation Partnership.

End of life (EoL) = The end of the product life cycle.

ENGO = environmental non-governmental organizations.

GWP (Global warming potential) = An indicator that allows comparison of the global warming impacts of different gases that contribute to global warming. It is a measure of how much energy the emissions of 1 ton of a gas will absorb over a given period of time, typically over 100 years, relative to the emissions of 1 ton of carbon dioxide (CO_2).

High-tech metals = Elements critical to modern advanced technologies or high-tech metals, such as gallium, germanium, niobium, rare earth elements (REE) and tantalum, are of great relevance in the development of emerging key technologies, including renewable energy, energy efficiency, electronics and the aerospace industry. These elements generally occur in minor to trace concentrations in the Earth's crust, having an average abundance from <0.1 ppb (parts per billion; 1 ppb = 0.0000001%) to several hundred ppm (parts per million; 1 ppm = 0.0001%), and are typically, but not exclusively, recovered from only a small number of mineral deposits.

HSC Sim = Process modelling and simulation software for designing mining and processing technologies, which includes an integrated LCA module.

ICT (Information and communication technology) = An extensional term for information technology (IT) that stresses the role of unified communications and the integration of telecommunications (telephone lines and wireless signals) and computers, as well as the necessary software, middleware, storage and audiovisual systems, that enable users to access, store, transmit, understand and manipulate information. ICT is an umbrella term that includes any communication device, encompassing radio, television, cell phones, computer and network hardware, satellite systems and so on, as well as the various services and appliances with them, such as video conferencing and distance learning.

ICT hardware = ICT hardware consists of all the physical parts of computers and related devices. It includes user equipment (smartphones and tablets, routers, modems, desktop and laptop PCs and public displays), entertainment and media equipment (TVs, other consumer electronic), access networks (mobile and fixed broadband), enterprise networks and data centres (Malmodin & Lundén 2018).

IoT (Internet of Things) = Describes the network of physical objects, or "things", that are embedded with sensors, software and other technologies for the purpose of connecting and exchanging data with other devices and systems over the Internet.

LCA (Life cycle assessment) = The compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.

LCD (Liquid-crystal display) = LCD is a flat-panel display that uses the light-modulating properties of liquid crystals combined with polarizers.

LED (light-emitting diode) = Technology commonly used in flat screen TV panels. LED s a semiconductor light source that emits light when current flows through it.

Lifetime = The period during which a product can be used by a consumer.

MECO matrix = A product-based environmental assessment tool concentrating on the categories, materials, energy, chemicals and other.

MET matrix = A product-based environmental assessment tool concentrating on the categories, materials, energy and toxicity.

Mineral deposit = A concentration or occurrence of a material of economic interest in or on the Earth's crust in such a form, quality and quantity that there are reasonable prospects for eventual economic extraction. A mineral occurrence of sufficient size and grade that it might, under the most favourable circumstances, be considered to have economic potential.

Mineral resource = The amount of a geological commodity that exists in identified mineral deposits. The location, quantity, grade or quality and densities, shape and physical characteristics of the ore body are known, estimated or interpreted from specific geological evidence, sampling and knowledge.

Mineral or ore reserve = A subgroup of a mineral resource, which has a known size and can be exploited at a profit. With a change in commodity prices, in mineral policy, or the development of mineral extraction technology, any currently uneconomic mineral resource may become a mineral reserve. It is important to understand that whatever the current mineral reserves are, they are just a fraction of all known and yet to be discovered mineral resources.

ODM (Original design manufacturer) = A company that designs and manufactures a product, as specified, that is eventually rebranded by another firm for sale.

OLED (Organic light-emitting diode) = An advanced form of an LED flat screen panel.

Planned obsolescence = Physical and technological obsolescence. It concerns different issues, such as a lack of repairability, planned degradation of the constituents, a decrease in aesthetic quality, design obsolescence and a lack of compatibility (e.g., when software updates are compromised).

PGM / PGE (Platinum group metals) = Platinum, palladium, rhodium, ruthenium, iridium and osmium.

Primary raw materials = **Virgin raw materials** = Mineral raw materials produced by mining.

Product life cycle = The consecutive and interlinked stages of a product system, from raw-material acquisition or the generation of natural resources to product manufacturing, use and final disposal or re-entering a new product life cycle.

Product development life cycle = The course of events that brings a new product into existence and follows its **growth** into a mature product and eventual critical mass and decline. The most common steps in the **life cycle** of a product include product development, market introduction, **growth**, maturity, and decline/stability.

REE (Rare earth elements) = This is a group of chemically quite similar metals, also called the lanthanides, consisting of lanthanum, cerium, praseodymium, neodymium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, terbium, ytterbium, lutetium and yttrium.

Secondary raw materials = Raw materials obtained by recycling primary raw materials.

Silicon metal = A pure metalloid form of the chemical element silicon (Si)

SLO (Social license to operate) = Acceptance or approval of activities by local communities and stakeholders, or more generally by society. The term originated in the mining industry but has also spread to other sectors that depend on access to land to perform their activities.

Smart-TV = Televisions with integrated Internet and interactive features.

Smartphone = A mobile phone that performs many of the functions of a computer, typically having a touchscreen interface, internet access, and an operating system capable of running applications.

Urban mining = Sourcing of raw materials from anthropogenic (or 'technogenic'), i.e., man-made sources, such as industrial and urban wastes and material side streams.

WEEE (Waste electrical and electronic equipment) = ICT hardware (or EEE) becomes e-waste when it has been discarded by the owner without the intention of re-use (STEP 2014). WEEE or e-waste covers all types of EEE and their parts at the end of their final life cycle.

INTRODUCTION

Mineral deposits formed millions or even billions of years ago through very special geological processes and under favourable conditions for their generation. Often, this took place deep within the Earth's crust. In order to be exposed or occur closer to the surface, allowing their examination and extraction, another long-time span has passed with substantial erosion. In this respect, nature is tricky: mineral deposits are not found everywhere but in certain places that need to be located.

A long time after their formation, humans learned how to use and apply metals and minerals for multiple purposes. Modern life consumes and requires huge amounts of different mineral natural resources. For this reason, geologists search for the mineral deposits all over the world. They work in very diverse contexts and conditions and face diverse challenges, determined not only by geology but also by the social, economic and political environments. Despite their hard work, many geologists do not find any significant or economically exploitable mineral deposits during their entire careers, and the average industry success rate in mineral exploration is only one in a thousand. This also means that if a thousand locations examined for a mineral deposit, just one may end up in a mine (Thomson & Joyce 1997, Moon & Evans 2006).

Proper investigation of a mineral deposit takes years to decades to complete, as it involves huge investments and a long permitting process if a mine is to be established. Even an originally very promising mineral deposit may not meet the requirements for an exploitable deposit due to its remote location, the lack of infrastructure, the commodity's market situation, a lack of funding, other competing land uses, incompatible livelihoods and values, or a lack of acceptance by the local community. The mining of a mineral deposit needs to be economically justified, with the deposit demonstrated to form a mineral reserve that is well known and can be exploited (Fig. 1). It also needs to be able to produce profit for its owners, and to be exploited with the least possible harm to the environment and local communities. However, increasing demand and prices may quickly change this situation, and this usually happens during commodity booms, when mining conflicts have also increased (Andrews et al. 2017, Conde 2017). Therefore, the responsibility of the mining industry towards the environment, communities and local livelihoods must be improved by minimising its adverse impacts.

Estimations of the available raw material resources are based on what is currently known and reported by companies exploring and exploiting

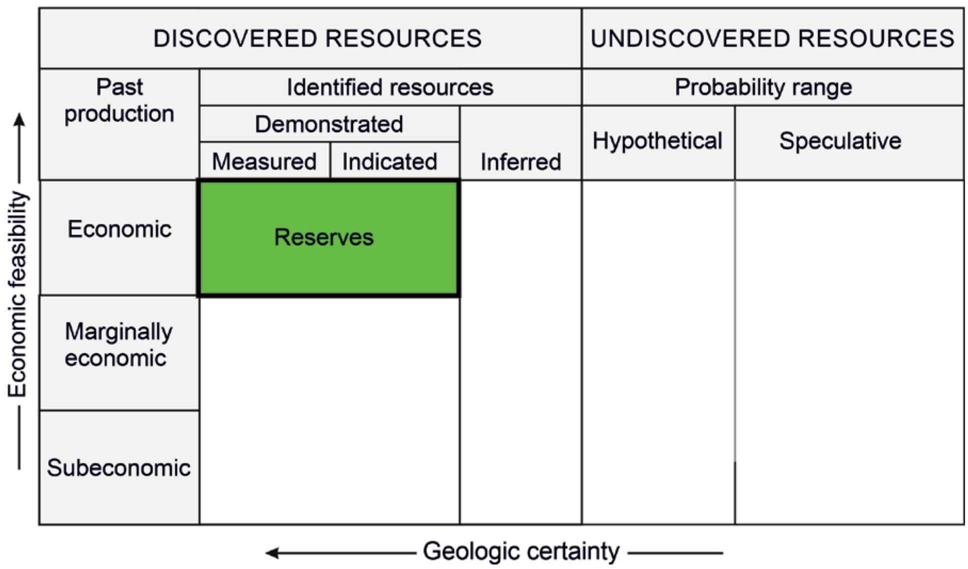


Fig. 1. Classification of mineral resources and reserves, modified from USGS (2021). Economic feasibility increases upwards and geological certainty increases to the left. Only economic ores, i.e., reserves, are mined. Hypothetical resources are the undiscovered resources in known types of mineral deposits in favourable geological settings where other well-explored deposits of the same types are known. Speculative resources may occur either in known types of deposits in favourable geological settings where mineral discoveries have not been made, or in types of deposits as yet unrecognised for their economic potential.

mineral deposits (Jowitt & McNulty 2021). These estimations are for the mineral reserves that can be economically exploited based on prevailing conditions (Fig. 1); thus, the metals and minerals that are reported do not represent all reserves on Earth, as more remain to be found (Meinert et al. 2016).

Minerals are the solid foundation of our modern societies and the backbone of the manufacturing industries. They are, in fact, needed in all economic sectors and services, food production included. The finding of mineral deposits and establishment of new mines are still currently necessary to maintain the security of the raw material supply for any national economy. Even though recycling has already become important for many commodities and is clearly growing, it cannot eliminate the need for additional primary resources (e.g., Herrington 2021, IEA 2021). Therefore, mineral exploration and mining are essential for meeting societal needs.

The path of the minerals continues towards materials. Material scientists develop metal alloys, ceramics and battery chemicals for cathode materials, as well as battery cells. For instance, product designers work on mobile electronic devices to meet the end-user requirements. In other words, there is a long production process and chain from mine to metals, from metals to materials, from materials to components, and from components to high-technology products. Many metals, such as copper and steel (nickel and iron), are used for decades by society until they are recycled or discarded.

As seen above, the pathway of minerals from the ground to the end user is typically a long journey, and this is not usually perceived by the public. Issues relating to the sources of raw materials and all upstream processes before a product reaches the store shelf is often not very transparent and is thus easily left unseen by the consumers. Regarding electronics, this perception is quite overwhelming. Electronics are manufactured using a large variety of metals that are extracted from mines all over the world (Bobba et al. 2020). The life cycle of electronic products is usually short and, especially in developing countries, the used products still often end up discarded with all their valuable metals without material recovery and recycling. This is also partly because they contain many metals in tiny amounts, which means that their recovery and recycling can be challenging or even impossible. Considering the challenge of obtaining minerals for society with all the time, work and investments involved, and the negative environmental and social impacts caused, this is clearly an unsustainable model.

Together with globalization, population growth, urbanization, emerging markets and climate change, digitalization is one of the ongoing and future megatrends (Rasmussen 2011, European Strategy and Policy Analysis System 2019). Digital technologies are also strategic technologies that not only sustain the enormous digital sector but are also enabling technologies for all the industries and technologies discussed in this report (Bobba et al. 2020). Our societies are digitalizing, and the industry producing hardware for its needs is rapidly expanding and diversifying. Electronics are also increasingly used for entertainment, to spend time and to make life easier. Often, devices and digital services are designed for the sake of their usability, and new properties and applications are continually developed, which may transcend their usefulness vs. achieved experience. Although an individual device requires just tiny amounts of mineral raw materials, the high total production volumes of these small devices mean a quite a significant demand for metals and minerals.

Digitalization is an essential part of the modern world, but still a rather new phenomenon. While digitalization is currently being applied in a variety of activities, including mineral exploration and mining (e.g., Jang & Topal 2020), digitalization and mineral raw materials are often understood as separate issues by the general public and policy makers. While the impact on the demand for metals and minerals by the transition to a fossil-free future has been relatively well studied, the demand for raw materials created by hardware (such as computers, fibre optical cables, computer chips and their building blocks, such as capacitors and others, diodes and screens) has been less examined (UNCTAD 2020). The physicality of digitalization remains hidden. For example, there are policies for raw materials and digitalization in EU, but not one that deals with them together. Of course, this concerns other sectors as well. Another aspect to consider is that the raw materials needed, for example, for the transition to green energy are largely the same commodities as needed by digitalization, although in very distinct proportions. However, few studies have examined their sufficiency (e.g., Bobba et al. 2020, UNCTAD 2020, IEA 2021, Michaux 2021). Indeed, when discussing the "raw materials of digitalization", a person may be referring to data, which can be "mined" (e.g., Laine 2015, Windsor 2016).

Therefore, a consortium formed by the Geological Survey of Finland (GTK), the Finnish Environment Institute (SYKE) and the Technical Research Centre of Finland (VTT) was requested by the Finnish Innovation Fund (Sitra) to investigate the topic, and to attempt to fill the gaps in information and to deal with both issues in a joint way. This report was produced by the consortium by addressing the need for information on the subject. The aim of the report is to present further steps to guide digitalization towards the more sustainable use of mineral raw materials, and especially their further recycling, to significantly lengthen their life cycle.

1 DIGITALIZATION: THE BIG PICTURE

Digitalization is a trend that is transforming activities in both the public and private sectors. It is not just about managing data in numerous information systems; it is the creation of value from the data. The digitalization of products, services and processes is disrupting competitive positions, existing industry boundaries and business networks by making the current products, services and processes obsolete (e.g., Millar et al. 2017). It is claimed to be reshaping the labour market by reducing certain duties and increasing others by creating completely new products and services (Arntz et al. 2016, Pajarinen & Rouvinen 2014). Digital technologies could support the empowerment of individuals and communities, create meaningful tasks and well-being and ecologically sound economic and societal systems that match the planetary carrying capacity. This all raises the question of how to utilise the opportunities provided by digitalisation in an environmentally, socially and economically sustainable way. More research is needed on the implications of the digital revolution, and increased efforts are required to develop long-term solutions that go beyond current thinking.

To proceed in this direction, the European Commission (2020a, e) has identified digitalization as a key factor in reaching the ambitions of the European Green Deal and the Sustainable Development Goals. Digital solutions are seen as important in advancing the circular economy, supporting the decarbonisation of all sectors and reducing the environmental and social footprint of products. Digitalization is also a major contributor to, and enabler of, a fully integrated life cycle approach in product and system design, which may lead to increased energy efficiency, reduced energy use, increased traceability of raw materials and products, and enabling the lifetime extension and recyclability of products.

Increasing electronic equipment waste, the valuable raw material content in electronic equipment (Forti et al. 2020) and the increasing reliance on foreign digital components and technology (Bobba et al. 2020) are some of the main reasons for growing interest in circularity initiatives at the EU level. The circular electronics initiative aims at ensuring that devices are designed for durability, maintenance, dismantling, repair, reuse and recycling. Furthermore, it includes a right to repair or upgrade to extend the life cycle of electronic devices and to avoid premature obsolescence. (European Commission 2020e)

1.1 Diverse roles of digitalization

Even though digital technologies are often perceived as non-material solutions, they rely on hardware and have their own environmental footprint. The main drivers of the information and communication technology (ICT) sector's environmental footprint include energy consumption and its greenhouse gas emissions, raw materials use in infrastructure and devices, and emissions to air, water and soil (Ojala et al. 2020). Key positive impacts include the role of digital technologies in reducing greenhouse gas emissions in other sectors (e.g., digital control systems, IoT), supporting environmental protection and nature conservation (e.g., monitoring devices) and facilitating climate change adaptation (ibid.). This can be also seen in the reduction of environmental footprints in other sectors.

Economic value

The digital economy is a major contributor of the global gross domestic product (GDP), and its share of total GDP is constantly rising. There have been various estimates of the total economic value of digitalization. For instance, considering the widest scope of digitalization, the World Economic Forum estimates that **the global value of digital transformation to society and industry will exceed €80 trillion by 2025** (European Parliamentary Research Service 2019). In contrast, the global digital economy was estimated to be worth €9.55 trillion in 2016, which equalled 15.5% of global GDP (Huawei & Oxford Economics 2017). This analysis included both the direct effects and indirect spill-over effects of ICT. Between 2000–2015, the digital economy grew 2.5 times faster than global GDP and almost doubled in size (ibid.). However, most of the value in the digital economy is produced in only a few economies: the United States (35%), China (13%), Japan (8%), and the share of the EU (together with Iceland, Liechtenstein and Norway) is 25%.

In the US, the digital economy accounted for 6.9% of GDP in 2017 (BEA 2019). However, this analysis did not consider spill-over effects to other sectors. The real value added of the digital economy rose almost 10% annually from 1997 to 2017 in comparison to a 2.3% rise for the overall economy (ibid.). The value added of the digital economy in the EU totalled €475 billion in 2017, equivalent to 3.6% of the EU's GDP (Eurostat 2021). In the EU, the value of ICT services was more than ten times as large as ICT manufacturing (ibid.).

Social and environmental impacts

Digital technologies have great potential to improve our life expectancy and quality of life (European Parliamentary Research Service 2019). The digital economy is a significant employer in the EU: the EU's ICT sector employed approximately 5.4 million people in 2017 (Eurostat 2021). However, the digital economy also causes considerable environmental impacts. These begin with the production of metallic raw materials by mining (see chapter 2). In digitalization, major drivers of environmental impacts include the growth forecasted in the number of internet protocol (IP) connected devices from 2.4 per capita in 2018 to 3.6 per capita in 2023 (29.3 billion in total) and rapidly rising network speeds for fixed, mobile and 5G (Cisco 2020). Global internet traffic is expected to double to 4.2 ZB from 2019 to 2022 (IEA 2020). Consequently, data creation and storage are drastically increasing. Furthermore, the increasing number of connections, amount of data creation and storage and number of devices increases the manufacturing of end-user equipment and supporting infrastructure, e.g., data centres. These developments will lead to rising electricity consumption, raw material consumption and emissions if the effects are not compensated with technological innovations and policies that increase the material and energy efficiency of ICT. In addition, digitalization consumes a share of renewable energy production that would be otherwise be used in energy-intensive sectors such as steel or cement manufacturing.

Prior studies on the sustainability of ICT have mainly focused on emissions and energy consumption. Estimates of the energy consumption of the digital economy range from 5.4% to 8% of total energy consumption (Belkhir & Elmeligi 2018, Hiekkanen et al. 2021, Malmodin & Lundén 2018). Regarding the electricity use of the sector, estimates from 0.5% to 6.4% of the total use have been presented for European countries (Hiekkanen et al. 2021). The energy consumption and emissions of the digital economy have been constantly rising in recent decades. For Western Europe, Hiekkanen et al. (2021) present a consensus value for the increase in energy consumption from 2010 to 2020 as 30%. Estimates of the global greenhouse gas emissions of the digital economy range from 2.6% to 5% of total global emissions based on the cited studies (Belkhir & Elmeligi 2018, LVM 2021, Malmodin & Lundén 2018). Estimated emissions and energy consumption vary considerably between studies depending on the scope of the study and the availability of data. However, it can be assumed that globally, the sectors' electricity consumption and, driven by the rising consumption and the rising need for IP-connected devices, the greenhouse gas emissions are growing. However, with the increasing adoption of renewable energy production, these emissions may decrease in the near future, especially in certain markets.

As stated, the digital economy is not immaterial. It is built on a physical infrastructure and its services are available via physical ICT devices. Their production requires large amounts of raw materials that are often critical for the national economies of the manufacturing countries. At the end of their lifespan, ICT devices should ideally be collected and reused or recycled. However, globally, as much as 82.6% of all e-waste is not properly documented, collected or recycled (Forti et al. 2020). Altogether, e-waste contains over 1000 different chemicals, many of which are hazardous. Moreover, when not properly recycled, materials used in ICT devices are made inaccessible for further use.

Among the few studies on the global material use of the digital economy, Malmodin et al. (2018) estimated that the **ICT and entertainment and media industries use about 0.5% of total raw materials**. However, for some raw materials, such as indium, gallium and germanium, the digital economy represents 80–90% of the total use. In comparison to energy use and emissions, the total raw material use is modest; however, the digital economy uses most of the total consumption for certain (critical) raw materials. Although their volumes are small, the tiny amounts per device make their recovery and recycling challenging from energy consumption, technological and economic points of view.

Value of ICT to other sectors

Although the environmental impact of the ICT sector is rising, the largest influence of the sector, according to the industry, is expected to be in enabling more efficient energy and raw material usage and environmental performance in other sectors (ITU 2012, Ojala et al. 2020). In addition, digital technologies contribute positively to productivity and economic growth (European Parliamentary Research Service 2019). Digital technologies foster the transition towards a circular economy by optimising production processes, enable the extension of product use cycles and replace physical products. A further potential for digital technologies is seen in environmental protection, nature conservation and climate change adaptation (Ojala et al. 2020). Digital technologies are also enabling and supporting technologies for the raw materials sector through enhanced mineral exploration, raw material processing optimization, raw material traceability, material passports (tracking possible 'conflict minerals', for example), and various solutions targeting critical material efficiency.

On the other hand, it has been argued that estimating the overall net effect of ICT is challenging and it is likely to remain unknown due to the complexity of direct and indirect impacts (Horner et al. 2016). In particular, the indirect impacts, both positive and negative, are not easily attributable exclusively to ICT, but are often to some extent connected. These are commonly referred to as rebound, indirect, second order or ripple effects (Börjesson Rivera et al. 2014).

1.2 Key digital technologies

Digitalization covers a wide range of digital technology trends, including virtualisation, sensor-based technologies including the Internet of Things (IoT), additive manufacturing, wireless communication technologies (e.g., 5G), robotization, digital platforms, digital twins, blockchain technologies, machine learning and artificial intelligence. The growing raw materials consumption of digital technologies and the dependency on raw material exports have been identified in the EU (Bobba et al. 2020). Some of these key technologies are summarised below.

Additive manufacturing – also known as 3D printing – is transforming traditional manufacturing processes. In additive manufacturing, objects are produced from a 3D model by joining materials layer by layer from a powder or liquid, for example, without the need for moulds, tools or dies (Kellens et al. 2017). It enables the international trade of designs instead of finished products (UNCTAD 2019).

Artificial intelligence (AI) can be broadly defined as a system capable of understanding its environment and making rational decisions accordingly (Nilsson 2010). Machine learning is a branch of artificial intelligence covering algorithms that discover rules behind patterns in a dataset, learn these rules and apply them to new situations (Hanski et al. 2018).

Blockchain is a form of distributed ledger technologies that allow secure and trusted transactions of multiple parties without an intermediary (UNCTAD 2019). The technology was first developed for Bitcoin cryptocurrency. Other use cases for blockchain technologies include digital identification and property rights.

The Internet of Things (IoT) refers to a group of Internet-connected devices (sensors, meters, etc.) in various types of equipment and machinery that can send and receive data (UNCTAD 2019). It is a development where equipment and machinery become elements of an information system, with the ability to capture, compute, communicate and collaborate around information (Bughin et al. 2010).

Fifth generation (5G) wireless communication technology enables the handling of massive volumes of data (UNCTAD 2019). 5G is linked to IoT and enables the connection of large amounts of sensors and smart devices into a network (ibid.). A significantly faster successor of 5G – the 6G network – is currently under development.

Robotization enables automated services and nearly automated production and therefore has an increasingly important role, for example, in the manufacturing industry.

Virtualisation, including virtual and augmented reality applications, has major applications on both the consumer side and in industrial use. The main application areas in the industry are currently in supporting training, planning, installation, maintenance and repair, and also in supporting the design and management of products and systems.

The wider market penetration of these technologies is leading to the increased consumption of ICT hardware and need for more extensive supporting infrastructure. The composition and volume of total system level materials consumption is, however, uncertain. The raw materials consumption of digital technologies is discussed in more detail in chapter 2 of this report and the raw materials consumption of some specific technologies is presented in Bobba et al. (2020). According to Ku (2018), the increase in raw materials consumption due to wider penetration of IoT is "not too alarming" when analysed from the perspective of data storage. However, this study did not consider data processing, data transmission or other key aspects of increasing the volume of IoT devices. In addition, smart devices and IoT systems may have considerably shorter life cycles compared to other parts of the infrastructure, which poses challenges to the management of the infrastructure life cycle (Kortelainen & Hanski, **in press**). One of the reasons for shorter life cycles is the dependence of devices on software.

1.3 Digital economy

The digital economy consists of three layers: the ICT sector, digital economy and digitalized economy (Fig. 2). First, the core aspects of the digital economy include fundamental innovations such as semiconductors and processors, core technologies including computers and telecommunication devices, and enabling infrastructure, i.e., the Internet and telecommunication networks (UNCTAD 2019). Secondly, IT sectors produce key products or services that rely on core digital technologies, which include digital platforms, mobile applications and payment services. Thirdly, there is a wider set of digitalizing sectors, including those where digital products and services are being increasingly used, that have already undergone a process of digital disruption. These include finance, media, tourism and transportation. Moreover, digitally literate or skilled workers, consumers, buyers and users are critical for the growth of the digitalized economy. (ibid.)

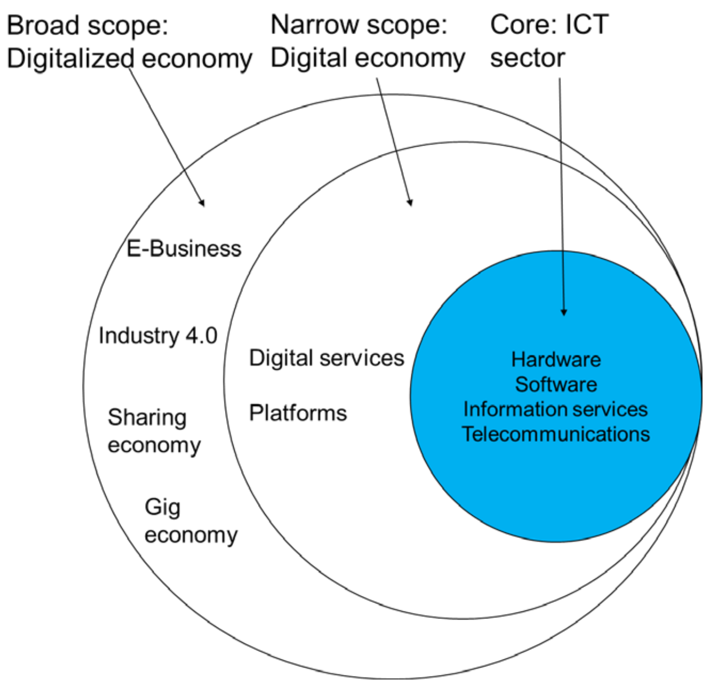


Fig. 2. Representation of the digital economy. After Bukht and Heeks (2018).

1.3.1 ICT sector

OECD (2011) provides a standard reference for the statistics and policy making in ICT. It offers another perspective on the digital economy (information economy in the report) by combining the ICT sector with the content and content production sectors. Statistics Finland (2021) includes the following economic activities as a part of the ICT sector:
– 261 Manufacture of electronic components and boards
– 262 Manufacture of computers and peripheral equipment
– 263 Manufacture of communication equipment
– 264 Manufacture of consumer electronics 268 Manufacture of magnetic and optical media
– 4651 Wholesale of computers, computer peripheral equipment and software
– 4652 Wholesale of electronic and telecommunications equipment and parts
– 582 Software publishing
– 61 Telecommunications
– 62 Computer programming, consultancy and related activities
– 631 Data processing, hosting and related activities, web portals
– 951 Repair of computers and communication equipment

Referring to UNCTAD (2019), the information and communication technology (ICT) sector consists of hardware manufacturing, software and IT consulting, information services and telecommunications. From the material consumption perspective and excluding energy consumption, ICT hardware is the most crucial part of the ICT sector.

1.3.2 ICT Hardware

ICT hardware consists of all the physical parts of computers and related devices. It includes user equipment (smartphones and tablets, routers, modems, desktop and laptop PCs and public displays), entertainment and media equipment (TVs, other consumer electronic), access networks (mobile and fixed broadband), enterprise networks and data centres (Malmodin & Lundén 2018). The main ICT hardware groups can be classified as:
- ICT end-user devices
- Data centres
- ICT and enterprise network devices and infrastructure

ICT end-user devices are also called electrical and electronic equipment (EEE), especially in the context of e-waste. EEE consists of products with circuitry or electrical components with a power or battery supply (Forti et al. 2020, STEP 2014). EEE product categories include 1) temperature exchange equipment, 2) screens and monitors, 3) lamps, 4) large equipment (washing machines, dryers, photovoltaic panels, etc.), 5) small equipment (vacuum cleaners, small electronic tools, electronic toys, etc.) and 6) small IT and telecommunication equipment (smartphones, PCs, routers, etc., Forti et al. 2020).

The IT core of data centres consists of a group of computing and storage resources. The key physical components include racks, routers, switches, storage systems and servers (Cisco 2021). Other key components in data centres include the power distribution system, the uninterruptible power supply (UPS) and other backup power systems, along with cooling systems and automation systems (Ojala et al. 2020).

ICT and enterprise network devices and infrastructure consist of connections using either fixed or wireless data transmission, as well as various systems that handle the switching and transmission of data. Networks can be divided in many ways, for example according to their regional hierarchy (topology), into internal networks, access networks (subscriber network), area networks and core networks. Networks can also be divided into public and private networks depending on whether they are used to provide communication services to an unrestricted or restricted group of users.

1.4 ICT hardware value chain

The ICT value chain consists of the production of mineral raw materials, design, manufacture, use and recycling, which all have their own sustainability challenges (Fig. 3).

Main life cycle stages		Challenges
smartphone	Raw materials acquisition	Increasing range and volume of elements Scarce, critical and non-renewable raw materials Resource intensive processing Challenging conditions in deposit locations Traceability of raw material sources Security of supply and import dependency Working conditions
	Design and manufacturing	Use of recycled materials Recyclability, repairability and updatability Environmental vs. functional perfomance Import dependency on components and products Working conditions
	Use phase	Short life cycles Consumers' needs vs. technology development Transparency and awareness in purchasing, use and repair
	End of life	Low collection and recycling rates Challenging recycling due to material complexity of products Lack of transparency regarding material composition of products

Fig. 3. Sustainability challenges along the whole value chain of electronic devices.

1.4.1 Primary (virgin) and secondary raw materials

Increasing amount of ICT hardware requires an accelerating intake of raw materials. When expanding out of ICT into the broader scope, including e-commerce, e-mobility, industry 4.0 with robots, microprocessors and process control, these sectors will require huge additional amounts of raw materials (UNCTAD 2020). The raw materials may come from primary or secondary sources. Primary raw materials are discussed at length in chapter 2. More efficient recovery of secondary materials from waste electrical and electronic equipment (WEEE) could significantly decrease the use of primary raw materials. However, there are obstacles. For example, recovery rates, particularly for critical metals, are very low and they are often difficult to increase due to thermodynamic limits in metallurgic processes, and deposits of secondary materials are becoming less accessible due to the miniaturization of devices (Wäger et al. 2015). However, their recovery and recycling might be possible later, if their flows can be merged with those metals coming from the end-of-life wind turbine components, for example. The availability of secondary raw materials in the European context is discussed at length in Huisman et al. (2017). Forti et al. (2020) assessed the amount of secondary raw materials in WEEE and their potential value (Table 1). This value assumes optimal recycling of all globally generated e-waste.

Table 1. Volume and potential value of raw materials of globally generated e-waste in 2019.

Element	Tons	Million €	Element	Tons	Million €
Silver	1 200	487	Indium	200	14
Aluminium	3 046 000	5 098	Iridium	1	4.2
Gold	200	7 973	Osmium	10	91
Bismuth	100	1.1	Palladium	100	2 970
Cobalt	13 000	871	Platinum	2	60
Copper	1 808 000	9 217	Rhodium	10	269
Iron	2 0466 000	20 725	Ruthenium	0.3	2.5
Germanium	10	0.34	Antimony	76 000	542

1.4.2 Design

Environmental product design, i.e., ecodesign, has been increasingly promoted by the European Commission during the last decades. ICT hardware is subject to several EU policies aiming to improve design aspects, such as the WEEE Directive 2002/96/EC and the Ecodesign Directive (Directive 2005/32/EC). The WEEE Directive was introduced to tackle the growing amount of WEEE by preventing the creation of WEEE as a first priority, contributing to the efficient use of resources and the retrieval of secondary raw materials through reuse, recycling and other forms of recovery, as well as improving the environmental performance of everyone involved in the life cycle of EEE (European Commission 2021b). The Ecodesign Directive set requirements for energy-using products, covering products dependent on energy input, or products or parts for the generation, transfer and measurement of energy. In 2009, the Directive was replaced by a more extensive Ecodesign Directive (Directive 2009/125/EC) which, in addition to energy-using products as in the previous directive, also covers products related to energy, e.g., products used in construction such as windows, insulation materials, or similar. The Ecodesign Directive is implemented through product-specific regulations, directly applicable in all EU countries.

The European Commission (2020a) introduced a new Circular Economy Action Plan, which is one of the cornerstones of the European Green Deal (European Commission 2020b) aiming towards climate neutrality by 2050. The Circular Economy Action Plan seeks to extend the Ecodesign Directives beyond energy-related products, also taking into account the EU Ecolabel Regulation (Regulation (EC) No 66/2010), product environmental footprints (Product Environmental Footprint, PEF, European Commission 2020f) and EU Common Criteria for Green Public Procurement (European Commission 2021d). Ecodesign is one of the main themes of the sustainable product policy for which the Commission is proposing legislative initiatives in its action plan. Through ecodesign, the European Commission aims to promote, for example, the durability, reusability, maintainability and repairability of products, improve their resource efficiency and reduce the environmental footprints. The Action Plan pays particular attention to certain sectors and product groups that use the most natural resources and have a lot of potential in the circular economy, such as electronics. It is set to bring several improvements to the circular design of electronics and ICT (European Commission 2020a, e), which include:

- Regulatory measures for electronics and ICT, including mobile phones, tablets and laptops under the Ecodesign Directive so that devices are designed for energy efficiency and durability, reparability, upgradability, maintenance, reuse and recycling;
- The ‘right to repair’, i.e., consumers will be able to repair and modify their appliances more easily;
- Introduction of a common charger for mobile phones;
- An EU-wide take-back scheme to return or sell back old mobile phones, tablets and chargers;
- Restrictions on hazardous substances in electrical and electronic equipment

Through design, it is also possible to influence the use of recycled material content and to support and develop digital passports to follow products through their life cycle (Adisorn et al. 2021).

1.4.3 ICT market and its main actors

In a rough simplification, the ICT value chain and market consist of five main actors: industry, consumers, policy makers, the state and the financing sector (Fig. 4). Each actor has its own role, and they interact with each other. The industry produces primary and secondary raw materials by mining and recycling, and it designs, manufactures, advertises and sells ICT devices. The industry depends on the financial market for investments and loans for its activities and there are requirements for this. Consumers purchase and consume products according to their needs and behaviours, creating the demand. They can also influence the industry and the financial sector. Policy makers create legislation and norms to regulate the industry and states (government) implement regulation and monitor industrial activities at national levels. Industry and the financial sector lobby them according to their interests. Consumers (citizens) elect policy makers and exert pressure on them and the government. Therefore, citizen-consumers have a significant role to play in the ICT market.

Beyond this level, there are also supranational and global levels of interaction and influence. Civil society (especially global environmental non-governmental organizations, ENGOs), the European Union (EU), the United Nations (UN) and the Intergovernmental Panel for Climate Change (IPCC), among others, influence the public debate and governmental policies and actions towards sustainability. For instance, the IPCC produces information on climate change, which has influenced the UN Global Sustainable Development Goals. The EU establishes regulation and policies for the digital and raw materials industry, having these drivers in mind, whereas civil society, with its ENGOs, demands sustainability and responsibility for the industry, consumers, the financing sector and governments.

