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Analysis of material efficiency aspects of personal computers product group

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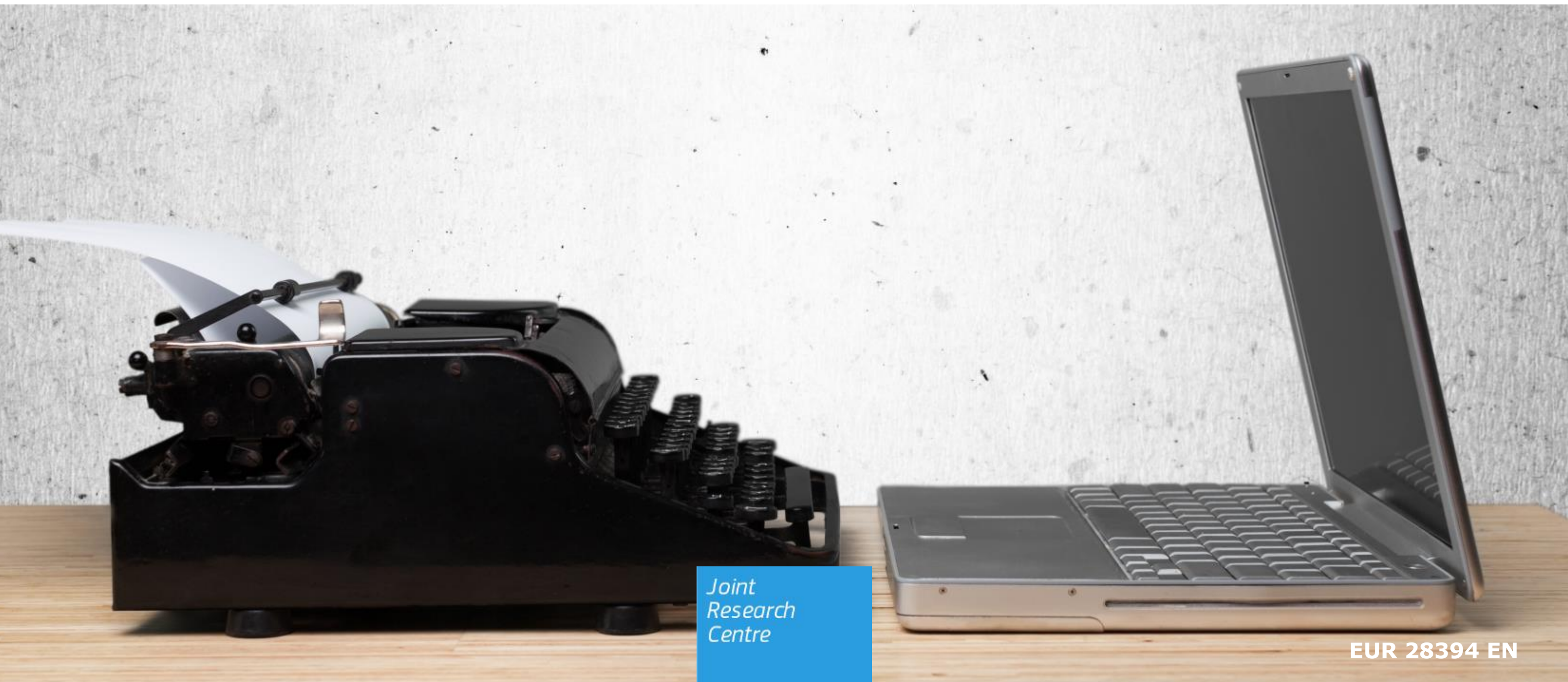
January 2018



Joint Research Centre

EUR 28394 EN

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JRC Science Hub
https://ec.europa.eu/jrc

EUR 28394 EN

PDF	ISBN 978-92-79-64943-1	ISSN 1831-9424	doi:10.2788/89220
Print	ISBN 978-92-79-64944-8	ISSN 1018-5593	doi:10.2788/679788

Luxembourg: Publications Office of the European Union, 2018

How to cite: Tecchio, P., Ardente, F., Marwede, M., Christian, C., Dimitrova, G. and Mathieux, F., Analysis of material efficiency aspects of personal computers product group, EUR 28394 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-64943-1, doi:10.2788/89220, JRC105156.

Contents

List of figures

List of tables

Acknowledgements

This report is part of the project 'Technical support for environmental footprinting, material efficiency in product policy and the European Platform on Life Cycle Assessment' (LCA) (2013-2017) funded by the Directorate-General for Environment.

The authors would like to thank Paolo Tosoratti, from the Directorate-General for Energy, Unit ENER.C.3 for all the support, guidance and suggestions provided during the project.

The authors would like to also thank Dr Larisa Maya-Drysdale and colleagues from Viegand Maagøe, for input data and suggestions provided for this work.

Finally, the authors of this report thank all of the stakeholders who contributed to this work with constructive comments and suggestions for all the information and suggestions provided, which were essential for the analysis of end-of-life practices for the product group.

Executive summary

This report has been developed within the project 'Technical support for environmental footprinting, material efficiency in product policy and the European Platform on Life Cycle Assessment' (LCA) (2013-2017) funded by the Directorate-General for Environment.

The report summarises the findings of the analysis of material-efficiency aspects of the personal-computer (PC) product group, namely durability, reusability, reparability and recyclability. It also aims to identify material-efficiency aspects which can be relevant for the current revision of the Ecodesign Regulation (EU) No 617/2013. Special focus was given to the content of EU critical raw materials (CRMs) ([1]) in computers and computer components, and how to increase the efficient use of these materials, including material savings thanks to reuse and repair and recovery of the products at end of life. The analysis has been based mainly on the REAPro method ([2]) developed by the Joint Research Centre for the material-efficiency assessment of products.

This work has been carried out in the period June 2016-September 2017, in parallel with the development of *The preparatory study on the review of Regulation 617/2013 (Lot 3) — computers and computer servers* led by Viegand Maagøe and Vlaamse Instelling voor Technologisch Onderzoek NV (VITO) (2017) ([3]). During this period, close communication was maintained with the authors of the preparatory study. This allowed ensuring consistency between input data and assumptions of the two studies. Moreover, outcomes of the present research were used as scientific basis for the preparatory study for the analysis of material-efficiency aspects for computers. The research has been differentiated as far as possible for different types of computers (i.e. tablet, notebooks and desktop computers).

The report starts with the analysis of the technical and scientific background relevant for material-efficiency aspects of computers, such as market sales, expected lifetime, bill of materials, and a focus on the content of CRMs (especially cobalt in batteries, rare earths including neodymium in hard disk drives and palladium in printed circuit boards). Successively the report analyses the current practices for repair, reuse and recycling of computers.

Based on results available from the literature, material efficiency of the product group has the potential to be improved, in particular the lifetime extension. The residence time ([4]) of IT equipment put on the market in 2000 versus 2010 generally declined by approximately 10 % (Huisman et al., 2012), while consumers expressed their preference for durable goods, lasting considerably longer than they are typically used (Wieser and Tröger, 2016). Design barriers (such as difficulties for the disassembly of certain components or for their processing for data sanitisation) can hinder the repair and the reuse of products. Malfunction and accident rates are not negligible (IDC, 2016, 2010; SquareTrade, 2009) and difficulties in repair may bring damaged products to be discarded even if still functioning.

Once a computer reaches the end of its useful life, it is addressed to 'waste of electrical and electronic equipment' (WEEE) recycling plants. Recycling of computers is usually based on a combination of manual dismantling of certain components (mainly components containing hazardous substances or valuable materials, e.g. batteries, printed circuit boards, display panels, data-storage components), followed by mechanical processing including shredding. The recycling of traditional desktop computers is perceived as non-

(1) Critical raw materials (https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_it).

(2) Ardente and Mathieux (2014). 'Identification and assessment of product's measures to improve resource efficiency: the case-study of an energy using product', *Journal of cleaner production* (http://doi.org/10.1016/j.jclepro.2014.07.058).

(3) *Preparatory study on the review of Regulation 617/2013 (Lot 3) — computers and computer servers (draft report).* Viegand Maagøe and VITO (2016). Prepared for European Commission DG Energy C.3 (https://computerregulationreview.eu/).

(4) The time of non-functioning or unused appliances in stock is included.

problematic by recyclers, with the exception of some miniaturised new models (i.e. mini desktop computers), which still are not found in recycling plants and which could present some difficulties for the extraction of printed circuit boards and batteries (if present). The design of notebooks and tablets can originate some difficulties for the dismantling of batteries, especially for computers with compact design.

Recycling of plastics from computers of all types is generally challenging due to the large use of different plastics with additives, such as flame retardants. According to all the interviewed recyclers, recycling of WEEE plastics with flame retardant is very poor or null with current technologies.

Building on this analysis, the report then focuses on possible actions to improve material efficiency in computers, namely measures to improve (a) waste prevention, (b) repair and reuse and (c) design for recycling. The possible actions identified are listed hereinafter.