ICT hardware used in the EU is typically produced elsewhere, especially in Asia. As an example, communications equipment manufacturing in the

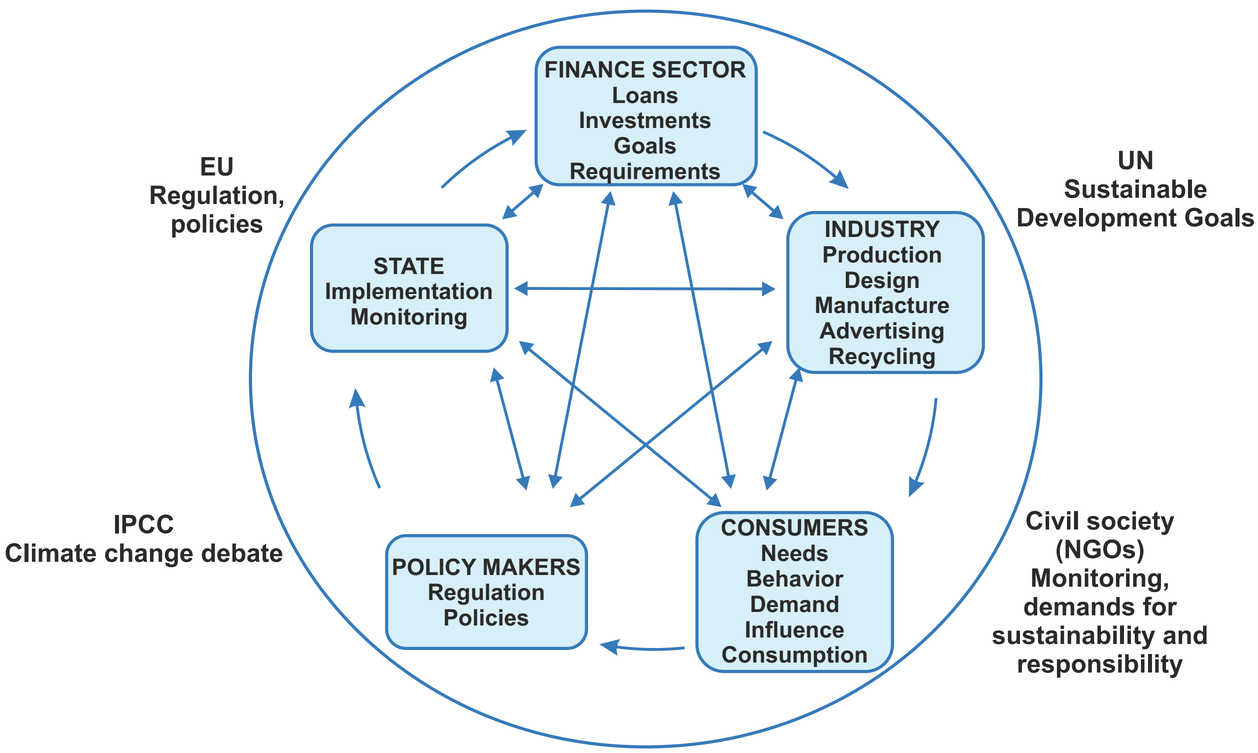


Fig. 4. Roles and interaction of the main actors of a simplified digital market with supranational entities and drivers influencing it towards sustainability.

EU has decreased from 207 million units in 2007 to just 2.8 million in 2017 (Rizos et al. 2019). In the EU-27, the main manufactured ICT products include electronic components and boards (57.2%), communication equipment (25.9%), computers and peripheral equipment (10.9%), consumer electronics (6.0%) and magnetic and optical media (0.1%) In the EU, the value added of ICT manufacturing is ten times less than that of ICT services (Eurostat 2021).

Recent sales of mobile devices

The global sales of mobile phones, laptops and tablet computers have remained relatively stable during the last few years, with a limited increase, and in the case of the laptops there has been a slight decrease. However, the surge in remote work and study due to the COVID-19 pandemic has increased the sales of laptops. After reaching its peak in 2011, laptop market growth has slowed down with the rise in alternatives such as smartphones and tablets. More and more consumers are shifting to smartphones and tablets for leisure usage, while keeping laptops for business purposes. In addition, the increasing durability and longer replacement cycles of laptops have all contributed to the slowing demand for them. Nonetheless, due to the continuous demand for laptops for commercial use, the market remains relatively stable.

With uncertainty persisting over COVID-19, remote work and study will probably continue into much of 2021 and some part of 2022. Therefore, it is expected that global laptop shipments to continue to grow slightly in 2021 and 2022. However, the demand is can be expected to gradually slowdown in 2023.

Global Li-ion battery markets

Despite the saturation of the electronics market, the sales of Li-ion batteries continued to grow primarily due to the staggering demand from electric vehicles (EV) (Tsiropoulos et al. 2018, Zhang 2020, Fig. 5). Within four years of their introduction, annual sales of Li-ion batteries for EVs surpassed those for electronics (Fig. 5). They have been witnessing an average year-over-year growth of 67%, and this trend is expected to continue. Overall, the market share of Li-ion batteries for EVs and stationary storage increased from about 5% early this decade to more than 60% in 2017.

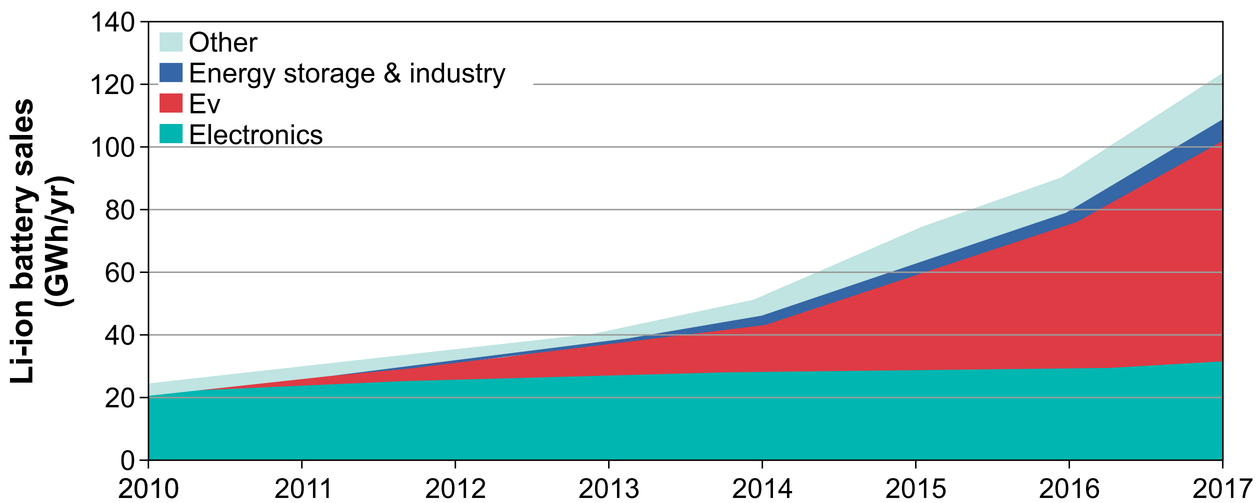


Fig. 5. Development of Li-ion battery sales. Source: Li-ion batteries for mobility and stationary storage applications Scenarios for costs and market growth. (Tsiropoulos et al. 2018)

1.4.4 Use phase and lifetime extension

Considering the sophistication and complexity of ICT hardware, its lifespan is relatively short. While earlier studies suggest smartphone product lifetimes of up to 5 years (Bakker et al. 2014), more recent studies indicate this period to be shorter than 2 years (Lu 2017, Cordella et al. 2021). Compared to smartphones, the product lifetime of smart TVs is generally longer, up to 5–10 years (Berwald et al. 2020). Such lifetimes can be considered as insufficiently short regarding sustainability. The fast pace by which the manufacturing industry also innovates creates a pressure on some customer segments to update their devices faster. Besides undisputable technological development, subjective "needs creation" also plays a role. This constant replacement of devices by consumers means a need for more primary and secondary raw materials, with all their impacts.

Finding ways to extend the lifetime of ICT is of high importance: for smartphones, the reduction in greenhouse gas emissions with a lifetime extended from 21.6 to 45.6 months equals the emissions of 546 000 smartphones (Rizos et al. 2019). The novel EU regulatory measures introduce design-oriented means such as the "right to repair" that aim for longer lifespans. Other means for extending lifespans include better coverage of repair points for devices, leasing, and lower taxes on repair.

There is a considerable albeit unused reuse potential in ICT hardware. According to Messmann et al. (2019), 19.2% of collected WEEE could be directly reused with little cleaning and another 39% could be reused after repair. However, 42% was too damaged to be repaired. In reality, only 0.5% of collected ICT hardware is reused and the rest is recycled (78.8%) or burnt (11%).

1.4.5 Recycling and e-waste

ICT hardware (or electronic and electrical equipment, EEE) becomes e-waste (WEEE) when it has been discarded by the owner without the intention of re-use (STEP 2014). WEEE covers all types of EEE and their parts. The amount of EEE is constantly increasing and these devices are, sooner or later, replaced due to defects, technical obsolescence or various other reasons.

An average European household contains 72 EEE devices, of which 11 are broken or not in use (Leroy 2020). At the global level, e-waste totalled approximately 53.6 million tons (Mt) in 2019 (Forti et al. 2020). Documented collection and recycling totalled 9.3 Mt, which is 17.4% of the generated e-waste (ibid.). In the EU, the recycling rate is estimated to be from less than 40% to 49% and e-waste is the fastest growing waste stream (European Parliament 2020). The EU is the frontrunner in documented e-waste, followed by Asia (11.7%), the Americas (9.4%), Oceania (8.8%) and Africa (0.9%) (Forti et al. 2020). Globally, the annual growth of e-waste has been greater than the growth of recycling and collection (2 Mt vs. 0.4 Mt). However, **the potential value of raw materials of current e-waste is estimated at €48 billion, assuming ideal recovery and recycling**. The annual amount of e-waste is forecasted to grow from 53.6 Mt to almost 75 Mt by 2030. Reusing e-waste as a source of secondary materials and products has considerable potential for reducing CO2 emissions. (Forti et al. 2020)

E-waste is regarded as one of the most problematic waste streams due to its considerable volume and partly hazardous content. In the EU, collected electronic and electrical waste consists of large household appliances (52.7%), consumer equipment and photovoltaic panels (14.6%), IT and telecommunications equipment (14.1%), small household appliances (10.1%) and other electronic equipment (8.4%). The recycling rate of e-waste in the EU varies from 81.3% in Croatia to 20.8% in Malta. (European Parliament 2020)

Key drivers of e-waste generation include higher levels of disposable income, urbanisation, industrialisation, higher consumption rates of EEE, short life cycles and few available repair options. In recycling e-waste, each product has different material contents, and is disposed of and recycled in different ways. Therefore, the products are unequally harmful to the environment and human health if not managed in an environmentally sound manner. (Forti et al. 2020). Some of the adverse impacts of e-waste are outsourced to developing countries via legal or illegal waste trade, where the lack of proper waste management leads to local human exposure and contamination, often of child labour working on the dismantling of e-devices in sub-human conditions (Puckett et al. 2018).

2 MINERALS AND METALS IN DIGITALIZATION

Almost the entire periodic system of elements can be found in digital technologies, with a particularly high share in the consumption of elements such as copper, gallium, germanium, gold, indium, platinum-group metals (PGMs), rare earths (REE) and tantalum. For example, UNCTAD (2020) referred to gallium, germanium, indium, rare earth elements (REEs), selenium, tantalum and tellurium as the "ICT elements". They are all "functional elements" that are essential raw materials for the building blocks of all ICT hardware, such as microchips and integrated circuits. The total value of all metal production (at the mine stage) in 2018 was around $660 billion. Iron ore, gold and copper - in that order – accounted for over 60% of this amount and other metals 39%, while the ICT elements identified together only represented 0.77% ($5 billion), excluding coal (UNCTAD 2020). In terms of production volumes, the share of these seven metals is even smaller, as most of them command a high price per ton. Total world production of metals was around 1 600 Mt (metal content) in 2018. The seven elements together amounted to 0.17 Mt, of which REEs accounted for around 95% (UNCTAD 2020). All the others are produced in miniscule amounts, from around 100 tons of germanium up to 3,000 t of selenium. The ICT elements thus represent only a tiny fraction of the total use of all metals, but for some of them, the digital economy accounts for 80–90% of total usage (Malmodin et al. 2018). While REEs and tantalum are primary products from specific mines, the other five elements are by-products from copper, bauxite, lead/zinc or coal mines, extracted in later process steps of smelting or refining. The global production, resources and reserves of raw materials important for ICT are presented in Table 2.

The raw material needs of digital technologies presented in this section are based on Bobba et al. (2020), UNCTAD (2020), Marscheider-Weidemann et al. (2016) and Ku (2018). In general, digitalization and increased data storage could require considerable increases in the consumption of some critical raw materials (CRMs) such as palladium, germanium, gallium, dysprosium and neodymium. In robotization, 19 out of 44 required raw materials are CRMs (defined as critical for the EU), which are mainly produced by China, South Africa and Russia. China (41%) and African countries (30%) are the dominant suppliers of several commodities needed in digitalization (Fig. 6).

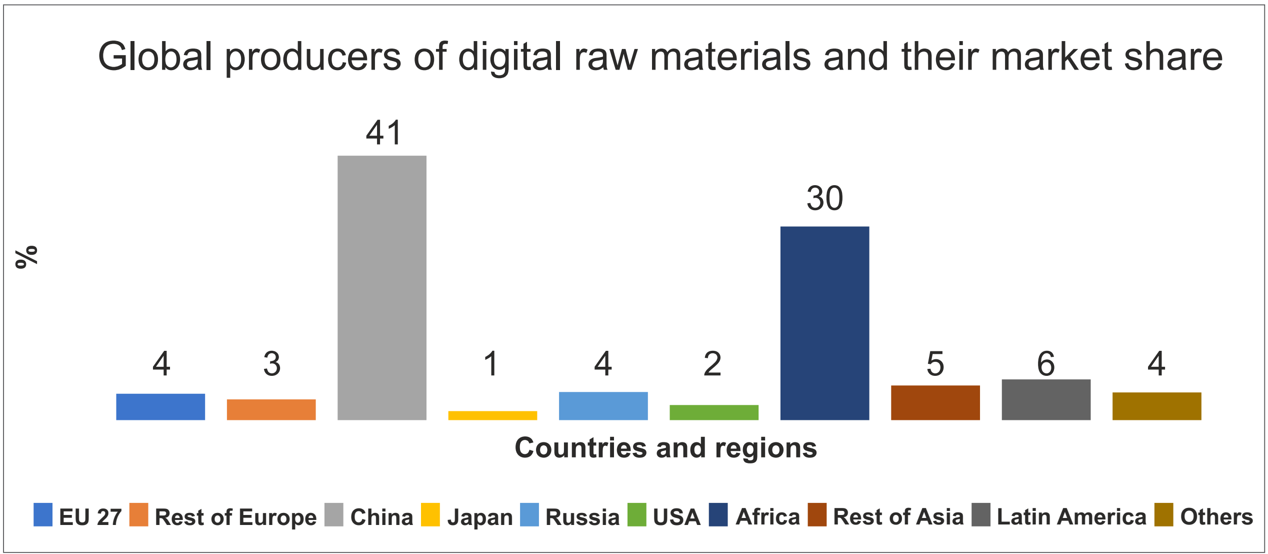


Fig. 6. Global key countries and regions in the digital raw materials supply chain for critical raw materials and their share of global production in % (after Bobba et al. 2020). The commodities included are: silver (Ag), gold (Au), boron (B), natural graphite, cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), gallium (Ga), germanium (Ge), indium (In), lithium (Li), magnesium (Mg), manganese (Mn), nickel (Ni), lead (Pb), platinum-group metals (PGM), rare earth elements (REE), silicon (Si), tin (Sn), strontium (Sr), titanium (Ti), and tungsten (W).

Table 2. Production and resources (metric tonnes of commodity) of the most important metals used in digitalization; 2018 data, unless otherwise indicated. Global and EU resources should be regarded as conservative and are most probably significantly less than there really is in the ground. For the EU, resource data for Romania, for example, are mostly lacking. The UK is not included in the EU figures. Question mark indicates no information or that the figure given is uncertain.

Mine production					Resources and reserves		
Metal	Global[1]	EU[2]	Finland[3]	Dominant global producers[1,4]	Global[1]	EU[1,2,5,6]	Finland[7]
Al[1]	327 000 000	1 693 000	0	AUS (26%), CHN, GUI, BRA	75 000 000 000	1 023 000 000	0
Cr	20 000 000	400 000	400 000	RSA (41%), TUR, KAZ, IND	>5 000 000 000	50 000 000	45 700 000
Cu	20 400 000	906 927	46 674	CHI (29%), PER, CNA, DRC, USA	2 100 000 000	21 000 000	5 242 400
Au	3300	31	8.7	CNA (14%), AUS, RUS, USA	50 000	1370	579
Ga	300[11]	0	0	CNA (90%)[11]	>1 000 000[12]	Not known	Not known
Ge	130[11]	0	0	CNA[11]	>35 000[12]	Not known	Not known
In	900[11]	0	0	CNA, KOR[11]	356 000	Not known	Not known
REE	206 400	0	0	CNA, USA, BUR	411 000 000	913 000	51 700
Se	2900[11]	615	100	CNA, JPN[11]	>100 000[12]	Not known	Not known
Ta	1700	14	0	DRC, BRA, RWA	>140 000[12]	600	477
Te	490[11]	45	0	CNA, JPN, RUS[11]	>31,000[12]	1,500	Not known
Ir	6.1	0	0	RSA (92%)	Not known	0	0
Ni	2 400 000	62 172	43 572	INS (25%), PHI, RUS, NCA	>130 000 000	9 900 000	5 637 000
Pd	199	1.58	1.58	RUS (40%), RSA	7200[5]	584	584
Pt	178	1.16	1.16	RSA (71%), RUS	13 000[5]	260	260
Ru	27.1	0	0	RSA (93%)	na	0	0
Si[8]	2 454 000	158 000	0	CNA (65%), RUS, NOR, USA	Very large	Large	Large?
Ag	26 500	1800	13	MEX (21%), PER, CNA, RUS	560 000[9]	143 000	2055
Sn	318 000	192	0	CNA (28%), INS, BUR, PER	9 500 000	114 000	1440

1 USGS (2021)
2 Brown et al. (2020)
3 Tukes (2021)
4 AUS = Australia, BRA = Brazil, BUR = Burma, CND = Canada, CHI = Chile, CNA = China, DRC = Dem. Rep. Congo, GUI = Guinea, IND = India, INS = Indonesia, JPN = Japan, KAZ = Kazakhstan, KOR = South Korea, MEX = Mexico, NCA = New Caledonia, NOR = Norway, PER = Peru, PI = Philippines, RSA = South Africa, RUS = Russia, TUR = Turkey, na = not available
5 Eynard et al. (2020), Latunussa et al. (2020), Minerals4EU 2021. 'not known' means that resources do exist but their volumes are not known.
6 Eilu et al. (2020)
7 Geological Survey of Finland (2021).
8 Silicon metal production from silica refineries – mine production data are not available. The raw material is quartz, for which reserves, and resources, are very large but their quality varies considerably. Only a small volume of all mined quartz is used as 'silicon metal' in alloy and electronic component production.
9 Reserves only, resources are much larger.
10 Bauxite (aluminium ore); note that China produced 61% of all refined Al metal.
11 Data for Ga, Ge, In, Se, and Te relate to refinery production, as mine production data are not available. For all of these, an **overwhelming majority of the metal in mined ore is not recovered at all**; it is the main metals of the respective ores (Al, Cu, Zn) that are recovered. For example, **for Ge, only about 3% of the metal is recovered from the ores mined that do contain potential by-product germanium**.
12 Only mineral reserves are known and only for a small number of major metal deposits, while resources are much larger – this also holds for the resources within the EU and Finland. For Ga, this is a resource estimate in bauxite ores, and a large volume is assumed to exist in zinc ores.

Key CRMs for the EU in these technologies include chromium, cobalt, molybdenum, natural graphite, nickel, magnesium, vanadium, copper, tin, antimony and bismuth (ibid.). Additive manufacturing utilises polymers and metal powders, such as aluminium-magnesium alloys, titanium, nickel and stainless steel, and additional alloying elements cobalt, hafnium, niobium, magnesium, scandium, titanium, vanadium, tungsten and zirconium.

From the raw material perspective, the digital ICT industry has three main features (Ku 2018):

- First, a wide and increasing range of elements are used to enable the desired electronic, magnetic, optical or mechanical properties needed for chips and devices.
- Second, the very large number of chips and devices that are produced each year suggests that even incremental increases in certain elements, per device, can amount to significant volumes of material relative to current supply.
- Third, the speed of technology introduction cycles can be faster than the time scales associated with other aspects of the supply chain.

However, other raw materials that are not used in the ICT equipment themselves, but essentially in the general and device-related infrastructure and hardware, are equally relevant to ensure its proper functioning and may become critical for the deployment of next-generation computing. For example, helium is used to create a low operating temperature close to absolute zero that, in ICT, is needed for quantum computing technologies, and for manufacturing supra- and semiconductors and optical fibre cables (Eynard et al. 2020). Thanks to committed substitution and recycling, users have been able to significantly reduce its demand (Elsner 2019); the previously very high demand for helium has not been achieved again in recent years, which is less likely to be due to a low interest in this noble gas than to user fears of renewed scarcity. The experienced short-term supply bottlenecks may prevent potential users from returning to helium as the preferred industrial gas, for the time being (Elsner 2019).

The global expansion of digital networks and services implies that more people have access to the Internet, thus fuelling the need for connected equipment and for connection infrastructure, such as power plants, electricity grids and fibre optics. Despite the enormous growth in sales for some electronic devices, the expected use of related CRMs would either stagnate or rise in relatively limited proportions (e.g., for palladium, gallium, dysprosium and neodymium; Bobba et al. 2020). The case of tantalum, for which electronics is currently the main application, is interesting: tantalum use in electronic applications alone could outpace the current use of this metal, all applications factored together. Similarly, the development of digital technologies and of electronic displays (including flat screens and touch screens) has boosted the consumption of indium used in indium-tin-oxide (ITO) thin films. From 1993 to 2013, indium experienced a more than fivefold growth in (primary) production (Tercero 2019). Indium is among the elements capturing a growing consideration due to its relatively high economic importance, lack of substitutes, extraction as a by-product from carrier metal ores, low recovery efficiency in processing currently applied at refineries, and non-existent recycling at the end of life of the devices (Werner et al. 2015, Frenzel et al. 2017, Ciacci et al. 2019). Another issue with indium is that not many refineries have been interested, at all, in recovering the metal from its main source, zinc concentrates; the same also holds for gallium and germanium. Globally, it is estimated that only about 3% of the Ge contained in zinc concentrates is recovered (USGS 2021).

The current global, EU and Finnish demand for raw materials important for ICT is presented in Table 3.

Table 3. Demand, import and recycling of the most important metals used in digitalization in the EU; 2018 data, unless otherwise indicated. The UK is not included in the EU figures. Demand by the Finnish electronics industry is not available. The main sources of information are Eynard et al. (2020), Latunussa et al. (2020) and USGS (2021). EoL = End-of-life products. Question mark indicates no information or that the figure given is uncertain.

Metal	Global demand	EU demand	EU ICT demand[1]	EU demand covered by imports	EU importing ore and concentrate from[2]	EU main sources of refined metal[2]	Recycled metal share of the global total demand	Global EoL recycling rate[3]
Al[4]	327 000 000	15 400[4]	1 500[5]	89%[4]	GUI, BRA	RUS, GER, MOZ, FRA	35%	60–90%
Cr	20 000 000	1 200 000	<1%	55%	RSA, TUR	RSA, FIN[6]	35%?[6]	>50%
Cu	24 500 000	2 570 000	385 500	69%	CHI, PER, BRA	GER, PLD, SPA, BEL	32%	17%
Au	4400	300	33	91%	?	?	23%	20–30%
Ga	300	27	27	100%[10]	?	UK, CNA	10–25%	0%
Ge	130	39	34	100%	None	CNA, UK, RUS, USA	30%	2%
In	900	30	27	100%[10]	None?	FRA, BEL, UK, CNA	25–50%	1%
REE	200 000	4000	460	100%	None	CNA, RUS	>1%	<1%
Se	2900	1200	120	25%	None	GER, BEL	<1%	0%
Ta	1700	400	300	100%	DRC, RWA, BRA	None	30%	0%
Te	490	27	22	70%?	?	UKR, unspecified	?	<1%
Ir	7.5	0.9	?	100%	RSA	RSA, UK	14%	20–30%
Ni	2 300 000	330 000	33 000?	70%	RSA, CND, BRA	RUS, FIN, UK, NOR	35%	83%[7]
Pd	290	59	2.4	99%	RUS, RSA	RUS, RSA, CND	29%	60–70%
Pt	255	64	0.6	98%	RSA, RUS	RSA, UK	27%	60–70%
Ru	33.5	2.5	1.2	100%	RSA	RSA, UK	11%	5–15%
Si	2 500 000	433 000	8500	64%	na[8]	NOR, FRA, CNA, BRA, GER, SPA	2%?	0%?
Ag	30 848	5261	310	64%	MEX, PER, ARG	GER, ITA, FRA, BEL	17%[9]	10–15%
Sn	371 000	37 300	18 000	100%	USA, THA	BEL, UK, PER, MLY, PLD	31%	40%

1 Demand in all electronics; EU: uncertain for nickel, no data for iridium

2 Decreasing order of importance; ARG = Argentina, BEL = Belgium, BRA = Brazil, CHI = Chile, CNA = China, CND = Canada, FIN = Finland, FRA = France, GER = Germany, GRE = Greece, GUI = Guinea, ITA = Italy, MEX = Mexico, MLY = Malaysia, MOZ = Mozambique, PER = Peru, PLD = Poland, POR = Portugal, RSA = South Africa, RUS = Russia, RWA = Rwanda, SPA = Spain, SWE = Sweden, THA = Thailand, TUR = Turkey, UK = United Kingdom, UKR = Ukraine, unspecified = unspecified countries

3 This figure does not include recycling from monetary and jewellery sources, and the percentage is, apparently, much lower for ICT for PGE, Au and Ag. The recycling rate varies between other types of EoL for all metals.

4 Bauxite (aluminium ore); recycling rates relate to aluminium metal

5 Demand in all electric applications, wires and cables included; the demand strictly for ICT is much less

6 Source of ferrochrome (56% Cr) instead of refined metal, as refined metal demand is <1% of the total Cr demand. Availability of scrap stainless steel is much lower than the EU domestic demand; hence the EU also imports scrap metal.

7 Nickel Institute (2021)

8 It is not known how much high-purity quartz is imported for silicon metal production. In any case, most of the quartz processed in the EU into silicon is of EU origin.

9 Silver Institute (2020)

10 This is for refined metal, as imports of ore and concentrate are not known.

The demand for CRMs in the search for better performing and cheaper materials or components of electronic appliances fosters substitution and could indeed either level off or keep increasing this demand (REEs, tantalum, palladium for electronic devices & appliances; germanium for optic fibres; Tercero 2019). Based on Ku (2018), it can be estimated that the storage in the global datasphere would require up to 80 000 tons of neodymium, about 120 times the current yearly EU demand for this metal. Using emerging technologies, such as ferroelectric RAM to store increasing amounts of data, instead of the current technology, would require up to 40 000 tons of platinum, which is about 680 and 140 times the current annual demand in the EU and globally, respectively. When considering such proportions and their expansion, it is good to keep in mind that other sectors compete with ICT for the same raw materials and processed materials, as well as components (Fig. 7). This applies, for example, to CRMs such as borates, gallium, indium, rare earths, cobalt, niobium and silicon metal. As the mineral commodities are traded on international markets, and as other key countries such as the USA and China are reliant on imports for some of them (e.g., for niobium, chromium, tantalum), their availability to the EU might become even more demanding. Competition between world regions for access to raw materials will become more acute as a result of the transition towards a low-carbon economy and based on new industrial strategies.

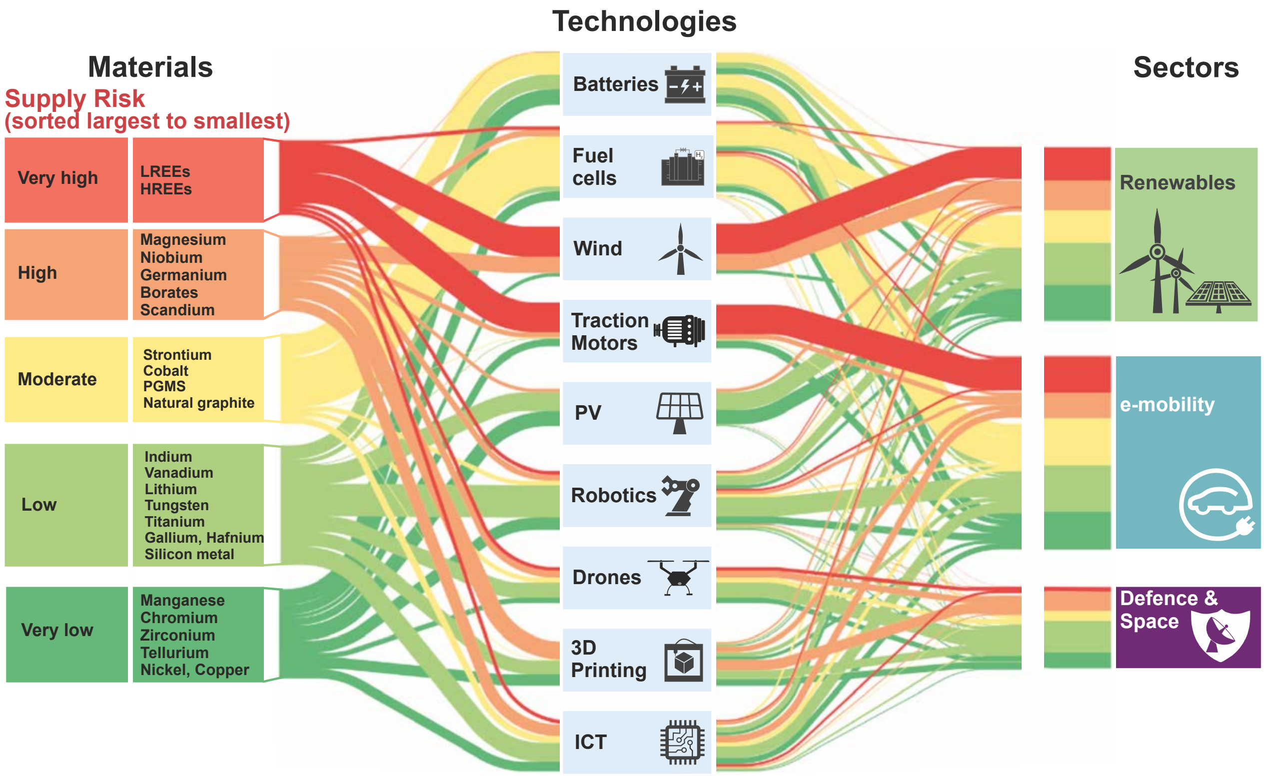


Fig. 7. Semi-quantitative representation of flows of raw materials and their current supply risks to the nine selected technologies and three sectors (based on 25 selected raw materials, after Bobba et al. 2020).

For example, the manufacture of electric cars and wind turbines also requires increasing amounts of neodymium and PGE (Fig. 7). However, as one of the REE, it is estimated that there would not be shortage of neodymium, although most of it is produced by China (60%), which can control its supply (UNCTAD 2020).

The trends presented above are based on Bobba et al. (2020) and consider a rather conservative and technology-constant approach to digitalization. Other authors argue that a much larger increase in the consumption of these materials in the future is to be expected due to the upgrading of production infrastructure and high consumption of new devices, including sensors and actuators (Bonilla et al. 2018). Supply risks might also be increased by the fact that the recycling potential of CRMs from ICT technologies will be largely limited or not feasible in the near future (Marscheider-Weidemann et al. 2016). However, geologically speaking, there is no scarcity of the ICT elements in the Earth's crust (UNCTAD 2020); for gallium, germanium and indium, the reserves and resources are gigantic. They are proportional to the resources of bauxite (for aluminium production), zinc and copper ores, all of which are produced in millions of tons every year and hence are available in huge quantities. It is also important to consider that even though ICT competes with other sectors for the same raw materials, the amount needed by ICT is only 0.5%. This is due to the small amounts of these raw materials used in ICT devices. However, as seen above, their demand is expected to expand considerably in a few decades, but the supply of these seven main ICT elements is in general not an issue (UNCTAD 2020). Only limited parts of what could potentially be extracted from the total volumes of the primary products are currently utilized. The small absolute production volumes needed make it realistic to also cover large future increases in demand for all seven elements with limited investment and within short time frames, possibly with the exception of REEs (UNCTAD 2020). Table 4 presents global mining, minimum resources and demand years for elements important for ICT, based on known reserves. It shows that the demand for many elements can continue to be supplied for a long time before the known reserves will be exhausted, but only for some decades for others.

Table 4. The ratio between global mine production and global known resources (metric tonnes of commodity) of the most important metals used in digitalization, and a calculation of how long the currently known resources would last with the current volume of mining. 2020 data by USGS (2021). The resources data should be regarded as conservative, most probably significantly less than what really exists and is extractable in the ground.

Metal	Global mining	Global minimum resources[1]	Global demand years of global resources
Al	327 000 000	75 000 000 000	229
Cr	20 000 000	5 000 000 000	250
Cu	20 400 000	2 100 000 000	103
Au	3 300	50 000	15
Ga[2]	300	1 000 000	3 333
Ge[2]	130	35 000	269
In[2]	900	356 000	396
REE	206 400	411 000 000	1 991
Se[2]	2 900	100 000	34
Ta	1 700	140 000	82
Te[2]	490	31 000	63
Ir[1]	6.1	700	115
Ni	2 400 000	130 000 000	54
Pd	199	7 200	36
Pt	178	13 000	73
Ru[1]	27.1	700	26
Si[1,3]	2 454 000	100 000 000 000	40 750
Ag	26 500	560 000	21
Sn	318 000	9 500 000	30

1 Global Ir and Ru resources each assumed at 10% of Pd resources; global Si resources certainly larger than global Al resources

2 Production data for Ga, Ge, In, Se, and Te relate to refinery production, as mine production data are not available. For all these, **an overwhelming majority of the metal in mined ore is not recovered at all**; it is the main metals of the respective ores (Al, Cu, Zn) that are recovered. For example, **for Ge, only about 3% of the metal is recovered from the ores mined that do contain germanium as a potential by-product**.

3 Silicon metal production from silica refineries – mine production data are not available. The raw material is quartz, for which reserves, and resources are very large, but their quality varies considerably. Only a small volume of all mined quartz is used as 'silicon metal' in alloy and electronic component production.

Therefore, the one problem regarding the availability of primary raw materials for ICT is the strong import dependency from a few main sources. However, the situation may be more striking for sectors competing for the same raw materials, such as e-mobility and renewable energy production, which require major volumes of the same raw materials than the ICT. A lack of sufficient production may compromise efforts to achieve a green transition and could drive a search for other solutions to achieve carbon neutrality (see IEA 2021 and Michaux 2021).

2.1 Current uses, and the production of commodities in digitalization

The minerals used in digitalization can be divided into three groups according to their applications (Table 2): 1) technology-critical elements, 2) battery metals and minerals and 3) other metals, elements and minerals. This division is somewhat arbitrary, however, as some commodities, such as cobalt, chromium, copper, graphite and nickel, are included in more than one of the groups.

The elements and minerals essential in the current and forecasted digital technology are presented in lists below for each group. They are based on Eynard et al. (2020) and Latunussa et al. (2020) and references therein.

2.1.1 High-tech metals

The technology-critical elements or high-tech metals, such as gallium, germanium, niobium and tantalum (Table 2), are of great relevance in the development of emerging key technologies, including renewable energy, energy efficiency, electronics and the aerospace industry. These elements are minor or trace elements in the Earth's crust, having an average abundance ranging from <0.1 ppb (parts per billion; 1 ppb = 0.0000001%) to several hundred ppm (parts per million; 1 ppm = 0.0001%), and are typically, but not exclusively, recovered from only a small number of mineral deposits. Most of them also are recovered as by-products of major metal ores, major exceptions being chromium, graphite and nickel, which are almost always mined as the main commodity of their respective ores. The high-tech metals and their applications in digital technology are listed in Table 5.

Table 5. High-tech commodities and their application in digitalization (Bobba et al. 2020).

Commodity	Applications in digital technology
Boron (B)	Semi-conductors and HDD permanent magnets
Chromium (Cr)	Plating and coatings of electronic components
Cobalt (Co)	HDDs, semi-conductors and integrated circuits
Gallium (Ga)	Semiconductors, LEDs, semiconductors for Blue-ray, mobile phones
Germanium Ge)	Glass for fibre-optic cables, infrared optics (night vision), semiconductors
Graphite (C)	Graphene
Indium (In)	Screens (as indium-tin oxide)
Magnesium (Mg)	High-performance Al–Mg alloys
Nickel (Ni)	Plating and anticorrosive coatings
Niobium (Nb)	Semiconducting magnets
Rare Earth Elements (REE)	Magnets, HDDs, displays, LED, lasers, circuit boards, memories.
Tantalum (Ta)	Capacitors
Thallium (Th)	Semiconductors, fibre optics
Tungsten (W)	Heat-resistant alloys in ICs, dielectric materials and transistors, vacuum-tube filaments

2.1.2 Battery minerals

The battery metals are metals or minerals commonly used in batteries, especially in lithium-ion batteries, which are crucial parts of portable two-way communications devices and computing devices. The minerals used in these are lithium, cobalt, nickel, manganese, aluminium as the battery cathode and predominantly graphite as the anode. Lithium is also to some extent used in the electrolyte.

The types of batteries used in these portable devices are guided by the limited amount of space available. Therefore, the batteries used are of a high energy density type. These types are lithium cobalt oxide (LiCoO2) or LCO, lithium nickel manganese cobalt oxide (LiNiMnCoO2) or NMC, and lithium nickel cobalt aluminium oxide (LiNiCoAlO2) or NCA.

To a large extent, the same metals and minerals are also important in the batteries of electric vehicles. However, the battery configuration differs, since the available space is less restricted in vehicles and an extended battery life is of higher importance (Buchman 2021). The commodities used in batteries are listed in Table 6 with their applications.

Table 6. Battery commodities and their applications in digitalization (Bobba et al. 2020).