(a) Waste prevention

a.1 Implementation of dedicated functionality ([5]) for the optimisation of the lifetime of batteries in notebooks: the lifetime of batteries could be extended by systematically implementing a preinstalled functionality on notebooks, which makes it possible to optimise the state of charge (SoC) of the battery when the device is used in grid operation (stationary). By preventing the battery remaining at full load when the notebook is in grid operation, the lifetime of batteries can be potentially extended by up to 50 %. Users could be informed about the existence and characteristics of such a functionality and the potential benefits related to its use.

a.2 Decoupling external power supplies (EPS) from personal computers: the provision of information on the EPS specifications and the presence/absence of the EPS in the packaging of notebooks and tablets could facilitate the reuse by the consumer of already-available EPS with suitable characteristics. Such a measure could promote the use of common EPS across different devices, as well as the reuse of already-owned EPS. This would result in a reduction in material consumption for the production of unnecessary power supplies (and related packaging and transport) and overall a reduction of treatment of electronic waste. The International Electrotechnical Commission (IEC) technical specification (TS) 62700, the Standard Institute of Electrical and Electronics Engineers (IEEE) 1823 and Recommendation ITU-T L.1002 can be used to develop standards for the correct definition of connectors and power specifications.

a.3 Provision of information about the durability of batteries: the analysis identified the existence of endurance tests suitable for the assessment of the durability of batteries in computers according to existing standards (e.g. EN 61960). The availability of information about these endurance tests could help users to get an indication on the residual capacity of the battery after a predefined number of charge/discharge cycles. Moreover, such information would allow for comparison between different products and potentially push the market towards longer-lasting batteries.

a.4 Provision of information about the 'liquid ingress protection (IP) class' for personal computers: this can be assessed for a notebook or tablet by performing specific tests, developed according to existing standards (e.g. IEC 60529). Users can be informed about the level of protection of the computer against the ingress of liquids (e.g. dripping water or spraying water or water jets) and in this way prevent one of the most common causes of computer failure.

The yearly rate of estimated material saving if dedicated functionality for the optimisation of the lifetime of batteries (a.1) were used ranges from around 2 360 to 5 400 tonnes (t)

([5]) E.g. a dedicated tool or software.

of different materials per year. About 450 t of cobalt, 100 t of lithium, 210 t of nickel and 730 t of copper could be saved every year.

The estimated potential savings of materials when EPS are decoupled from notebooks and tablets (a.2) are in the range 2 300-4 600 t/year (80 % related to the notebook category, and 20 % to tablets). These values can be obtained when 10-20 % of notebooks and tablets are sold without an EPS, as users can reuse already-owned and compatible EPS. Under these conditions, for example, about 190-370 t of copper can be saved every year. This estimate may increase when the same EPS can be used for both notebooks and tablets (at the moment the assessment is based on the assumption that the two product types were kept separated).

Further work is needed to assess the potential improvements thanks to the provision of information about the durability of batteries (a.3), and about the 'liquid-IP class' (a.4). The former option (a.3) has the potential to boost competition among battery manufacturers, resulting in more durable products. The latter option (a.4) has the potential to reduce computer damage due to liquid spillage, ranked among the most recurrent failure modes.

(b) Repair/reuse

b.1 and b.2 Provision of information to facilitate computer disassembly: the disassembly of relevant components (such as the display panel, keyboard, data storage, batteries, memory and internal power-supply units) plays a key role to enhance repair and reuse of personal computers. Some actions have therefore been discussed (b.1) to provide professional repair operators with documentation about the sequence of disassembly, extraction, replacement and reassembly operations needed for each relevant component of personal computers, and (b.2) to provide end-users with specific information about the disassembly and replacement of batteries in notebooks and tablets.

b.3 Secure data deletion for personal computers: this is the process of deliberately, permanently and irreversibly erasing all traces of existing data from storage media, overwriting the data completely in such a way that access to the original data, or parts of them, becomes infeasible for a given level of effort. Secure data deletion is essential for the security of personal data and to allow the reuse of computers by a different user. Secure data deletion for personal computers can be ensured by means of built-in functionality. A number of existing national standards (HMG IS Standard No 5 (the United Kingdom), DIN 66399 (Germany), NIST 800-88r1 (the United States (US)) can be used as a basis to start standardisation activities on secure data deletion.

The estimated potential savings of materials due to the provision of information and tools to facilitate computer disassembly were quantified in the range of 150-620 t/year for mobile computers (notebooks and tablets) within the first 2 years of use, and in the range of 610-2 460 t/year for mobile computers older than 2 years.

Secure data deletion of personal computers, instead, is considered a necessary prerequisite to enhance reuse. The need to take action on this is related to policies on privacy and protection of personal data, as the General Data Protection Regulation (EU) 2016/679 and in particular its Article 25 on 'data protection by design and by default'. Future work is needed to strengthen the analysis, however it was estimated that secure data deletion has the potential to double volume of desktop, notebook and tablet computers reused after the first useful lifetime.

(c) Recyclability

c.1 Provision of information to facilitate computer dismantling: computers could be designed so that crucial components for material aspects (e.g. content of hazardous substances and/or valuable materials) can be easily identified and extracted in order to be processed by means of specific recycling treatments. Design for dismantling can focus on components listed in Annex VII of the WEEE directive ([6]). The 'ease of dismantling' can be supported by the provision of relevant information (such as a diagram of the product showing the location of the components, the content of hazardous substances, instructions on the sequence of operations needed to remove these components, including type and number of fastening techniques to be unlocked, and tool(s) required).

c.2 Marking of plastic components: although all plastics are theoretically recyclable, in practice the recyclability of plastics in computers is generally low, mainly due to the large amount of different plastic components with flame retardants (FRs) and other additives. Marking of plastic components according to existing standards (e.g. ISO 11469 and ISO 1043 series) can facilitate identification and sorting of plastic components during the manual dismantling steps of the recycling.

c.3 FR content: according to all the recyclers interviewed, FRs are a major barrier to plastics recycling. Current mechanical-sorting processes of shredded plastics are characterised by low efficiency, while innovative sorting systems are still at the pilot stage and have been shown to be effective only in certain cases. Therefore, the provision of information on the content of FRs in plastic components is a first step to contribute to the improvement of plastics recycling. Plastics marking (as discussed above) can contribute to the separation of plastics with FRs during the manual dismantling, allowing for their recycling at higher rates (in line with the prescription of IEC/TR 62635, 2015). However, detailed information about FRs content could be given in a more systematised way, for example through the development of specific indexes. These indexes could support recyclers in checking the use of FRs in computers and in developing future processes and technologies suitable for plastics recycling. Moreover, these indexes could support policymakers in monitoring the use of FRs in the products and, in the medium-long term, to promote products that use smaller quantities of FRs. An example of a FR content index is provided in this report.

c.4 Battery marks: the identification of the chemistry type of batteries in computers is necessary in order to have efficient identification and sorting, and thus to improve the material efficiency during the recycling. It is proposed to start standardisation activities to establish standard marking symbols for batteries. The examples of the 'battery-recycle mark', developed by the Battery Association of Japan (BAJ), and the current standardisation activities for the IEC 62902 (standard marking symbols for batteries with a volume higher than 900 cm^3) may be used as references to develop ad hoc standards.

The benefits of actions for the design for recycling can be relevant. In particular, the proposed actions should contribute to increase the amounts of materials that will be recycled (6 350-8 900 t/year), in particular plastics (5 950-7 960 t/year of additional plastics), but also metals such as cobalt (55-110 t), copper (240-610 t), rare earths as neodymium and dysprosium (2-7 t) and various precious metals (gold (0.1-0.4 t), palladium (0.1-0.4 t) and silver (2-7 t)). Compared to the amount of materials recycled in the EU (2012 data), these values would represent a recycling increase of 1-2 % for cobalt, 2-5 % for palladium, and 13-50 % for rare earths.

([6]) 'Design for dismantling' is also in line with the principles of the WEEE directive, which in Article 4 states that appropriate measures should be encouraged 'so that the ecodesign requirements facilitating reuse and treatment of WEEE established in the framework of Directive 2009/125/EC are applied'.

Abbreviations

ABS	acrylonitrile butadiene styrene
AC	alternating current
ATA	advanced technology attachment
BAJ	Battery Association of Japan
BaU	business as usual
BFR	brominated flame retardants
BOA	bill of attributes
BoM	bill of materials
CAS	CESG Assured Service
CD-ROM	compact disc — read-only memory
CESG	Communications-Electronics Security Group
CPU	central processing unit
CRMs	critical raw materials
DC	direct current
DG	Directorate-General
EEE	electrical and electronic equipment
EERA	European Electronics Recycling Association
EMI	electromagnetic interference
eMMC	embedded multimedia card
EoL	end of life
EPS	external power supply
EuRIC	European Recycling Industries' Confederation
FR(s)	flame retardant(s)
GF	glass fibre
GfK	Growth from Knowledge
GHG	Greenhouse gas
GPP	green public procurement
GPU	graphics processing unit
GSM	Global System for Mobile Communications (*Groupe Spéciale Mobile*)
GSMA	GSM Association
HDD	hard disk drive
HP	Hewlett-Packard
IC	integrated circuit
ICT	information and communications technology
IDC	International Data Corporation
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IP	ingress protection
IT	information technology
ITU	International Telecommunication Union
IZM	Institut für Zuverlässigkeit und Mikrointegration
JRC	Joint Research Centre
LAN	local-area network
LCA	life-cycle assessment
LCD	liquid-crystal display
LCO	lithium-cobalt-oxide
LED	light-emitting diodes
LFP	lithium-iron-phosphate

LIB	lithium-ion batteries
LMO	lithium-manganese-oxide
MFA	material flow analysis
MOST	Maynard operation sequence technique
MoU	memorandum of understanding
NCA	nickel-cobalt-aluminium
NiMH	nickel-metal-hydride
NIR	near infra-red
NMC	nickel-manganese-cobalt-oxide
ODD	optical disk drive
OEM	original equipment manufacturer
OLED	organic light-emitting diodes
PATA	Parallel ATA
PBB	polybrominated biphenyls
PBDEs	polybrominated diphenyl ethers
PC	personal computer
PCB	printed circuit board
PMMA	poly(methyl methacrylate)
PWD	password
QR	quick response
RAL	Reichs-Ausschuss für Lieferbedingungen
RAM	random-access memory
REE	rare earth elements
RoHS	restriction of hazardous substances
ROM	read-only memory
SATA	Serial ATA
SBS-IF	Smart battery systems implementers forum
SD	secure digital
SIM	subscriber identification module
SoC	state of charge
SoH	state of health
SSD	solid-state drive
TS	technical specification
UK	United Kingdom
US	United States
USB	universal serial bus
WEEE	waste of electrical and electronic equipment
WLAN	wireless local-area network
XML	extensible markup language
XRF	x-ray fluorescence
ZIF	zero insertion force

List of definitions

Built-in functionality: a functionality provided by the product that does not rely on components which are not already included in the said product.

Component: constituent part of a device which cannot be physically divided into smaller parts without losing its particular function (EN 50625-1:2014).

Disassembly: non-destructive taking apart of an assembled product into constituent materials and/or components (from Standard BS 8887-2:2009).

Dismantling: taking apart of an assembled product into constituent materials and/or components (based on the definition of disassembly from Standard BS 8887-2:2009).

Display panel: electronic display assembly (e.g. liquid-crystal display or other technologies) together with their casing where appropriate (revised from Directive 2012/19/EU).

Firmware: system, hardware, component, or peripheral programming provided with the product to provide basic instructions for hardware to function inclusive of all applicable programming and hardware updates.

Secure data deletion: the effective erasure of all traces of existing data from storage media, overwriting the data completely in such a way that access to the original data, or parts of them, becomes infeasible for a given level of effort.

State of charge (SoC): the '[…] remaining battery capacity expressed as percentage of full-charge capacity' (SBS-IF, 1998) and hence the 'fuel gauge' indicating the currently available battery charge. The SoC may also be defined as the remaining battery capacity expressed as a percentage of the design capacity (also 'rated capacity', as stated by the manufacturer).

State of health (SoH): the ratio between a battery's full-charge capacity over the initial (design) capacity expressed in percentage. The SoH indicates how much of its (initially theoretically available) capacity a battery has retained at a given time.

Technical documentation: documentation made available by manufacturers on websites, concerning repair/recycling of products, kept available for a specified number of years after the last product has been placed on the market.

User documentation: documentation made available by manufacturers for end-users, on websites and user manuals, kept available for a specified number of years after the products have first been placed on the market.

We consider *resource efficiency* as a combination of *energy efficiency* and *material efficiency*. Thus, *material efficiency* does not directly regard resources used to produce energy, nor energy used during the lifecycle of products (Tecchio et al, 2017).

Definitions concerning *personal computer product categories* and *parts* used in this report are listed in the preparatory study on the review of Regulation 617/2013 (Lot 3) — computers and computer servers led by Viegand Maagøe and VITO (2017) (https://computerregulationreview.eu/).

1 Introduction

This report has been developed within the project 'Technical support for environmental footprinting, material efficiency in product policy and the European Platform on LCA' (2013-2017) funded by the Directorate-General for Environment. The report aimed to analyse the material efficiency of the personal-computer product group, and to identify relevant and workable criteria on material efficiency that could be used for the revision of the Ecodesign Regulation (EU) No 617/2013, which is currently underway.

Nowadays, most modern industrial operations are based on a linear model in which materials are extracted and processed, products are made and are eventually disposed of at the end of their lifespans. As evidenced by growing material scarcity around the globe, this linear 'take, make, dispose' model is inherently unsustainable (Ellen MacArthur Foundation, 2016). The European Commission is committed to a sustainable, low-carbon, material-efficient and competitive circular economy (European Commission, 2015a), a strategy that includes the shifting of the concept from 'waste' to 'resources', boosting the market for secondary raw materials and taking a series of actions to encourage recovery of CRMs. In particular, the analysis herein presented responds to the commitment of giving emphasis to circular economy aspects in future product requirements under the Ecodesign directive.

The analysis is based on the REAPro ([7]) method developed by the Joint Research Centre (JRC) for the resource-efficiency assessment of products (Ardente and Mathieux, 2014), and it followed the results of previous assessments of specific product groups (e.g. electronic displays, washing machines, dishwashers, enterprise servers, computers, vacuum cleaners) in the context of the Ecodesign directive or of EU Ecolabel regulation.

We consider resource efficiency as a combination of energy efficiency and material efficiency. Thus, *material efficiency* does not directly regard resources used to produce energy, nor energy used during the lifecycle of products (Tecchio et al, 2017).

The present report begins with an analysis of the current situation for the personal-computer product group, including: a presentation of background information including market data, bill of materials and the environmental performance of this product group (Section 2); an analysis of recycling, repair/reuse practices for this product group (Section 3). Based on this analysis, a series of material-efficiency 'hot spots' for computers is identified (Section 4). Successively the report introduces some requirements that could be potentially applied to this product group in the context of the Ecodesign directive, addressing material saving (Section 5), repair/reuse (Section 6) and recycling (Section 7). Benefits associated to these requirements are formalised and, when possible, quantified.

([7]) Resource-efficiency assessment of products.

2 Background information

2.1 Market data

As reported by Viegand Maagøe and VITO (2017) on the *Review of Regulation (EU) 617/2013 (Lot 3) — computers and computer servers (draft report)*, sales and stock data of personal computers [8] within the EU market can be derived by analysing past sales and market trends. Database platforms such as Statista (2016) were consulted by which market analysts estimate the worldwide shipment of desktop computers, notebooks and tablets.

Table 1 provides the projections of estimated sales for different product categories in the European market, focusing on 2020, 2025 and 2030. Market projections are confirmed by recent studies, for example the work published by Risk & Policy Analysts Limited (2014). According to that study, the European market accounted for around 20 % of global tablet sales in 2010, but market analysts are expecting this proportion to decrease as the European market becomes saturated; for the same reasons, market analysts are expecting the global sales of notebooks to decrease in the coming years. Again according to elaborations made by Risk & Policy Analysts Limited (2014) and values reported by Statista, the share of the EU market can be estimated to be in the range of 34-37 % for global notebook sales.

Table 1 — Estimated annual sales (2012-2030) for product categories in the EU market (Viegand Maagøe and VITO, 2017). Values in millions of units.

Product categories	**2012**	**2013**	**2014**	**2015**	**2020**	**2025**	**2030**
	million units/year						
Notebook	50.66	47.21	46.79	42.40	41.66	41.55	41.74
Desktop computer	19.13	15.77	14.84	12.74	12.05	13.47	13.60
Integrated desktop	0.77	0.63	0.59	0.51	0.48	0.54	0.54
Thin client	1.35	1.35	1.43	1.31	1.37	1.37	1.37
Integrated thin client	0.13	0.13	0.14	0.13	0.14	0.14	0.14
Tablet/slate	28.46	44.74	45.21	40.79	38.38	38.47	38.56
Portable all-in-one	0.21	0.19	0.19	0.17	0.17	0.17	0.17
Workstation	0.71	0.75	0.80	0.79	0.79	0.82	0.85
Small-scale server	0.17	0.18	0.19	0.20	0.21	0.22	0.23
Total computers	101.59	110.95	110.19	99.05	95.24	96.73	97.20

From Table 1 it is possible to note that main shares of the market sector will be represented by notebook computers, tablet/slate computers and desktop computers (almost 97 % of the total number of computers in 2030). The shipments of tablets grew significantly until

[8] Definitions of product categories are available in the preparatory study on the review of Regulation 617/2013, prepared by Viegand Maagøe and VITO (2017).

2014, when the European market became saturated. The shipments of desktop computers and notebooks are already gradually decreasing.

A more-detailed market analysis was focused on the two main typologies of storage that can be used for personal computers: hard disk drives (HDDs) and solid-state drives (SSDs). The two typologies exist for both internal and external data storage.

HDDs are traditional spinning hard drives consisting of a metal platter with a magnetic coating on which a read/write head gets access to the data while the platter is spinning. The more-recent SSDs, instead, store data on interconnected flash memory chips. SSDs are generally more expensive but also faster than HDDs. According to pcmag.com ([9]), SSDs also have better durability. SSDs have no mechanical parts in motion, even though they do wear out over time. Thanks to a command technology that dynamically optimises read/write cycles, however, the likelihood of encountering read/write errors in SSDs in the first 6 years of use is very low.