Commodity	Applications in digital technology
Cobalt (Co)	Used in the cathode of LCO, NMC and NCA-type batteries
Graphite (C)	Anode in all battery types
Lithium (Li)	Used in the cathode and in the electrolyte
Manganese (Mn)	Used in the cathode of NMC batteries
Nickel (Ni)	Used in the cathode of NMC and NCA-type batteries
Vanadium (V)	Used in stationary batteries but not in mobile devices or electric vehicle batteries

2.1.3 Other metals

Third group, "other metals", is a large and heterogeneous group of metals and elements that are commonly used in electronics and other digital solutions. This group consists of base metals used in constructing ICT and other hardware (aluminium, chromium, copper, nickel), precious metals (gold, silver, platinum-group elements) and some special elements of high importance, such as silicon metal. The commodities of this group are listed in Table 7.

Table 7. Other commodities and their applications in digitalization (Bobba et al. 2020).

Commodity	Applications in digital technology
Aluminium (Al)	Device casings and frames, wires, cables
Chromium (Cr)	Stainless-steel casings and frames
Copper (Cu)	Main conductor metal in electronics, connectors, transformers, printed circuits, cables, wiring, contacts, ICs, semi-conductors
Gold (Au)	Connectors, switch and relay contacts, solder joints, connection wires and strips, memory chips and circuit boards
Iridium (Ir)	Crucibles for growing single crystals for lasers, scanners, LEDs, and surface-acoustic-wave (SAW) filters and other applications; OLED screens
Nickel (Ni)	Stainless-steel casings and frames
Palladium (Pd)	Multi-layer ceramic capacitors, LCDs, printed circuit boards. In the future, use in micro-electric capacitors may become significant
Platinum (Pt)	Printed circuit boards, glass in displays, memories
Ruthenium (Ru)	Electrical contacts for thermostats and relays, hard disk drives
Silicon metal (Si)	Semiconductors, transistors, printed circuit boards and integrated circuits, computer chips
Silver (Ag)	Soldering and brazing alloys, printed circuit boards. Sensitive systems and specialty electronics where high conductivity over a small distance is prioritized by electrical contacts, switches and passive electronic components such as multi-layer ceramic capacitor. 5G devices.
Tin (Sn)	Solders

2.2 EU in the global context of production and demand of natural resources for digitalization

Raw materials are key enablers for all sectors of the EU economy. Digital technologies require many raw materials that are classified as CRMs by the EU (Bobba et al. 2020). CRMs are considered to be those that have high economic importance for the EU and a high supply risk. Some of the raw materials, in particular those assessed as CRMs (European Commission 2020c), are essential prerequisites for the development of strategic sectors such as renewable energy, electric mobility, defence and aerospace, and digital technologies. The growing acceptance and use of the concept of criticality and critical materials by politicians and industry have made the risks of future imbalances in supply and demand of these elements come into focus at an early stage in the development cycle. In Europe, China, Japan and the United States, broad R&D programmes have been started to shed light on all possible aspects of the demand and supply of critical elements. Research topics include the search for possible substitutes, ways to increase supply and how alternate technologies could be facilitated and future deficits with concurring price swings avoided. All these efforts should hopefully result in reduced risks. Improved rates of recycling will also influence the demand for virgin materials, and with the present emphasis on sustainability, such aspects have become more important. Currently, EU industry is largely dependent on imports for many raw materials, and in some cases is highly exposed to vulnerabilities along the supply chain (Bobba et al. 2020). This especially concerns digitalization (Tables 2 and 3). In this regard, Europe is also dependent on other countries (mainly from South-East Asia) for high-tech components and assemblies (Bobba et al. 2020). This was globally demonstrated by the recent obstruction of the Suez Channel, even though it lasted for only a couple of weeks, and by the current serious water shortages in Taiwan, both of which interrupted the microchip supply for global manufacturing industries.

As shown by Table 2, the EU produces most of the important commodities used in digitalization, and also has its own resources and reserves, whereas Finland has slightly more deficient production, resources and reserves of them. According to Table 2, the EU's deficiency in such commodities is especially striking regarding Al, Ir, and Ru and most of the ICT elements. The same concerns Finland, with the addition of Sr and Sn. As already stated earlier, the main producers are outside the EU.

For instance, Table 3 presents the demand, imports and recycling of metals used in digitalization in the EU. It shows the EU's strong general dependence on imports of raw materials, which is over 50% in all commodities used in ICT. The demand covered by imports is particularly high (70–100%) for Al, Ni, PGE (Pt, Pd), and those materials with an absolute lack of production in EU, which are mentioned above and especially concern most of the ICT elements.

Recycling covers from ca. 2% to 35% of the total global demand. The global product end of life (EoL) recycling rate (RR) varies from 0% (Si) to 90% (Al). The RRs of Ni, PGE and Cr are quite high (>50%–83%), whereas those of Cu, Ru, Ag and Si are non-existent to low (at about 0%–17%), and they are unknown for many of the ICT elements. Therefore, recycling is not able to replace primary production, at least currently. However, as digitalization consumes only 0.5% of the raw material needs when compared to other industrial sectors, recycling could be a viable option to help to reduce the need for primary raw materials in ICT, which are mostly imported, and to increase the EU's self-sufficiency in raw materials. However, the ICT sector must compete with other manufacturing sectors for the same raw materials and cannot therefore solely rely on recycling. The situation presented in Tables 5 and 6 can be well illustrated by the map in Figure 8 depicting the global production of primary natural resources. Figure 8 shows that, as already mentioned above, most of the commodities for digitalization come from abroad, mainly from China and Africa, many of which are CRM.

Bobba et al. (2020) considered the supply risks for the top 25 elements for several EU industrial sectors, including critical and non-critical materials. From these, the top 16 elements for the digital industry were selected, which are listed in Table 8 together with their supply risk levels.

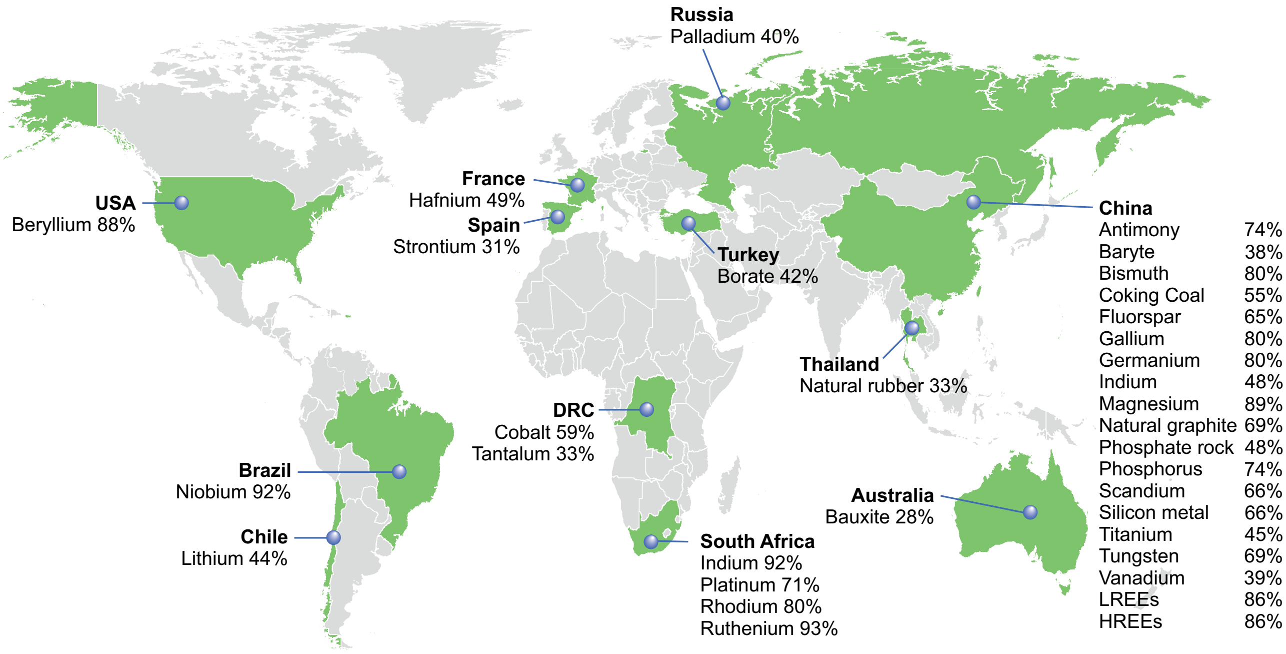


Fig. 8. The dominant critical raw material (CRM) producers and their share of global production (after Blengini et al. 2020). These are the CRMs for the EU. Also note that this map presents 2016 data, and a few major changes have taken place since. For example, Australia has overtaken Chile as the largest lithium producer, and the share of REE production by China as decreased to about 65% (USGS 2021).

Table 8. The top 16 critical and non-critical raw materials used in digital technologies, in decreasing order of supply risk (after Bobba et al. 2020). Light rare earth elements (LREEs), heavy rare earth elements (HREEs) and platinum group metals (PGMs) are groups of metals with relatively similar chemical and physical characteristics. Note that the 'low' supply risk is also above the criticality threshold, whereas 'very low' is below that threshold, although the criticality of chromium, manganese and zirconium is just below the threshold.

Element	Supply risk
LREEs	Very high
Magnesium metal (Mg)	Very high
Germanium (Ge)	High
Borates (B)	High
Cobalt (Co)	Moderate
PGMs	Moderate
Natural graphite	Moderate
Vanadium (V)	Low
Titanium (Ti)	Low
Gallium (Ga)	Low
Silicon metal (Si)	Low
Manganese (Mn)	Very low
Chromium (Cr)	Very low
Zirconium (Zr)	Very low
Silver (Ag)	Very low
Copper (Cu)	Very low

While the criticality of materials applies to the wider European industrial landscape, many CRMs are particularly essential for ICT devices and advanced electronics. Europe's reliance on foreign digital components and technology is increasing as it falls behind in the production of key digital technologies. In 2017, the **EU's overall trade deficit for high-tech components and products stood at €23 billion,** largely due to sizeable Chinese imports (European Political Strategy Centre 2019). A semi-quantitative analysis by Bobba et al. (2020) revealed that the EU consumption of some CRMs, such as palladium, gallium, dysprosium and neodymium (the latter two are REEs), for these technologies is likely to increase soon.

The EU will strive to achieve technological sovereignty in some critical digital technology areas (e.g., blockchain, quantum computing and data sharing). For digital technologies, technological sovereignty requires that the EU secures access to key raw materials and processed materials and redevelops manufacturing opportunities for key digital components and assemblies in the EU. This requires significant investment in R&D to match the pace of other countries and regions. The EU must also strongly develop manufacturing opportunities for components and assemblies.

According to Bobba et al. (2020), the leading role of the EU concerning the collection and management of WEEE and in standardization, also concerning the material efficiency of electronic equipment, could also be an asset to reduce the supply risk concerning raw materials for digital technologies. A prerequisite for this digital re-industrialization will be the securing of access to key raw materials that are essential to these technologies (for example REEs, gallium, germanium and PGMs) and the development of capabilities for processed materials. In this context, despite being an allied country, the manufacturing sector of the EU will, in near future, also face increasing competition for raw materials from industries of the US (cf., White House 2021).

According to EU Science Hub (2020), these examples given by Bobba et al. (2020) indicate that a secure supply of raw materials, both from primary and secondary sources, together with continued research and innovation policies for substitution and more sustainable product design, is a sine qua non, i.e., an essential action, for competitive and resilient EU industries, their recovery from the COVID-19 crisis and the transition towards green and digital industries.

2.2.1 The EU Mineral Policy

The following description of EU's mineral policy is based on Kivinen and Käpyaho (2019). In 2008, the European Commission (EC) published the Raw Materials Initiative (RMI), the purpose of which is to focus political attention on the uninterrupted availability of raw materials in the EU area. The premise for the initiative was to reduce the strong dependency of European industry on imported mineral raw materials and to reduce the financial impacts of possible interruptions in import. Mineral raw materials and their availability are indeed the focus of the initiative. The RMI can be considered as the starting point for the growing political attention given to minerals in the EU over the past decade. This has reflected in the drafting of national minerals strategies and the targeting of research funding, both nationally and at the EU level. After the RMI was published, Finland was the first EU country to draft its own national minerals strategy in 2010.

The Raw Materials Supply Group is a group of experts that advises the EC on matters concerning raw materials and monitors the implementation of the RMI. The RMI also influenced the drafting of the EC's CRM list. The list has influenced the targeting of policy measures and research funding. The list was published for the first time in 2011 and was then updated in 2014 and 2017. The newest update was published in 2020 (Blengini et al. 2020).

In 2012, the EU Commission launched the European Innovation Partnership on Raw Materials (EIP-RM). The objective of this innovative partnership was the acceleration of innovation activities by combining the private and public research, development and innovation chain throughout Europe. New members have recently been appointed to the EIP-RM's high-level steering group, the Sherpa group, and its operative working groups, and representatives from universities, research institutes and companies are among these members. The objective is for the groups to also be able to influence the content of the upcoming 9th Framework Programme (following the EU's Horizon 2020 programme), so that research and innovation activities related to raw materials would continue to be highly prioritized in the EU's agenda. It seems clear that the Commission will continue to consider research and innovation activities concerning the circular economy of raw materials a priority in the coming years. This, in turn, will shift the focus of research to the themes of secondary raw materials, the recyclability of materials, reuse and improved product design. The European Institute of Innovation & Technology on Raw Materials (EIT-RM) innovation community, which was established in 2015, has also strongly influenced the minerals sector's research funding. The objective of the EIT-RM community is to improve the efficient transfer of research data to society, so that society can utilize this in the form of new products and business and can train new entrepreneur-oriented people. EIT-RM is one of the EU's key instruments for developing innovation activities related to minerals. The EIT-RM annual project application rounds have stimulated the minerals sector's project activities and at the same time increased the popularity of the minerals sector's training in the EU area. Companies, research institutes and universities act as partners in the EIT-RM. Additionally, the European Research Area - Network on the Industrial Handling of Raw Materials for European Industries (ERA-MIN) network for mineral sector financiers and national research programmes operates in the EU area.

2.2.2 Finland

Finland is an important metal producer in the EU and has been among the most preferred mining investment destinations in the world for many years in the Fraser Institute's annual surveys (e.g., Stedman et al. 2020). This is due to a significant set of factors being positive: a bedrock favourable for many types of mineral deposits; high-quality and easily accessible geoscientific, mineral deposit and other relevant data; full coverage of high-quality infrastructure; reliable legislation; and economic and political stability. Finland also has an extensive mining and metallurgy industry cluster with processing plants, refineries, smelters (Fig. 9), and globally recognised mining and processing technology providers.

The Finnish primary metal production is presented in Table 9 and the currently active mines in Figure 10. In 2020, there were nine metal mines and 27 industrial mineral mines. The main metals and minerals produced in Finland are steel, copper, nickel, zinc, chromium, apatite and talc. Finland is also a significant producer of cobalt and produces some aluminium, gold, silver and platinum. Finland has the largest gold mine (Kittilä) and the only chromium and phosphate mines (Kemi and Siilinjärvi) in the EU. Sakatti in Sodankylä will follow Talvivaara as the EU's biggest nickel mine if it obtains all the necessary permitting for mining. Finland is also the only cobalt producer in Europe, with two mines (Talvivaara and Kevitsa, Horn et al. 2021). Other cobalt mine projects (Juomasuo, Rajapalot, Hautalampi) are in the pipeline and a lithium mine is planned in central-western Finland (Fig. 10). There are also many ongoing mineral exploration projects for several commodities, including vanadium, cobalt, nickel and graphite. These projects are expected to contribute to the electrification of the EU's transport sector with the battery minerals they will produce.

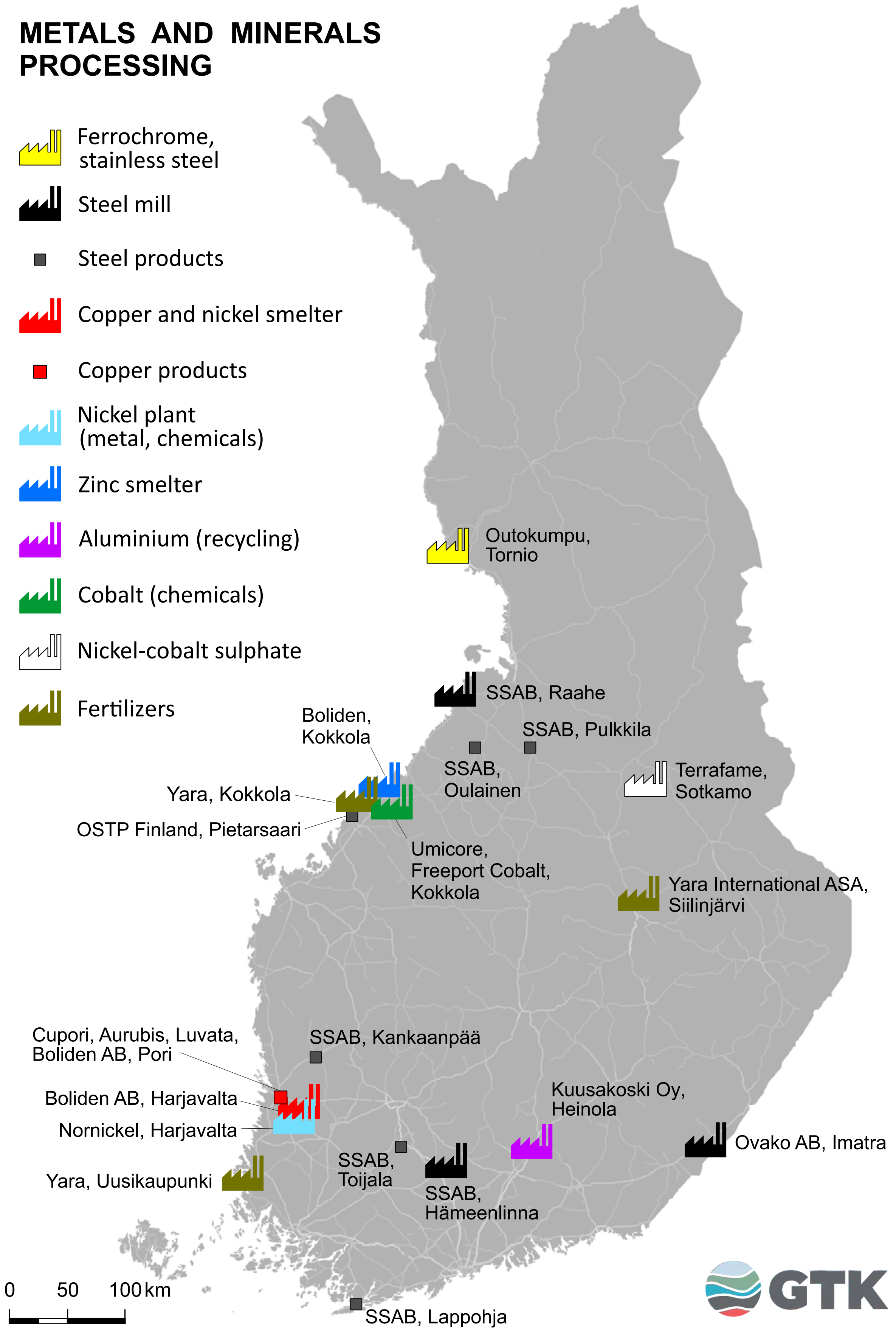


Fig. 9. Smelters and processing plants in Finland in 2020 (© Geological Survey of Finland).

Table 9. Metal production from mines in Finland in 2020.

Commodity	Unit	Amount
Cobalt (Co)	(t)	1 559
Copper (Cu)	(t)	36 278
Gold (Au)	(kg)	8 668
Lead (Pb)	(t)	1 530
Nickel (Ni)	(t)	41 429
Palladium (Pd)	(kg)	858
Platinum (Pt)	(kg)	1 277
Silver (Ag)	(kg)	54 833
Zinc (Zn)	(t)	61 213

As can be seen from Table 8 and Figures 10 and 11, several of the commodities used in digitalization are produced in Finland (Ag, Au, Co, Cr, Cu, Ni, Pb, Pd, Pt and Zn), and mine projects focused on additional related commodities (Li, Nb, REE and V) are in the pipeline. The Finnish mine production of and resources for the digitalization-related commodities are included in Table 5. Even though Finland is an important producer of mineral raw materials, the country imports most of them. However, it proved impossible to determine how much of Finnish metal production is used in ICT manufacturing in Finland or elsewhere.

It might be useful to compare Finnish mine production and metal resources (Table 5) with the estimated EU ICT demand presented in Table 6. Such a comparison shows that Finland could provide a significant share of raw materials for digitalization needed by the EU; this is especially the case for chromium, cobalt, gold, nickel, palladium and platinum. When taking into account the output of metal refineries and smelters, the Finnish potential to cover the needs of European digitalization is even more substantial for cobalt, nickel, palladium and platinum. In addition, Finland has an untapped resource for a number of commodities essential for digitalization, but which are only needed in moderate to small volumes: antimony, beryllium, graphite, hafnium, lithium, manganese, niobium, scandium, high-purity silica (for silicon metal) and tantalum (Geological Survey of Finland 2021). However, this does not mean that Finland can alone supply the EU's entire raw materials needs for ICT, as metals are shared among other sectors as well, such as e-mobility and renewables, which are expected to experience an exponential growth in demand for raw materials (Bobba et al. 2020). This is especially relevant for silver, gold, chromium, copper, nickel, lead and zinc, whose main demand is in other sectors of manufacturing and construction.

The volume index of Finnish industrial production, including metals and electric and electronics, is illustrated in Figure 12. For more information on the Finnish mining sector, see Vasara (2018).

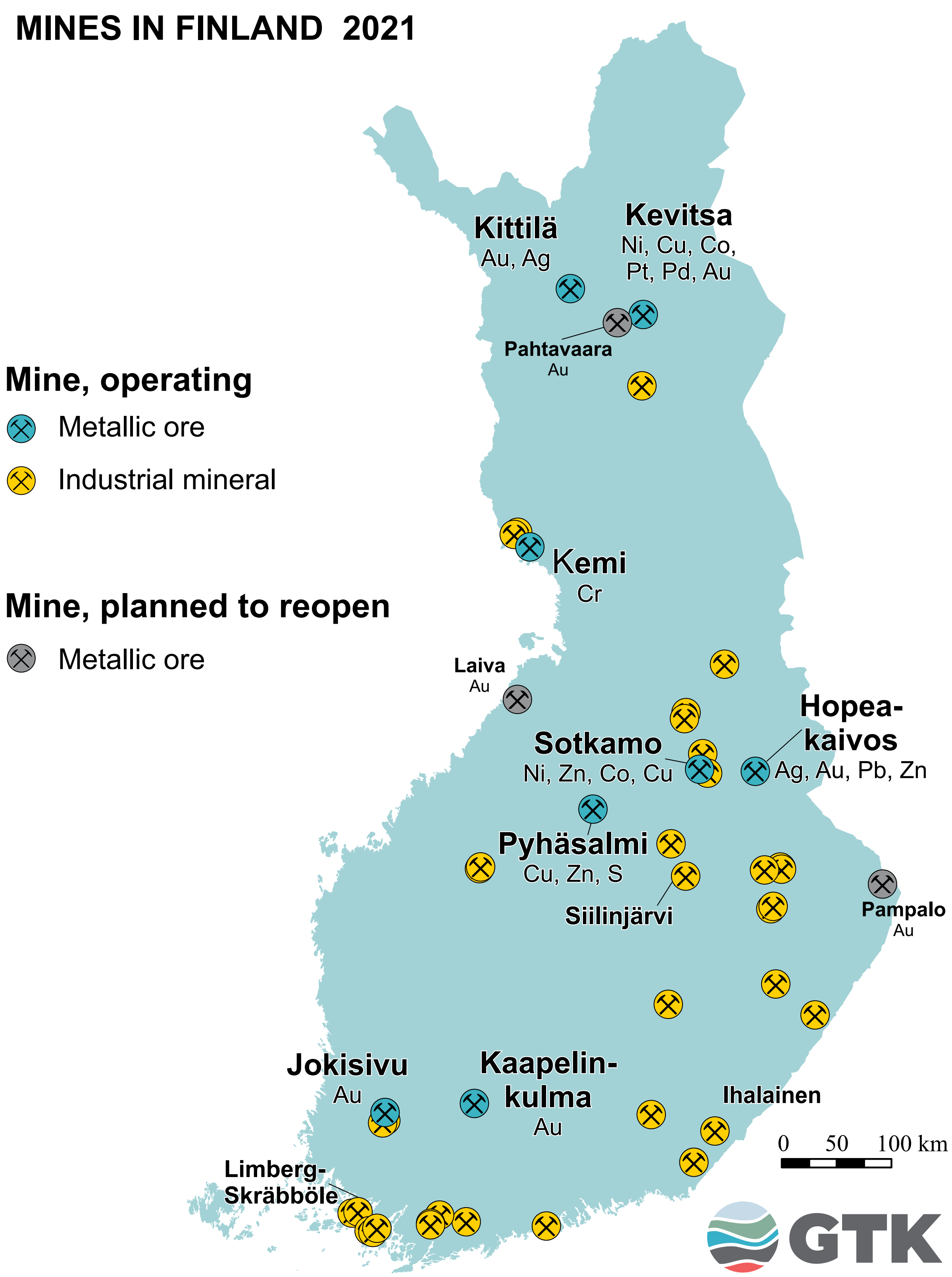


Fig. 10. Metal and industrial mineral mines with their commodities in Finland in 2019 (© Geological Survey of Finland).

Fig. 11. Mine projects with their commodities in Finland in 2019 (© Geological Survey of Finland).

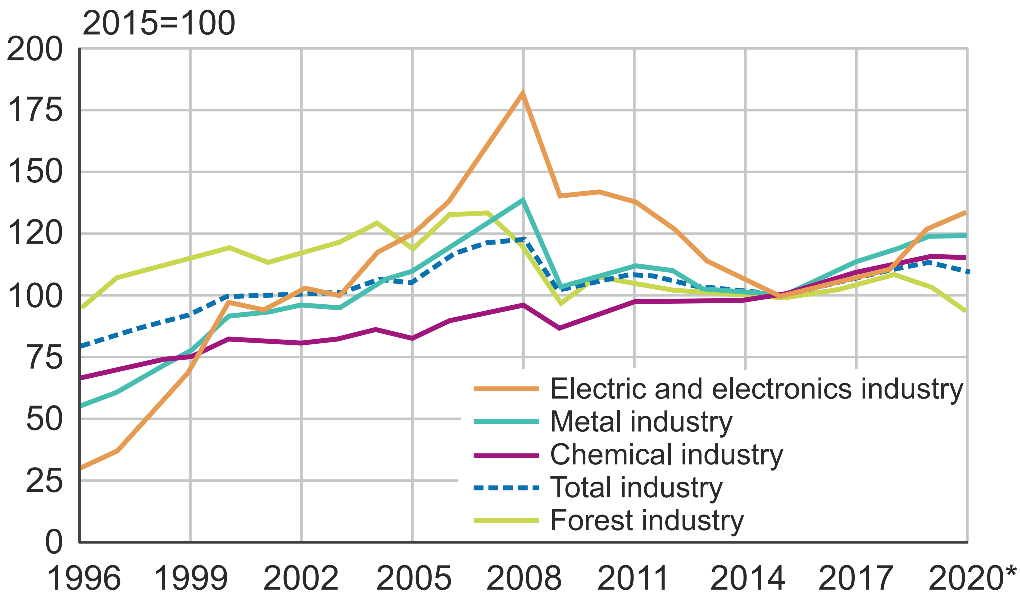


Fig. 12. Volume index of the production of manufacturing industries in Finland (Statistics Finland 2021).

2.3 Sustainability of primary raw materials production for digitalization

Even though digitalization requires only 0.5% of the total volume of raw materials needed by the industrial sectors, it has a significant impact along the whole value chain. The mining and processing of primary raw materials causes environmental and social impacts, especially if not properly managed. The environmental impacts include local biodiversity loss, direct and indirect CO2 emissions (especially in processing), and contamination of surface and groundwater by acid drainage, dust, noise and landscape changes (especially regarding open pits and tailings) (e.g., Jain et al. 2016). As examples of poor management, there are also potentially serious environmental risks, such as tailing dam ruptures, which can severely and fatally impact on local communities and habitats in the vicinities of mines. Two recent examples of such accidents were the Mariana and Brumadinho mines in Minas Gerais State in Brazil (Koppe 2021).

Corporate Social Responsibility

With proper responsible measures and management, most of these impacts and risks can be mitigated or at least minimised. When these procedures are not determined by legislation, the three pillars of sustainability (Elkington 1997) – social, environmental, economic – may be used to guide voluntary actions carried out by companies beyond the bottom line established by legislation. This model of integrating the pillars of sustainability as a self-regulating business model is also known as corporate social responsibility (CSR).

A number of different guidelines and responsibility reporting systems exist for this purpose. They started to be developed at the end of the 1990s, when the mining industry faced increasing opposition from local communities, ENGOs and indigenous people all around the world (Thomson & Boutilier 2011). One example of such approaches is the Canadian initiative Towards Sustainable Mining (TSM). It sets out a series of principles and criteria for social, economic and environmental stewardship towards sustainable mining. However, the sustainability and CSR of mining have also been criticised (Whitmore 2006, Hilson 2012, Slack 2012). As mining exploits non-renewable natural resources and has adverse impacts, it is considered to have weak sustainability. In this sense, its sustainability may be improved by measures to minimize such negative impacts. In addition, the use phase of the mined metals will be able to improve the value chain's sustainability impact, as many metals are used for extensive periods, such as steel (Fe, Ni) and Cu, and their life cycle can also be prolonged by recycling.

However, what calls attention to many industrial sectors, not only mining, is their need for multiple guidelines and diverse reporting systems to operate sustainably. It seems to be symptomatic of the fact that sustainability has not been at the heart and core of their business. In other words, sustainability may be and not automatic for them, but it needs to be learned to adapt to a world with rapidly changing environmental values. Actually, the mining industry reacted to general criticism fairly late, at the end of the 1990s and the beginning of the 2000s due to increased resistance to mining all over the world. This reaction occurred only a few years before the sudden increase in demand for natural resources as a result of the economic growth in China, which caused a global mining boom in the 2000s. As a result, mining conflicts multiplied all over the world.

To improve the acceptance of the mining industry, the tools for sustainable and socially responsible mining, developed in the 1990s and the 2000s, have been embraced and deployed by companies to a varying extent. Social values have rapidly changed, which also has an impact on attitudes towards mining and its acceptance. Therefore, creating, developing and comparing different methods, tools, reporting standards and best practices that promote the CSR of mining companies and their acceptance is still important. The discussion on them will probably continue as long as there are problems and conflicts related to mining.

Social impact management

The social impacts can be positive or negative. When effectively managed, mining can bring jobs, economic development, infrastructure and benefit sharing, even for remote places (distributive fairness, Zhang et al. 2015). However, it can also damage local nature-based livelihoods, such as agriculture, forestry, herding, and tourism, on which local communities may depend or which are important to them. Therefore, responsible mining takes the existing land use (e.g., nature conservation) and livelihoods in account in its planning and risk evaluation for the local communities and its own business. In this sense, some places might be more challenging for the establishment of mines than others, or even so-called “no-go zones” for the local communities (Goodland 2012). Although mineral exploration and mining should be conducted in places where a mineral deposit is supposed to be or is located, their local context matters (Mercer-Mapstone et al. 2018). Other adverse social impacts may be related to human right abuses, financing armed groups, corruption, the escalation of gender inequalities and health and safety issues, common in developing countries (e.g., European Commision 2020d).

Social license to operate

The acceptance and approval of mining and mineral exploration by the local community or by society, i.e., the social license to operate (SLO), is a prominent issue in access to land (Thomson & Boutilier 2011). Therefore, the local context should be considered when planning and deciding on such operations (Mercer-Mapstone et al. 2018). In this sense, environmental management and innovations, corporate reputation and conduct also matter for local communities and society (Provasnek et al. 2017, Eerola 2021b).

In addition to identifying and addressing environmental impacts well in advance and during operation, appropriate and respectful target selection, attitude, communication and stakeholder engagement are crucial parts of responsible mining and mineral exploration, and these activities should be in place and effectively practiced by the companies. They show procedural fairness, i.e., that local people are respected and heard (Zhang et al. 2015). Potential no-go zones are recommended to be taken into account in planning to avoid costly conflicts (Goodland 2012).

CSR and SLO-related activities (stakeholder engagement, benefits sharing) are recommended to be applied from the very beginning of mineral exploration and mining (e.g., Thomson & Boutilier 2011, Eerola 2017). Each misconduct, or in the worst case, a serious mine accident, wherever it takes place, may have severe consequences. Beyond the damage they can cause to nature and people, they affect not only the company, but also the entire industry and other companies with good social and environmental performances. As the world is globally interconnected due to instantaneous online communication facilitated by digitalization, such events may affect the debate on mining at every level, from local to global and vice versa (Eerola 2017, Fig. 13).

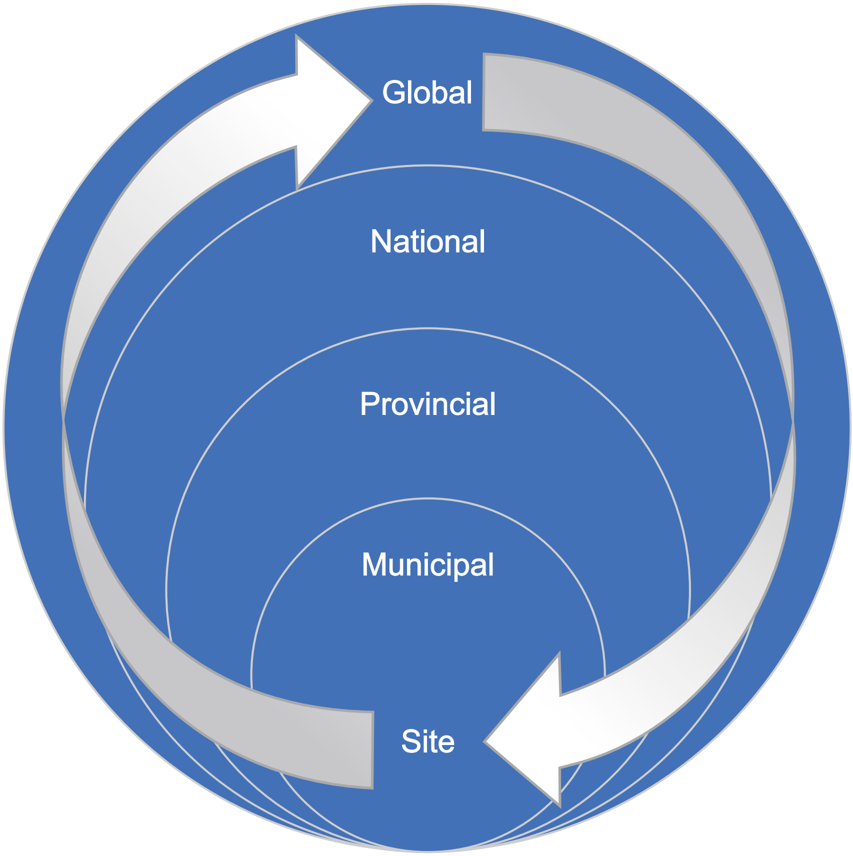


Fig. 13. Interaction of interconnected regional levels of mining debate facilitated by digitalization. A local site-level incident somewhere may reflect instantaneously in the global, national and local mining debate, and vice versa (after Eerola 2017).

The SLO is the top priority of the mining industry (Ernst & Young Ltd 2020), as the lack of it may hamper mineral exploration and mining projects. Therefore, a lack of legitimacy and the SLO may be serious obstacles to expand mining, which is needed for the energy transition and to increase the EU's self-sufficiency in raw materials. Consequently, the mining industry needs to develop its activities towards more sustainable practices and improve its public image in order to make its activities more viable. This is especially important if its expansion is needed to fulfil the material requirements of the energy transition.

Conflict minerals and their traceability

Unfortunately, there are many bad examples and serious global challenges regarding sustainable mining, especially in developing countries. The use of children, semi-slavery and political prisoners as a labour force, low or non-existent salaries, sub-human working conditions and severe environmental impacts are some of the problems still surrounding primary raw materials production. In fact, many raw materials used in electronics come from such contexts. These might be even related to the financing of conflicts and/or causes of them, such as in Afghanistan and the Democratic Republic of Congo (DRC), infamous for its conflict minerals.

These so-called conflict minerals, namely tin, tungsten, tantalum and gold, also referred to as 3TG, are natural resources extracted in politically unstable areas, where military or paramilitary groups benefit from their extraction and finance their activities through their revenues. The DRC is one of the main producers of several important natural resources such as Ta and Co. The main end use of tantalum (over 60%) is in electronics. Ta capacitors are embedded in many consumer electronics and are therefore relevant to modern society. For instance, Co is consumed in increasing amounts by the battery industry, needed in the green energy transition, but also in the batteries of ICT devices. Thus, while CRMs are related to the supply risk and economic importance, conflict minerals are related to sustainability aspects.