According to Statista (2016), it is possible to estimate the shipments (and therefore the production) of computers with HDDs and computers with SSDs from 2012 to 2017. The source estimates that shipments of HDDs will decline in the future while SSD shipments will show an increase. Projections to 2020 were developed (Figure 1). The year 2020 could then be identified as the most probable break-even point between the two trends.

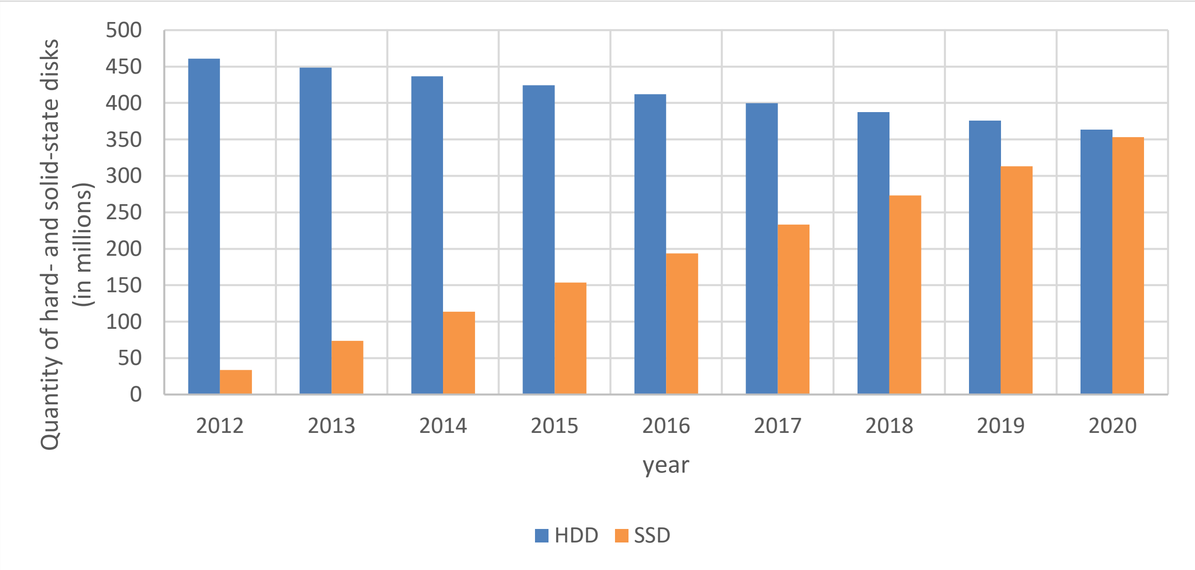

Figure 1 — Shipments of hard- and solid-state disk drives (HDD/SSD) (in millions) worldwide in computers from 2012 to 2017 (Statista, 2016) and projections for 2018-2020 (own elaboration).

Although it is not forecast that SSDs will significantly reduce the usage of HDDs, a technological breakthrough could cause the price of SSDs to drop significantly, which in turn would drive replacement of HDDs by SSDs (Sprecher et al., 2014a).

2.2 Expected lifetime

Expected lifetime of products is key information to estimate potential end-of-life (EoL) flows, and several figures can be found in literature for the personal-computer product group. Hennies and Stamminger (2016) discussed *types of obsolescence*, describing ‘functional obsolescence’, which is induced by innovations, new features and new

([9]) *PC Magazine* digital edition, provides lab-tested reviews, how-to guides and news about the latest tech trends.

interfaces, and 'desire obsolescence', which is brought about through the desire for trends, designs and lifestyles that makes products old-fashioned. These two types of obsolescence are playing a role also for the personal-computer product group, and are not negligible reasons for their relatively short (compared to other electric and electronic equipment, such as household appliances for instance) lifetime.

As previously stated, several lifetime figures can be found in literature, especially for notebook computers. A survey conducted by the Öko-Institut (Germany) shows that the average duration of the first use of a notebook ranges from 5 to 6 years (Prakash et al., 2016a). Hennies and Stamminger (2016) reported an average lifetime of 5 years before notebooks are discarded. A Dutch study reported a lifetime of 7 years (Wang et al., 2013), while a recent survey conducted among Austrian residents reported 4.1 years, as a useful lifetime (namely the time until a replacement is bought).

Viegand Maagøe and VITO (2017) reported a typical lifetime of 5 years for notebooks, 6 years for desktop computers, and 3 years for tablets; the authors relied on literature findings, expert assumptions and industry inputs (see Table 2).

Table 2 — Typical lifetime of computers and related products according to Viegand Maagøe and VITO (2017).

Product category	**Typical lifetime, years**
Notebook	5
Desktop	6
Integrated desktop	6
Thin client	5
Integrated thin client	5
Tablet/slate	3
Portable all-in-one	5
Workstation	7
Small-scale servers	6

Hennies and Stamminger (2016) also reported the fate of notebooks after the first use: most of them are not discarded, even when they are defective. Some 41 % are set aside (50 % in the case of *defective* notebooks), only 23 % are disposed of and 33 % are passed on.

Huisman et al. (2012) took into consideration this behaviour and analysed the residence time, (average lifetime including the time of non-functioning or unused appliances in stock). Different types of equipment put on the market for all years between 1990 and 2010 were considered by the authors. From their analysis, basically all appliances show decreasing residence times. For IT equipment put on the market in 2000 versus 2010, for instance, the residence time declined by approximately 10 %. The shortening trend for IT product lifespan was identified also in less recent studies, in China (Yang et al., 2008) and India (Dwivedy and Mittal, 2010).

The Austrian resident survey, mentioned before, also compared the *first-use time* (products in use, time until a replacement is bought) of notebooks (4.1 years) with the *desired lifetime* (the time consumers desire the product to be functioning). The latter was, on average, 7 years (Wieser and Tröger, 2016). From these results, Wieser and Tröger (2016) highlighted that consumers want durable goods to last considerably longer than they are used. If asked to spontaneously name a product for which the expected lifetime (the time people expect the product to work) is shorter than expected, notebook computers were ranked in the sixth place (after mobile phones, TVs, washing machines, coffee machines and dishwashers).

Table 3 — Use time and desired lifetime of products (Wieser and Tröger, 2016). n= number of respondents (population interviewed: 1 009 Austrian residents).

	First use time (n=574)	Desired lifetime (n=996)
Notebooks	4.1 years	7.0 years

Another survey, this time conducted between 2014 and 2016 among Swiss consumers highlighted that nowadays notebook users expect longer lifetimes, compared to the past. The survey showed how the *desired lifetime* of notebooks nowadays is 20 % higher than the desired lifetime of the product type they used in the past (Thiébaud-Müller et al., 2017).

Other main findings from Thiébaud-Müller et al. (2017) are as follows.

- The median service lifetime of notebooks (at the moment the notebook is not in use anymore, therefore stored or disposed of) is reported to be 5 years, while the median intended (desired) first service time is reported to be 6 years.
- The median 'second service lifetime' (the active use of a second-hand notebook) is 2 years.
- The median 'storage time' (the time between the active use of a new device and its final disposal or its transfer to a different user) is 1 year.
- About 60 % of the notebooks go to storage after first use, about 10 % to second use and 20 % to collection schemes ([10]).
- A large share of the devices stored go to second use. This means that in total nearly 30 % of all notebooks in Switzerland go to second use.
- About 20 % of the devices in second use go to third use. The analysis of the change over time of the service lifetime (histogram) show no significant trend for the temporal change of the service lifetime for notebooks.

Finally, the Growth from knowledge (GfK) consumer panel collected the average first-use time in Germany, 2004-2007 and 2010-2012. The first-use time seems to have a peak in 2005/2006 with 6 years and declines to 5.1 years in 2012. The reasons for replacement and whether the notebooks have a second life were not determined (Prakash et al., 2016b).

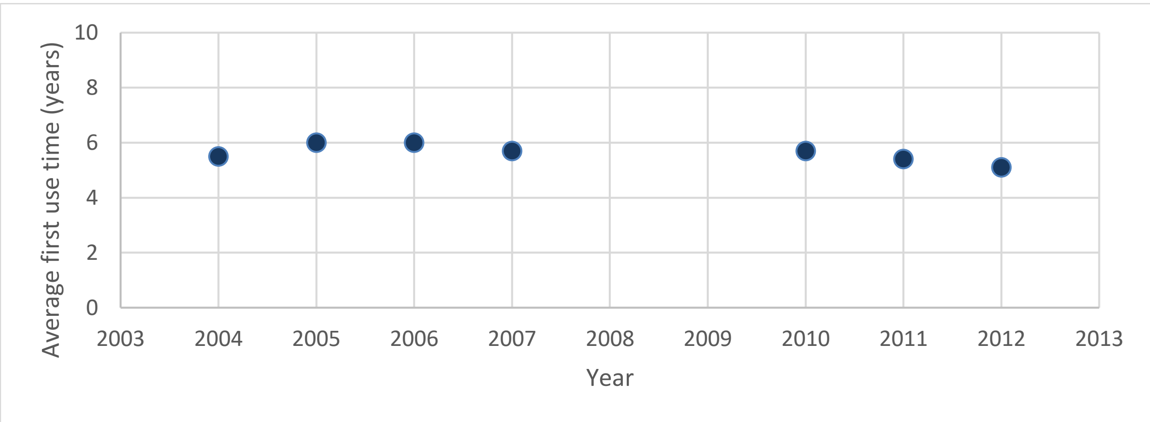

Figure 2 — Average first-use time of notebooks in Germany (n=2 268 in 2012, lowest value n=244 in 2004; 2008, 2009: not specified) (Prakash et al., 2016b).

([10]) Remaining 10 % go to donation, municipal waste, or unknown.

As a final remark, consumer behaviour can also be listed as a reason for the present problem of increasing amounts of electronic waste (the 'desire obsolescence'). As prices fall, consumers can receive incentives to buy new appliances instead of continuing to use their current ones (Aladeojebi, 2013).

2.2.1 External power-supply lifetime

The *active* lifetime of EPS used for portable devices is estimated to be 5 years, aligned with the expected lifetime of notebooks (Table 2). Accordingly, when the lifetime of the device is shorter (e.g. 3 years for tablets, see Table 2), the active life of EPS is reduced as well. The *overall* lifetime, instead, is largely determined by the lifetime of electrolytic capacitors an EPS is made of (IEC/TS 62700, 2014). The *overall* lifetime (i.e. the age of discarded appliances) is often significantly longer than the active lifetime, as the *stocking in a drawer* phenomena is common in the case of small electric devices (Bio Intelligence Service, 2007). Risk & Policy Analysts Limited (2014) estimated that only 5 % of consumers dispose of their old mobile phone when they purchase a new one and a typical consumer keeps an old handset for 2.37 years before it enters the waste stream. The same delay can be assumed to their related EPS. Furthermore, according to IEC/TS 62700 (2014), if one EPS is used for several computers simultaneously, the lifetime may become shorter (each manufacturer decides on the lifetime of electrolytic capacitors considering how many years the computer is used (IEC/TS 62700, 2014)).

2.2.2 Battery lifetime

Battery durability is a key feature for users. In a survey conducted by the IDC (2010) ([11]), 68 % of respondents confirmed that the battery lifetime on their notebook computers was not sufficient for their business needs, and over half stated that battery failures caused problems for their business. The most common problem was lost productivity, cited by 45 % of respondents, followed by lost/delayed sales (22 %) and loss of critical company data (17 %).

The durability of batteries potentially limits the lifetime of the device it is powering, if battery replacement is economically not feasible, or technically not possible. This may lead to early disposal of devices and thus contradicts the overall objective of material efficiency. This is especially important concerning lithium-ion batteries ([12]) (LIB), not only do LIB contain a high amount of critical materials such as cobalt (see Section 2.4.1), they also involve substantial environmental impacts during their manufacturing (Section 2.6).

Battery durability is determined by a battery's specific *cycle life* and *calendar life*. *Cycle life* is usually described by the number of charge/discharge cycles a battery can withstand before losing a certain portion of its initial capacity. A cycle is defined as 'an amount of discharge approximately equal to the value of design capacity' (SBS-IF, 1998), with design capacity referring to the theoretical capacity of a new battery (pack) (also: 'rated capacity' during a 5-hour discharge, as declared by the manufacturer). Today's LIB inevitably lose a minor amount of their capacity with each charging cycle due to a number of physical and chemical processes (Broussely et al., 2005; Sarre et al., 2004; Schmalstieg et al., 2014; Vetter et al., 2005). A battery's cycle life is determined by many factors, such as the quality of the manufacturing processes, the temperature while charging and discharging and the cycle depth, among others (Vetter et al., 2005). *Calendar life* is described by the portion of capacity a LIB inevitably loses over time, even though it is not in use, for example while in storage. The rate at which an LIB loses capacity over time is also determined by a number of factors, such as the surrounding temperature and its SoC (Vetter et al., 2005).

It has been found that one major factor determining both the cycle life and calendar life of LIB is the SoC. The SoC is the '[…] remaining battery capacity expressed as a percentage

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([11]) International Data Corporation, Framingham, Massachusetts (MA), US (www.idc.com).
([12]) See Section 2.3.5 for detail on other types of batteries.

of full-charge capacity' (SBS-IF, 1998) and hence the 'fuel gauge' indicating the currently available battery charge. Studies have shown that the cycling of a battery around a very high SoC (between 90 and 100 %) is particularly damaging and cell capacity fades comparatively quickly. However, when cycled around an average SoC of 50 % (between 45 and 55 % SoC), the cycle life increases dramatically (Schmalstieg et al., 2014). Similarly, calendar life increases with lower levels of SoC: as can be seen in Figure 3 (part a), the capacity of battery cells with higher SoC fades considerably quicker compared to those with lower SoC when in storage. For example, after 300 days of storage at 50 °C, a battery with 90 % SoC has lost more than 20 % of its capacity, while a battery with 10 % SoC has lost only around 5 %. Hence, it can be concluded that a high SoC during use and storage of a notebook battery can be expected to shorten its useful life considerably.

Ideal conditions for storing a battery over a longer period is said to be at around 50 % SoC. This avoids the damaging effects of a high SoC on one hand and, on the other hand, avoids running into very low SoC through self-discharge, where battery cells may be damaged irreversibly via deep discharge (e.g. Apple, 2016).

Usually battery life is stated in charge/discharge cycles before the original capacity degrades to 80 %: for consumer products being between 300 and 500 cycles (Battery University, 2016a) and up to 1 000 cycles (Apple, 2016). For heavy users who charge their notebooks or tablets every day, this would amount to a total lifetime of the battery to up to 1.4 years (500 cycles, 1 cycle per day) or 2.8 years (1 000 cycles, 1 cycle per day), respectively. Of course, batteries can continue to be used even below 80 % capacity, although the runtime of the device will be decreased.

However, as discussed above, the number of charging cycles alone is not sufficient to predict the lifetime of LIB. This is also indicated in a study examining the durability of notebooks used for several years in office environments (administration) in Germany. It was found that the cycle frequency was quite low, with around 50 % of the notebook batteries only accumulating 30 cycles or less per year. Hence, it was assumed that the notebooks had mostly been used stationary (possibly with docking stations). However, despite the low cycle count, the capacity had decreased dramatically in many cases (Clemm et al., 2016). This indicates how the cycle count alone is not a good indicator to project battery durability and that factors such as the surrounding temperature and average SoC, among others, need to be taken into account.

Data from industry show how the SoH (the ratio between a battery's full-charge capacity over the initial (design) capacity) is projected under varying use patterns (Table 4). It is shown that the capacity is expected to fade quicker in a notebook used stationary in a docking station and charged only once a week, compared to a notebook cycled daily. While no difference is expected under low power loads (word processing, email), the effect is pronounced under moderate and high power load. Hence, the factors increasing capacity fade are high temperatures and high discharge rate, rather than the cycle count.

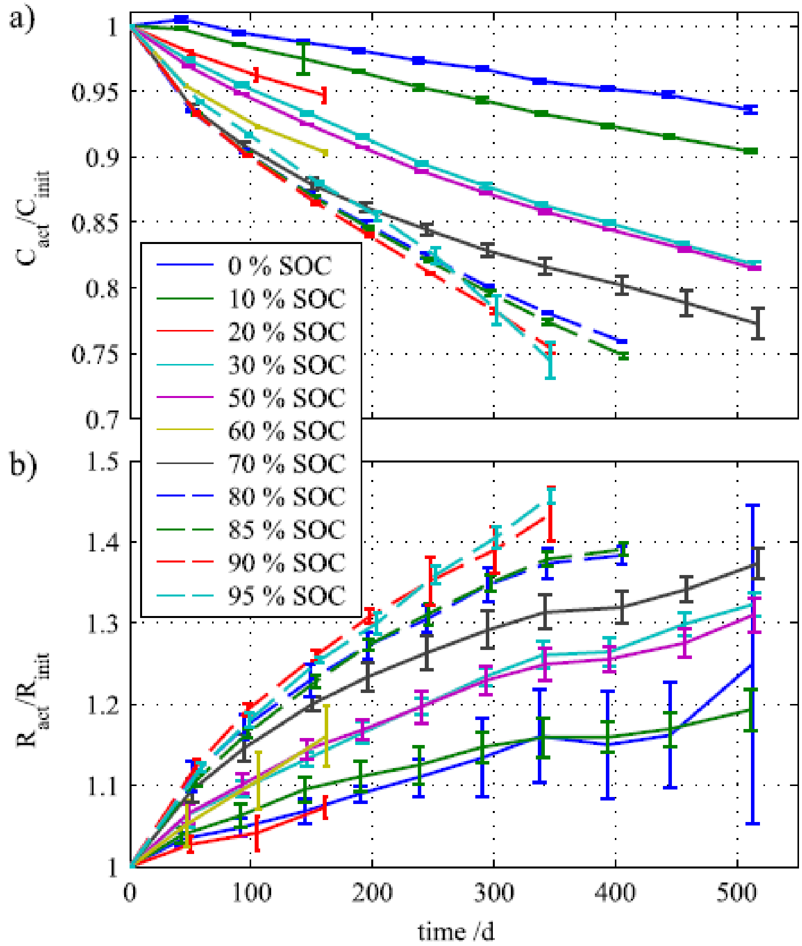


Figure 3 — Calendar ageing of nickel-manganese-cobalt-oxide (NMC) cells over time depending on SoC at an elevated temperature (50 °C). Capacity fade (ratio between current and initial capacity) under varying SoC over time (in days) is shown in diagram (a) and the corresponding increase in internal resistance (ratio between current and initial resistance) in the cells in (b) (Schmalstieg et al., 2014)

Table 4 — Full-charge capacity projections after 1 year of use (HP Inc., 2016)

Power load (applications)	**Mobile computer battery cycled daily (25 ºC (77 ºF))**	**Stationary computer (with docking station) Battery cycled weekly (> 35ºC (95 ºF))**
Low (word processing, internet, email) >	80 %	80 %
Moderate (wireless, spreadsheets, database management)	80 %	70 %
High (computer-aided design, 3D games, DVDs, high LCD brightness)	60 %	50 %

2.3 Bill of materials

The present section illustrates a number of available studies investigating the composition of computers and computer components. These references have been used to estimate the average bills of materials (BoMs) for desktop computers, notebooks, tablets, EPS and batteries. Reference values were also retrieved by using information directly collected by the authors of the present report, or public declarations by manufacturers.