Unfortunately, the expansion of digitalization and, for example, electrification is largely dependent on unsustainably produced minerals. In an attempt to avoid the use of conflict minerals, the traceability of raw materials is being developed. Traceability means that the origin of a mineral can be traced back to its producing mine (and country), for instance using its characteristics, such as known geochemical and/or isotopic composition as a fingerprint. Therefore, for example, Co or Ta produced in the DRC can be identified, allowing their purchase by smelters and the industry to be avoided. Several ongoing international initiatives are developing traceability, such as the Battery Passport (World Economic Forum 2021) and the Certification of Raw Materials (CERA 2021). However, it should also be noted that people and companies having nothing to do with conflicts are economically dependent on the mining of these commodities in the DRC or Afghanistan. The ending of their production may cause severe local social impacts in already poor and multi-problematic countries. Therefore, as the EU is largely dependent on the production of primary raw materials in the DRC, it should support the development of this production in a managed and progressive manner with measures to mitigate its adverse impacts and role in such conflicts.

Most of the persistent problems of developing counties are related to deep social inequality and a lack of participation. Resource-rich but poor countries may be strongly dependent on natural resource production and susceptible to inequality, poverty, corruption, dictatorships, constant political and economic instability, and conflicts. This is known as the resource curse (e.g., Natural Resource Governance Institute 2015). Although challenging, direct international interventions in such situations may be a solution, but there are no easy or quick ways to overcome such problems. The problems have deep historical and market-based foundations and reasons. However, consumers need to be aware of this, and also of the origin of the raw materials in their ICT devices. Therefore, the raising of public and consumer awareness is the first step. There are international campaigns focused on this. A shift in the market rational and its requirements in a more sustainable direction by consumers could be a game changer.

Sufficiency of raw materials for the ICT sector: future perspectives

Numerous recent reports and assessments have forecasted increasing competition for mineral raw materials between the current uses and the demand from the global transition to a low-carbon society (e.g., Hund et al. 2020, IEA 2021, White House 2021). This has resulted in discussion and worries in all sectors of the economy, in industries and in nature protection: who (which manufacturers in which countries) will get the required raw materials, how much more mining is really needed, is it possible to open new mines, how much will commodity prices increase, and what will be the effects of changes in mining and manufacturing on economies in general and on different sectors of economies, as well as on the societies and natural environments of countries and regions (Bobba et al. 2020, Herrington 2021, IEA 2021, Michaux 2021).

The effects of raw material availability on the ICT sector (in strict sense) mostly appear to be minor. This is because the manufacturing of ICT devices is estimated to demand only about 0.5% (by weight) of all mineral raw materials produced (Malmodin et al. 2018, UNCTAD 2020). In particular, the demand for base, ferrous and most of the precious metals (aluminium, chromium, cobalt, copper, gold, iron, lead, magnesium, manganese, molybdenum, nickel, niobium, palladium, platinum, silver, titanium, tungsten, vanadium and zinc) will most probably be minor to minuscule compared to the needs of infrastructure, housing, financing and vehicle manufacturing (Tables 3 and 5 and references therein). Note, however, that we do not here include electricity production or storage (such as battery manufacturing) in the ICT sector. The demand in the ICT sector alone for any of the commodities listed above will most probably not mean a need to open new mines for these metals.

Any increase in the production of major metals and the precious metals gold, palladium platinum and silver may provide more CRMs for the ICT sector. This comes from the fact that a very large range of the raw materials needed by the ICT sector, both those currently seen as critical and those not (yet) so critical, are dominantly or completely by-products of the mining of other metals. Such by-product metals include antimony, arsenic, bismuth, gallium, germanium, hafnium, indium, iridium, ruthenium, scandium, selenium, tellurium, and thallium (Frenzel et al. 2017, Mudd et al. 2017, Eynard et al. 2020, Latunussa et al. 2020).

There are two issues here, however: 1) The recovery of these by-products from ores is currently at a rather low level (except for the very rare precious metals iridium and ruthenium), as such recovery often means very little, if any, added profit for the mining, refining and smelting companies. Here, incentives from governments will probably be needed, unless the demand for a by-product commodity increases or a new cheaper technology becomes available, making a significant profit from the recovery of a commodity attractive (Lusty & Gunn 2016); 2) If the demand for a raw material in a sector other than ICT is very large, it may seriously affect the availability of this raw material for ICT manufacturing. This also will increase the price of such a commodity and may consequently make the related ICT device, or part of it, more expensive, possibly even not profitable to be produced. The most likely situation in which the latter issue may arise is if the government of a globally major CRM producer country decides to direct all the said commodity to use by its own industries, largely restricting any export of the commodity. We have seen this taking place a few times, most recently in China for REE.

A major partial exception to the by-product context is formed by the REE beryllium and tantalum. Much of the REE come as by-products from phosphate and iron mining, and some of the beryllium and tantalum is a by-product of lithium, niobium or tin mining (Zhou et al. 2017, Latunussa et al. 2020, USGS 2021). The forecasted large increase in demand means that mines where any of these metals, especially the REE, forms the main product will be needed much more than is presently the case (Bobba et al. 2020, IEA 2021). Most of the REE are consumed by the energy sector, where the demand has shown a constant and strong increase for many, but not all, of the REE. This naturally also means higher prices for any REE needed by the ICT sector, as all REE always come from the same deposits. For beryllium, the same effect can be caused by an increase is its main demand in specialty alloys. For tantalum, the demand from sectors other than ICT is minor and does not form any significant competitive threat to access to the metal for the ICT sector.

Considering the huge forecasted increases in the demand for raw material in the transition to a low-carbon society, we assume the following mineral commodities needed by the ICT device manufacturing to be potentially most affected by the energy-related demand: platinum, palladium, REE and scandium. The increasing demand for REE mainly comes from their use in magnets in electric motors in vehicles and wind turbines, for platinum and palladium in fuel cell and hydrogen power technology, and for scandium in high-strength alloys and fuel cells (e.g., Latunussa et al. 2020).

Mining, refining and smelting of metals and manufacturing components for digital technologies may have large negative effects on the climate (CO_2), environment and social and economic sustainability of a locality, region and country. This is especially the case in developing countries, where energy production is typically based on coal, related regulations and laws are weak and corruption widespread. As the demand for commodities and components is forecasted to increase with the strong move towards a low-carbon society, recycling will be able to cover only a fraction of the demand, and more mining and mineral processing will become unavoidable. It is hence important that metals and components are produced in countries with strict environmental and social legislation, with as little CO_2 release as possible, and with a secure and resilient supply. This means a greater need for mining, mineral processing and component production in first-world countries than currently takes place, in Europe, the Nordic countries and Finland. In Europe, geology favours the North. Of the metals needed for ICT manufacture, significant chromium, cobalt, copper, lithium, graphite, hafnium, nickel, niobium, platinum-group metal, REE, scandium, tantalum, titanium and vanadium resources occur in Finland. A similar mineral potential, significant for the host countries and for Europe, is also present in Greenland, Norway and Sweden (Kolb et al. 2016, Eilu et al. 2020). In addition, the Nordic countries have access to abundant low-carbon energy, with extensive development towards low-CO_2 manufacturing adding environmental benefit for the local mineral-based industries.

3 CASE STUDIES – SMARTPHONES AND SMART TVS

Electronics have diverse applications. There is a multitude of electronic equipment for different purposes and new models and applications are created all the time. Some are more commonly used by consumers than others in their daily life. **Smartphones and laptops are good examples of widespread mass**

consumption. They have also been quite well investigated regarding their primary raw material compositions. Therefore, one of these, the smartphone, was selected to be examined in this study in more detail. Another selected example is the smart TV. It is a quite recent phenomenon, but its market has expanded rapidly. Smart TVs have become the "new normal" in most households and public spaces.

Smartphones have become a crucial part of modern life. More than 90% of adults in many EU member states own a smartphone and some own and use more than one device (Rizos et al. 2019). However, the production, use and disposal of smartphones carry a significant environmental and social burden. This includes direct and indirect emissions from the extraction and processing of raw materials, the production of intermediate materials, components and the smartphones, their use and recycling, poor working conditions and related adverse health effects, and the contribution of smartphone disposal to the accumulation of e-waste (Rizos et al. 2019).

For smartphone devices, **the highest environmental impact in their manufacture is caused by the extraction of raw materials, manufacturing of components and assembly of the final products** (Rizos et al. 2019, Gurita et al. 2018). Increased market penetration and **relatively short life cycles** keep the sales of smartphones at a high level, even though the global peak sales of smartphones may already have been reached (Mongardini & Radzikowski 2020).

Smart TVs are quickly replacing "normal" TVs, as 70% of TV shipments were already smart TVs in 2018. Annual global smart TV sales totalled almost 210 million units in 2019 and are expected to rise to 250 million units over the next five years. (Statista 2021a). Their sizes are also increasing, together with their energy consumption.

Due to larger screens and thus substantially larger energy use, the environmental impact of smart TVs is more focused on the use phase (Berwald et al. 2020). However, smart TVs also contain CRMs, and extending their use phase is proven to have a positive environmental impact (Berwald et al. 2020, Prakash et al. 2016).

An important aspect in the total environmental impact of both smartphones and smart TVs is energy and raw materials usage in the network infrastructure. Ercan et al. (2016) estimated that the global warming potential (GWP) is 43 kg CO2 for their data centres, access networks, and IP core network per individual smartphone. This is more than double the 19 kg CO2 GWP of smartphone manufacture. Therefore, the total annual GWP of a smartphone is 62 kg CO2. This study, however, only considered the energy use when calculating the infrastructure impacts. As data traffic has considerably increased since 2010, when the data on which the analysis is based were collected, it is plausible that the energy use of the network infrastructure has increased drastically and that the GWP has therefore also increased per device. Additionally, this sets requirements for investing in existing and new ICT infrastructure to cope with the increasing traffic, which increases the raw materials consumption of ICT. The case studies in this report focus on end-user devices, and this important aspect is therefore left out of the scope of this study.

3.1 Main components

3.1.1 Smartphones

Smartphones can be divided into four main components: the electronics, screen, battery and casing (Fig. 14). The main electronic components in smartphones include a printed circuit board (PCB), magnets, wiring, microphone, soldering and chips. Solder is used to join electrical components together. The use of a smartphone requires, in addition to the device itself, various other supporting elements. These include the charger, data and voice subscription, and other voluntary accessories. These either protect and customize a device (e.g., cases) or augment its use (e.g., headphones). The use of a smartphone also requires other essential components, most of which are seemingly immaterial. In addition to the already mentioned mobile subscription, which is a gateway for consumers to the network providers' telecommunications network, apps are used on the phones, as well as different cloud and streaming services, and all other online services that require physical infrastructure in the form of data centres and the core Internet network. This part of the product system remains for the most part hidden from consumers, and often outside the system boundaries in impact assessments for single devices. Consequently, for a typical consumer, it is impossible to imagine the overall material and energy intensity of smartphone use.

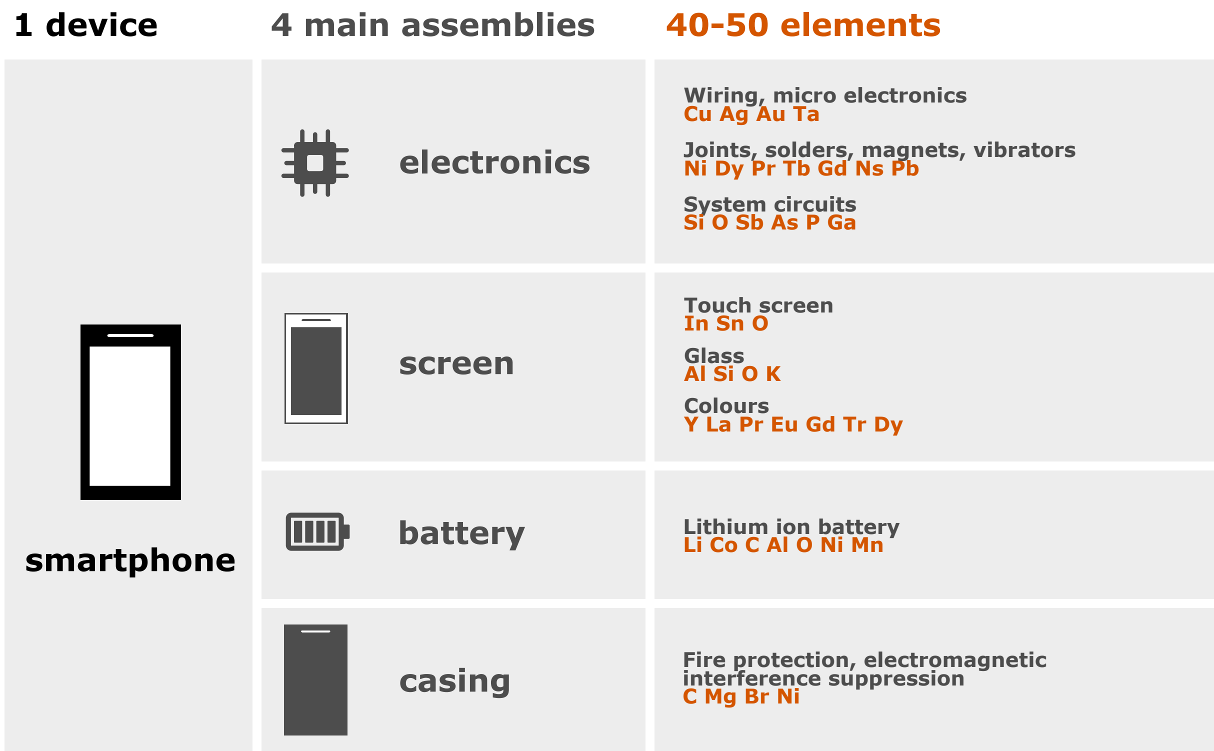


Fig. 14. A smartphone, its main components and elements.

The term "mobile phones" covers "feature phones" (with a keypad instead of a touch display) and smartphones (new generation mobile phones with a large touch display, an operating system to run applications, and Internet connectivity). Smartphones have been exceeding global feature phone sales since 2014 (Bookhagen et al. 2020). In Finland, smartphone sales have been considerably higher than the sales of feature phones for even longer. Therefore, in this study, we focus on smartphones, which account for the majority of mobile phones sold in recent years.

3.1.2 Smart TVs

Smart TVs (or connected TVs) refer to televisions with integrated Internet and interactive features allowing users, for example, to browse the Internet, view photos and stream music and videos, as well as access streaming television and internet radio. Technology-wise, they are a convergence of computers, televisions and digital media players. Smart TVs can also be enabled by external devices, including smartphones, game consoles or other network-connected devices (Wikipedia 2021).

The main components of a smart TV include the display panel, stand, power supply and logic or main board, including PCBs. A specific teardown of a smart TV based on LED technology is presented in Samsung (2011). The display is one of the key components of smart TVs, and there are a variety of display technologies, such as plasma display panels (PDP) and liquid crystal displays (LCD), as well as light-emitting diode (LED) and its variants organic light-emitting diode (OLED) and quantum dot LED (QLED) TVs. This report focuses on the material needs of all display technologies with a specific focus on a rising display technology, i.e., the OLED supply chains. The display can be divided into the bezel, crystal black panel, optical sheet, LGP or light guide plate, LED, bottom chassis and covers.

The main board and other electronics include core semiconductor components, processors, graphics processing, wiring and tuners. Other components include terminals and modules, including HDMI, USB, WiFi and Bluetooth, video cameras, touch buttons, speakers and different sensor solutions, e.g., light sensors for adjusting brightness. External components include wall mounts or stands and remote controls and other accessories. The components of particular interest in relation to critical and precious raw materials are the display, background lights in some LCDs, and electronics (e.g., assembled PCBs, power supply and wiring) (Buchert et al. 2012).

3.2 Value chain and main actors

3.2.1 Smartphones

Smartphones are part of the consumer electronics market segment, including a wide range of other products such as televisions, tablets, headphones and audio devices. In 2017, the whole EU consumer electronics sector represented 1.32% of household expenditure and the manufacturing of consumer electronics reached a turnover of €60 billion (Rizos et al. 2019). The total global smartphone market was 1.37 billion devices in 2019 (Mongardini & Radzikowski 2020). In context, the world population was estimated at 7.7 billion in mid-2019 and, therefore, it equalled a new smartphone for almost 18% of the total population during 2019.

In the current state, the value chain of smartphones is mostly linear (Rizos et al. 2019), but it should be made circular (Fig. 15). It consists of the following phases:

1. Extraction of raw materials
2. Manufacturing of components
3. Smartphone assembly
4. Transport and sales
5. Use
6. Reuse, remanufacturing and upgrade (product life extension)
7. Recycling
8. Disposal, export or hibernation

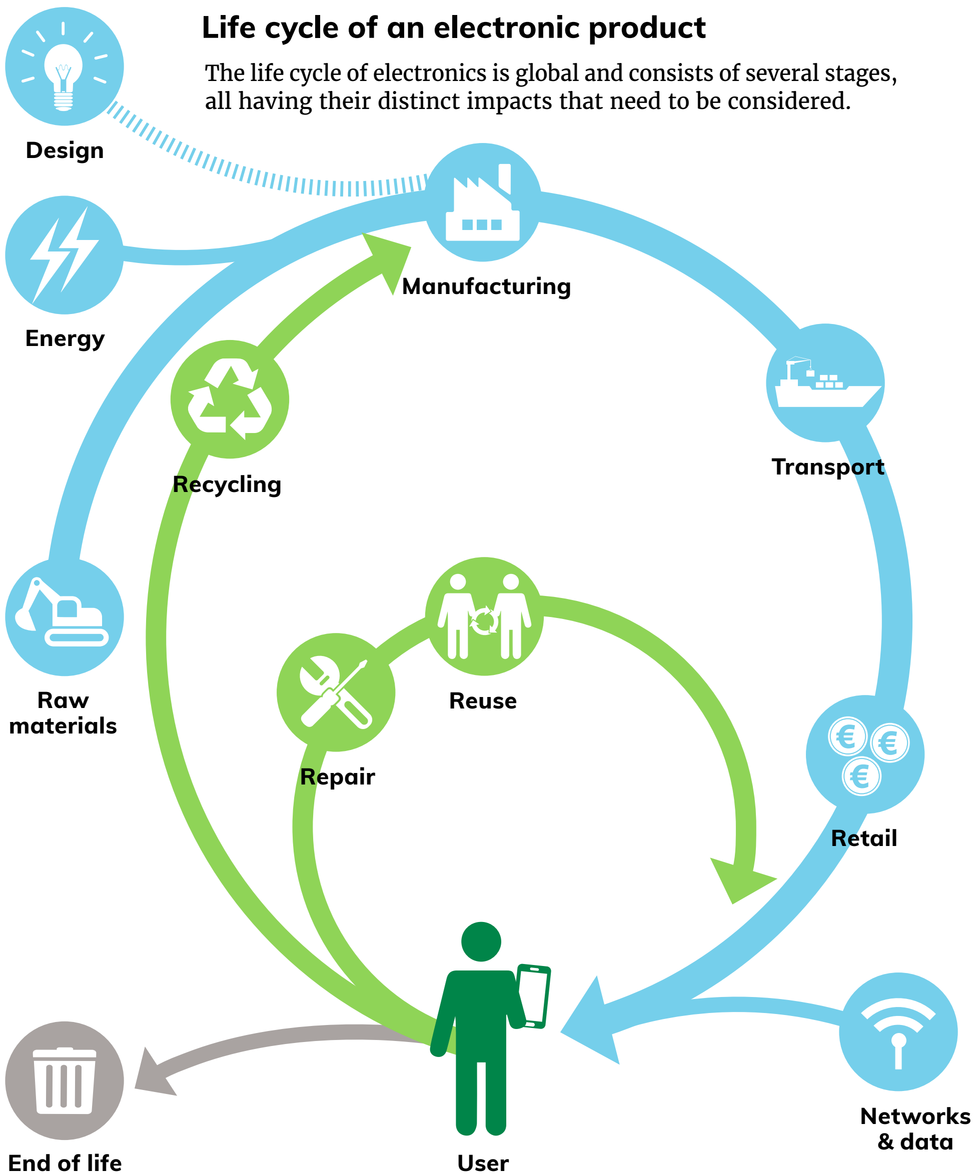


Fig. 15. The life cycle of a smartphone.

The manufacturing of mobile phone components and assembly of the devices mostly take place in Asia, especially in China, South Korea, Malaysia, India, Singapore, Vietnam and Taiwan (Rizos et al. 2019). South Korea is the main supplier of smartphone components and semiconductor products, which accounted for over 17% of its exports in 2017. Smartphones accounted for 5.7% of Chinese exports in 2017. Smartphone supply chains are complex and brand owners have typically outsourced component manufacturing and the assembly of phones. For example, iPhones contain components from more than 200 suppliers from all over the world (Ethical consumer 2019). The main component manufacturers for smartphones include chips, the power supply and RF devices from Qualcomm (USA), semiconductor products and storage from Toshiba (Japan), integrated circuits and various other components from Foxconn and TSMC (Taiwan), storage products from Micron Technology (USA), microcontrollers from Renesas (Japan) and touch screens from Sharp (Japan) and Wintek (Taiwan). Smartphone battery market leaders include TDK ATL (Japan), LG and Samsung (both South Korea). There are several protective casing manufacturers for smartphones, such as OtterBox (US). Once the components have been sourced from manufacturers, they are taken to a factory for assembly. Original design manufacturers (ODMs) are major players in smartphone manufacturing, which design, manufacture and assemble smartphones according to the needs of brand owners. Some of the largest ODMs include Wingtech, Huaqin, Longcheer (all China) and Pegatron, Wistron and Compal (all Taiwan) (OMDIA 2020). In China, the largest company assembling (and designing) smartphones is Foxconn, and iPhones are made at its Zhengzhou facilities in China (Ethical consumer 2019).

In Europe, the volumes of computer and electronic products manufacturing have been declining and the manufacturing of telecommunications equipment has radically decreased, dropping from 207 million units in 2007 to 2.8 million units in 2017 (Rizos et al. 2019). Even though European smartphone brands exist that assemble their products in Europe, the manufacturing of smartphone components takes place in Asia (ibid.). Some of the European electronic manufacturers for smartphones include Bosch, NXP and STMicroelectronics.

Continuing the value chain to the sales phase, the total sales of mobile phones in Europe have decreased in recent years, dropping from 307 million in 2007 to 182 million units in 2017. In comparison with manufacturing, the sales stage typically takes place in Europe. The upfront price of smartphones for the consumer is often reduced with an attached contract with a carrier. In the US, leasing and early upgrade programmes are more common than in Europe. (Rizos et al. 2019)

Regarding the use phase, smartphones are typically used by one consumer, after which they are discarded. However, the lifetime of the devices can be extended by reuse, refurbishment or remanufacturing. Several online platforms offer a marketplace for reusing smartphones. Examples of refurbishment companies for smartphones include manufacturers and brand owners and other companies such as Recommerce Group (France) and Swappie (Finland). Remanufacturing is currently practiced at the global level, but not on a large scale in Europe (Gurita et al. 2018). However, a large share of smartphones hibernates in households and some of them are even disposed of in general waste. A rather small but rising share of smartphones is collected, and their valuable raw materials content is recovered and recycled. Nevertheless, the fraction of recovered materials during the recycling process is relatively low (14–22%, Reuter et al. 2018) due to the product and material complexity discussed in section 3.6. Examples of major European smartphone and other ICT equipment recyclers include Umicore (Belgium), Boliden and Stena Recycling (Sweden) and Kuusakoski (Finland). Additionally, smartphones may be exported outside the EU. Table 10 presents the main actors in the smartphone value chain.

Table 10. Main actors in the smartphone value chain.

Part of the value chain	Europe	Rest of the world
Raw materials extraction	Barium: Sachtleben Bergbau, M-I SWACO Chromium: Outokumpu Copper, zinc, silver: KGHM Polska Miedz, Boliden, Terrafame, Lundin Mining Gold: AgnicoEagle, Boliden Iron: LKAB Magnesium: Grecian Magnesite, Magnesitas De Rubián, Magnesitas Navarras, Nedmag, SLOVMAG, SMZ Nickel, cobalt, palladium: Terrafame, Boliden Silicon metal: Elkem Silica sand: Sibelco, Hoffmann Mineral, Brogardsand, Elkem, CAOBAR Strontium: Canteras Industriales, Solvay Titanium: Kronos	• Companies: Rio Tinto, BHP, Vale, AngloAmerican, Barrick, Freeport-McMoran, Jinchuan, Impala Platinum, SibayneStillwater, FQM, Vedanta, Zijin Mining • See the main non-European producer countries in Table 2
Component manufacturing	• Several component manufacturers have manufacturing facilities in Europe, e.g., Foxconn • Electronics: Bosch, STMicroelectronics, NXP	• Mainly in Asia: China, South Korea, Malaysia, Singapore, India and Taiwan, also the US • Screen: Samsung, LG, Foxconn, Tianma, Sharp, Wintek • Battery: TDK ATL, Samsung, LG • Electronics (chips, etc.): Foxconn, TSMC, Micron Technologies, Toshiba, Qualcomm, Renesas • Casing (assembly): Foxconn, Pegatron
Assembly of devices	-	• Mainly in Asia: China, South Korea, Malaysia, Singapore, India, Vietnam and Taiwan, Brazil • Companies: Foxconn, Samsung, Sony, LG, Huawei, Xiaomi, Oppo, Pegatron, Wistron, Compal, Wingtech, Huaqin, Longcheer
Use phase, incl. sales	• Sales: Telecom providers (carriers), brand owners, retailers and shopping websites • Consumers, leasing or early upgrade programmes in the US	
Life cycle extension	• Refurbishment: some manufacturers and brand owners, e.g., Samsung and Apple, and other companies, e.g., Recommerce Group and Swappie • Reuse: various online platforms for customer-to-customer selling, vendors for used devices	Not in the focus of this study
Collection and Recycling	• Collectors: telecom providers (carriers), municipalities, producers, recyclers and retailers • Recyclers: Umicore, Boliden, Stena Recycling, Kuusakoski	Not in the focus of this study
Disposal	• Consumers: hibernation or disposal in general waste • Companies: exporting smartphones as second-hand phones or e-waste	Not in the focus of this study

3.2.2 Smart TVs

Smart TV revenues are estimated to amount to €145.42 billion in 2021 and most revenue is generated in China (€37.70 billion in 2021). The global smart TV market is expected to rise and reach €248.40 billion by 2025 and grow by 293.32 million units. From the sales perspective, LCD is currently the dominant display technology, followed by QLED and OLED. The introduction of 4K, and 8K, resolution-equipped televisions, coupled with the shifting preference towards OLED and QLED displays, is expected to emerge as a major trend in the smart TV industry. (Grand view Research 2017a, Grand view Research 2017b, Digital TV Europe 2020)

Key brand owner companies in the smart TV sector are mainly from South Korea, China and Japan: Koninklijke Philips NV (the Netherlands), LG Electronics Inc., Panasonic Corp., Qingdao Haier Co. Ltd., Samsung Electronics Co. Ltd., Sharp Corp., Sony Corp., Videocon Industries Ltd, VIZIO Inc. and Xiaomi Corp (Technavio 2020). Samsung and LG manufacture their own (O)LED panels, whereas Sony and Panasonic procure their panels from LG. In recent years, Chinese companies have also entered the manufacturing market. (Grand view Research 2017a)

The OLED case

OLED displays are used extensively in smartphones and smart TVs. OLED-display revenues are expected to increase from €26.4 billion to €42.5 billion from 2020 to 2025, covering smartphones, smart TVs and other use cases (e.g., automotive displays). OLED TVs are expected to account for 58% of all OLED panels by 2025. (DSCC 2020)

The sales of OLED materials are expected to grow by 17% annually to €1.9 billion in 2023 (DSCC 2019). The main raw material for OLED is silica sand, which is used to form aluminosilicate glass, mainly consisting of silicon (99.5%), which is mixed with some combination of aluminium, sodium and magnesium. For silica sand, the key companies include Sibelico (Belgium), US Silica (US), Emerge Energy (US), Badger Mining (US) and Wuxi Quechen Silicon Chemical Co. (China).

OLED value chains include many companies. The main producers of material mixtures and chemical compounds for OLED include UDC (US), Merck (US), Novaled (South Korea), Idemitsu Kosan, SFC, LG Chem, DowDuPont, Sumitomo, Duksan Neolux, Samsung SDI and others (Macro Polo 2021, Bardsley Consulting et al. 2014). Other critical actors include manufacturing equipment suppliers and testing companies such as Canon, Seiko Epson, Coherent, Applied Materials, Beneq and Laytec located in Europe, Asia and the US. OLED display manufacturing is concentrated in South Korea, with a minority of production in China and Japan. Samsung is currently the largest OLED manufacturer, and LG and Chinese companies such as BOE and China Star Optoelectronics Technology are other main providers.

For display glass manufacturing, the main companies are Corning (US), Asahi Glass (Japan) and Nippon Electric Glass (Japan). Integrated circuits (ICs) are manufactured, for example, by Samsung (South Korea), Novatek (Taiwan), Himax (Taiwan), Silicon Works (South Korea) and Synaptics (US).

The main OLED display components include substrates made of glass or film (plastic), organic semiconductor molecules (or organic stack materials) deposited on the substrate and electrodes (cathode and anode) that are located on both sides of the substrate. Other main OLED components include encapsulation materials such as sealant and cover glass.

Organic stack materials include materials for manufacturing the following layers: hole injection (HIL), hole transport (HTL), emissive, blocking (BL) and electron transport layers (ETL). Companies producing organic stack materials for OLED include Sumitomo Chemical, Konica Minolta, DuPont, Pioneer, Universal Display Corporation (UDC) and Merck. A more specific list of OLED materials suppliers is provided in Table 11.

Table 11. Key actors in the smart TV value chain: Focus on OLED displays.

Part of the value chain	Europe	Rest of the world
Raw materials extraction	Barium: Sachtleben Bergbau, M-I SWACO Chromium: Outokumpu Copper, zinc, silver: KGHM Polska Miedz, Boliden, Terrafame, Lundin Mining Gold: AgnicoEagle, Boliden Iron: LKAB Magnesium: Grecian Magnesite, Magnesitas De Rubián, Magnesitas Navarras, Nedmag, SLOVMAG, SMZ Nickel, cobalt, palladium: Terrafame, Boliden Silicon metal: Elkem Silica sand: Sibelco, Hoffmann Mineral, Brogardsand, Elkem, CAOBAR Strontium: Canteras Industriales, Solvay Titanium: Kronos	Companies: Rio Tinto, BHP, Vale, AngloAmerican, Barrick, Freeport-McMoran, Jinchuan, Impala Platinum, SibayneStillwater, FQM, Vedanta, Zijin Mining See the main non-European producer countries in Table 2 Silica • US Silica (US) • Emergy Energy (US) • Badger Mining (US) • Wuxi Quechen Silica (China)
Manufacturing of material mixtures and chemical compounds	• **Organic stack materials** – **BASF, Merck, Novaled** • **Substrates** – **St. Gobain, ArcelorMittal, Schott** • **Encapsulation materials** – **Henkel, Delo**	• **Countries**: US, Japan, South Korea, China • **Organic stack materials** – Sumitomo Chemical, Konica Minolta, DuPont, Pioneer, Universal Display Corporation (UDC), and Merck • **Substrates** – Pilkington, DuPont, LG Chem, Asahi Glass, PPG • **Encapsulation materials** – Samsung, DuPont, UDC, 3M
Component manufacturing	• **Manufacturing equipment and testing:** – Laytec, Beneq	• **Countries:** South Korea, China, Japan, US • **OLED panels:** – Samsung, LG, Sharp, Hisense Group, TCL, BOE, OLEDWorks • **Manufacturing equipment and testing for panels:** – Canon, Seiko Epson, Coherent, Applied Materials
Assembly of devices	• Samsung assembles smart TVs in several European countries, e.g., Slovenia, Hungary and Romania	• **Countries:** South Korea, China, Brazil, India, US • **Companies:** Samsung, LG, Sony, Panasonic, Videocon industries
Use phase, incl. sales	• Sales: Retail, brand owners • Consumers	
Life cycle extension	• Refurbishment: manufacturers and brand owners, retailers • Reuse: various second-hand online platforms	Not in the focus of this study
Collection and Recycling	• Collectors: brand owners, municipalities, producers and other retail • Recyclers: Umicore, Boliden, Kuusakoski	Not in the focus of this study
Disposal	• Consumers: Hibernation or disposal	Not in the focus of this study

For organic stack materials (Bardsley Consulting et al. 2014):

- Minimising waste is an important objective, e.g., "less than 1% of the precious metals, such as iridium or platinum, that enter the supply chain are actually embedded in the final OLED product."
- The cost of developing high-performance chemicals forms a major portion of the sales price of key materials, e.g., phosphorescent dopants in the emitter layer and ion dopants in transport layers that contain critical raw materials such as iridium, although in low quantities.
- A key manufacturer of phosphorescent dopants is UDC and a key manufacturer of ion dopant is Novaled from materials produced by BASF.

For substrates, the key materials are borosilicate glass and plastic substrates. Companies producing substrates include glass manufacturers such as PPG, Asahi Glass and Pilkington (Nippon Sheet Glass), and Guardian Industries are developing integrated substrate solutions. Clear plastic substrates are being explored by companies such as Agfa, BASF, DuPont Teijin Films and Samsung. (Bardsley Consulting et al. 2014)

The assembly of smart TVs takes place in several countries and continents. For instance, Samsung assembles smart TVs in at least 11 countries, including in the EU (Tab tv 2019). As with smartphones, smart TVs are typically used by one consumer, after which they are discarded. Additionally, smart TVs have similar collection and recycling pathways as smartphones. Table 11 introduces some of the key actors in the smart TV value chain.

3.3 Main elements and raw materials composition

The environmental and social impacts of the extraction and processing of virgin raw materials are discussed at length in chapter 2. While the manufacture of ICT hardware is often responsible for most environmental impacts, the extraction and processing of virgin materials, especially for gold, silver, palladium and plastic, can make a significant contribution (Rizos et al. 2019). As an example, to manufacture a single smartphone, roughly 260 times more rock needs to be mined than the weight of the smartphone (ibid.). Using secondary raw materials may greatly reduce the environmental impacts of raw materials use. As an example, mining cobalt uses between 140–2100 MJ energy per kilo of material, whereas the energy use from scrap is 20–140 MJ per kilo (Rizos et al. 2019).

3.3.1 Smartphones

A wide range of elements and compounds are used in the electronics of a phone. The chip, the processor of the phone, is made from pure silicon. Silicon does not conduct electricity without being 'doped' with other elements; this process involves the silicon being bombarded with a variety of different elements, which can include phosphorus, antimony, arsenic, boron, indium or gallium. The micro-electrical components and wiring in the phone are mainly composed of copper, gold and silver. Tantalum is also used, being the main component of micro-capacitors. (Compound Interest 2014). For smartphones, the PCB contains 90% of the measured Au, 98% of Cu, 99% of Pd, 86% of In and 93% of Ta. The Au, Pd, Cu, Pt, Ta, In and Ga contents of a smartphone PCB are significantly higher than the metal content in currently mined ores. (Bookhagen et al. 2020)

Solder was, in past years, usually composed of tin and lead, but in recent years, lead-free alternatives have been sought, many of which use a combination of tin, silver and copper. The microphone, cameras, vibration units (for notifications and haptic feedback) and speaker of the phone contain magnets, which are usually neodymium-iron-boron alloys, although dysprosium and praseodymium are often also present in the alloy. (Compound Interest 2014, Muller 2013). Magnets contain 96% of the measured REE and 40% of the measured Ga, with higher concentrations than ores for REE and Ga. For Co and Ge, the metal content in smartphones (w/o batteries) is lower than in ore. (Bookhagen et al. 2020)

Touch **screens** are mainly manufactured from aluminosilicate glass, which is mixture of aluminium oxide and silicon dioxide. A thin, transparent, conductive layer of indium tin oxide is deposited on the glass in order to allow it to function as a touch screen. Several of the REE are also present in very small quantities and enable the colours displayed on the screen to be produced. (Compound Interest 2014, Muller 2013)

The majority of today's phones use lithium-ion batteries. These batteries tend to use lithium cobalt oxide as the positive electrode in the battery and the negative electrode is formed from carbon in the form of graphite. The battery itself is usually housed in an aluminium casing. (Compound Interest 2014)

A typical **phone casing** is either stainless steel or aluminium and glass for the back cover. Low-priced phones may also have plastic casings. The casing often contains flame retardant compounds – brominated flame retardants are still often used, but efforts are being made to minimise the use of these, utilising other organic compounds. (Compound Interest 2014, Muller 2013)

A modern smartphone contains approximately 40–80 different elements (Fig. 14). According to Apple, 90% of the total mass shipped by the company in 2019 consisted of 14 materials: aluminium, cobalt, copper, glass, gold, lithium, paper, plastics, rare earth elements, steel, tantalum, tin, tungsten and zinc (Apple 2020). According to Bookhagen et al. (2020), an average smartphone consists of 45% metals, 32% glass, 17% plastics and 6% others, i.e., materials that could not be mechanically separated. Table 12. Main elements in smartphones. In Rizos et al. (2019), the total weight of the exemplary smartphone is 164 g and the "others" category consists of glass, glues, etc. Bookhagen et al. (2020) did not consider the smartphone battery and the average weight of a smartphone is 110 g in their study. For Fairphone, the data are based on the bill-of-materials (BOM) as stated by the suppliers and they also consider raw materials inside electronic components, and the total weight is 190.4 g (Proske et al. 2020). The proportions and total mass are the authors' own calculations based on data in the referenced publications. introduces the main elements in smartphones based on Rizos et al. (2019), Bookhagen et al. (2020) and Proske et al. (2020).