2.3.1 Desktop computers

Several BoMs are available for desktop computers, even if not always directly comparable. A material flow analysis (MFA) at the level of specific materials was conducted by Van Eygen et al. (2016), who provided the average materials composition of desktop computers: ferrous metals (37 %), aluminium (5 %), copper (4 %), precious metals (0.01 %), other non-ferrous metals (1 %), plastics (19 %), minerals and others (34 %). Other studies provided more-specific BoMs. Among the most recent, the studies conducted by Song et al. (2013) and Teehan and Kandlikar (2013) can be cited.

Song et al. (2013) analysed a Dell desktop-computer unit (Table 5), but did not disclose which model. Teehan and Kandlikar (2013), on the other hand, worked on a specific Dell Optiplex 780 Minitower desktop (Table 6). According to Dodd et al. (2016, 2015), within the production phase of desktop computers, specific components can be identified as environmental ‘hot spots’ such as the motherboard (often referred also as ‘mainboard’) and other printed circuit boards (PCBs), the CD-ROM, the HDD and the power supply. CRMs and precious metals, such as silver, gold and palladium, contained in the motherboard and other PCBs, can be relevant for various environmental impact categories.

Table 5 — Desktop-computer bill of materials (BoM) according to Song et al. (2013). Packaging included.

Categories	**Weight (kg)**	**Percentage**
Iron housing	4.95	47.28 %
Plastic housing	0.16	1.53 %
Printed circuit board	0.66	6.30 %
CD-ROM/DVD ROM	0.75	7.16 %
Power-supply unit	1.62	15.47 %
Hard disk	0.55	5.25 %
Cable	0.14	1.34 %
Radiator (Al)	0.57	5.44 %
Fan	0.07	0.67 %
Packaging	1.00	9.55 %
Total mass	**10.47**	**100 %**

Table 6 — Desktop-computer BoM according to Teehan and Kandlikar (2013). Packaging excluded.

Categories	**Unit**	**Value**
Power supply (excluding integrated circuits (ICs))	kg	1.46
Casing mass	kg	6.17
Circuit boards (excluding ICs)	kg	1.03
ICs (packages)	kg	0.04
Other Mass	kg	1.96
Total mass	**kg**	**10.66**
ICs (die area, mm^2)	mm^2	500

2.3.2 Notebook computers

The BoMs of notebooks was derived from the available scientific literature, in particular LCA studies or MFA focused on notebooks (Chancerel and Marwede, 2016; Kahhat et al., 2011; Kasulaitis et al., 2015; Seagate, 2016; Talens Peiró et al., 2016; von Geibler et al., 2003). The several sources of data converge on the assumption about the overall mass of a notebook being in the range of 2-3 kg, with smaller weights identified in more-recent references (Grzesik-Wojtysiak and Kukliński, 2013; Hischier and Wäger, 2015; Houlihan, 2013; Talens Peiró et al., 2016).

It is noticed that these references are characterised by different levels of detail (in some cases at the level of components and in other cases at the level of materials), depending on the scope of the study. Moreover, some of these studies are relatively old and refer to computer models produced in the last decade.

A detailed breakdown of notebook composition was published in a recent JRC technical report (Talens Peiró et al., 2016). Table 7 provides the reference BoM for the notebook product group. Table 8 lists the BoMs of two computer components, storage system (HDDs) and optical disk drives (ODD), by using information published in the JRC report devoted to the analysis of material-efficiency requirements for enterprise servers (Talens Peiró and Ardente, 2015). Table 9 illustrates the list of substances for SSDs ([13]), derived from information published by a manufacturer (Seagate, 2016).

The average composition of PCBs in notebooks is detailed in Table 11 (Chancerel and Marwede, 2016); the composition of cables was derived from the Standard IEC TR 62635 (2012), that specifies the material composition of cables: 76 % polymers; 24 % copper. For composition of batteries, the work carried out by Clemm et al. (2016) was used (see Section 2.3.5 for details).

Based on these references, Table 10 summarizes the reference BoM of an average notebook computer. This BoM will be used in the following sections for the assessments of potential requirements on material-efficiency aspects.

As computer technologies are evolving quickly, it is reasonable to think that certain components will become less and less common in the future (e.g. ODD), or will be replaced

([13]) Information on the composition of SSDs in the literature is still limited/partial, as well as the estimation on how this technology will evolve in the future and how intensively it will be used in the computer product group. The list of substances for SSDs have been here presented for the sake of completeness, while the presence of SSD in computers was not considered in the assessments in the following sections.

by new technologies (e.g. HDDs replaced by SSDs). However, Kasulaitis et al. (2015) analysed the case study of notebooks, in terms of bill of attributes (materials and components) to be used for LCA or MFA studies, and stated that for the notebooks cohort of their work, there was surprisingly little variation over time for the same product type (i.e. 14.1-inch notebooks).

Table 7 — BoM for notebooks, modified from Talens Peiró et al. (2016b) with mass of battery as in Clemm et al. (2016)

Components	**Materials**	**[g]**
Plastic polymers	Plastic blend with flame ret. (PC+GF20 FR40)	109
	Plastic blend with flame ret. (PC ASA CF10 — FR40)	129
	Poly-methyl methacrylate (PMMA)	105
	Unspecified plastics	103
Metals	Aluminium	189
	Magnesium alloy	177
	Steel (including screws)	77
Display panel	Glass + other (unspecified)	160
Batteries	Prismatic battery: Li-ion	260
	Button battery: lithium manganese dioxide	3
PCBs	Motherboard	167
	RAM cards	17
	CPU	4
	Other PCBs	77
Other components	ODD	212
	Storage system	96
	Fan	10
	Small LCD	5
	Speakers	5
	Lamps	8
	Cables	17
	Total	**1 930**

Table 8 — BoM of HDDs and ODDs (Talens Peiró and Ardente, 2015)

HDD	**[%]**	**ODD**	**[%]**
Aluminium	45.0 %	Low alloyed steel	60.8 %
Steel	31.2 %	Copper	3.7 %
Ferrous based	8.7 %	Aluminium	0.5 %
Copper	0.4 %	Plastics (HDPE)	14.8 %
Magnet	3.9 %	Plastics (ABS)	6.3 %
PCB	3.9 %	Plastics (PC)	3.7 %
Plastic (PCABS)	3.9 %	PCB	10.1 %
Plastic (PCGF)	3.0 %		

Table 9 — Composition of SSDs (Seagate, 2016)

Substance	**[%]**	**Substance**	**[%]**
Al	30.27 %	Ag	0.91 %
Fe	15.01 %	Hva-2 (PDM)	0.86 %
Fused silica	9.00 %	Calcium monoxide	0.83 %
Epoxy resin	6.11 %	Nickel	0.80 %
Al_2O_3	4.79 %	Benzenedicarboxylic acid polymer	0.69 %
Copper (metallic)	4.77 %	Disodium-oxide	0.60 %
Magnesium silicate talc	3.25 %	Epoxy resin	0.47 %
Si	3.15 %	Pegoterate- (inn)	0.37 %
Tantalum	2.68 %	Phenol polymer	0.36 %
LCP polymer	1.89 %	Zinc	0.33 %
Dioxygen	1.81 %	Magnesium (metal)	0.33 %
Sn	1.77 %	Aromatic polyimide polymer	0.31 %
Vinyl silicone oil	1.69 %	Chromium	0.29 %
Fibrous-glass-wool	1.44 %	Barium titanate(IV)	0.25 %
Pigment black 28	1.35 %	Diiron-trioxide	0.18 %
C	1.22 %	Flowers of zinc	0.16 %
Proprietary	0.92 %	Other materials	1.14 %

Table 10 — Summary BoMs considering Table 7 and Table 8

Components	Materials	[g]	[%]
Plastic polymers	Plastics (including those from storage systems, ODD and cables)	515.0	26.7 %
PCBs (motherboard, RAM, CPU, others)	Various (*)	265.0	13.7 %
PCBs (storage systems and ODD)	Various (*)	71.2	3.7 %
Batteries	Various	262.6	13.6 %
Metals components	Steel and ferrous	225.1	11.7 %
	Aluminium	211.7	11.0 %
	Magnesium alloy	177.0	9.2 %
	Copper	12.1	0.6 %
	Rare earth element (in magnets)	1.9	0.1 %
Display panel	Glass + various (**)	160.0	8.3 %
Others	Various (**) (in fan, small LCD, speakers and lamps)	28.0	1.5 %
	Total (rounded up)	**1 930**	**100 %**