There is considerable variation in the specific raw material content of smartphones. For instance, the Fe content varied from 3.69 g to 31.66 g in smartphones studied by Bookhagen et al. (2020). Plastics, aluminium, copper and steel are dominant in terms of weight, as well as the non-specified "others category". However, several materials that only account for a small share of the weight are important in terms of their economic value, supply risks or environmental and social concerns during their extraction (Rizos et al. 2019). To give a perspective on the total amounts of raw materials in smartphones, Gurita et al. (2018) estimated the total quantity of 7 key precious or critical metals in smartphones put on the market between 2009–2015 in Germany. The quantities were as follows: 3.46 tons of gold, 35.13 tons of silver, 1.27 tons of palladium, 725.58 tons of cobalt, 1.04 tons of gallium, 1.15 tons of praseodymium and 5.76 tons of neodymium (ibid.). Table 13 presents the raw and intermediate material sources for mobile phones.

Table 12. Main elements in smartphones. In Rizos et al. (2019), the total weight of the exemplary smartphone is 164 g and the "others" category consists of glass, glues, etc. Bookhagen et al. (2020) did not consider the smartphone battery and the average weight of a smartphone is 110 g in their study. For Fairphone, the data are based on the bill-of-materials (BOM) as stated by the suppliers and they also consider raw materials inside electronic components, and the total weight is 190.4 g (Proske et al. 2020). The proportions and total mass are the authors' own calculations based on data in the referenced publications.

Material type	Weight by material type (% of total)	Element	Average weight (% of total) (Rizos et al. 2019)	Estimates of average weight (% of total) Bookhagen et al. 2020)[4]	Fairphone weight (% of total) (Proske et al. 2020)
Metals	49.5 (45%) to 73.39 g (44.8%)	Aluminium	31.89 g (19.4%)	5–15 g (4.5–13.6%)	
		Copper	14.26 g (8.7%)	7–11 g (6.4–10.0%)	8.145g (4.3%)
		Iron / Steel	14.02 g (8.5%)	3.69–31.66 g (3.4–28.8%)	
		Silicon metal		10 g (9.1%)	
		Cobalt	8.35 g (5.1%)	0.01–0.1 g (<0.1–0.1%)	11.24g (5.9%)
		Nickel		0.8–6 g (0.7–5.5%)	
		Magnesium	3.26 g (2.0%)	0.2–20 g (0.2–18.2%)	
		Chromium		0.005–8 g (<0.1–7.3%)	
		Lithium	0.93 g (0.6%)		5.2g (2.7%)
		Tungsten	0.30 g (0.2%)	0.1–1 g (0.1–0.9%)	0.013g (<0.1%)
		Silver	0.21 g (0.1%)	0.01–0.1 g (<0.1–0.1%)	0.044g (<0.1%)
		Tin	0.1 g (<0.1%)	0.7–1 g (0.6–0.9%)	2.48g (1.3%)
		Zinc		0.1–1 g (0.1–0.9%)	
		Strontium		0.1–1 g (0.1–0.9%)	
		Barium		0.1–1 g (0.1–0.9%)	
		REE (e.g., Neodymium)		0.1–1 g (0.1–0.9%)	0.17g (<0.1%)
		Manganese		0.1–1 g (0.1–0.9%)	
		Titanium		0.1–1 g (0.1–0.9%)	
		Molybdenum		0.01–0.1 g (<0.1–0.1%)	
		Zirconium		0.01–0.1 g (<0.1–0.1%)	
		Gold	0.03 g (<0.1%)	0.01–0.1 g (<0.1–0.1%)	0.143g (<0.1%)
		Tantalum	0.02 g (<0.1%)	0.01–0.1 g (<0.1–0.1%)	
		Palladium	0.01 g (<0.1%)	<0.01 g (<0.1%)	0.0075g (<0.1%)
		Indium	0.01 g (<0.1%)	<0.01 g (<0.1%)	
Glass	35.2 g (32%)				
Plastics	18.7 (17%) to 33.74 g (20.6%)				
Others	6.6 (6%) to 57.23 g (34.9%)				

Table 13. Raw and intermediate material sources for mobile phones, based on the latest available information (2018–2020 data). Note that for Finland, and for the entire European Union, very little, if any, information exists on how much of the locally produced raw materials are, in fact, used in the production of ICT devices. Question mark indicates items for which no information was found or the information given is uncertain.

	From mines in these areas (relative to global production)			**Commodity use in material mixtures and chemical compounds which are made in:**		
Region	**Finland**	**Rest of Europe[1]**	**Rest of the world (largest producers)[1,2,3]**	**Finland**	**Elsewhere in Europe[5,6]**	**Elsewhere in the world (country mentioned if it dominates)[5,6]**
Ag	Very little	Moderate: POL, SWE, SPA	MEX, PERU, CNA, RUS, PLD, AUS, CHI	Silver ingots	Silver ingots	Silver ingots, solder and brazing metal alloys, wiring metal alloys, silver oxide
Al[4]	0	Minor: GRE	AUS, GUI, CHI, BRA	Aluminium ingots	Al ingots, alloys	Al ingots (CNA), high-purity alumina, alloys, Li-Ni-Co-Al-oxide
Au	Minor	Minor: BUL, SWE	CNA, AUS, RUS, USA, CND	Gold doré ingots; inert electric conductor alloys	Doré and pure gold ingots; inert electric conductor alloys	Doré and pure gold ingots; inert electric conductor alloys
Ba[4]	0	Minor: GER, UK	USA, INA, MOR	?	Barium carbonate	Barium carbonate
Ca	Minor	Moderate	CNA, USA, INA[7]	Calcium oxide and hydroxide	Calcium oxide and hydroxide, metal alloys	Calcium oxide and hydroxide, metal alloys
Cl	0	Moderate: GER, FRA	CNA, USA; INA[8]	Chlorine gas	Chlorine gas, pure Cl salts	Chlorine gas, pure Cl salts
Co	Minor	0	DRC (RUS, AUS, PHI)	Cobalt sulphate and other Co chemicals, Co metal	Alloys, Co metal, Co sulphate and other Co chemicals	Alloys (CNA), cobalt metal, Co sulphate (CNA), Li-Ni-Co-Al-oxide
Cr	Minor	0	RSA, KAZ, TUR	Stainless steels	Stainless steels	Stainless steels (CNA), non-ferrous alloys
Cu	Minor	Moderate: POL, SWE, SPA, BUL	CHI, PERU, CNA, DRC, USA, AUS	Copper metal, ultra-pure copper, alloys	Copper metal, ultra-pure copper, alloys	Copper metal, ultra-pure copper, alloys
Fe	0	Minor: SWE	AUS, BRA, CNA, INA	Carbon steels, stainless steels	Carbon steels, stainless steels	Carbon steels (CNA), stainless steels (CNA), lithium-iron phosphate
In	0	Probably very little (by-product of zinc)	CHI, KOR	0	Indium metal, solder and other alloys	indium metal, solder and other alloys, In-tin oxide (CNA, KOR), In phosphide, In-Ga arsenide, In-Ga nitride
Li	0	Minor: POR	AUS, CHI, CNA	0	Lithium carbonate, lithium hydroxide[9]	Lithium oxide (CNA, USA, CHI), Li carbonate (CNA, USA, CHI, ARG, AUS), Li hydroxide (CNA, ARG, AUS). Li-Co oxide, and other Li compounds (CNA, KOR, JPN)
Mg[4]	0	Minor: SPA, AUT, SLO, GRE	CHI, BRA, RUS, TUR	Alloys?	Alloys	Mg metal (CNA 90%), strong light-metal alloys,
Mn	0	Very little: ROM	RSA, AUS, GAB,	Steel	Steel, non-ferrous alloys, manganese oxide	Steel, non-ferrous alloys, manganese oxide, high-purity Mn, electrolytic Mn flakes, Li-Ni-Mn-Co oxide, Li-Mn oxide
Mo	0	Very little: POL	CNA, CHI, USA, PERU	?	Carbon steel, stainless steel	Carbon steel, stainless steel

Table 13. Cont.

	From mines in these areas (relative to global production)			**Commodity use in material mixtures and chemical compounds which are made in:**		
Region	**Finland**	**Rest of Europe**[1]	**Rest of the world (largest producers)**[1,2,3]	**Finland**	**Elsewhere in Europe**[5,6]	**Elsewhere in the world (country mentioned if it dominates)**[5,6]
Ni	Minor	0	IND, PHI, RUS, AUS	Nickel metal, stainless steels, nickel sulphate	Nickel metal, stainless steels, nickel sulphate	Nickel metal, stainless steels, non-ferrous alloys, Ni sulphate, Li-Ni-Mn-Co oxide, Li-Ni-Co-aluminium oxide
Pd	Very little	0	RUS, RSA, CND	Palladium ingots and powder	Palladium ingots and powder	Palladium ingots and powder, conductor alloys stable in high temperatures, palladium plating salts
REE	0	0	CHA, USA, BUR, AUS	0	Alloys, oxides, individual metals	REE oxides, carbonates and alloys, and individual REE metals (CNA >80%)
Si metal[4]	0	Minor: NOR	CNA, RUS, USA, BRZ	Silicon crystals	Silicon metal, silicon crystals	Silicon metal (CNA), silicon crystals, silicon chemicals, silicon wafers
Sn	0	Very little: UK, POR, SPA	CNA, INS, BUR, PERU, BRZ, BOL	?	Tin ingots, brass, bronze	Tin ingots, solder alloys, In-tin oxide, brass, bronze
Sr	0	Major: SPA	CNA, MEX, IRA	?	Strontium carbonate	Strontium carbonate
Ta	0	0	CNG, BRA, RWA, NIG	?	Tantalum metal and pentoxide, superalloys	Tantalum metal and pentoxide, superalloys, carbides, chemicals
Ti	0	Moderate: NOR	CNA, RSA, AUS, CND	Steel	Steel, light-weight alloys	Steel, light-weight alloys. Titanium sponge and ingot (CNA, RUS, JPN)
W	0	Minor: SPA, POR	CNA (VTN, RUS, BOL)	Steel	Steel, non-ferrous alloys, tungsten metal and chemicals	Steel, non-ferrous alloys; tungsten powder and tungsten chemicals (CNA)
Zn	Minor	Moderate: SWE, IRE, SPA, POR	CNA, AUS, PERU, IND, USA	Zinc slabs, non-ferrous alloys	Zinc slabs, non-ferrous alloys, zinc sulphate	Zinc slabs (CNA), non-ferrous alloys, zinc sulphate
Zr	0	0	AUS, RSA, CNA, MOZ	?	Zirconium oxide, zirconium metal	Zirconium oxide, zirconium metal

1 USGS (2021)

2 BGS (2020)

3 ARG = Argentina, AUS = Australia, BOL = Bolivia, BRA = Brazil, BUL = Bulgaria, BUR = Myanmar, CHI = Chile, CNA = China, CND = Canada, CNG = Congo Kinshasa, GAB = Gabon, INA = India, IND = Indonesia, IRA = Iran, JPN (Japan), KAZ = Kazakhstan, KOR = South Korea, MEX = Mexico, MOR = Morocco and West Sahara, MOZ = Mozambique, NIG = Nigeria, NL = Netherlands, NOR = Norway, POR = Portugal, RSA = South Africa, RUS = Russia, RWA = Rwanda, SPA = Spain, SWE = Sweden, TUR = Turkey, UK = United Kingdom, UKR = Ukraine, VTN = Vietnam

4 Mined ore for Al: bauxite (aluminium ore), Ba: baryte, Mg: magnesium salts, Si metal: quartz

5 Eynard et al. (2020)

6 Latunussa et al. (2020)

7 Sourced from carbonate rocks, which are abundant across the globe. A very small fraction of mined carbonate rocks is used to produce calcium. Hence, the countries mining most of the carbonate rocks are not relevant in this context.

8 Chlorine is sourced from sodium and potassium salts, of which a rather small fraction is used to produce chlorine. Salt production is referred to in the row for the mining of Cl.

9 So far, only 1% of lithium used in Europe has been used in batteries (Latunussa et al. 2020).

3.3.2 Smart TVs

The raw material compositions of smart TVs vary between different types of display panel technologies, and between smart TV brands and models. There is also some variation between studies and data sources. From the weight perspective, glass is the main material in a smart TV. Cerium is used to improve the screen colour. The electronics and case consist of plastics, copper, tin, zinc, silicon, gold and chromium. (Techwalla 2021)

For instance, the raw materials content of a plasma TVs is 29% glass, 21% steel, 19% aluminium, 10% plastics, 1% copper and 20% others (Panasonic 2019). Plasma TVs use neon, xenon and argon gases with phosphor gas for the cells that form the display (Techwalla 2021). A sample LCD TV's raw materials content is 43% steel, 33% plastic, 11% glass, 2% aluminium and 11% others (Panasonic 2019). The main component in an LCD TV, i.e., the LCD panel, is composed of Si (25.4%), Al (7.55%), Ca (4.7%), Sr (3.7%), Mg (0.9%), Cl (0.1%), Sn (0.09%), Fe (0.08%), P (0.05%) and In (0.03%) (De la Torre et al. 2018). Focusing on key elements such as indium, rare earths and precious metals, the content of LCD and LED TVs is presented in Table 14.

Table 14. Raw material composition of LCD and LED TVs based on data from Buchert et al. (2012). The focus is on certain precious metals and critical raw materials.

Raw material	Content per LCD TV (mg)	Content per LED TV (mg)	Use
Silver (Ag)	575	575	Electronics (PCB, contacts, wiring)
Gold (Au)	138	138	Electronics (PCB, contacts, wiring)
Indium (In)	254	254	Display
Palladium (Pd)	44	44	Electronics (PCB, contacts, wiring)
Yttrium (Y)	110	4.8	Display
Gallium (Ga)	0	4.9	Display
Europium (Eu)	8.1	0.09	Display
Lanthanum (La)	6.8	0	Display
Cerium (Ce)	4.5	0.3	Display
Gadolium (Gd)	0.63	2.3	Display
Terbium (Tb)	2.3	0	Display
Praseodynium (Pr)	<0.13	0	Display

As the "standard" size of smart TVs has grown considerably from about 35 inches to 55–65 inches currently, it can be assumed that the raw material consumption per unit has also grown drastically. Displays and the related electronics consume considerable amounts of precious and CRMs. The Prosum project (Mathieux et al. 2017) has collected some estimates of the quantity of metals in screens placed on the market each year. For 2020, the estimates were 48 tons for Ag, 12.5 tons for Au, 16 tons for In, 35 tons for Nd and 2 tons for Pd. Table 15 presents the raw and intermediate material sources for smart TVs.

Table 15. Raw and intermediate material sources for smart TVs, based on the latest available information (2018–2020 data). Note that for Finland and for the entire EU, very little, if any, information exists on how much of the locally produced raw materials are, in fact, used in ICT device production. The 'doré ingot' is a type of gold ingot which is not purified from silver and other impurities. Question mark indicates items for which no information was found or the information given is uncertain.

Smart TV	From mines in these areas (relative to global production)			Use in material mixtures and chemical compounds that are made in:		
	Fin-land	Rest of Europe[1]	Rest of the world (largest producers)[1,2,3]	Finland	Elsewhere in Europe	Elsewhere in the world (country mentioned if it dominates)[5,6]
Ag	Very little	Moderate: POL, SWE, SPA	MEX, PERU, CNA, RUS, PLD, AUS, CHI	Silver ingots	Silver ingots	Silver ingots, solder and brazing metal alloys, wiring metal alloys, silver oxide
Al[4]	0	Minor: GRE	AUS, GUI, CHI, BRA	Aluminium ingots	Aluminium ingots, alloys	Al ingots (CNA), high-purity aluminium, alloys, Li-Ni-Co-Al oxide
Ar[7]	Minor	Moderate: GER, UK, FRA, NL	USA, CNA, BRA, JPN	Pure argon gas	Pure argon gas	Pure argon gas
Au	Minor	Minor: BUL, SWE	CNA, AUS, RUS, USA, CND	Gold doré ingots; inert electric conductor alloys	Doré and pure gold ingots; inert electric conductor al-loys	Doré and pure gold ingots; inert electric conductor alloys
Ca[8]	Minor	Moderate	CNA, USA, INA	Calcium oxide and hydroxide	Calcium oxide and hydroxide, metal alloys	Calcium oxide and hydroxide, metal alloys
Cl[9]	0	Moderate	CNA, USA, INA	Chlorine gas	Chlorine gas, pure Cl salts	Chlorine gas, pure Cl salts
Cr	Minor	0	RSA, KAZ, TUR	Stainless steels	Stainless steels	Stainless steels (CNA), non-ferrous alloys
Cu	Minor	Moderate: POL, SWE, SPA, BUL	CHI, PERU, CNA, DRC, USA, AUS	Copper metal, ultra-pure copper, alloys	Copper metal, ultra-pure copper, alloys	Copper metal, ultra-pure copper, alloys
Fe	0	Minor: SWE	AUS, BRA, CNA, INA	Carbon steels, stainless steels	Carbon steels, stainless steels	Carbon steels (CNA), stainless steels (CNA)
In	0	Probably very little (by-prod-uct of zinc)	CHI, KOR	0	Indium metal, solder and other alloys	Indium metal, solder, other alloys, In-tin oxide (CNA, KOR), In phosphide, In-Ga arsenide, In-Ga nitride
Mg[4]	0	Minor: SPA, AUT, SLO, GRE	CHI, BRA, RUS, TUR	Alloys?	Alloys	Mg metal (CNA 90%), strong light-metal alloys,
Ne[7]	0	Moderate: GER, UK, FRA	CNA, USA, RUS, UKR	0	Pure neon gas	Pure neon gas
P	Minor	0	CNA, MOR, USA, RUS	0	0	Phosphorus sulphides, oxides and very pure phosphoric acid (CNA)
Pd	Very little	0	RUS, RSA, CND	Palladium ingots and powder	Palladium ingots and powder	Palladium ingots and powder, conductor alloys stable in high temperatures, Pd plating salts

Table 15. Cont.

Smart TV	From mines in these areas (relative to global production)			Use in material mixtures and chemical compounds that are made in:		
	Fin-land	Rest of Europe[1]	Rest of the world (largest producers)[1,2,3]	Finland	Elsewhere in Europe	Elsewhere in the world (country mentioned if it dominates)[5,6]
REE	0	0	CHA, USA, BUR, AUS	0	Alloys, oxides, individual metals	REE oxides, carbonates and alloys, and individual REE metals (CNA >80%)
Si metal[4]	0	Minor: NOR	CNA, RUS, USA, BRA	silicon crystals	silicon metal, silicon crystals	silicon metal (CNA), silicon crystals, silicon chemicals, silicon wafers
Sn	0	Very little: UK, POR, SPA	CNA, INS, BUR, PERU, BRZ, BOL	?	Tin ingots, brass, bronze	Tin ingots, solder alloys, indium-tin oxide, brass, bronze
Sr	0	Major: SPA	CNA, MEX, IRA	?	Strontium carbonate	Strontium carbonate
Xe[7]	Minor	Moderate: FRA, GER	USA, UKR, CNA, BRA, JPN	Pure xenon gas	Pure xenon gas	Pure xenon gas
Zn	Minor	Moderate: SWE, IRE, SPA, POR	CNA, AUS, PERU, IND, USA	Zinc slabs, non-ferous alloys	Zinc slabs, non-ferrous alloys, zinc sulphate	Zinc slabs (CNA), non-ferrous alloys, zinc sulphate

1 USGS (2021)
2 BGS (2020)
3 ARG = Argentina, AUS = Australia, BOL = Bolivia, BRA = Brazil, BUL = Bulgaria, BUR = Myanmar, CHI = Chile, CNA = China, CND = Canada, CNG = Congo Kinshasa, GAB = Gabon, INA = India, IND = Indonesia, IRA = Iran, JPN (Japan), KAZ = Kazakhstan, KOR = South Korea, MEX = Mexico, MOR = Morocco and West Sahara, MOZ = Mozambique, NIG = Nigeria, NL = Netherlands, NOR = Norway, POR = Portugal, RSA = South Africa, RUS = Russia, RWA = Rwanda, SPA = Spain, SWE = Sweden, TUR = Turkey, UK = United Kingdom, UKR = Ukraine, VTN = Vietnam
4 Mined ore for Al: bauxite (aluminium ore), Ba: baryte, Mg: magnesium salts, Si metal: quartz
5 Eynard et al. (2020)
6 Latunussa et al. (2020)
7 The noble gases Ar, Ne and Xe are not mined but are separated from the air (Elsner 2019).
8 Sourced from carbonate rocks, which are abundant across the globe. A very small fraction of mined carbonate rocks is used to produce calcium, so the countries mining most of the carbonate rocks are not relevant in this context.
9 Chlorine is sourced from sodium and potassium salts, of which a rather small fraction is used to produce chlorine. Salt production is referred to in the row for the mining of Cl.

Copper and cobalt are mainly mined in countries of the Global South such as Peru, Chile and the DRC. While copper mining is quite organized and practiced by mining companies in South America, in the DRC, cobalt is also produced by artisanal miners, involving child labour. As the environmental restrictions on the activity are not as tight in the Global South as in the Global North (e.g., the EU), the impacts of mining are major in the countries of the former region. This has resulted in unsustainable mining with environmental degradation and social unrest.

3.4 Design

There are various drivers for improving the design of electronic devices from a sustainability point of view. These include, among others, policies and legislation, increased customer awareness of environmental and social issues or supply security issues. From a policy perspective, the EU's green and digital transition combines the areas of digitalization and sustainability, which should ensure that the ongoing digital development will consider the sustainability impacts in tandem.

Digital solutions are important in advancing the circular economy, supporting the decarbonisation of all sectors and reducing the negative environmental and social impacts of products. Digitalization is also a major contributor to, and enabler of, a fully integrated life cycle approach in product and system design, which may lead to increased energy efficiency, reduced energy use, increased traceability of raw materials and products, and enabling the lifetime extension and recyclability of products. It has been estimated that product design determines up to 80% of the overall environmental impact of a product throughout its life cycle, which underlines the importance of sustainable and circular design.

Different approaches exist for renewing the design of electronic devices in such a way that it supports sustainability and circularity. These include, but are not limited to, the increased use of recycled raw materials, selecting non-toxic materials, avoiding difficult-to-recycle composite materials, improving repairability, maintainability and recyclability, and extending the lifetime. Ecodesign, as a design and management method, integrates these issues into product development, and thus proactively reduces, avoids or eliminates adverse environmental impacts that occur at different stages of the life cycle (Horn et al. 2021). In terms of electronic devices, such issues as the design and selection of materials, decisions on the computing power of the devices and on the type of components used, repairability or replaceability of components and the recyclability of materials may be extensively considered during the design phase. In particular, strengthening the pre-material recycling options is a primary focus of design-for-X approaches (Bartie et al. 2019), i.e., utilizing opportunities to reuse or repair the devices or components before materials recycling. In addition, the used raw materials and chemicals have safety data sheets and relevant information for safe handling (REACH). Legislation should also ensure the safe utilization of secondary materials, and access to and the transparency of information on hazardous chemicals, materials and products should be sufficient.

There is relatively long path from raw materials to digital devices: raw materials are needed to produce materials, materials go into components and components into devices. The design guidelines can be applied in material design, in component design and in device design. At the material level, decisions are made relating to material chemistries and preferences for using abundantly available elements or renewables over critical ones. Currently, many composite materials and alloys are used that are not easily recycled. Toxic elements may also be used in material alloys. On the component level, the re-design of joints and components for increased repairability are important actions to support sustainability through the life cycle of a digital product. Through product design, it is also possible to influence the use of recycled materials and to support and develop digital passports to follow products through their life cycle. Digital product passports, in particular, could support the circularity, strengthen the pre-material recycling options and support efficient recycling. Ecodesign would need a systems approach to understand the impacts of design choices and their influence and demand on the supply chain and raw materials.

The “Ten Golden Rules” for integrating environmental aspects into product design presented by Luttropp and Lagerstedt (2006) are an example of an approach to facilitate the integration of reasonable environmental demands into the product development process. The tool provides a common foundation, which can be used to prepare guidelines for the addressing of product-design challenges. These guidelines cover the use of toxic substances, production efficiency, weight reduction, repairability, longevity, material choices, modularity and the availability of manuals for upgradability, as well as joint design.

In addition, there are several other guidelines or frameworks for ecodesign implementation listed, for instance by Horn et al. (2021). These supporting tools can be organized, for example, into

- life cycle-based approaches (e.g., streamlined LCA tools),
- environmentally supported computer-assisted design or process modelling (computer-aided design tools integrating environmental criteria into the design phase, e.g., EcoCAD, HSC Sim),
- different matrix tools (MECO or MET matrices),
- checklists (Ten Golden Rules, Lofthouse guide),
- design-for-X tools (design-for-X, and other implementation and integration tools).

Nevertheless, the use of these tools and the level of ecodesign integration has remained at a relatively low level (Dekoninck et al. 2016, Jönbrink & Melin 2008, Pigosso et al. 2013).

The substitution of materials and compounds can be seen as a design solution to reduce the supply risk of materials. Currently, some materials, alloys and composites are toxic, critical, conflict materials or challenging to recycling. The object of substitution can be a material, a product or a function. Substitution is often mentioned as a solution to materials-related challenges and raw material supply risks. Substance for substance, metal for metal or element for element substitution tasks need to be 'fitted' to the existing system, while material for material, component for component, product for product or function for function substitutions allow more options to select from. Nevertheless, several limitations currently also exist to how far substitution can solve raw material-related problems, such as the environmental impacts of the substitute, sub-optimization between various metals, or the arbitrariness of the studies (EASAC 2016).

Substitution example: The design selection of primary materials versus secondary materials will considerably impact on the product's embodied energy and CO2 footprint. Comparisons between the CO2 footprint of primary and secondary materials can be made e.g., with Ansys GRANTA 2021 program. In short, relying exclusively on recycled materials, an electronic device's CO2 footprint could decrease by up to 90% compared to a design only utilising primary raw materials.

3.4.1 Smartphones

Raw materials

The current trends in smartphone design and functionality emphasize the use of specialty metals, which creates an increased demand for metals such as indium, lanthanum, lithium and tantalum. In addition, specialty ceramics and toughened glass are increasingly being used. Newer generations of smartphones cause greater environmental impacts, especially due to their increasing computational power and generally due to an increase in dimensions (Watson et al. 2017). If designed for disassembly and recycling, end-of-life smartphones can be a valuable source of high value secondary materials. However, once smartphones are mixed with other WEEE flows, material recovery becomes more challenging. Moreover, in some cases, the low economic viability of material recycling and low cost of raw materials does not motivate the reuse or saving of raw materials. Although phone manufacturers have started using more secondary materials in their products, the recycled material content of smartphones, and particularly of high-grade materials, remains relatively low.

Repairability and obsolescence

Currently, most smartphones are not designed to be easily repairable, and batteries are not replaceable by users. Some manufacturers may even deliberately choose a supposedly more durable design over repairability. Even in cases where repair is technically possible, devices do not necessarily work properly when using non-OEM (original equipment manufacturer) components. Unauthorised service points might also be denied access to OEM components (Watson et al. 2017).

Smartphones may become obsolete rather quickly, be it intentional or not. So-called planned obsolescence (Guiltinan 2009) can be defined as physical and technological obsolescence. It concerns different issues, such as a lack of repairability, planned degradation of the constituents, a decrease in aesthetic quality, design obsolescence, and a lack of compatibility (e.g., when software updates are compromised) (Cenci et al. 2021). Although all issues are important, the lack of compatibility is of special concern in smartphones and other devices that depend on software and are connected to the Internet.

Software obsolescence is a situation in which a device is technically capable of performing the functions it was designed for, but its manufacturer deliberately stops supporting the device. In state-of-the-art electronic devices, software has become one of the core functionalities and devices cannot properly, or safely, function without up-to-date software. This leads to shortening of product lifespans. Moreover, software is typically out of the consumers' control.

The responsibility for minimising the risks of rapid obsolescence, planned or otherwise, lies not only with the smartphone producers but also the producers of the components and software.

Transparency

Many smartphone manufacturers have taken action to include environmental and sustainability principles in their design processes. Examples from the world's biggest smartphone brand companies such as Huawei, Apple, Samsung, LG and Sony Mobile show that these may include requirements for the use of recycled materials, circular design, better energy performance, resource efficiency and reduced use of heavy metals and hazardous substances. However, companies often do not disclose specific details of the sustainability criteria they use. There is a lack of transparency in terms of how these criteria are manifested in the final products, how widely they are used across the manufacturer's product portfolios and how they have improved over the years.

In contrast, Fairphone has a mission to design a smartphone that would incorporate Design for Environment in the core of its business model. While Fairphone's market share has remained small, it has led by example on issues such as transparency, product life extension, working conditions across the supply chain and greater use of recycled materials.

Modularity

The concept of modular smartphones has received attention over the years, but none have made it to large-scale mass production. Modular smartphones offer the possibility of replacing broken components, and updating, upgrading or expanding the phone and its features. Fairphone, PuzzlePhone (not launched) and formerly Google's project ARA or ZTE's modular phone (the development of both discontinued) are examples of modular smartphone models. The challenges of modular design relate, for example, to the phones being larger and requiring more materials to produce. This, in turn, would need to be balanced by longer life cycles.

The Circular Strategies Framework for consumer electronics created by the Ellen MacArthur Foundation suggests that to achieve the highest efficiency in terms of material recovery and cost savings, smartphones do not necessarily need to be fully modular, but should be designed to be at least partially modular. In practice, this means that the printed circuit boards (PCBs), screens, batteries and shells should be easy and rapid to separate. Furthermore, a recyclability study performed by Fairphone (2017) demonstrated how easy dismantling, as a pre-process to recycling, can help in the recovery of a wider array of materials with lower environmental impacts, as it gives more flexibility to use different recycling routes for different modules.

3.4.2 Smart TVs

Raw materials

Even though the raw materials used for smart TVs are to a high degree similar to those for smartphones, specific raw materials, such as glass, plastics, different gases used for the displays and, for example, cerium are used in much larger quantities. After the introduction of flat LCD (later LED) panels, televisions became considerably lighter compared to the older generation utilizing CRT technology. Despite the continuous emphasis on designing increasingly thinner TVs, the material requirements are no longer decreasing. On the contrary, the size of a TV that is considered standard nowadays would have been unimaginable a decade or two ago. Moreover, new display technologies, curved or rollable displays, HDR and 3D images and other technological feats require more sophisticated electronic components than ever before, similarly to smartphones.

Repairability and obsolescence

Electronic components in smart TVs are highly sophisticated nowadays. Smart TVs are connected devices. They run operating systems similar to those of smartphones. They not only project an image on the screen, but also process and enhance the received signal into the image, and for this require computing power. The more complex they become, the more difficult they are to repair and recycle.

Rather specifically for TVs, they are prone to display damage. Older CRT screens were made of thick glass and could not be easily damaged in households. Currently, flat LED panels are only protected by a thin layer of glass or plastic. Due to the increasing size of displays and delicate stands, they are also more likely to be accidentally damaged. While it is technically possible to replace a broken TV panel, such repair is often economically unfeasible. Moreover, the technical development in smart TV design is as rapid as in other electronic devices, such as smartphones, which might not motivate consumers to repair their older TV sets.

3.5 Purchase, use and lifetime extension

Electronic devices are purchased either by consumers or organizational buyers (businesses or the public sector). Whether the purchaser is a private consumer, or an organizational buyer has an impact on the purchasing criteria. In general, the purchase decision is driven by the thought process that leads a customer from identifying a need, generating options, and choosing a specific product and brand. This thought process can be influenced by many factors relating to the specific situation and product being purchased, and others relating to the person who is making the decision. Little research has been carried out on the drivers of purchasing decisions related to the sustainability of a smartphone, as most research has focused on marketing or advertising strategies (see, e.g., Martins et al. 2019, Lee et al. 2017).

Consumers increasingly say they expect their electronic devices to be sustainably produced, easy to dismantle, repair and recycle. However institutional buyers, public procurers and especially consumers lack awareness of reliable sustainability standards and what criteria can be used to inform sustainable purchasing decisions (Judl et al. 2018). As for organizational buyers, there are more possibilities to impact on the purchasing decision through structured criteria, sourcing policies or the implementation of a sustainability-based code of conduct. For example, the EU (European Commission 2021a), the USA and Japan (Ministry of the Environment Japan 2016) have sustainable procurement guidelines or registries, which enable a systematic and transparent sustainability integration. The most recent example from the EU is the Circular and Fair ICT pact initiated by the Dutch Ministry of the Environment. The aim of the pact is to create a network of procurers, all contributing to a large collective demand for circular and fair laptops and smartphones. This, in turn, helps ICT producers change their business and accelerates new innovations. To date, seven EU countries have signed the pact.

It is increasingly important to find ways to reduce the need for consuming new electronic devices, reuse existing electronic devices and their functioning parts and expand the number of people using them. This can be achieved, for instance, with lifetime extension of electronic devices or by utilizing different sharing or ownership models. The lifespan can be extended through design, creating a network of repair points, legislative requirements for repair and lower taxes on repair and software upgrades (Judl et al. 2018).

3.5.1 Smartphones

Purchase

The number of smartphones sold to end users between the 2007 and 2021 has grown by a factor of 12 (from 122 million units in 2007 to 1535 million units in 2021), the highest growth occurring between the years 2007–2015 (Statista 2021b). Shabrin et al. (2017) have defined seven factors that influence smartphone purchase decisions: brand, convenience, dependency, price, social influence, product features and social needs. The purchase decision represents a powerful everyday behavioural area capable of affecting the product system's societal and environmental impacts (Mao et al. 2020). To drive purchasing decisions towards a more sustainable basis, nudging can be used, which proposes positive reinforcement and indirect suggestions as ways to influence behaviour and decision making (Thaler & Sunstein 2008).

To support the purchasing decision, some standards and product labels are available that have been specifically developed to help customers purchase more sustainable smartphones. The criteria vary among programmes, but they generally include energy use, sustainable material use, product life extension, hazardous materials, conflict minerals and social responsibility. However, the adoption of these standards has been relatively slow so far, and there is a need for greater awareness and cross-cutting engagement from purchasing organizations, consumers and policymakers.

- **TCO Certified** is an independent sustainability certification for IT products, including smartphones, displays and computers. The criteria used for TCO Certified cover environmental and social responsibility from a life cycle perspective. Compliance with all criteria is independently verified. TCO Certified is a type 1 Ecolabel in accordance with ISO 14024. This means that the development of criteria is based on scientific principles and involves multiple stakeholders and experts in an open development process. Currently, no mobile phone models carry this certification.
- **ECOLOGO Certification:** UL (Underwriter Laboratories) has produced a life cycle-based environmental sustainability standard for mobile phones. Several models of Samsung, Huawei, LG, HTC and others have achieved the standard. The US EPEAT registry uses this standard as part of its environmental criteria for mobile phones.
- **The Blue Angel** (Blauer Engel) is an environmental label of the federal government of Germany, which also includes requirements for mobile phones. New requirements putting more

emphasis on social sustainability were developed and published in 2017. However, no mobile phone models have yet achieved the certification based on the new criteria.

Use phase and lifetime extension

From a raw materials perspective, it is important to find ways to extend the lifespan of smartphones. While the lifespan of mobile phones was reported to have decreased from 4.8 to 4.6 years (-3%) between 2000 and 2005 (Bakker et al. 2014), modern smartphones hardly ever last or are used for that long. It is estimated that the average replacement time of smartphones globally is currently around 21 months (Lu 2017). The EU Waste Framework Directive (Directive 2008/98/EC of the European Parliament and of the Council, European Parliament 2008) and Waste Law (646/2011) set the basic rules for waste management, recycling targets and the use of recycled raw materials, stating that products need to be long lasting, repairable and easily recyclable after use.

Production, including raw materials sourcing, manufacturing and assembly, accounts for 81% of greenhouse gas emissions over the life cycle of a smartphone with a 21.6-month lifetime (Rizos et al. 2019). It should be noted that the energy consumption is largely dependent on the use profile of the smartphone, and this study focuses on an "average" smartphone user. Extending the average lifespan lowers the greenhouse gas emissions of smartphones, as fewer devices need to be manufactured and less raw materials therefore extracted. Rizos et al. (2019) estimated that the total emissions of the EU's smartphones would be reduced from 70.2 m tonnes CO_2 with a 21.6-month lifetime to 49.9 m tonnes with 33.6-month lifetime, and all the way to 39.7 m tonnes with 45.6-month lifetime. The timeframe of this analysis was 10 years and the reported savings are equal to the emissions of 364 000 smartphones (with a 33.6-month lifetime) and 546 000 smartphones (with a 45.6 month lifetime).

Consumers increasingly view refurbished smartphones in a positive light (Mugge et al. 2017, Judl et al. 2018). The perceived environmental benefits of refurbishing, and awareness of these, have a positive impact on consumers' intentions to purchase refurbished smartphones (Mugge et al. 2017).

In contrast to the new smartphone market, the refurbished phone market grew by 9.2% in 2019 to 206.5 million devices and is expected to reach a market value of €55 billion (or about 350 million devices) by 2024 (IDC 2021). As the total market for new devices in 2019 was 1.37 billion, the refurbished market already amounts to 15% of the new devices market. The market for refurbished smartphones has existed in developing countries since the 2000s and is also becoming more popular in developed countries due to a large number of fully functional and relatively new models becoming available on the second-hand market (Rizos et al. 2019). Consequently, several new European companies have emerged in the refurbished smartphones market (ibid.). The refurbished phone market will also be a significant employer in the future. Rizos et al. (2019) estimated that if the sales of refurbished phones were to rise from a baseline of 10% to 30%, the number of jobs would increase from 14 500 to 29 000 (20%) or 43 000 (30%).

Business models focusing on the leasing of smartphones can contribute to an effectively longer lifetime of higher-end smartphones bought by early adopters. Through leasing, these consumers get access to the latest device, which after a certain period (6 months, one year or two years) is resold to a second user. There are also models that go beyond traditional leasing. An example is Fairphone's phone-as-a-service model, where ownership of the product is retained by the smartphone company and the device or its modules can be leased to multiple subsequent customers (Bakker et al. 2014). This type of model can thus facilitate take-back and the reuse or recycling of materials and components, leading to improved resource efficiency (ibid.).

3.5.2 Smart TVs

Use and lifetime extension

Smart TVs are generally discarded when outdated or broken. A functioning device is usually kept in the household or given away or sold for second use. Estimates of the lifetime of a smart TV range from 5 to 10 years, which is down from 10–15 years with CRT TVs. In contrast to smartphones, the main environmental impact is linked to electricity consumption and is generated during the use phase (69–86% of GWP), whereas production accounts for 13–29% of GWP. However, research suggests that a longer lifetime of over 10 years could be beneficial from an environmental standpoint. (Berwald et al. 2020)

Even though the main environmental impacts occur during the use phase, long-lived TVs have lower environmental impacts in comparison to short-lived TVs, even though short-lived TVs are generally replaced with more energy efficient alternatives (Prakash et al. 2016). However, for PCBs (93% of manufacturing GWP) and other crucial components, the greatest environmental benefit is reached when designing them for reliability. From an environmental perspective, the lifetime of the TV should be longer if the replaced component has a major environmental impact (Berwald et al. 2020).

There are several identified challenges in repairing smart TVs. The popularity of thin displays and use of adhesives in fixing on the back cover makes it difficult to disassemble without specific tools. Additionally, smart TVs with OLED displays use complex and more integrated electronics in comparison to older models, which is a challenge in repairing them. The advantage of OLED is that it consumes less energy compared with LEDs or other earlier technologies (Berwald et al. 2020).

As smart TVs are connected devices running on an operating system, they are prone to software obsolescence in the same way as smartphones. Thanks to their modularity in the form of input ports (HDMI, USB), however, even a TV with outdated software can be used as a smart TV with the help of external set-top boxes. In this case, online content is not streamed by the TV itself, but by the set-top box device (e.g., Google Chromecast or Apple TV), or a smartphone or a computer connected to that device. Potential security threats caused by software not supported by the OEM manufacturer can be limited by disconnecting the smart TV from the Internet.

3.6 Recycling

While the manufacturing of ICT hardware is often responsible for most environmental impacts, the extraction and processing of virgin materials, especially for gold, silver, palladium and plastic, can make a significant contribution (Rizos et al. 2019). To manufacture a single smartphone, roughly 260 times more rock needs to be mined than the weight of the smartphone (ibid.). Using secondary raw materials may greatly reduce the environmental impacts of raw material use. Chapter 2 discussed at length the environmental and social impacts of the extraction and processing of virgin raw materials. This chapter focuses on the enablers of and barriers to recycling, recycling rates for raw materials, the recycling potential and recycling processes for smartphones and smart TVs.

Efficient recycling reduces the demand for primary raw materials and therefore reduces the environmental impacts of raw material production. It has been estimated that recycled metals have considerably (50–90%) smaller carbon footprints than virgin ones (Wernet et al. 2016, Rizos et al. 2019). As an example, cobalt mining uses between 140–2100 MJ energy per kilo of material, whereas the energy use from scrap is estimated as 20–140 MJ per kilo (Rizos et al. 2019). In the future, the footprint of primary raw materials is expected to increase as lower-grade ore deposits are used. In addition, recycling conserves the value of secondary materials, reduces the EU's material import dependency and reduces the negative social and environmental impacts linked to the production of certain metals. The EU is striving for increased recycling rates, more efficient recycling and increased use of secondary raw materials, for instance through the WEEE Directive (Judl et al. 2020). In addition, ICT manufacturers and brand owners are setting targets for recycling and the recycled content in their products. Apple, for instance, uses 99% recycled tungsten and 98% recycled REE in the newest iPhones, and seven products have total recycled content of at least 20% (Apple 2021).

3.6.1 Enablers and challenges to recycling

Carrier metals are a key concept for recycling electronic and electric devices. Carrier metals are relatively easily recyclable and they enable the recycling of minor metals. Current electronic devices are not typically designed from the perspective of recycling and metallurgy, which is a challenge for recycling technologies. Furthermore, if a device contains several metals, it is plausible that some of these will be lost in recycling processes. An example of a good carrier metal is lead, which has, however, been partially designed out of phones due to its negative environmental and health impacts. Carrier metals play a crucial role in the effectiveness of metal recycling, and there are therefore arguments for keeping lead in smartphones and emphasizing the risk management measures in handling lead during the recycling process (Judl et al. 2020).

The primary focus of design should be the reuse or remanufacture of devices and components instead of recycling them. Ecodesign is an approach for promoting these aspects and it is discussed at length in section 3.3. The benefits of ecodesign and material savings can be enhanced through value network co-operation. Recyclers could provide a critical input for material and modular product structure designs and recyclability aspects. Designers are generally not aware of the concept of carrier metals. Life-cycle management should be an integral part of the circular economy to reduce negative environmental as well as economic impacts. It supports the management of the entire life cycle and focuses actions on the parts with the greatest impact (Judl et al. 2020).

One strategy for design can be the substitution of the 'difficult-to-recycle' elements and materials. Substitution can be element for element, material for material, component for component, product for product, system for system, product for service, and so on. Substitution can be seen as one solution to the challenge of recycling certain materials by substituting them with easily recyclable alternatives. Substitution takes place by the means of material development, product design and with new business models. Substitution can be widely interpreted to cover the replacement of toxic or hazardous materials and conflict materials and the use of less material, i.e., creating a lighter weight product.

The composition of discarded smartphones and other ICT devices is heterogeneous, and valuable and critical materials are found in several components, e.g., pure metal components, PCBs, screens and different alloys. The weight and value of the material content in components are not usually correlated, as metals in small quantities typically account for the entire monetary value of recycled smartphones (Judl et al. 2020). Enhanced information on recycled volumes and the composition of WEEE could enable new businesses based on reusing or recycling WEEE.

For smartphones, the small size of recycled devices is also a drawback, as they contain less of the valuable raw materials. Recycling small and complex devices containing tens of different metals, plastics, glass and glues is a challenge. Different material compositions require different recycling process. The monetary raw material value of a single smartphone is around €1. Therefore, a huge and steady flow of devices should be available for recycling in order to make it feasible. This might be the case with wind turbines, when they become available for recycling. In addition, the volatility of raw material market prices is a challenge to the feasibility of recycling and willingness to invest in more efficient recycling infrastructure. (Judl et al. 2020)

Losses in the recycling process are inevitable. However, losses during the life cycle and recycling processes of ICT devices can be minimized with design and technological choices and policies. **Understanding which components, alloys or raw materials can be reused or recovered from the devices and what resources must be invested in the recycling process is crucial**. This should also guide consumers in their purchasing decisions and organizations in developing recycling and products. This could also support efforts to tackle a persistent problem in recycling e-waste: the lack of consumer awareness (Judl et al. 2020).

The sustainability of both smartphone and smart TV recycling is a major challenge. One key aspect is to minimise the e-waste stream that ends up in countries without appropriate e-waste recycling as a result of legal or illegal trade or other informal routes. Even though the yield from manual recycling is better in developing countries in comparison with automated recycling in developed countries, these waste streams lead to pollution and adverse health impacts (Judl et al. 2018). Therefore, it should be ensured that the countries where e-waste and refurbished smartphones are exported have the appropriate recycling infrastructure, collection systems in place and good working conditions and wages for the employees.

3.6.2 Recycling rates for ICT raw materials

Recycling 100% of all raw materials of electronic devices is currently not environmentally feasible (Reuter & van Schaik 2012). WEEE recycling rates (RR) are, in general, quite low in comparison to larger equipment, cars or the construction sector, but they are expected to rise in the future (Judl et al. 2020). European policy and the regulatory framework, e.g., the WEEE Directive of 2012, set targets for the collection of WEEE. However, the targets are mass-based and do not consider element or compound criticality or economic value (Gurita et al. 2018). This results in the unnecessary loss of critical and precious metals in recycling (ibid.). Of the REEs, only 1% are recycled and 35 metals have under 1% RR (Judl et al. 2020). Recycling of precious and critical metals could have larger environmental benefits (Bookhagen et al. 2020). In summary, new holistic approaches are needed to complement the current mass-based or purely economic-driven approaches that define which metals are important and how they need to be targeted (Bookhagen et al. 2020).

However, to better align smartphones and smart TVs with the circular economy targets and framework, the focus should be on reusing EEE rather than recycling WEEE. For instance, in Finland, 88% of WEEE materials are recycled, but only less than 1% are reused (Judl et al. 2020). The RR and recycling input rate (RIR) of key raw materials for EoL smartphones and smart TVs is presented in Tables 3 and 16. The EoL RIR measures the quantity of EoL scrap contained within the total amount of metal available to manufacturers.

Table 16. Recycling of key raw materials for end-of-life (EoL) smartphones and smart TVs, with their recycling rates (RR) and recycle input rates (RIR) in the EU (UNEP 2013, Eynard et al. 2020, Latunussa et al. 2020). See also Table 3.

Raw materials	RR%	RIR%	Comments
Aluminium	60 to >90	12	EoL scrap aluminium includes a wide range of products including aluminium beverage cans or food packaging, components from aircraft, cars or other vehicles, articles arising from the demolition of buildings such as window profiles, and discarded equipment. If the EU had processed domestically the flow of aluminium waste and scrap exported in 2015, the EoL RIR would have increased to 16%.
Arsenic	<1		There is no mentionable documented recycling of arsenic taking place.
Carbon		3	Currently, there is no scale for specific Li-ion battery recycling that would embark on dismantling the battery, instead of using graphite as a heat source in the pyrometallurgical process.
Cobalt		22	Hard metals, batteries and catalysts can be collected and recycled. Cobalt-bearing EoL scrap can be found in used jet engines, used cemented carbide cutting tools, spent rechargeable batteries, magnets that have been removed from industrial or consumer equipment and spent catalysts. Recycling of EoL products is an important source of cobalt for the EU.
Copper	37	17	Nearly all copper products can be recycled repeatedly without a loss of product properties. Secondary copper constitutes a significant input to the processing. As European-mined copper is not sufficient to meet the demand, the EU is highly dependent on refining and on smelting imported concentrates, as well as on recycling production scrap and EoL products. In the EU, the processing included 1959 kt of secondary copper in 2014.
Gold	20–29		While there are substantial stocks of gold in use comprising jewellery, central bank holdings, private investment and industrial fabrication, it is unlikely that much of this will ever re-enter the supply chain. In general, jewellery and religious artefacts are viewed either as sacred or as precious assets handed down from one generation to another. Central banks view gold as an important reserve asset and, in recent years, they have been more likely to buy than sell gold. In electronic devices, much of the gold is not recovered because they are not efficiently collected at the end of their lifetime. The majority of gold recycling, about 90%, is from high-value source materials such as jewellery, gold bars and coins, which contain a significant proportion of gold alloyed with one or more other metals. Gold derived from recycling industrial source materials, such as waste from electrical and electronic equipment, provided the other 10% of secondary supply, up from about 5% in 2004. In printed circuit boards and mobile phones, the gold concentration is estimated to be between 200 and 350 g/t. Apart from the challenge of efficient collection of these devices at the end of their life, it is technically very difficult to extract the gold and other precious metals (palladium and silver). Gold is also recycled from a wide variety of intermediate products and by-products from mining and metallurgical operations. These include, for example, anode slimes and flue dusts from copper and lead smelters, complex concentrates of lead, zinc, silver and gold, and by-products from gold mining, such as sludges and residues. The EoL RR estimate does not include recycling of jewellery and coins, because there is typically no EoL management for these products.
Indium	~70		New scrap used in the secondary production of indium mainly consists of spent ITO sputtering targets. It is estimated that over 70% of the indium from the starting targets is recovered. Precise data on the amount of secondary indium recovered from scrap are not available, although it is estimated to be similar to the quantity of primary production. NREL estimated that the production of refined indium from secondary supply reached 610 tons in 2013 (Latunussa et. al. 2020). Previously, the Indium Corporation estimated that approximatively 1500 tons of refined indium was produced in 2011, including 950 tons of recycled indium.

Table 16. Cont.

Raw materials	RR%	RIR%	Comments
Lead	80		Lead has one of the highest recycling rates of all materials in common use to date. More refined lead is produced by recycling than from mines. Global annual secondary lead production amounted to 6300 kt on average over the period 2012–2016, representing 57% of the total metal output. Secondary refined lead production in the EU increased by 3% over the period 2012–2016, with an average output of about 1146 kt per year, which was 80% of the EU total refined lead production. Most of the secondary lead comes from scrap lead-acid batteries, lead pipe, sheet, and cable sheathing. Scrap lead from the building trade is usually relatively clean and is re-melted without the need for smelting, although some refining operations may be necessary. Lead batteries are the only battery system that is almost completely recycled. In the EU, recycling efficiencies of lead-acid batteries for a vast majority of countries were above 75% in 2017; 99% of the automotive lead-based batteries that were collected were recycled during the period 2010–2012. More than 95% of the lead sheet used in the construction industry for roofing was collected and recycled. Pipe scraps, sludge, dross and dusts were also recycled. Even though the use of lead has been actively reduced due to it being detrimental to human health, it is still a key enabler in the CE, as it is capable of dissolving and carrying a multitude of technological elements. Molten lead has unique properties that means it can act as an efficient liquid carrier for critical raw materials such as In, Bi, Cd and Te. (Blanpain et al. 2019)
Lithium	0	0	The only waste flow with lithium recycling potential is spent Li batteries. Recycling of lithium-ion batteries, which is a complex and costly process hindered by the wide variety of chemistries and battery formats, has attracted much attention during the last years due to the constantly increasing significance of Li-ion batteries, especially in the rapidly growing electric vehicle sector. Nowadays, the recovery of lithium from batteries is technically feasible, but until 2017, industrial-scale recycling was not considered cost-effective in comparison with primary supplies. As a result, the main focus of Li-ion battery recycling plants has been the recovery of other metals with a higher economic value than lithium. Recycling of Li-ion batteries has the potential to create a continuous and secure secondary stream of lithium supply for the EU in the future, under conditions that will make it economically attractive, e.g., higher lithium prices.
Manganese	>50	9	
Magnesium		12–13	At the EU level, the magnesium recycling capacity is about 75 000 t/y (mostly for new scrap).
Nickel	45	34	Nickel can be recycled without loss of quality and sourced as a secondary raw material to be used in many of its applications; large tonnages of secondary or “scrap” nickel are currently used to supplement newly mined ores.
Silicon		0	Most chemical applications of silicon metal are dispersive, thus not allowing for any recovery. Silicon metal used in the electronics industry is of higher quality than for other applications. Most of the silicon scrap generated during crystal ingot and wafer production for electronic applications can therefore be used in the photovoltaic industry. There is no functional recycling of silicon metal in aluminium alloys. In the industry buying metallurgical-grade silicon, for economic and environmental reasons, recycling streams exist as well as separate or specialized processes for the utilization of any side streams. However, very little material is sold back to the market by metallurgical silicon users. Although there are new functional recycling plants for silicon metal, it has not been possible to quantify the precise updated end of life recycling input rate for silicon metal. The recycling input rate was estimated to remain low.

Table 16. Cont.

Raw materials	RR%	RIR%	Comments
Silver	30–50 (100% for electronics)	19	A significant proportion of silver is recycled during the manufacturing process. An estimated 5200 t of both old and process silver scrap was recycled in 2014, after this flow had been almost twice as high in 2010 and 2011. Jewellery, silverware and coins have very high recycling rates, typically greater than 90%, due to their ease of collection and recycling. High-grade jewellery scrap is usually re-alloyed on-site rather than being refined. Jewellery sweeps, the fine dust generated in the polishing and grinding of precious metals, are usually smelted to form an impure silver, which is electro-refined. Because of the much lower value of silver scrap, recycling techniques applicable to gold are uneconomical for silver. Low-grade silver scrap is instead returned to a smelter for processing. However, the EoL RR varies considerably according to the application: 0–5% for vehicles (electric and electronic parts), 10–15% for electronics, 40–60% for industrial applications and 40–60% for others. For applications where silver use is less dissipative, such as in electric and electronic parts in vehicles and electronics, losses occur in collection, shredding and metallurgical recovery operations. For electronics specifically, recovery rates at state-of-the-art metallurgical plants can be close to 100% of the silver contained, if the printed circuit boards are appropriately collected and pre-treated. In comparison to electronics, industrial applications such as photography and catalysts have a relatively low recycling rate.
Tantalum		<1	The recycling rates for tantalum vary depending on the type of material and stage in the supply chain. At the processor level, it is in the company's interest to achieve as high a yield as possible. Tantalum can be recovered from scrap, incineration bottom ash, superalloys, pyrometallurgical slag and tin slag. Tantalum is commonly extracted from scrap, slags or scraps through high temperature digestion in sulphuric acid, resulting in a highly purified tantalum and niobium. Recycling of used items containing tantalum occurs, but it is primarily 'preconsumer', that is, from within the upstream supply chain itself, rather than from end-users. Processor scrap and other secondary materials are also an important part of the tantalum supply. Scrap generated during manufacturing, for example of capacitors, is returned to processors. The main source of this recycled material is from the electronics industry (capacitors, sputtering targets, etc.). Estimates from various sources indicate that about 30% of new demand for tantalum in any year is met with such material, a figure that hardly varied for a few decades. In the EU, various recyclers and processors count tantalum in their activities. Some key actors in tantalum recovery operate in Germany, Estonia, France (from kaolin mining) and Spain.
Tin	40–60	~30	The EoL RR depends on the applications, with tinplate in food and beverages cans having the highest, followed by solders in electronics. The EoL RIR of tin, including refined and unrefined forms, was calculated as 30.7% in 2016, down from 31.4% in 2015, with re-refined tin contributing approximately 16%.
Rare Earth Elements		<1	Today, the EoL RIR is still very low, especially in Europe, because of the lack of efficient collecting systems and prohibitive costs of building REE recycling capacities. Higher RIR for europium, yttrium and terbium are reported only thanks to the recycling of fluorescent lamps. Recycling is often difficult because of the way that REE are incorporated as small components in complex items or are part of complex materials. The processes required are energy intensive and complex. Nevertheless, as for many metals, new scrap generated during the manufacture of alloys is an important secondary source, mainly in a closed loop (30% of magnet alloys end up in scrap during manufacture).
Phosphate rock	24–76	17	The EoL RIR should translate the % by which recycling of biogenic waste flows substitutes the use of mineral phosphate fertilizers (i.e., primary input material). Van Dijk et al. (2016) estimated recycling rates of 70% in crop production, 24% in animal production, 52% in food production and around 76% in non-food applications of phosphorous, in 2015. However, there are currently no useable data on the rate of effective reuse of phosphorus for manures and other organic forms, which replace the use of fertilizer or other phosphate rock-derived chemicals. Therefore, there is a need to generate appropriate data and define indicators for this recycling rate, in coherence with indicators for other policies.

3.6.3 Smartphones

The collection of discarded mobile phones from consumers is a persistent problem (Reck & Graedel 2012), for which, for example, different take-back systems need to be developed. Unused mobile phones typically sit in people's drawers, and the RR for mobile phones in Europe is only 12–15% (Rizos et al. 2019). Relatively small amounts of metal, as shown in section 3.1, add up to a relatively high quantity of raw materials with a large number of devices. Bookhagen et al. (2020) studied 53 metallic elements from smartphones with regard to metal prices, metal production and content in comparison to mined ores. Batteries were not included in this study. According to the study, the total raw materials value of a smartphone is €0.81. However, the market prices may change, as the prices of certain crucial raw materials, such as Au, are volatile. The Au content is low (16.83 mg per device), but still constitutes the highest value, with a current share of approximately 72% of the total value for all measured metals, followed by Pd (10%). Approximately 82% of the total metal value can be recycled with current standard recycling methods for Au, Cu, Pd and Pt, which only comprise 6 wt% of the total device.

To put the metal content of smartphones into context, there are up to 700 million hibernating mobile phones in EU households, which altogether contain 14 920 tonnes of gold, silver, copper, palladium, cobalt and lithium with a value of over €1 billion (Rizos et al. 2019). At the global level, the pure metal value of the 7.42 billion smartphones sold in the years 2012–2017 is €7.6 billion at November 2019 prices, with gold accounting for 72% of the value (Bookhagen et al. 2020). The value of the metal content is, therefore, a solid argument for recycling smartphones, even though not all of it can be feasibly recovered. Additionally, for Au, Pt, Pd and Cu, the metal content in smartphones is much higher than that in primary ores (Bookhagen et al. 2020).

Current recycling technology is focused on economic viability, not on recycling rare or critical metals. For some critical metals such as Ga, Ge or Ta, the relatively low raw materials content and monetary value in a single smartphone adds up to 20–25% of the annual global raw materials production of these metals when considering the total mobile phone production between 2012 and 2017. For these critical metals, recycling could contribute significantly to global production and lower price volatilities. (Bookhagen et al. 2020)

Fairphone has published the raw material content and its recyclability potential in their smartphones (Proske et al. 2020). The impact has been assessed for some of the most crucial elements and materials, including gold, copper, tin, tungsten, lithium, cobalt and neodymium.

Table 17. Impact of recycled content as input raw materials (Proske et al. 2020).

Element or material	Weight	Contributing components	Estimated benefit of SRM	Recycling process	Market for SRM
Gold	0.143 g	Battery, PCBs	Increase in GWP, decrease in other categories	Well established	Well established, 33% of production recycled
Copper	8.145 g	PCBs	Decrease in GWP	Well established	Well established, 37% of production recycled
Tin	2.45 g	Solder paste	Decrease in GWP	Well established	Well established, 31% of production recycled
Tungsten	0.013 g	Vibration motor	-	Well established	Well established, 35% of production recycled
Lithium	5.2 g	Battery	-	Recycling not yet cost-effective	No market for secondary lithium
Cobalt	11.24 g	Battery	-	Well established	Well established, 35% of production recycled
Neodymium	0.17 g	Vibration motor (magnet)	-	Recycling methods not at an industrial scale, recycling rate below 1%	Market is small and not well developed

To evaluate recycling decisions and their environmental impacts and to set recycling targets for specific metals, it is crucial to understand the recycling process as a whole. The appropriate recycling process is typically determined case-by-case. The more complex the product and large the material variety, the more resources are put into the recycling process and the more metals are lost during recycling (Judl et al. 2020). The ICT recycling process can be divided into sorting and collection, mechanical pre-treatment and separation, and metallurgical refinement.

Sorting and collection

At the end of their lifetime, the goal is that smartphones are collected for recycling or reuse. Municipalities and commercial actors are responsible for organizing the collection of ICT devices (Judl et al. 2020). However, sorting by consumers also has a considerable impact on the effectiveness of recycling and recovery. The best practices for smartphone collection include providing multiple easily accessible collection sites such as recycling parks, the device sale points or other bins placed in strategic locations (Rizos et al. 2019), avoiding additional transport requirements. However, there are limited incentives for consumers to return their smartphones for recycling, and e-waste collection rates remain low (ibid.). New practices are developing to encourage consumers to return discarded smartphones in line with the WEEE Directive. These include offering discounts for returning old devices when buying new ones and increasing awareness of the proper disposal of smartphones (Rizos et al. 2019).

In addition, extended producer responsibility (EPR) is mandatory for smartphone producers in many jurisdictions or countries. EPR schemes require producers to ensure the waste is recycled appropriately and does not end up in landfills. Parts of the waste stream end up in countries without appropriate e-waste recycling because of exports or informal routes. These waste streams lead to pollution and adverse health impacts on people working in the informal e-waste sector (Judl et al. 2018).

Mechanical pre-treatment and separation

The goal of pre-treatment and separation is to create good quality fractions for refinement. Several factors, including material viscosity, shape, the charge of particles and pH affect the efficiency of the separation process. Mechanical pre-treatment and separation start with removing the battery from the smartphone, which enables better recovery of raw materials. Batteries and the smartphone are sent to end-processing facilities for final recycling and recovery of materials. In recycling, the devices are generally shredded and grinded. The grinded materials, including the dust, are separated for further treatment using various technologies. There are processes in place for the recycling of smartphones, but according to Rizos et al. (2019) and Judl et al. (2020), several barriers limit the opportunities for further developing such approaches (see sections 3.5.3–3.5.5).

Metallurgical refinement to recover valuable raw materials

Refined fractions from mechanical pre-treatment and separation are inputs for metallurgic refinement. Pure metal fractions can be smelted and resold. Other fractions are sent to pyro-, hydro- or electrometallurgical treatment or to a combination of these (Judl et al. 2020). Current recycling practices aim at the recovery of gold, palladium, silver and tin from the smartphone and cobalt recovery from the battery. However, there is considerable potential in the removal of gallium-containing integrated circuits (ICs) and the recovery of gallium or reuse of ICs and recovery of REE from batteries. (Chancerel et al. 2015)

3.6.4 Smart TVs

TV screens and monitors accounted for a combined total of 6.7 Mt of e-waste globally in 2019 and have shown a decrease of 1% from the level in 2014. This is largely due to the replacement of heavy CRT screens with lighter flat panel displays in the e-waste. Therefore, the total mass of this e-waste is reducing, even though the number of devices continues to grow (Forti et al. 2020)

The collection and recycling process of smart TVs follows same general pathways as with smartphones. The recyclable material content is also similar to smartphones, although the larger size increases the quantities of specific raw materials. In LCDs, the main recyclable raw materials are indium tin oxide (ITO), base metals (aluminium), precious metals (copper, gold, silver, etc.), glass, copper in cables, metals in speakers and plastics (ABS, sheets) (Akcil et al. 2019). Panasonic (2019) claims to reach a 99% resource recycling rate for TVs, consisting of 10% thermal recycling and 89% material recycling. Material recycling refers to reuse as parts or raw materials of new products, whereas thermal recycling means using the heat generated when burning disposable parts as energy.

3.6.5 Enablers and challenges to smartphone recycling

Enablers of smartphone recycling

Lead is used in smartphone components such as circuit boards, batteries and PVC products. Lead as a carrier metal makes the recycling of other substances easier. However, it is a highly toxic element, which is why the use of lead should be carefully controlled.

The same principles concerning recycling of smart TV expressed in 3.6.1 apply for smartphones as well.

3.7 Interviews

Within the study, semi-structured interviews were carried out to assess different aspects of smart device sales processes, purchasing decisions, consumer awareness and requirements, as well as organizational procurement practices. The interviews increased the practical relevance of the study and helped to identify the most significant challenges and solutions related to raw materials of the chosen electronic devices. Stakeholders participating in either consumer or organizational sales were interviewed to gather insights into the drivers behind the purchasing decisions of Finnish customers, whether raw material or sustainability related issues are raised by the purchaser, the most significant challenges preventing circularity, reusability and lifetime extension, and what the general trends in the field are.

In total, 6 interviews were conducted, and the interviewees were chosen to represent the consumer and organizational customer sectors, as well as new and refurbished device sales. The interviewees mainly represented smartphone sales, and to a lesser degree also smart TV sales. The questionnaire covered issues related to the drivers behind the purchasing decisions (e.g., technical issues, sustainability and environmental considerations, used raw materials, recyclability, repairability), the typical length of life cycles, the main restrictions behind life cycle extension, future sectoral trends in terms of sustainability and the main challenges related to the more sustainable use of raw materials. In addition, those actors involved in organizational sales were asked questions related to procurement policies and possibilities for extending the life cycle of work phones. For a detailed list of the interview questions, see Appendix 1.

Factors impacting on the purchasing decision

By far the most important factors impacting on the purchasing decision for a smartphone or a smart TV are the performance, design and the brand, alongside the price. In particular, as for the smart phones, the technical requirements, such as fast Internet connection capabilities, an advanced camera setup, as well as the brand and operating system are typical factors that customers consider as important. Sustainability or raw material-related factors were seldom in the buyers' interests or mentioned as drivers behind the purchasing decision. Often, it was mentioned that social pressure exists to purchase a new, high-end model, or that the purchase entails a certain social status, especially with younger buyers. In terms of consumer customers, there were seen to be different customer categories; some customers were named as early-adopters, requiring new, high-performance devices at a fast pace, while other customers were less inclined to follow rapid renewal cycles. As for organizational customers, the renewal cycle is usually defined in organizational guidelines and is not a subject of personal preferences.

Even though sustainability issues are increasingly discussed by different societal actors (media, the general public, manufacturers), the interviews revealed that real actions by consumers were still inadequate, and in effect also actions by businesses. The sustainability of the phone manufacturer or raw material suppliers were notably seldom asked about by consumers, even though a marginal segment was more aware of and interested in, for example, conflict minerals, the carbon footprint or other sustainability issues. On the other hand, organizational customers appeared to have a more structured approach to covering supplier networks and related sustainability issues. However, increasing emphasis was given to the length of the device's life cycle and its repairability. Examples of these included inquiries regarding the expected length of the life cycle considering the 4G/5G transition, the continuity of operating system software support, the expected longevity of the battery and repairability. In general, there also appeared to be an increasing interest in purchasing used, yet refurbished phones, especially by consumers. In terms of organizational customers, used phones were not common, due to higher security requirements. In addition, organizational buyers procure greater numbers of phones at one time, and the availability of refurbished phones of the same type cannot be guaranteed by retailers.

Both consumer and organizational buyers have shown interest in take-back schemes, which have been established or are currently under development by several companies. These schemes often emphasize economic factors instead of sustainability issues, but they were still named as increasingly popular approaches and effectively increasing reusability and recycling. In addition, phone-as-a-service models have been increasing in popularity, especially in the organizational context, even though some retailers also provided this service to consumers.

During the purchasing situation, many buyers rely on the information provided by frontline sales personnel. Due to the primary interest in performance, brand and price, it is widely recognized that raw materials or sustainability issues in general have gained little or no interest from sales personnel. Some retailers indicated that general training materials about sustainability issues exist (less for raw material-related issues), but these still play a minor role. As for the future, some actors believe that retailers may also take a more active role in raising public awareness.

Factors impacting on the purchasing decision:

- Brand, performance, price
- Availability of software updates
- Life cycle longevity (battery, components, entire device)
- Repairability
- Take-back scheme with financial incentives
- Phone-as-a-service (organisational customers)

Challenges and suggestions related to life cycle extension

One of the key issues straining natural resource use is the short life cycles of the devices. Several important challenges were named as hindering the extension of smartphone life cycles. In general, the first life of a smartphone was estimated to be around 2–3 years. The second life was considered to be an additional 1–2 years, if it had one. The main reasons for not achieving longer life cycles mainly related to consumption habits, device design and policies.

A lack of awareness and poor care, as well as peer pressure, are associated with the increasing consumption volumes and short life cycles. For example, insufficient knowledge about the possibility to repair a broken or malfunctioning device or the length of a warranty are common reasons for replacing the device. Smartphones can often be repaired, even though the user may not consider this as an option. However, in some cases, the repair costs (labour and spare parts/components) may exceed the price of a new device, or for less common devices, suitable spare parts may not be available, both of which can be seen as additional motives to replace the device prematurely. As smartphones are a rapidly evolving product group and new features, designs and brands impact on the product category at a fast pace, the desire to have a new phone with new features may influence the consumer's eagerness to buy a new phone, even though the old one may still be fully functional and up to date. Nevertheless, since the visual appearance of smartphones is no longer changed as dramatically with each new model, the aesthetics were not seen to provoke the need for new devices as much as before. In the case of organizational customers, the common policy to replace a phone when broken or malfunctioning, instead of repairing it, may be difficult to overcome, even though the actual user may be willing to repair the phone.

Product design decisions not only define the aesthetics, but also durability, longevity, repairability and how well a product preserves its value. A repeatedly mentioned design issue concerned operating system software support, due to the manufacturers' discontinuation of software support after a certain period. Due to smartphones being connected devices, software is an essential part of the product. Once it is no longer supported, the device often reaches the end of its life due to reduced performance, limited functionality and potential vulnerability to online threats. This period can be short in many cases, which, in effect, prevents longer life cycles. However, even for smartphones with longer than average software support, this is not particularly long (3–6 years). How software updateability impacts on the life cycle length of devices with longer life cycles (such as household devices), as they are being upgraded with connectivity and other smart applications, needs to be studied further. The lack of software support was also seen as a regulatory issue, since there is no proper policy in place banning unsustainable practices.

The interviewees were able to suggest improvements to overcome these challenges and to extend the life cycles of smartphones. In general, all respondents agreed that raising of awareness about different factors impacting on the sustainability and raw material issues would have a positive impact on consumer habits, general transparency, value chain sustainability and shared responsibility between the different actors. Consumers need, and should be given, more information about the repairability, warranties, proper care and sustainability information. Even though frontline sales personnel were seen as often having a general interest in the topic and having available materials related to sustainability issues, a more structured approach to training might be considered. Also, in sales situations, it may be considered whether the devices sold can be used for a longer period of time, also considering future requirements, such as RAM use, software updatability and future-proof connectivity, rather than only responding to current needs. In addition, on a higher level, some respondents mentioned the urge to get robust policies in place that support full life cycle considerations, the right to repair and the responsibility of manufacturers to offer spare parts and software support for the devices.

Life cycle extension bottlenecks:
- Lack of awareness of repairability and warranty
- Repair costs too high; lack of spare parts
- Lack of software updates
- Insufficient legislation
- Bored of old design
- Automatic replacement policy instead of repair (organisational customers)

Suggestions to extend life cycles:
- Awareness raising
- Also considering future needs in sales/purchases
- Policy development (e.g., right to repair, repair labour taxation)
- More extensive use of insurance and guarantee period

Future trends

The interview respondents had been able to closely follow the development of the industry and on a practical level. Even though people may still lack interest in sustainability matters and the concrete actions taken to include these in purchasing decisions, the general consensus is that issues relating to the raw materials of smartphones, as well as to sustainability issues of the entire value chain, are increasing in importance. Both the appreciation of the products and awareness of what their impacts are and where the raw materials are sourced from has increased in recent years and was seen by the respondents as likely to gain even more importance in the future (within 5 years). Increasing data usage, remote connections and the energy efficiency of 5G networks are also important topics from a sustainability perspective, and these also indirectly impact on the sales of new devices. Carbon footprint calculations and ecolabeling were raised as future trends to be considered by all value chain actors. As for raw material-related issues, some of the respondents mentioned that the use of natural resources, related environmental and social issues, as well as the recycling of these materials will be focus areas in the future. In addition, the so-called inner loops of the circular economy, such as refurbishment, servitization and upgradability, will be supported and demanded by customers. Nevertheless, a disconnection between the mining of raw materials and the use of phones is clearly visible; the complex global value chains may reduce the interest of smartphone users in clearly unsustainable practices at mine sites, as they are not directly traceable to the product or visible to the consumers.

Future trends:

- Awareness of sustainability and raw materials issues is increasing
- Data usage is increasing
- Ecolabels, the carbon footprint, CE and the use of natural resources are becoming more important
- More focus on recycling, refurbishment and upgradeability

Overall sustainability challenges

The interviewees raised several issues as the most critical challenges related to the raw materials use of smartphones, such as consumer behaviour and general consumer awareness. According to the respondents, consumer habits still indicate that consumers are not systematically willing to invest in more sustainable products, even though general interest in sustainability has increased. Regarding the consumption of electronics, a certain level of cognitive dissonance exists, which means that even though users might be aware of the acute sustainability pressures, this is not put into practice in the purchasing decisions. This may also be based on the lack of scientific studies demonstrating the broader issue of sustainability challenges related to electronic devices, i.e., what the various environmental impacts of the value chain are, which life cycle phases impact the most, how the social impacts can be measured, what is the transparency and validity of the sustainability claims of individual manufacturers, and so on. Since the price of mainstream devices is relatively low, frequent purchases are easy and affordable, at times even cheaper than repairing the old one. Devices with a presumably longer lifespan due to design are, on the other hand, increasingly more expensive. In addition, the collection rate and recycling of obsolete devices was seen to be poor. This lack of recycling (in addition to the increasing sales volumes) increases the raw material requirements globally. This was mentioned to relate to consumer behaviour and awareness, but was also seen to require more financial incentives, such as sharing the residual value of the metals between the user and the recycler. In absolute terms, however, this would be a marginal price, since the recycled raw materials from one individual smartphone do not have a significant value.

The problems related to the sourcing of primary materials and the responsibility of mining companies, especially regarding severe human rights issues, conflict minerals and environmental disasters, were named as critical challenges for entire value chains. However, it was discussed that even though the media raises these issues periodically, they remain vague and distant from an individual user’s decision-making factors. The amount of information available to a buyer weighing the purchase of one phone over the other, especially regarding either of them having a better primary material sourcing process, is very limited. A new smartphone labelling scheme has been developed by European actors, which is a voluntary initiative scoring the environmental performance of mobile phones based on an assessment of life cycle and circular economy indicators (durability, repairability, recyclability, climate efficiency and resource efficiency).

Additionally, increasing data usage and the related environmental impacts were mentioned as important sustainability issues, even though not necessarily related to the raw materials use of the devices. The transition from 4G to 5G networks was mentioned by network operators as a means of achieving lower overall environmental impacts of the use phase due to the greater energy efficiency of 5G networks. However, the absolute energy efficiency gains remain uncertain; if mobile data consumption is not drastically increased, then the overall impacts of networks may decrease, but if data consumption continues to increase as in the recent past, it may outweigh the benefits.