(*) detail provided in separate tables; (**) unspecified

Table 11 — Average composition of PCBs in notebooks (Chancerel and Marwede, 2016)

Material in PCB	Average composition	Material in PCB	Average composition
Ag	0.11 %	Pd	0.02 %
Al	5.00 %	Sn	1.60 %
As	> 0.01 %	Sr	0.04 %
Au	0.02 %	Ta	0.58 %
Ba	0.56 %	Zn	1.60 %
Be	0.01 %	***Glass:***	
Bi	0.01 %	SiO_2	18.00 %
Cd	> 0.01 %	B_2O_3	3.00 %
Cl	0.10 %	K_2O	0.20 %
Co	0.01 %	CaO	6.00 %
Cr	0.35 %	MgO	0.35 %
Cu	19.00 %	NaO	0.20 %
Fe	4.00 %	***Plastics:***	
Ga	> 0.01 %	C	30.00 %
Mn	0.75 %	Br	3.50 %
Ni	0.60 %	Sb	0.30 %
Pb	0.98 %		

2.3.3 Tablets

A tablet can be defined as a 'type of computer lacking a physical keyboard, relying solely on touchscreen input, having solely a wireless network connection (e.g. Wi-Fi, 3G), and primarily powered from an internal battery (with connection to the mains for charging, not primary powering of the device)' (Schischke et al., 2014, 2013). In their analysis, Schischke et al. (2014) purchased and disassembled a total of 21 different tablet computers. The selection of the 21 included several criteria, such as the market relevance (sales rankings, reviews, novelty), the price category (EUR 120-600), the display size (diagonal 7-10 inches), and performance (CPU, RAM, storage, battery, operation system).

The BoMs of the different tablets were retrieved by the authors of the mentioned work during disassembly tests. Table 12 shows the average BoM derived from the disassembly of 21 tablets, as well as the average BoMs of tablets with Al-housing and of tablets with plastic housing.

Table 12 — BoMs of 20 tablets, tablets with aluminium housing, and tablets with plastic housing (all averages) (Schischke et al., 2014)

	Tablets all 20 (average)	**Al-housing (average)**	**Plastic housing (average)**
	[g]	**[g]**	**[g]**
Aluminium	41.5	103.7	0.0
Steel sheet	3.9	0.0	6.6
Magnesium	14.8	4.2	21.8
Plastics (unmarked)	4.0	0.0	6.7
ABS	1.0	2.5	0.0
Polycarbonate	13.1	0.0	21.8
Polycarbonate + GF	9.0	0.0	15.0
ABS+PC	24.6	21.9	26.4
Display panel	226.8	226.8	226.7
Printed circuit board/auxiliary boards (with electromagnetic interference (EMI) shielding)	44.0	52.0	38.6
Speaker	3.3	3.4	3.2
Battery	124.6	150.1	107.6
Components: average weight	510.5	564.6	474.5
Tablet: average weight	**528.7**	**583.1**	**492.3**
Other components ([14])	18.1	18.5	17.9

([14]) Components whose weight is less than 10 g, such as screws or small cables.

2.3.4 External power supplies

EPS ([15]) are used with electronic devices (such as notebooks and tablets) that require power, but do not contain internal components to derive the required voltage and power from the grid power (source). The EPS transfers power to the device by converting voltage and current characteristics from the source to the desired load levels. Most EPS nowadays are based on the switching-mode technology. A switching-mode power supply aims to minimise the amount of energy wastage occurring in the conversion thanks to continuous switches between low-dissipation, full-on/full-off states and thanks to negligible dissipation transitions.

Table 13 provides the best-available data on BoMs of EPS (compositions consider both materials and components). Values reported by the Bio Intelligence Service (2007) and prepared by Dimitrova (2012) were used to set out the reference compositions, considering the 60 W EPS relevant for the tablet case study and the 90 W EPS for the notebook one.

EPS manufacturers, however, are now able to reduce the mass of EPS for notebooks to less than 100 g, for an output power of 65 W (FINsix®, 2016). The most recent data about the average total mass of EPS for tablets and notebooks is reported by Risk & Policy Analysts Limited (2014). In this recent study, values of 114 g (mass of EPS used by tablets) and 440 g (mass of EPS used by notebooks) were indicated as reference values.

Table 13 — BoMs for EPS. Different sources.

Source:	(Bio Intelligence Service, 2007; Dimitrova, 2012)		(von Geibler et al., 2003)	(ecoinvent)*
EPS type/function:	60 W notebook	90 W notebook	Power adapter	power adapter, for notebook
Components and materials — [g] and (%)				
Plastics				
Bulk plastics	37 (*14.1 %*)	51 (*12.9 %*)	-	-
Tec Plastics	48 (*18.3 %*)	73 (*18.4 %*)	-	-
Polyvinyl chloride (PVC)	-	-	35.7	35.6
High-impact polystyrene (HIPS)	-	-	89.3	88.9
Ferrous metals				
Ferro	2 (*0.8 %*)	3 (*0.8 %*)	-	-
Steel	-	-	178.5	178.5
Non-ferrous metals				
Non-ferro	80 (*30.4 %*)	93 (*18.5 %*)	-	-
Copper	-	-	53.6	53.6
Electronics	96 (*36.5 %*)	176 (*44.4 %*)	-	-
Cables and plugs				
Cables	-	-	-	117.0
Plugs	-	-	-	58.5
Total weight (g)	**263**	**396**	**357**	**532**

(*) Based on von Geibler et al., 2003.

([15]) The device is also known as an AC adapter, AC/DC adapter, power adapter, DC power supply or battery charger. The IEC/TS 62700 (2014) defines it as the component that provides DC current to the device (a notebook computer, in the context of the standard).

2.3.5 Batteries

Data from Berger (2012) indicated the market share of the different LIB subchemistries in tablets and notebooks in 2011, together with projections until 2020. Figure 4 shows that lithium-NMC cathodes are expected to increase in market share in notebooks as well as in tablets, while the share of lithium-cobalt-oxide (LCO) cathodes is expected to decrease (partly due to cost), as well as lithium-nickel-cobalt-aluminium (NCA) cathodes. According to Berger (2012), NCA is used in top-of-the line products only, which require the longest operational time, while LCO (lower energy than NMC) is used for lower priced products.

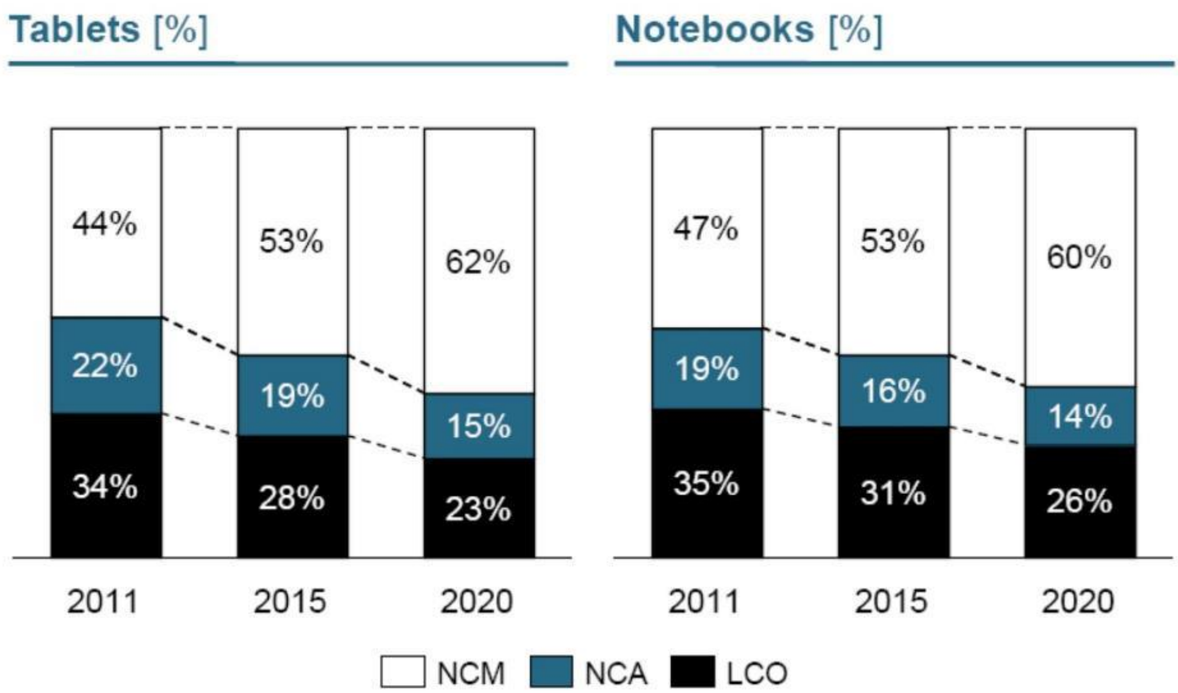
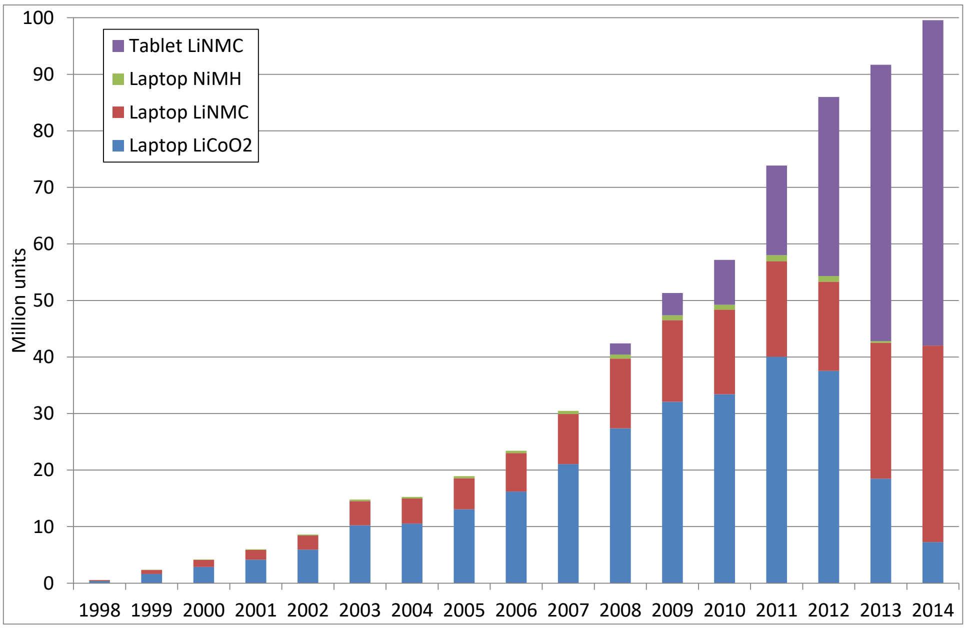