Overall sustainability challenges related to thelife cycles of smartphones

– Environmental and social impacts related to raw material sourcing
– Consumption habits, cognitive dissonance
– Low prices of mainstream devices, high prices of high-end devices
– Recycling/collection problems, lack of design-for-recycling
– Increasing data usage and related environmental impacts
– Lower energy efficiency of legacy networks

4 CHALLENGES AND RECOMMENDATIONS

A general presumption is that digital technologies support the empowerment of individuals and communities, well-being and ecologically sound economic and societal systems that match the planetary carrying capacity (Kiiski Kataja 2016). However, this raises the question of how to utilise the opportunities provided by digitalisation in an environmentally, socially and economically sustainable way. Within this study, the focus has been on examining the impacts of the mineral raw materials required by digitalisation from a broader perspective at a system level, i.e., how to increase the value they provide to society during their life cycle and how to reduce related negative environmental and social impacts. Several sustainability challenges related to digitalization and its raw materials exist. Building on the case studies (smartphones, smart TVs), but also extending to other digital devices, where appropriate, the challenges are presented below, along with recommendations to overcome these challenges.

The recommendations are mainly targeted at policymakers but ultimately require changes to be made by various other stakeholders as well, such as private sector companies from the raw materials, manufacturing or recycling industries, the financing sector and consumers.

4.1 Valuable raw material content in electronic equipment

The range and volume of elements used in ICT devices is continually increasing, and at a faster pace than before. The wide variety of metals, often critical specialty metals, enables the desired electronic, magnetic, optical or mechanical properties of electronic components. At the same time, the rapidly evolving technical development and increased consumption of products containing electronic components is driving the demand for a larger variety of specialty metals. When coupled with the shortening life cycles of devices, insufficient and inefficient recycling, the demand for mining primary metals is mounting. From a consumer perspective, returning devices to a collection point is a good start, but does not ensure that all valuable contents may be recovered. Even with a well-functioning recycling system, the recycled materials will not be able to satisfy the material demand for electronics. A further problem arises from the operational timescales of mines (average 30–50 years), which are far shorter than the geological processes that form mineral deposits (thousands to millions of years). This seems to make metal mining inherently unsustainable on human timescales, since economically extractable mineral deposits will become exhausted before replenishment by natural processes (Jowitt et al. 2020). Nevertheless, metals are a material that maintains its physical properties practically forever, which means that if the life cycle is well designed and properly managed, there could be a potential for interminably long uses of the material.

The challenges related to the mining and processing of these valuable metals include their environmental and social impacts. These are also in some cases associated with poor working conditions, human rights violations, health and safety issues and corruption, especially in developing countries. In addition, the acceptance of mining and mineral exploration by local communities or by society, i.e., the SLO, can be lost and eventually also lead to the loss of a project's legal permits. These impacts are greater in countries with weak or non-existent environmental protection legislation and law enforcement. Nevertheless, as ore deposits can only be found in such places where special geological processes have had suitable conditions for their generation, the technological and societal maturity in these areas, as well as the existence of sustainable mining frameworks, is not a given. Specific raw materials-related topics, such as conflict minerals and the lack of transparency, have been named as severe sustainability challenges in the sector.

Recommendations:

- Design (materials and products)
  - Valuing sustainability and circularity as a product design, component design and materials design requirement.
  - Introducing a systems approach to design to consider the value of raw materials throughout the product life cycle.
  - Introducing design factors that consider a longer life cycle and enhance the repairability and recycling of devices
  - Maximizing the share of recycled materials in ICT devices.
  - Increasing the substitution of composite materials and other difficult-to-recycle materials with easy-to-recycle materials.
  - Increasing the substitution of materials containing critical raw materials with abundantly available elements and renewables.
  - Phasing out substances that are harmful to humans or the environment. However, with regard to carrier metals (see section 3.6.1), the trade-offs between using the harmful substances and the benefits they create in terms of recycling efficiency need to be weighed, in addition to the rigorous management of harmful substances.
  - Designing digital traceability and product lifecycle management solutions to support the circularity and sustainability of digital devices.
- Supply chain
  - Developing comprehensive regulation for manufacturers for sourcing CRMs, conflict minerals such as cobalt and lithium, as well as establishing a compliance monitoring system.
  - Introducing incentives for industry to go beyond compliance.
  - Reinforcing voluntary responsible sourcing of raw materials, e.g., by introducing sourcing guidelines and active involvement in industry initiatives that have a measurable impact.
- Awareness raising
  - Increasing transparency and the traceability of the materials used in ICT devices, digitalisation and the supporting infrastructure, their sources, as well as the use of secondary materials. This can be achieved by material passports (e.g., the Battery Passport) or digital product passports containing product-related information about the raw materials and can also be utilised for easier recycling.
- Infrastructure and capacity development
  - Improving the responsibility of primary production by developing and applying best practices and regulation for the mitigation of environmental and social impacts.
  - Building up capacity for recycling discarded devices and processing old tailings. Establishing a well-functioning secondary material market.
  - Introducing recycling facilities that focus not only on recycling materials on the elemental level, but also on recycling material compounds.
  - Improving collection logistics, e.g., through company take-back programmes.
- Financial incentives
  - Increasing public investment support for building up the recycling capacity and clean, resource-efficient primary production.
  - Developing financial incentives by the public sector for the use of secondary raw materials in products and processes. Since the processing of metals from secondary resources (in comparison to primary ones) is in general more resource efficient, this should also be reflected in the price of these metals.

4.2 Supply security

The security of supply closely relates to the availability of raw materials but is raised here as a separate topic. Currently, two main factors can be considered as the most significant challenges regarding the raw materials and manufacturing of ICT devices in the EU: 1) most of the mineral raw materials needed for electronics are imported from Asia and Africa, and 2) the devices and their components are mostly manufactured in Asia. This causes a critical double dependency on raw material and device imports to the EU (Bobba et al. 2020). As digitalization is a strategic issue, this dependency is a major challenge for the EU's supply security. The realization of a climate-neutral digital economy, and a stronger Europe, depends on available, affordable and responsibly sourced raw materials. In the case of securing imports, sound trade politics, i.e., in this case resource diplomacy, is one of the key issues in maintaining the raw material inflow without shortages (Bobba et al. 2020). However, this may be challenging to keep up in a world experiencing rapid and constant change in which nations and regions are competing for resources and power.

Many factors influence the supply of raw materials. For example, the high demand will raise prices, in turn making exploration, mining and refining projects, as well as substitution and recycling commercially more attractive and viable. Nevertheless, the current low price for some materials makes investment in future capacity less feasible, considering that these investments require a high capital investment over a long period. This may also affect the recycling of metals, which may be uneconomical for some commodities. The technical possibilities for upscaling extraction and refining capacities also play a role, as does the legal framework for mining activities. All factors combined determine supply 'flexibility' for the future.

Along with globalization, the manufacturing industry has moved on a large scale to developing countries and emerging markets, especially to China. This is well illustrated, especially regarding components such as microchips. This is due to several reasons, often related to financial productivity gains, such as tax avoidance and evasion, as well as minimal environmental regulation, low labour costs and poor employees' rights in the target countries. This has caused a dependency on imports from such countries. To overcome these challenges, policy initiatives have recently been proposed (e.g., Digital Europe 2019), which include the development of a domestic ICT manufacturing industry through incentives and regulation.

The incentive for local availability and production of raw materials has also been a focus of several EU policies for a decade. However, the acceptance of mining activities by local communities and society in the EU is one of the main challenges for the activity, as it may be opposed (e.g., Badera 2014, Kivinen et al. 2020). This makes the needed expansion of mining a challenging issue in the EU. This has been well illustrated regarding the recently activated exploration for battery minerals, for example in Finland, which has faced resistance (Eerola 2021a). Therefore, there is an urgent need for responsible mining following sustainable environmental and social practices by minimizing impacts in order to gain acceptance from local communities, stakeholders and society in general. This may be possible through the application of CSR and best practices by the industry, together with incentives and forcing of legislation by the states and the EU. At the same time, recycling should be developed in the EU and its member countries to be more efficient and to reduce the need for primary raw material production and imports.

Recommendations

- Design (materials and products)
  - Valuing raw material availability, circularity and sustainability as a design requirement.
  - Introducing a systems approach to design to consider the availability of raw materials and risks throughout the product life cycle.
  - Increasing the substitution of materials containing critical raw materials with non-critical raw materials
  - Requiring trade-offs between technical performance and raw material use (particularly the use of specialty metals) to be made transparent and integrated into the product development process. This enables a critical view of the desired performance factors in relation to the raw materials they require.
  - Increasing the use of secondary raw materials and recycled materials in digital products.
  - Requiring design-for-recycling approaches to be used for materials that cannot be sub-

stituted. This, in turn, will improve supply security by strengthening the use of European secondary resources.
  - Designing digital solutions to support traceability to close the raw material loops for second and further cycles.
- Supply chain
  - Enforcing more sustainable sourcing of REEs and other minor elements, obtained as subproducts from current mines or by reactivating already closed mines and old tailings of suitable deposits.
- Awareness raising
  - Raising awareness about the general security of supply, especially in the context of EU-level digitalization efforts and the EU data strategy. This will enable transparency regarding the fact that if a strong dependence on digitalization is built, it will also require resources and raw materials. Reports, such as the present one, aim to fill this requirement, but more diverse materials are required and should be targeted at various stakeholders.
- Infrastructure/capacity development
  - Improving the recycling of ICT devices, e.g., by improving collection and increasing the recycling efficiency and capacity within the EU, to keep the mineral raw materials obtained from recycling in use.
  - In order to gain acceptance of mineral exploration and mining in the EU, the mining industry needs to improve its activities in a sustainable manner.

4.3 Life cycle length

Most ICT devices are currently not designed to be easily repairable, to have long life cycles or to be produced from easily recyclable material combinations. For example, the life spans of smartphones reported in literature were approximately 4.5–5 years in 2005 (Bakker et al. 2014), but currently, modern smartphone life spans are less than half of this, being around 21 months (Lu 2017). Even though this may seem like a long time in the context of rapid technological development, it could be longer, given the technical capabilities of the devices themselves, as well as their components and materials. The short life cycles of ICT devices put immense pressure on the raw material requirements of the manufacturing industry, as increasing amounts of critical and rare elements are needed to fulfil the demand. Furthermore, many ICT devices are not designed to be easily repairable. The lack of availability of original replacement components and awareness of consumers about when smartphones can be repaired, as well as high labour costs, hinders the extension of the life cycle of many smartphones.

Software support is a design factor heavily impacting on the length of a device's life cycle, especially concerning the IoT and smart devices in the future. The length of software support depends on the willingness of the manufacturer to provide it, as well as on hardware design that facilitates upgrades. The lack of software support during the lifetime of a smartphone might result in it becoming obsolete while its components are still fully functioning (Watson et al. 2017). According to the interviews, consumers increasingly view the concept of refurbished smartphones in a positive light. The perceived environmental benefits and awareness of refurbishing have a positive impact on consumers' intention to purchase refurbished smartphones. Nevertheless, consumers are becoming increasingly aware of the limitations to software updates for older phones, which impacts on their willingness to buy older, but otherwise functioning, devices.

The European Commission's Circular Economy Action Plan is set to bring several improvements to the circular design of electronics and ICT, including ecodesign, the 'right to repair', the introduction of a common charger, an EU-wide take-back scheme to return or sell back old mobile phones, tablets and chargers, and restrictions on the use of hazardous substances in electrical and electronic equipment. Even though these developments are already required by the EU, there is still some way to go before implementing them within the EU, as well as transferring these best practices outside of the EU.

Recommendations

- Design (materials and products)
  - Extending the lifespan through design improvements, i.e., ecodesign. Design choices improve the durability, repairability, remanufacturing and upgradeability of devices, and the recyclability/remanufacturing of components, compounds and elements.

  - Providing software updates for as long as the physical device works. Alternatively, make it possible to install a third-party operating system after official software support is no longer provided.
- Awareness raising
  - Increasing consumer awareness of the 2-year legal guarantee period, which is a protection against faulty goods, or goods that do not look or work as advertised. The 2-year legal guarantee period applies to all goods sold in the EU. As it is not a phone-specific guarantee, but applies to all products sold in the EU, general awareness raising is needed.
  - Impacting on the consumer's interest in buying new devices, especially in situations when the old device can still be used. The often unwarranted need to buy a new device may be caused by excessive marketing, peer pressure or other motivations, in which case a "nudge" by presenting the sustainability impacts of unnecessary consumption may be required.
- Infrastructure development
  - Enabling the establishment of independent repair points.
  - Ensuring a supporting regulatory environment for repair and software upgrades, securing consumers' rights to buy spare parts, use diagnostic tools and access repair manuals to make the universal right to repair a reality.
  - Minimizing the hibernation of devices by allowing second life cycles, increasing the number of collection points and supporting or generating second-hand platforms.
- Public procurement
  - Including repairability, the preference for refurbished ICT devices and service/leasing contracts as key criteria for contracts. Initiatives such as the Circular and Fair ICT Pact can be used to support the change.
- Financial incentives
  - Issuing tax rebates for repair labour and spare parts to encourage repair activities.
  - Supporting phone and other ICT device companies offering leasing or product-as-a-service models that ensure product life extension with a legitimate second-hand market and a plan for the end of life of used smartphones.
- Regulation
  - Requiring and demanding a compulsory declaration of the product lifetime, that links legal warranty to the expected lifetime and ensure spare parts availability will also contribute to elife cycle extension. However, due to the global nature of value chains, and the manufacturer mainly being located in China or the US, these requirements need to cover a larger geographic scope than current legislation allows.

4.4 Purchasing and use

Current consumption or purchasing patterns have led to rapidly increasing volumes of different electronic devices in households. An average European household contains 72 electronic devices, of which 11 are broken or not in use. The fact that consumers do not bring broken devices to recycling or allow unused devices to be reused by another user is one of the key challenges that need to be addressed. Moreover, the typical life cycles of smartphones, for example, are 2–3 years, which puts an additional strain on the raw material requirements of the sector, as devices, including all included materials, are discarded or hibernated within 1–3 years. From a raw materials perspective, the idea of discarding a material that has formed millions or billions of years ago, and which may be exhausted during a few years of use, is clearly disproportionate. Consumers, public procurers and buyers at smartphone retailers and network companies have a significant role to play in determining what kind of functionality is expected from smartphones and how they are designed and produced, as this increases the need for diverse metals. Consumers increasingly say they expect their smartphones to be sustainably produced and easy to dismantle, repair and recycle. The same also applies to other electronic devices. However, based on the interviews, these expectations are still seldom put into practice or seen to affect the purchasing decision. However, the buyers, be they consumers, public or other procurers, lack awareness about reliable sustainability standards and what criteria can be used to inform sustainable purchasing decisions.

Another issue is low consumer awareness of minimum guarantee periods, which can be an obstacle to longer product lifetimes. The EU Consumer Sales Directive defines a two-year legal warranty on products sold within the EU. However, consumers do not often know their rights and in some cases are misled by retailers about the warranty length.

In terms of the use phase of the devices, the main drivers of the ICT sector footprint include energy consumption and its greenhouse gas emissions, which can be assumed to increase even further in the future, due to increasing data transfer, remote access and other factors. From the perspective of natural resource consumption, extending the life cycle will have a considerable impact on the sufficiency of raw materials, as already mentioned in section 5.2. However, it is not only the design of a device that impacts the life cycle's length; it is often also the consumer's behaviour. For example, a lack of awareness and poor care, as well as peer pressure, were associated with short life cycles in the interviews. Insufficient knowledge about the possibility to repair a broken or malfunctioning device or the length of a warranty are common reasons for replacing the device prematurely.

Recommendations

- Design (materials and products)
  - Valuing the efficient use of materials and products in product life cycle design. Designing products so that they are easy to share to support their availability.
  - Targeting stable product performance through use phase with life cycle management design and design for maintenance.
- Awareness raising
  - Informing consumers and organisational buyers about the sustainability impacts of ICT devices by manufacturers and the public sector. The information needs to be on a standardised basis, to enable comparisons between different devices.
  - Raising awareness (mainly by certification bodies) about the environmental labels and sustainability standards available to guide purchasing decisions.
  - Increasing consumers' capabilities to consider alternatives between different device options or alternatives for buying and owning a device, such as buying a second-hand device or leasing.
  - Informing users about the sustainability impacts of more responsible use of devices, e.g., repairability, warranties, proper care and screen protectors.
- Manufacturer requirements
  - The awareness of consumers needs to be raised by the manufacturers in order that purchasing decisions will be made on a more sustainable basis, which is on the manufacturers' responsibility. Manufacturers need to be required to increase the transparency of supply chains, provide validated information about various sustainability impacts to their customers and, if required, also disclose the data and methods used for assessing the sustainability impacts of their products.
  - Producing and communicating information about how the life cycle of the devices can be extended by the users.
  - The general business model of increasing numbers of used devices may be switched, for example, to a service-based model of offering devices on a leasing basis. The model should emphasize an earnings logic, that the longer the user is satisfied with the device, the more profit is gained.
- Public procurement
  - Introducing procurement guidelines considering various sustainability impacts, including the transparency of raw materials sourcing, repairability and recyclability
- Financial incentives
  - Creating more effective financial incentives by the public sector for consumers to guide decision making towards longer life cycles, more sustainable products and recycling. These may involve a deposit system, but also incentivizing repair activities.

4.5 Electronic waste and recycling

The rapidly growing WEEE stream is a problem. At the end of their lifespan, ICT devices should be collected and reused or recycled. However, as much as 82.6% of all e-waste is not properly documented, collected or recycled (Forti et al. 2020). In general, the problem concerns several areas: the willingness to return old devices, building up a well-functioning collection infrastructure, as well as improving or expanding resource-efficient sorting and recycling capacities globally. In addition, for many metals included in ICT devices, the technical limitations to metallurgical processes may impact on the recovery rates of specialty metals available in small quantities, and secondary materials are not easily recoverable due to the miniaturization of devices. Often, the specialty metals available in very small quantities are lost in recycling process to side streams or dusts. In fact, recycling 100% of all raw materials of electronic devices is currently not environmentally feasible (Reuter & van Schaik 2012). Therefore, the aim should be to first increase repairability and reusability, secondly improve remanufacturing (reuse of components), thirdly increase the recycling of compounds and only fourthly the recycling of the materials on an elementary basis.

WEEE contains over 1000 different chemicals, many of which are hazardous, which means that the globally unaccounted flows of e-waste, still ending up in landfills in some parts of the world, pollute the environment with different emissions and hazardous substances. The current recycling technology is focused on economic viability, not on recycling rare or critical metals, and this can lead to an unbalanced availability of secondary critical materials.

Recommendations

- Design (materials and products)
  - Implementing design-for-recycling principles in the design phases. This requires in-depth metallurgical knowledge in order to enable the use of optimal material combinations and other design choices improving the metallurgical performance of the recycling process.
  - Prioritizing material compounds that can be recycled as such, rather than requiring full liberation on an elemental level. The hierarchy in design for recycling may follow the general guideline: 1) increased repairability and reusability, 2) improved remanufacturing (reuse of components), 3) recycling of compounds, 4) recycling of the materials on an elementary basis.
  - Enforcing material detection systems, such as material passports or digital product passports containing product-related information about the raw materials. This will improve the recycling process and ensure maximal yields.
  - Introducing a systems approach to design for recycling in order to find the most suitable recycling options for digital devices.
- Awareness raising
  - Ensuring transparency about the final destinations of WEEE.
  - Increasing awareness to increase consumers' willingness to bring their old, unused devices to general collection points. At best, the collection logistics should be optimized in general and should not rely on separate devices being returned individually to stores.
- Development of recycling capacity
  - Fostering the development of WEEE collection and recycling infrastructure by enabling optimized collection logistics and ensuring sufficiently large capacities to provide efficiency gains from large-scale processing. Alternatively, emerging small-scale, increasingly selective technologies need to be enhanced.
  - Improving the local collection points to ensure easy, clear and least emissions collection logistics.
  - Allowing refurbishers outside of WEEE schemes to participate in the second-hand market through certification standards.
  - Participating in global e-waste clean-up by material offsetting (discarded phones are collected from countries without appropriate recycling infrastructure to be appropriately recycled) when putting new devices on the market.
  - Harmonizing EU-directives and national legislation and regulations related to increasing recycling rates. There are still regulations that actively prevent the development of an optimal recycling system for WEEE.
- Manufacturer requirements
  - Establishing take-back schemes that allow the recovery of valuable materials to be reused in new products.

5 CONCLUSIONS

5.1 Need for improved system design, sustainable consumption and production processes, and circular material flows

The lack of proportion between the time required for the formation of the needed natural resources and the time they provide value for society is substantial. The discovery and extraction of metals demands time, work, investments and causes environmental and societal impacts. Nevertheless, these natural resources possess the required properties to enable digitalization, a link that is not always transparent for various societal actors. Furthermore, the ongoing trend with regard to digitalization is not encouraging; the life cycles of the products in which these valuable metals are used are shortening and the volumes are growing. In addition, the required variety of metals is increasing; there is a need for different specialty metals to provide society with new technologies and new functionalities. In addition to putting a strain on primary production, the complexity of these products, as they typically consist of 50–80 different elements, also complicates their recycling (Fig. 16). The need for metals of ICT will compete with the metal use required by the transition to green energy, or other potential applications, and in this case, it remains a question either for the market and price changes or policymakers to decide in which use metals will provide more value for society.

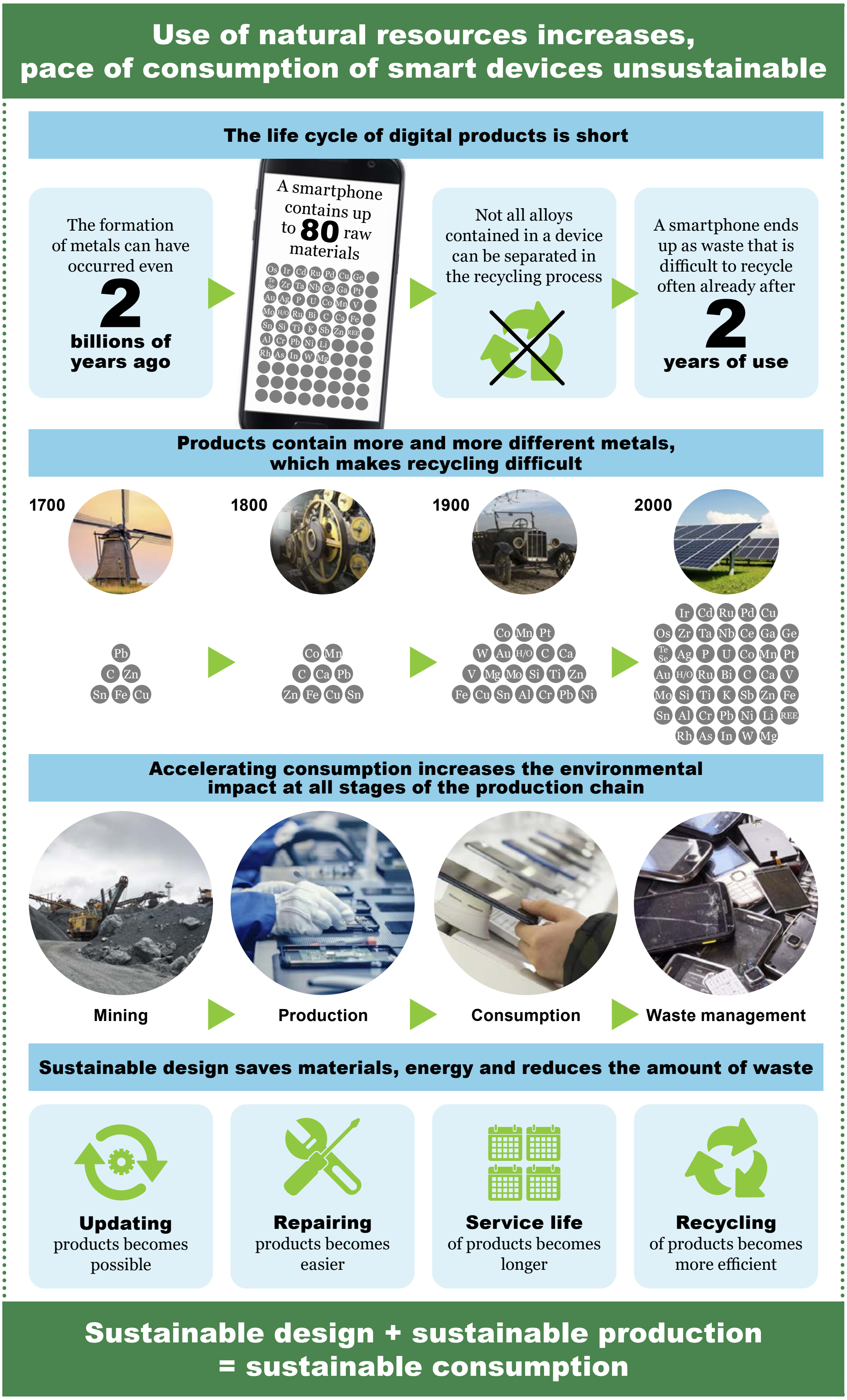
Many of the specialty raw materials are only needed in tiny amounts in ICT devices, and in absolute terms, their current demand is estimated to be only 0.5% of the total raw materials need. Thus, even if ICT competes with other sectors for the same raw materials and their demand increases, their shortage for ICT is not expected. An issue adding complication and underlining the mutual dependence between sectors is that the more digitalization advances and expands, the more energy is needed, which on the other hand increases the need for even more raw materials for green energy production. It is expected that the demand for raw materials for renewable energy and e-mobility production cannot be satisfied, which may compromise the green energy transition if other solutions are not proposed (IEA 2021). Most of the ICT elements are abundantly available, but outside of the EU, which means that the EU is strongly dependent on their imports, thus posing a challenge to supply security.

In summary, the main challenges regarding ICT raw materials are:

1. Increasing consumption, for example due to marketing, increasing wealth and product development
2. An increasing need for raw materials
3. The use of critical and conflict minerals
4. Competition with other industrial sectors (e-mobility, renewable energy)
5. The short lifespan of ICT products
6. Limited repairability and updatability of ICT products
7. The disproportional time span between the formation, exploration, discovery, production and use of raw materials in ICT
8. The increasing complexity of ICT products: the required variety of raw materials is expanding, and more complex mixtures of raw materials are being used
9. Due to the complexity of ICT products, their recycling is challenging
10. Import dependency, supply security, criticality and conflict minerals (devices, components and raw materials)

These challenges illustrate the need for circular solutions designed to improve the sustainability of the entire system. To approach these problems concerning ICT devices, there is need to **improve the system design and the policy-related framework** related to these products. In addition, there is a need to substantially **improve the current production and manufacturing processes and consumption behaviours**. This area is wide, as it covers the manufacturer's responsibility to impact on design decisions to improve reusability and recyclability, and abolish unsustainable practices aimed at increasing consumption.

Although a shift in attitudes, policies and actions towards more sustainable and responsible practices is ongoing, one of the drivers for continuous economic growth comes from consumption, which is



Source: SYKE, GTK. 2021. © SYKE. Photos: Adobe Stock.

Fig. 16. Examples of the challenges related to the circularity and sustainability of electric devices.

constantly stimulated by both business and governments. Hence, **consumers** have a possibility to play a crucial role in curbing the sustainability impacts of ICT devices through the adoption of sustainable consumption/trade/procurement patterns. These are based on favouring longer life cycles, repair, purchases of refurbished devices and the reduction of overall consumption. In order to achieve this, consumers need further and more transparent information about the products they are about to purchase and use. However, even when well informed about the negative impacts of manufacturing and use of ICT devices, consumers will face cognitive dissonance due to pervasive marketing and other drivers.

Manufacturers' actions are required to improve the sustainability of the entire system. It needs to be supported by more sustainable material development and product design, since 80% of the life cycle impacts are determined in the design phase. Through design, it is possible to influence the need for increasing volumes and numbers of raw materials, extend the life cycles and close material loops. This can be achieved by phasing out composite materials, alloys and hazardous substances to improve recyclability. Re-thinking materials, joints and components for increased repairability, as well as considering the use of recycled materials is important. Manufacturers may also develop and maintain digital passports to follow products through their life cycle and to provide required information to various stakeholders, such as consumers, recyclers and investors. These passports could support and strengthen the pre-material recycling options and design-for-X approaches, which utilize opportunities to reuse or repair devices or components before materials recycling. The substitution of CRMs and compounds can be seen as a design solution to reduce their demand and decrease the supply risk of raw materials.

All these changes, however, need to be supported by **policies**, i.e., effective incentives and regulation. An effective policy framework may ultimately require a more holistic system-level design, which considers potential trade-offs, rebound effects and cross-sectoral impacts between different sectors in order to support more sustainable decision making. When considering the overall consumption of raw materials by society and the impact it causes, a major system change is needed involving all the relevant actors.

The potential solutions related to the resource use of ICT devices are:

1. Ecodesign: material and product-level design
2. The development of traceability and digital material and product passports
3. More optimized recycling
4. New and more circular sharing, and ownership models
5. Increased self-sufficiency of the responsible supply chain in the EU
6. Decreased consumption through awareness raising, diverse incentives and legislation
7. A shift from material consumption and production to services, using CE business models, e.g., product as a service

In summary, it is expected that the market will shift towards more sustainable practices along the whole value chain, instead of business as usual. Consumers, industry, decision makers and investors have an important role to play in this.

Topics for further research

Several topics were identified for which information is currently lacking. Those topics are listed below and are recommended for further investigations:

- Relative proportions in the use of and demand for raw materials by other industrial sectors
- Reliable data and predictions of future raw material needs
- The level of sustainable use of raw materials
- Do the benefits of ICT to other sectors exceed the life cycle impacts of ICT?
- The raw materials need of key digitalization technologies such as IoT, 5G and virtualisation
- The quantities of raw materials needed for ICT network infrastructure required by digitalization: the cases in this study focused on two end-user devices, smartphones and smart TVs
- Recovered and lost elements during the recycling of smartphones and smart TVs and their quantities
- Material efficiency of ICT manufacturing processes. As an example, only 1% of precious metals used in OLED production end up in the final OLED product
- Definition of optimal recycling pathways for ICT devices; recovery and environmental impacts need to be optimized
- Mixed EoL material flow compositions and amounts

REFERENCES

Adisorn, T., Tholen, L. & Götz, T. 2021. Towards a Digital Product Passport Fit for Contributing to a Circular Economy. Energies, 14, 2289. Available at: https://doi.org/10.3390/en14082289

Akcil, A., Agcasulu, I. & Swain, B. 2019. Valorization of Waste LCD and Recovery of Critical Raw Material for Circular Economy: A Review. Resources, Conservation and Recycling 149 (November 2018), 622–37. doi: 10.1016/j.resconrec.2019.06.031

Andrews, T., Elizalde, B., Le Billon, P., Oh, C. H., Reyes, D. & Thomson, I. 2017. The Rise in conflict associated with mining operations: What lies beneath? Toronto: Cirdi. 126 p. Available at: https://cirdi.ca/wp-content/uploads/2017/06/Conflict-Full-Layout-060817.pdf. [Accessed 11 August 2021].

Apple 2021. Apple environmental progress report. Available at: https://www.apple.com/environment/pdf/Apple_Environmental_Progress_Report_2021.pdf. [Accessed 3 June 2021].

Arntz, M., Gregory, T. & Zierahn, U. 2016. The Risk of Automation for Jobs in OECD Countries: A Comparative Analysis, OECD Social, Employment and Migration Working Papers. OECD Publishing.

Badera, J. 2014. Problems of the social non-acceptance of mining projects with particular emphasis on the European Union – a literature review. Env. & Soc.-econ. St. 2, 27–34. doi: 10.1515/environ-2015-0029

Bakker, C., Wang, F., Huisman, J. & Den Hollander, M. 2014. Products That Go Round: Exploring Product Life Extension through Design. Journal of Cleaner Production 69, 10–16. doi: 10.1016/j.jclepro.2014.01.028

Bardsley Consulting, Navigant Consulting, SB Consulting & SSLS 2014. "Manufacturing Roadmap–Solid-State Lighting Research and Development." U.S. Department of Energy (September). Available at: https://www1.eere.energy.gov/buildings/publications/pdfs/ssl/ssl_mfg_roadmap_aug2014.pd. [Accessed 3 June 2021].

BEA 2019. Measuring the Digital Economy: An Update Incorporating Data from the 2018 Comprehensive Update of the Industry Economic Accounts, 1–12. Available at: https://www.bea.gov/system/files/2019-04/digital-economy-report-update-april-2019_1.pdf. [Accessed 4 June 2021].

Belkhir, L. & Elmeligi, A. 2018. Assessing ICT global emissions footprint: Trends to 2040 & recommendations. J. Clean. Prod. 177, 448–463. Available at: https://doi.org/10.1016/j.jclepro.2017.12.239

Berwald, A., Clemm, C. & Prewitz, C. 2020. Environmental evaluation of current and future design rules. Deliverable 2.5 of PROMPT project. Available at: https://prompt-project.eu/wp-content/uploads/2020/07/PROMPT_20200429_Environmental-Evaluation-of-Current-and-Future-Design-Rules.pdf. [Accessed 19 May 2021].

Blanpain, B., Reuter, M. & Malfliet, A. 2019. Lead Metallurgy is Fundamental to the Circular Economy. Socrates Policy Brief. Available at: https://kuleuven.sim2.be/wp-content/uploads/2019/02/SOCRATES-Policy-Brief-2019-Lead.pdf. [Accessed 12 May 2021].

Blengini, G. A., Latunussa, C. E. L., Eynard, U., Torres de Matos, C., Wittmer, D., Georgitzikis, K., Pavel, C., Carrara, S., Mancini, L., Unguru, M., Blagoeva, D., Mathieux, F. & Pennington, D. 2020. Study on the EU's list of Critical Raw Materials, Final Report. 152 p. doi: 10.2873/11619

Bobba, S., Carrara, S., Huisman, J., Mathieux, F. & Pavel, C. 2020. European Commission, Critical materials for strategic technologies and sectors in the EU – a foresight study. Publications Office of the European

Union, 2020. 100 p. Available at: https://ec.europa.eu/docsroom/documents/42881. doi: 10.2873/58081. [Accessed 19 May 2021].

Bonilla, S. H., Silva, H. R .O., da Silva, M. T., Gonçalves, R. F. & Sacomano, J. B. 2018. 'Industry 4.0 and Sustainability Implications: A Scenario-Based Analysis of the Impacts and Challenges'. Sustainability, 10, 3740. Available at: https://doi.org/10.3390/su10103740

Bookhagen, B., Bastian, D., Buchholz, P., Faulstich, M., Opper, C., Irrgeher, J., Prohaska, T. & Koeberl, C. 2020. Metallic Resources in Smartphones. Resources Policy 68(May), 101750. doi: 10.1016/j.resourpol.2020.101750

Börjesson Rivera, M., Håkansson, C., Svenfelt, Å. & Finnveden, G. 2014. Including second order effects in environmental assessments of ICT. Environ. Model. Softw. 56, 105–115. Available at: https://doi.org/10.1016/j.envsoft.2014.02.005

Buchert, M., Manhart, A., Bleher, D. & Pingel, D. 2012. Recycling Critical Raw Materials from Waste Electronic Equipment. Commissioned by the North Rhine-Westphalia State Agency for Nature, Environment and Consumer Protection Authors, 49, 30–40. Available at: https://www.oeko.de/oekodoc/1375/2012-010-en.pdf. [Accessed 19 May 2021].

Buchman, I. 2021. BU-205: Types of Lithium-ion. Battery University. Available at: https://batteryuniversity.com/learn/article/types_of_lithium_ion. [Accessed 31 May 2021].

Bughin, J., Chui, M. & Manyika, J. 2010. Clouds, big data, and smart assets: Ten tech-enabled business trends to watch. McKinsey Q. Available at: https://www.mckinsey.com/industries/technology-media-and-telecommunications/our-insights/clouds-big-data-and-smart-assets-ten-tech-enabled-business-trends-to-watch#. [Accessed 3 June 2021].

Bukht, R. & Heeks, R. 2018. Defining, conceptualising and measuring the digital economy. Int. Organ. Res. J. 13, 143–172. Available at: https://doi.org/10.17323/1996-7845-2018-02-07

Cenci, M. P., Scarazzato, T., Munchen, D. D., Dartora, P. C., Veit, H. M., Bernardes, A. M. & Dias, P. R. 2021. Eco-Friendly Electronics–A Comprehensive Review. Advanced Materials Technologies. Available at: https://doi.org/10.1002/admt.202001263

CERA 2021. Certification of raw materials. Available at: https://www.cera4in1.org/certification/system-and-standards. [Accessed 3 May 2021].

Chancerel, P., Marwede, M., Nissen, N. F. & Lang, K. D. 2015. Estimating the Quantities of Critical Metals Embedded in ICT and Consumer Equipment. Resources, Conservation and Recycling 98, 9–18. doi: 10.1016/j.resconrec.2015.03.003

Ciacci, L., Werner, T. T., Vassura, I. & Passarini, F. 2019. 'Backlighting the European Indium Recycling Potentials'. Journal of Industrial Ecology, Vol. 23, No. 2, 2019, 426–437.

Cisco 2020. Cisco Annual Internet Report (2018-2023). Available at: https://doi.org/10.1016/s1361-3723(20)30026-9

Cisco 2021. What Is a Data Center. Available at: https://www.cisco.com/c/en/us/solutions/data-center-virtualization/what-is-a-data-center.html. [Accessed 3 January 2021].

Compound Interest 2014. The Chemical Elements of a Smartphone. Available at: http://www.compoundchem.com/2014/02/19/the-chemical-elements-of-a-smartphone/. [Accessed 21 January 2021].

Conde, M. 2017. Resistance to mining. A review. Ecological Economics 132, 80–90. doi: org/10.1016/j.ecolecon.2016.08.025

Cordella, M., Alfieri, F. & Sanfelix, J. 2021. Reducing the carbon footprint of ICT products through material efficiency strategies: A life cycle analysis of smartphones. J. Ind. Ecol. 1–17. Available at: https://doi.org/10.1111/jiec.13119

De La Torre, E., Vargas, E., Ron, C. & Gámez, S. 2018. Europium, Yttrium, and Indium Recovery from Electronic Wastes. Metals 8(10). doi: 10.3390/met8100777

Digital Europe 2019. A stronger digital Europe. Our call for action towards 2025. Brussels, Digital Europe. 50 p. Available at: https://www.digitaleurope.org/wp/wp-content/uploads/2019/02/DIGITALEUROPE-%E2%80%93-Our-Call-to-Action-for-A-STRONGER-DIGITAL-EUROPE.pdf. [Accessed 4 June 2021].

Digital TV Europe 2020. "Global Smart TV Sales to Increase 21% by 2024." Available at: https://www.digitaltveurope.com/2020/02/20/global-smart-tv-sales-to-increase-21-by-2024/. [Accessed 19 May 2021].

DSCC 2019. OLED Materials Market to Double in Four Years. Available at: https://www.displaysupplychain.com/blog/oled-materials-market-to-double-in-four-years. [Accessed 19 May 2021].

DSCC 2020. OLED Panel Revenues Will Grow to $51 Billion by 2025. Available at: https://www.displaysupplychain.com/blog/oled-panel-revenues-will-grow-to-51-billion-by-2025. [Accessed 19 May 2021].

EASAC 2016. Priorities for critical materials for a circular economy. EASAC Policy report 29. German National Academy of Sciences Leopoldina. Available at: https://www.leopoldina.org/uploads/tx_leopublication/2017_01_EASAC_Critical_Materials.pdf. [Accessed 18 May 2021].

Eerola, T. 2017. Corporate social responsibility in mineral exploration – The importance of communication and stakeholder engagement in earning and maintaining the social license to operate. Geological Survey of Finland, Report of Investigation 233. 69 p. Available at: http://tupa.gtk.fi/julkaisu/tutkimusraportti/tr_233.pdf

Eerola, T. 2021a. Finland. In: Lesser, P. (ed.) SLO good practices and recent disputes. Illustrative Examples Across Europe. Mining and Metallurgical Regions of Europe (MIREU) Project, Brussels, 17–42. Available at: https://mireu.eu/sites/default/files/2021-06/Illustrative%20Examples%20Report.pdf. [Accessed 31 July 2021].

Eerola, T. 2021b. New low impact mineral exploration technologies and the social license to explore. Insights from corporate websites in Finland. Cleaner Environmental Systems 3, 100059. Available at: https://doi.org/10.1016/j.cesys.2021.100059

Eilu, P., Hallberg, A., Bergman, T., Bjerkgård, T., Feoktistov, V., Korsakova, M., Krasotkin, S., Lauri, L., Litvinenko, V., Philippov, N., Sandstad, J. S. & Shchiptsov, V. 2020. Fennoscandian Ore Deposit Database. Annual update (end-2019 data). Available at: http://en.gtk.fi/informationservices/databases/fodd/index.html. [Accessed 2 February 2021].

Elkington, J. 1997. Cannibals with forks. The triple bottom line of 21st Century business. Oxford: Capstone. 245 p.

Elsner, H. 2019. Noble gases – supply really critical? DERA Rohstoffinformationen 39. 164 p. Available at: https://www.deutsche-rohstoffagentur.de/DE/Gemeinsames/Produkte/Downloads/DERA_Rohstoffinformationen/rohstoffinformationen-39_en.pdf?__blob=publicationFile&v=2. [Accessed 3 February 2021].

Ercan, M., Malmodin, J., Bergmark, P., Kimfalk, E. & Nilsson, E. 2016. Life Cycle Assessment of a Smartphone. ICT for Sustainability 2016. doi: 10.2991/ict4s-16.2016.15

Ernst & Young Ltd 2020. Top 10 business risks and opportunities for mining and metals in 2021. Available at: https://www.ey.com/en_gl/mining-metals/top-10-business-risks-and-opportunities-for-mining-and-metals-in-2021. [Accessed 25 May 2021].

Ethical consumer 2019. "Mobile Phones." Available at: https://www.ethicalconsumer.org/technology/shopping-guide/mobile-phones. [Accessed 19 May 2021].

EU Science Hub 2020. CRM List 2020. Available at: https://rmis.jrc.ec.europa.eu/?page=crm-list-2020-e294f6. [Accessed 12 May 2021].

European Commission 2011. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. A renewed EU strategy 2011-14 for Corporate Social Responsibility. COM/2011/0681 final. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52011DC0681. [Accessed 8 May 2021].

European Commission 2020a. A new Circular Economy Action Plan For a cleaner and more competitive Europe. Brussels. Available at: https://ec.europa.eu/environment/strategy/circular-economy-action-plan_fi. [Accessed 8 May 2021].

European Commission 2020b. Combatting conflict minerals. Available at: https://ec.europa.eu/trade/policy/in-focus/conflict-minerals-regulation/. [Accessed 12 May 2021].

European Commission 2020c. Critical raw materials. Available at: https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en. [Accessed 27 May 2021].

European Commission 2020d. EU 'GPP criteria' -database. Available at: https://ec.europa.eu/environment/gpp/eu_gpp_criteria_en.htm. [Accessed 24 September 2021].

European Commission 2020e. Shaping Europe's Digit al Future. COM(2020) 67 final. Available at: https://ec.europa.eu/info/sites/default/files/communication-shaping-europes-digital-future-feb2020_en_3.pdf. [Accessed 12 May 2021].

European Commission 2020f. Results and deliverables of the environmental footprint pilot phase. Available at: https://ec.europa.eu/environment/eussd/smgp/PEFCR_OEFSR_en.htm. [Accessed 10 December 2020].

European Commission 2021a. EU green public procurement criteria for computers, monitors, tablets and smartphones. Commission staff working document SWD (2021) 57 Final. Available at: https://ec.europa.eu/transparency/documents-register/detail?ref=SWD(2021)57&lang=en. [Accessed 8 May 2021].

European Commission 2021b. Waste from Electronic and Electric Equipment. Available at: https://ec.europa.eu/environment/topics/waste-and-recycling/waste-electrical-and-electronic-equipment-weee_fi. [Accessed 20 May 2021].

European Parliament 2008. Directive 2008/98/EC of the European Parliament and of the Council on waste and repealing certain Directives. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32008L0098&from=EN. [Accessed 3 June 2021].

European Parliament 2020. E-waste in the EU: facts and figures. Eur. Parliam. News. Available at: https://www.europarl.europa.eu/news/en/headlines/society/20201208STO93325/e-waste-in-the-eu-facts-and-figures-infographic. [Accessed 3 June 2021].

European Parliamentary Research Service 2019. Digital transformation. Available at: https://www.europarl.europa.eu/RegData/etudes/BRIE/2019/633171/EPRS_BRI(2019)633171_EN.pdf. [Accessed 3 June 2021].

European Strategy and Policy Analysis System 2019. Global trends to 2030. Challenges and choices for Europe. ESPAS Report 2019. 43 p. Available at: https://www.iss.europa.eu/content/global-trends-2030-%E2%80%93-challenges-and-choices-europe. [Accessed 19 May 2021].

Eurostat 2021. ICT sector–value added, employment and R&D. Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php/ICT_sector_-_value_added,_employment_and_R%26D#The_size_of_the_ICT_sector_as_measured_by_value_added. [Accessed 3 January 2021].

Eynard, U., Georgitzikis, K., Wittmer, D., Latunussa, C. E. L., Torres de Matos, C., Mancini, L., Unguru, M., Blagoeva, D., Bobba, S., Pavel, C., Carrara, S., Mathieux, F., Pennington, D. & Blengini, G. A. 2020. European Commission, Study on the EU's list of Critical Raw Materials, Factsheets on Non-critical Raw Materials. 589 p. Available at: https://rmis.jrc.ec.europa.eu/uploads/CRM_2020_Factsheets_non-critical_Final.pdf. doi: 10.2873/587825. [Accessed 3 April 2021].

Fairphone 2017. Fairphone's report on recyclability. Does modularity contribute to better recovery of materials? Available at: https://www.fairphone.com/wp-content/uploads/2017/02/FairphoneRecyclabilityReport022017.pdf. [Accessed 24 June 2021].

Forti, V., Baldé, C. P., Kuehr, R. & Bel, G. 2020. The Global E-waste Monitor 2020. Available at: http://ewaste-monitor.info/. [Accessed 19 May 2021].

Frenzel, M., Mikolajczak, C., Reuter, M. A. & Gutzmer, J. 2017. Quantifying the relative availability of high-tech by-product metals – the cases of gallium, germanium and indium. Resources Policy 52, 327–335.

Gartner 2021. Gartner IT Glossary. Available at: https://www.gartner.com/en/information-technology/glossary. [Accessed 19 May 2021].

Geological Survey of Finland 2021. Mineral Deposit Database. Available at: https://gtkdata.gtk.fi/mdae/index.html. [Accessed 2 February 2021].

Goodland, R. 2012. Responsible mining: The key to profitable resource development. Sustainability 4, 2099–2016.

Grand View Research 2017a. Smart TV Market Analysis Report. Available at: https://www.grandviewresearch.com/industry-analysis/smart-tv-industry. [Accessed 19 May 2021].

Grand View Research 2017b. Smart TV Market Size to Reach 292.55 Billion by 2025. Available at: https://www.grandviewresearch.com/press-release/global-smart-tv-market. [Accessed 19 May 2021].

Guiltinan, J. 2009. Creative Destruction and Destructive Creations: Environmental Ethics and Planned Obsolescence. Journal of Business Ethics 89, 19–28. Available at: https://doi.org/10.1007/s10551-008-9907-9

Gurita, N., Fröhling, M. & Bongaerts, J. 2018. Assessing Potentials for Mobile/Smartphone Reuse/Remanufacture and Recycling in Germany for a Closed Loop of Secondary Precious and Critical Metals. Journal of Remanufacturing 8(1–2), 0–22. doi: 10.1007/s13243-018-0042-1

Hanski, J., Ahonen, T., Uusitalo, T., Vainio, H. & Valkokari, P. 2018. Smart Asset Management: Stories from the World of Digital Services. Available at: https://www.researchgate.net/publication/335161420_Smart_Asset_Management_Stories_from_the_World_of_Digital_Services. [Accessed 3 June 2021].

Herrington, R. 2021. Mining our green future. Nature Reviews Materials. doi: 10.1038/s41578-021-00325-9

Hiekkanen, K., Seppälä, T. & Ylhäinen, I. 2021. Energy and Electricity Consumption of the Information Economy

Sector in Finland. Available at: https://www.etla.fi/julkaisut/energy-and-electricity-consumption-of-the-information-economy-sector-in-finland/. [Accessed 3 June 2021].

Hilson, G. 2012. Corporate social responsibility in the extractive industries: Experiences from developing countries. Resources Policy 37, 131–137.

Horn, S., Gunn, A. G., Petavratzi, E., Shaw, R. A., Eilu, P. Törmänen, T. Bjerkgård, T., Sandstad, J. S. Jonsson, E., Kountourelis, S. & Wall, F. 2021 Cobalt resources in Europe and the potential for new discoveries. Ore Geology Reviews 130, 1–25. Available at: https://doi.org/10.1016/j.oregeorev.2020.103915

Horner, N. C., Shehabi, A. & Azevedo, I. L. 2016. Known unknowns: Indirect energy effects of information and communication technology. Environ. Res. Lett. Available at: https://doi.org/10.1088/1748-9326/11/10/103001

Huawei & Oxford Economics 2017. Digital Spillover–Measuring the true impact of the digital economy. Available at: https://www.huawei.com/minisite/gci/en/digital-spillover/files/gci_digital_spillover.pdf. [Accessed 3 June 2021].

Huisman, J., Leroy, P., Tertre, F., Söderman, M. L., Chancerel, P., Cassard, D., Amund, N., Wäger, P., Kushnir, D., Rotter, V.S., Mählitz, P., Herreras, L., Emmerich, J., Hallberg, A., Habib, H., Wagner, M. & Downes, S. 2017. ProSUM Project Urban mine and Mining wastes–Final report. Available at: http://www.prosumproject.eu/sites/default/files/DIGITAL_Final_Report.pdf. [Accessed 3 June 2021].

Hund, K., La Porta, D., Fabregas, T. P., Laing, T. & Drexhage, J. 2020. Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition. International Bank for Reconstruction and Development/The World Bank. 110 p.

IDC 2021. IDC Forecasts Worldwide Market for Used Smartphones to Reach 351.6 Million Units with a Market Value of $65 Billion in 2024. Available at: https://www.idc.com/getdoc.jsp?containerId=prUS47258521. [Accessed 5 March 2021].

IEA 2020. Data Centres and Data Transmission Networks. Available at: https://www.iea.org/reports/data-centres-and-data-transmission-networks. [Accessed 3 January 2021].

IEA 2021. The role of critical minerals in clean energy transitions. Special Report of the World Energy Outlook (WEO) team of the IEA. Paris: IEA. 283 p. Available at: https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

ITU 2012. Toolkit on environmental sustainability for the ICT sector 314. Available at: https://www.itu.int/dms_pub/itu-t/oth/4B/01/T4B010000060001PDFE.pdf. [Accessed 3 June 2021].

Jain, R. K., Cui, Z. & Domen, J. K. 2016. Environmental impact of mining and mineral processing. Management, monitoring, and auditing strategies. Amsterdam: Elsevier. 307 p. Available at: https://doi.org/10.1016/C2014-0-05174-X

Jang, H. & Topal, E. 2020. Transformation of the Australian mining industry and future prospects. Transactions of the Institutions of Mining and Metallurgy 129, 120–134. Available at: https://doi.org/10.1080/25726668.2020.1786298

Jowitt, S. M. & McNulty, B. A. 2021. Geology and mining: mineral resources and reserves: their estimation, use, and abuse. SEG Discovery 125, 27–36.

Jowitt, S., Mudd, G. & Thompson, J. 2020. Future availability of non-renewable metal resources and the influence of environmental, social, and governance conflicts on metal production. Communications Earth & Environment 1, 13.

Judl, J., Horn, S., Pesu, J., Savolainen, H. & Kautto, P. 2020. ICT-päätelaitteisiin liittyvät materiaali-, energia- ja ilmastokysymykset. Available at: https://julkaisut.valtioneuvosto.fi/handle/10024/162378. [Accessed 3 June 2021].

Judl, J., Tilkanen, J., Riddlestone, S. & Rubbens, C. 2018. Creating sustainable smartphones: Scaling up best practice to achieve SDG 12. Transform Together Report. Available at: https://transform-together.weebly.com/uploads/7/9/7/3/79737982/report_-_creating-sustainable-smartphone_scaling-up-best-practice-to-achieve-sdg-12.pdf. [Accessed 3 June 2021].

Kellens, K., Baumers, M., Gutowski, T. G., Flanagan, W., Lifset, R. & Duflou, J. R. 2017. Environmental Dimensions of Additive Manufacturing: Mapping Application Domains and Their Environmental Implications. J. Ind. Ecol. 21, S49–S68. Available at: https://doi.org/10.1111/jiec.12629

Kiiski Kataja, E. 2016. Megatrends 2016 – The future happens now. Memo 14.1.2016. Available at: https://media.sitra.fi/2017/02/28142600/Megatrends_2016.pdf. [Accessed 26 May 2021].

Kivinen, M. & Käpyaho, E. 2019. The European Union's minerals policy. In: Vasara, H. (ed.) State and outlook of the mining industry. Ministry of Economic Affairs and Employment of Finland. Mining Industry Sector Report 1/2018. 35 p. Available at: https://tem.fi/documents/1410877/2851374/Sector+Reports+-+Mining+Sector/38402832-eeca-470a-aba4-a0fc-25ce35da/Sector+Reports+-+Mining+Sector.pdf. [Accessed 3 June 2021].

Kivinen, S., Kotilainen, J. & Kumpula, T. 2020. Mining conflicts in the European Union: environmental and political perspectives. Fennia 198, 163–179. Available at: https://doi.org/10.11143/fennia.87223

Kolb, J., Rosa, D., Thrane, K. & Keiding, J. K. 2016. Greenland. In: Boyd, R., Bjerkgård, T., Nordahl, B. & Schiellerup, H. (eds) Mineral resources in the Arctic. Geol. Surv. Norway, Spec. Publ., 162–189.

Koppe, J. C. 2021. Lessons Learned from the Two Major Tailings Dam Accidents in Brazil. Mine Water and the Environment 40, 166–173. Available at: https://doi.org/10.1007/s10230-020-00722-6

Kortelainen, H. & Hanski, J. *in press*. Asset life cycle management for Smart Grids: Challenges and implications. International Journal of Strategic Engineering Asset Management.

Ku, A. Y. 2018. Anticipating critical materials implications from the Internet of Things (IOT): Potential stress on future supply chains from emerging data storage technologies. Sustain. Mater. Technol. 15, 27–32. Available at: https://doi.org/10.1016/j.susmat.2017.10.001

Laine, J. 2015. Paremman palvelun nimissä – digitaalinen raaka-aine heti jaettavaksi! Talouselämä 24.08.2015. Available at: https://www.talouselama.fi/kumppaniblogit/tiedon-blogi/paremman-palvelun-nimissa-digitaalinen-raaka-aine-heti-jaettavaksi/0765acd3-e960-3c31-9f83-7a763c1a79c5. [Accessed 8 April 2021].

Latunussa, C. E. L., Georgitzikis, K., Torres de Matos, C., Grohol, M., Eynard, U., Wittmer, D., Mancini, L., Unguru, M., Pavel, C., Carrara, S., Mathieux, F., Pennington, D. & Blengini, G. A. 2020. European Commission, Study on the EU's list of Critical Raw Materials, Factsheets on Critical Raw Materials. 819 p. Available at: https://rmis.jrc.ec.europa.eu/uploads/CRM_2020_Factsheets_critical_Final.pdf. doi: 10.2873/92480

Lee, E. B., Lee, S. G. & Yang, C. G. 2017. "The Influences of Advertisement Attitude and Brand Attitude on Purchase Intention of Smartphone Advertising." Industrial Management and Data Systems 117(6), 1011–36. doi: 10.1108/IMDS-06-2016-0229

Leroy, P. 2020. Issues of concern. Presentation at E-waste Forum 2020 at 18 November 2020. WEEEForum.

Lu, T. 2017. "Almost Half Of Smartphone Users Spend More Than 5 Hours A Day on Their Mobile Device." Counterpoint. Available at: https://www.counterpointresearch.com/almost-half-of-smartphone-users-spend-more-than-5-hours-a-day-on-their-mobile-device/. [Accessed 19 May 2021].

Lusty, P. A. & Gunn, A. G. 2016. Challenges to global mineral resource security and options for future supply. Geol. Soc. London Publ. 393, 265–276.

Luttropp, C. & Lagerstedt, J. 2006. EcoDesign and The Ten Golden Rules: generic advice for merging environmental aspects into product development. Journal of Cleaner Production, 14 (15–16), 1396–1408.

LVM 2021. ICT-alan ilmasto- ja ympäristöstrategia. Available at: https://julkaisut.valtioneuvosto.fi/handle/10024/162910. [Accessed 19 May 2021].

Macro Polo 2021. Big Picture: OLED Display. Available at: https://macropolo.org/digital-projects/supply-chain/oled-display/. [Accessed 19 May 2021].

Malmodin, J. & Lundén, D. 2018. The energy and carbon footprint of the global ICT and E & M sectors 2010–2015. Sustain. 10. Available at: https://doi.org/10.3390/su10093027

Malmodin, J., Bergmark, P. & Matinfar, S. 2018. A high-level estimate of the material footprints of the ICT and the E&M sector. 5th International Conference on Information and Communication Technology for Sustainability 52, 168–148. Available at: https://doi.org/10.29007/q5fw

Mao, Y., Lai, Y., Luo, Y., Liu, S., Du, Y., Zhou, J., Ma, J., Bonaiuto, F. & Bonaiuto, M. 2020. Apple or Huawei: Understanding Flow, Brand Image, Brand Identity, Brand Personality and Purchase Intention of Smartphone" Sustainability 12(8), 3391. doi: 10.3390/su12083391

Marscheider-Weidemann, F., Langkau, S., Hummen, T., Erdmann, L. & Tercero Espinoza, L. 2016. Raw materials for emerging technologies. DERA Rohstoffinformationen 28, 1–16.

Martins, J., Costa, C., Oliveira, T., Gonçalves, R. & Branco, F. 2019. How Smartphone Advertising Influences Consumers' Purchase Intention. Journal of Business Research 94, 378–87. doi: 10.1016/j.jbusres.2017.12.047

Mathieux, F., Ardente, F., Bobba, S., Nuss, P., Blengini, G. A., Dias, P. A., Blagoeva, D., Torres De Matos, C., Wittmer, D., Pavel, C., Hamor, T., Saveyn, H., Gawlik, B., Orveillon, G., Huygens, D., Garbarino, E., Tzimas, E., Bouraoui, F. & Solar, S. 2017. Critical Raw Materials and the Circular Economy. Background report, Report EUR 28832 EN. Available at: https://doi.org/10.2760/378123

Meinert, L. D., Robinson, G. R. & Nassar, N. T. 2016. Mineral resources: reserves, peak production and the future. Resources 5, 14. doi: 10.3390/resources5010014

Mercer-Mapstone, L., Rifkin, W., Louis, W. R. & Moffat, K. 2018. Company-community dialogue builds relationships, fairness, and trust leading to social acceptance of Australian mining developments. Journal of Cleaner Production 184, 671–677.

Messmann, L., Boldoczki, S., Thorenz, A. & Tuma, A. 2019. Potentials of preparation for reuse: A case study at collection points in the German state of Bavaria. J. Clean. Prod. 211, 1534–1546. Available at: https://doi.org/10.1016/j.jclepro.2018.11.264

Michaux, S. 2021. The mining of minerals and the limits to growth. Geological Survey of Finland, Open File Work Report 16/2021. 68 p. Available at: https://tupa.gtk.fi/raportti/arkisto/16_2021.pdf

Millar, C., Lockett, M. & Ladd, T. 2017. Disruption: Technology, innovation and society. Technol. Forecast. Soc. Change. Available at: https://doi.org/10.1016/j.techfore.2017.10.020

Minerals4EU 2021. Minerals Intelligence Network for Europe. Available at: http://www.minerals4eu.eu/. [Accessed 29 May 2021].

Ministry of the Environment Japan 2016. Introduction to Green Purchasing Legislation in Japan. Available at: https://www.env.go.jp/policy/hozen/green/kokusai_platform/2015report/handbook_eng.pdf. [Accessed 12 May 2021].

Mongardini, J. & Radzikowski, A. 2020. Global Smartphone Sales May Have Peaked: What Next? Available at: https://www.imf.org/en/Publications/WP/Issues/2020/05/29/Global-Smartphones-Sales-May-Have-Peaked-49361. [Accessed 19 May 2021].

Moon, C. J. & Evans, A. M. 2006. Ore, mineral economics and mineral exploration. In: Moon, C. J., Whateley, M. K. G. & Evans, A. M. (eds) Introduction to mineral exploration. 2nd ed. Hong Kong: Blackwell Publishing, 3–18.

Mudd, G. M., Jowitt, S. M. & Werner, T. T. 2017. The world's by-product and critical metal resources part I: Uncertainties, current reporting practices, implications and grounds for optimism. Ore Geology Reviews 86, 924–938.

Mugge, R., Jockin, B. & Bocken, N. 2017. How to sell refurbished smartphones? An investigation of different customer groups and appropriate incentives. Journal of Cleaner Production 147, 284–296.

Muller, A. 2013. The Chemistry of the Mobile Phones. Available at: https://www.ngu.no/upload/Publikasjoner/Rapporter/2013/2013_026.pdf. [Accessed 19 May 2021].

Natural Resource Governance Institute 2015. The resource curse. The political and economic challenges of natural resource wealth. NRGI Reader 2015. 6 p.

Nickel Institute 2021. Nickel recycling. Available at: https://nickelinstitute.org/policy/nickel-life-cycle-management/nickel-recycling/. [Accessed 2 February 2021].

Nilsson, N. 2010. The Quest for Artificial Intelligence: A History of Ideas and Achievements. Stanford University.

OECD 2011. Guide to Measuring the Information Society 2011. OECD Guide to Measuring the Information Society 2011. Available at: https://doi.org/10.1787/9789264113541-en

Ojala, T., Mettälä, M., Heinonen, M. & Oksanen, P. 2020. The ICT sector, climate and the environment–interim report of the working group preparing a climate and environmental strategy for the ICT sector in Finland. Ministry of Transport and Communications. Available at: https://julkaisut.valtioneuvosto.fi/handle/10024/162473. [Accessed 3 June 2021].

OMDIA 2020. Handset ODM Industry White Paper. Available at: https://omdia.tech.informa.com/-/media/tech/omdia/whitepapers/handset-odm-industry-white-paper.pdf. [Accessed 28 May 2021].

Pajarinen, M. & Rouvinen, P. 2014. Computerization Threatens One Third of Finnish Employment. ETLA Brief No 22. Available at: http://pub.etla.fi/ETLA-Muistio-Brief-22.pdf. [Accessed 3 June 2021].

Panasonic 2019. Recycling Processes. Available at: https://panasonic.net/eco/petec/process/. [Accessed 19 May 2021].

Prakash, S., Dehoust, G., Gsell, M., Schleicher, T. & Stamminger, R. 2016. Einfluss der Nutzungsdauer von Produkten auf ihre Umweltwirkung: Schaffung einer Informationsgrundlage und Entwicklung von Strategien gegen „Obsoleszenz“. Available at: https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/texte_11_2016_einfluss_der_nutzungsdauer_von_produkten_obsoleszenz.pdf. [Accessed 19 May 2021].

Proske, M., Sanchez, D., Clemm, C. & Baur, S. J. 2020. Life Cycle Assessment of the Fairphone 3. Fraunhofer-Institut IZM. doi: 10.1109/EVER.2014.6844034

Provasnek, A., Sentic, A. & Schmid, E. 2017. Integrating Eco-Innovations and Stakeholder Engagement for Sustainable Development and a Social License to Operate. Corp. Soc. Responsib. Environ. Mgmt. 24, 173–185. doi: 10.1002/csr.1406

Puckett, J., Brandt, C. & Palmer, H. 2018. Holes in the Circular Economy: WEEE Leakage from Europe. A Report of the e-Trash Transparency Project. A Rep. e-Trash Transpar. Proj. 120. Available at: http://wiki.ban.org/images/f/f4/Holes_in_the_Circular_Economy-_WEEE_Leakage_from_Europe.pdf. [Accessed 19 May 2021].

Rasmussen, R. O. (ed.) 2011. Megatrends. TemaNord 2011, 527. Copenhagen: Nordic Council of Ministers. 205 p.

Reck, B. & Graedel, T. 2012. Challenges in Metal Recycling. Science 337(6095). Available at: https://doi.org/10.1126/science.1217501

Reuter, M. & van Schaik, A. 2012. Opportunities and Limits of WEEE Recycling –Recommendations to Product Design from a Recyclers Perspective. Electronics Goes Green 2012+, ECG 2012 – Joint International Conference and Exhibition, Proceedings. IEEE.

Reuter, M., van Schaik, A. & Ballester, M. 2018. Limits of Circular Economy: Fairphone Modular Design Pushing the limits. World of Metallurgy – Erzmetall 71, 68–79.

Rizos, V., Bryhn, J., Alessi, M., Campmas, A. & Zarra, A. 2019. Identifying the Impact of the Circular Economy on the Fast-Moving Consumer Goods Industry: Opportunities and Challenges for Businesses, Workers and Consumers – Mobile Phones as an Example. Study. European Economic and Social Committee. Available at: https://www.eesc.europa.eu/sites/default/files/files/qe-03-19-510-en-n.pdf. [Accessed 19 May 2021].

Samsung 2011. Smart TV: Piece by Piece. Available at: https://news.samsung.com/global/smart-tv-piece-by-piece. [Accessed 19 May 2021].

Shabrin, N., Khandaker, S., Bin, S., Kashem, A., Hie, C. K. & Susila, T. 2017. Factors Affecting Smartphone Purchase Decisions of Generation-Y. The Journal of Contemporary Issues in Business and Government 23(1), 47–65.

Silver Institute 2020. World Silver Survey 2020. 83 p. Available at: https://www.silverinstitute.org/wp-content/uploads/2020/04/World-Silver-Survey-2020.pdf

Slack, K. 2012. Mission impossible? Adopting a CSR-based business model for extractive industries in developing countries. Resources Policy 37, 179–184. Available at: https://doi.org/10.1016/j.resourpol.2011.02.003

Statista 2021a. Global smart TV unit sales from 2018 to 2025. Available at: https://www.statista.com/statistics/878372/smart-tv-unit-sales-worldwide/. [Accessed 28 May 2021].

Statista 2021b. Smartphone sales worldwide 2007-2021. Available at: https://www.statista.com/statistics/263437/global-smartphone-sales-to-end-users-since-2007/. [Accessed 12 May 2021].

Statistics Finland 2021. Manufacturing. Available at: https://www.stat.fi/tup/suoluk/suoluk_teollisuus_en.html. [Accessed 28 May 2021].

STEP 2014. Solving the E-Waste Problem (Step). White Paper. One Global Definition of E-waste. Step 3576. 13 p. Available at: https://www.step-initiative.org/files/_documents/whitepapers/StEP_WP_One%20Global%20Definition%20of%20E-waste_20140603_amended.pdf. [Accessed 3 June 2021].

Tab tv 2019. Where are Samsung TVs made. Available at: https://en.tab-tv.com/?p=18624. [Accessed 28 May 2021].

Technavio 2020. Smart TV Market by Distribution Channel and Geography–Forecast and Analysis 2020–2024. Available at: https://www.technavio.com/report/smart-tv-market-industry-analysis. [Accessed 19 May 2021].

Techwalla 2021. How Are TVs Made? Available at: https://www.techwalla.com/articles/how-are-tvs-made. [Accessed 19 May 2021].

Tercero, L. 2019. Report on the Future Use of Critical Raw Materials. SCRREEN Project D.2.3, 2019.

Thaler, R. H. & Sunstein, C. R. 2008. Improving decisions about health, wealth, and happiness. New Haven, CT: Yale University Press. 293 p.

Thomson, I. & Boutilier, R. G. 2011. The social license to operate. In: Darling, P. (ed.) SME Mining and Engineering Handbook. Society of Mining Metallurgy and Exploration. Littleton, 1779-1796.

Thomson, I. & Joyce, S. A. 1997. Mineral exploration and the challenge of community relations. On Common Ground Consultants Inc. Available at: http://oncommonground.ca/wp-content/downloads/mineral.html. [Accessed 3 June 2021].

Tsiropoulos, I., Tarvydas, D. & Lebedeva, N. 2018. Li-ion batteries for mobility and stationary storage applications. EUR 29440 EN. Luxembourg: Publications Office of the European Union. doi: 10.2760/87175, JRC113360

UNCTAD 2019. Digital economy report 2019. Available at: https://unctad.org/system/files/official-document/der2019_en.pdf. [Accessed 28 May 2021].

UNCTAD 2020. Digital economy growth and mineral resources. Implications for developing countries. UNCTAD Technical Notes on ICT for Development 16. 42 p. Available at: https://unctad.org/system/files/official-document/tn_unctad_ict4d16_en.pdf. [Accessed 18 June 2021].

UNEP 2013. Metal Recycling: Opportunities, Limits, Infrastructure. A Report of the Working Group on the Global Metal Flows to the International Resource Panel. Available at: https://wedocs.unep.org/handle/20.500.11822/8423. [Accessed 3 June 2021].

USGS 2021. Mineral commodity summaries 2021. U.S. Geological Survey. 204 p. Available at: https://doi.org/10.3133/mcs2021

Vasara, H. 2018. State and outlook of the mining industry. Ministry of Economic Affairs and Employment of Finland. Mining Industry Sector Report 1/2018. 35 p. Available at: https://tem.fi/documents/1410877/2851374/Sector+Reports+-+Mining+Sector/38402832-eeca-470a-aba4-a0fc25ce35da/Sector+Reports+-+Mining+Sector.pdf. [Accessed 3 June 2021].

Wäger, P., Hirschier, R. & Widmer, R. 2015. Advances in intelligent systems and computing, In: ICT Innovations for Sustainability. Available at: https://doi.org/10.1007/978-3-319-09228-7

Watson, D., Gylling, A. C., Tojo, N., Throne-Holst, H., Bjørn Bauer, B. & Milios, L. 2017. Circular Business Models in the Mobile Phone Industry. TemaNord, 2017, 560. doi: 10.6027/TN2017-560

Werner, T. T., Mudd, G. M. & Jowitt, S. M. 2015. Indium: key issues in assessing mineral resources and long-term supply from recycling. Applied Earth Science (Trans. Inst. Min. Metall. B) 124, 213–226.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E. & Weidema, B. 2016. The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment. [online]. 21(9), 1218–1230. Available at: http://link.springer.com/10.1007/s11367-016-1087-8. [Accessed 21 June 2021].

White House 2021. Building resilient supply chains, revitalizing American manufacturing, and fostering broad-based growth. 100-Day Reviews under Executive Order 14017. 250 p. Available at: https://www.whitehouse.gov/wp-content/uploads/2021/06/100-day-supply-chain-review-report.pdf

Whitmore, A. 2006. The emperor's new clothes: Sustainable mining? Journal of Cleaner Production, 14, 309–314.

Wikipedia 2021. Smart TV. Available at: https://en.wikipedia.org/wiki/Smart_TV. [Accessed 19 May 2021].

Windsor, R. 2016. Digital assets: the raw materials of digital transformation. DAM News. Available at: https://digitalassetmanagementnews.org/digital-asset-management-value-chains/digital-assets-the-raw-materials-of-digital-transformation/. [Accessed 4 June 2021].

World Economic Forum 2021. Global Battery Alliance. Available at: https://www.weforum.org/global-battery-alliance. [Accessed 25 May 2021].

Zhang, A., Moffat, K, Lacey, J., Wang, J., González, R., Uribe, K., Cui, L. & Dai, Y. 2015. Understanding the social licence to operate of mining at the national scale: a comparative study of Australia, China and Chile. Journal of Cleaner Production 108, 1063–1072. Available at: https://doi.org/10.1016/j.jclepro.2015.07.097

Zhang, M. 2020. Global demand for laptops gets pandemic push. Counterpoint. Available at: https://www.counterpointresearch.com/laptop-demand-gets-pandemic-push/. [Accessed 3 June 2021].

Zhou, B., Li, Z. & Chen, C. 2017. Global potential of rare earth resources and rare earth demand from clean technologies. Minerals 7, 203. doi: 10.3390/min7110203

Legislation:

Waste Law 646/2011. Available at: https://www.finlex.fi/fi/laki/alkup/2011/20110646

APPENDIX 1

Interview questions:

1. What are buyers (B2B, B2C) interested in when purchasing a smartphone?
   a. Performance, design, brand
   b. The manufacturer's approach to sustainability issues
   c. Repairability, software support, recyclability, phone-as-a-service/leasing, recycled material content, life cycle length
   d. What raw materials are included in the device, or how many different raw materials it consists of, from where they are sourced, whether they include conflict minerals, or whether there are there other environmental/social concerns
   e. Used/refurbished phones
   f. Which of these is most important?
   g. For companies offering refurbished phones, an additional question: where do the old phones come from?
2. Are the frontline sales personnel able to answer these questions, if they are raised? Is there any sales training about these issues?
3. Do customers contact you about issues related to raw material sourcing or environmental concerns during the use phase?
4. How long is the use phase, typically? For first or subsequent use phases?
5. Do old devices have a resale value, or do buyers ask what the resale value is?
6. What are the main restrictions in terms of life cycle length (e.g., hardware malfunctioning, lack of software support, lifetime of the components (broken screen/glass, battery), trends or other? What could your organization do to improve this?
7. What would you suggest to extend the life cycle of the devices (e.g., policies, business, technical, social actions)?
8. Can different customer segments be identified with regard to their environmental consciousness?
9. Are any trends visible regarding what the sector will look like in the future?
10. How familiar are you with the sustainability issues related to these value chains, e.g., human rights issues, environmental footprints, the composition of the devices or raw material sourcing?
11. In general, what do you think are the most pressing challenges for the raw material use of ICT devices?
    a. Challenges related to primary raw material extraction?
    b. Challenges related to recycling?
    c. Other challenges related to sustainability (social and environmental)?
    d. Challenges related to consumer habits?
    e. Challenges related to the security of supply of critical raw materials?
    f. Challenges related to regulations?

Additionally, for B2B:

1. Does the procurement policy include any criteria regarding the circularity (see above) or environmental impacts of the phones?
2. If a work phone is broken, is it automatically replaced, or is repair considered? When is repair considered, e.g., due to a broken screen, an old battery, other?
3. In general, how long is a phone used by the employee?
4. Can the employee, if she/he wants, also choose a phone with fewer environmental impacts, a used/refurbished phone or other circularity-based products?
5. Do mobile phone manufacturers open a dialogue about the environmental considerations of their products?

All GTK's publications online at hakku.gtk.fi

gtk.fi