Figure 4 — Types of batteries used and expected to be used by notebooks and tablets (Berger, 2012)

It should be noticed that lithium-ion batteries are currently the only relevant battery type used in the product groups in the scope of this report. Other types, such as nickel-metal-hydride (NiMH), nickel cadmium (NiCd), or lead-acid (Pb) batteries are not relevant, and neither are other lithium-ion subchemistries, such as lithium-iron-phosphate (LFP) and lithium-manganese-oxide (LMO), which are used in industrial and automotive applications due to their specifications.

Data from Berger (2012) were confirmed by Chancerel et al. (2016), who indicate the volumes of the different LIB subchemistries in notebooks and tablets which are put on the market and the estimated volumes of such waste batteries in the EU. Figure 5 shows that NMC cathodes are expected to increase in market share in both notebooks and tablets, while the share of LCO and NiMH cathodes is expected to decrease. No distinction has been made between NMC and NCA cathodes. The overall volume of batteries put on the market for notebooks and tablets combined increased to around 100 million units in 2014. Figure 5 further shows the expected volumes of waste batteries generated in the EU with projections until the year 2020.

No further evidence on the extent to which NCA is used for notebook or tablet batteries could be produced. Various sources point out that NCA does not play a role in mobile consumer devices due to cost and safety concerns (Battery University, 2016b; Investing News, 2016), however, available data are inconclusive.



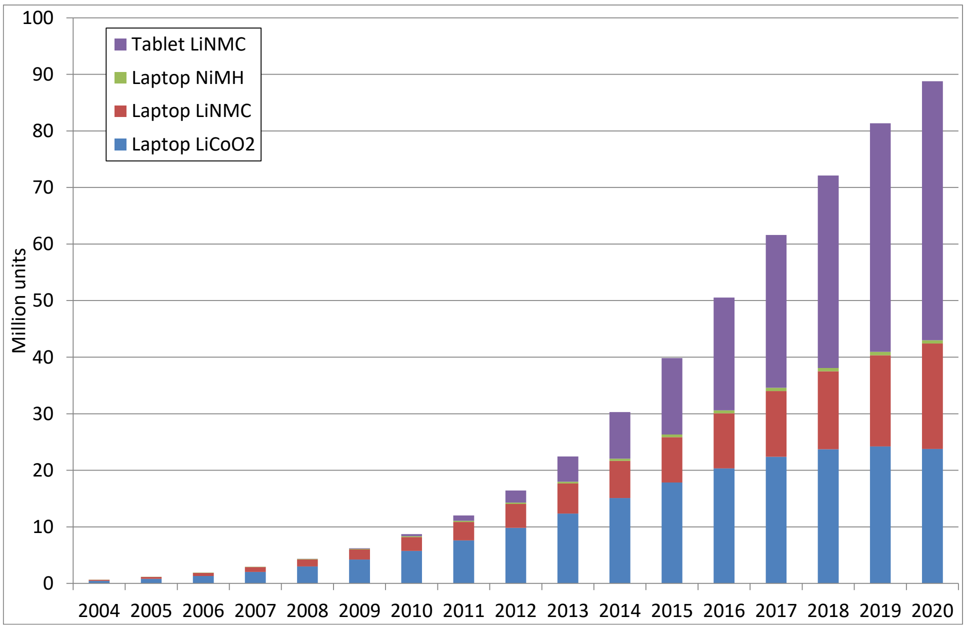


Figure 5 — Volumes of the different lithium-ion battery subchemistries in notebooks (Laptop NiMH, Laptop LiNMC and Laptop LiCoO2) and tablets (Tablet LiNMC) put on market (top) and the estimated volumes of such waste batteries generated (bottom) in the EU (Chancerel et al., 2016).

A study on the lifetime and environmental impacts of notebook batteries (Clemm et al., 2016) includes a BoM for a notebook-battery pack manufactured in 2013, based on LCO. Material and environmental data on the battery cell were surveyed directly from one of the largest battery-cell manufacturers worldwide. The notebook-battery pack consisted of four cells, a battery-management system, housing and cables. While data on the battery cell were surveyed directly from the manufacturer, the mass and composition of the housing, cables were approximated from a comparable tablet battery pack and scaled by weight. The composition of the battery-management system (PCB assembly) was approximated via a battery-management system from another notebook-battery pack. Table 14 lists the mass of each of the components of the notebook battery.

Table 14 — Mass of components of the notebook battery (Clemm et al., 2016).

Battery component	**Mass [g]**
Cells (4 pcs) (detailed in Table 15)	238.0
Housing	12.3
PCB	3.3
Cables	6.4
Total battery mass	**259.6**

Table 15 lists the main cell components, subcomponents, materials and weights for a representative LCO prismatic notebook battery cell from primary industry data (Clemm et al., 2016).

Table 15 — BoM of an LCO notebook-battery cell from one of the largest cell manufacturers worldwide (Clemm et al., 2016).

Cell component	**Subcomponent**	**Material**	**Mass per cell [g]**
Cathode	Active mass	Lithium-cobalt-oxide (LiCoO2, LCO)	24.62
	Additive	Soot	0.51
		Polyvinylidene fluoride (PVDF)	0.51
	Conductor	Aluminium	3.40
	Component mass		**29.04**
Anode	Active mass	Graphite	12.18
	Additive	Soot	0.13
		Styrene-butadiene rubber (SBR)	0.19
	Conductor	Copper	4.82
	Component mass		**17.32**
Electrolyte	Solvent	Carbonate (ethylene carbonate and propylene carbonate)	7.5
	Salt	Lithium hexafluorophosphate (LiPF6)	0.8
	Component mass		**8.3**
Separator	Polyolefin	Polyolefin	2.27
	Component mass		**2.27**
Passive components	Housing	Aluminium	2.36
	Positive pole	Aluminium	0.1
	Negative pole	Nickel	0.1
	Positive internal pole	Aluminium	0.01
	Negative internal pole	Copper	0.01
	Isolation material	Polypropylene	0.001
	Component mass		**2.581**
Total mass per cell			**59.51**

The consumption of energy and auxiliaries during the production of one such cell is listed in Table 16.

Table 16 — Consumption of energy and auxiliaries during the production of one cell as detailed in Table 15 (Clemm et al., 2016).

Inputs	**Amount**
Electricity	0.2346 kWh
Steam	0.0975 kg
Water	0.6425 kg
Nitrogen	0.00795 Nm^3

Table 17 presents a detail of the composition of an average battery for notebooks, based on the expected trend of different battery types in computers (Figure 5), recent data provided by Chancerel et al. (2016) and composition of exemplary batteries from literature (Clemm et al., 2016; Kushnir, 2015).

Table 17 — Average composition of LCO, NMC and NCA batteries for notebooks

Type	**LCO**	**NMC**	**NCA**	
Market shares (2020)	26.00 %	60.00 %	14.00 %	
Elemental composition				**Average**
Co	22.80 %	3.60 %	2.30 %	8.4 %
Li	2.70 %	1.30 %	1.90 %	1.7 %
Ni	0.20 %	3.60 %	12.10 %	3.9 %
Cu	8.00 %	15.90 %	13.30 %	13.5 %
References	(Clemm et al., 2016)	(Kushnir, 2015)	(Sommer et al., 2015)	-

2.4 Content of precious and critical raw materials

Raw materials are crucial to Europe’s economy, and securing reliable and unhindered access to certain raw materials is a growing concern within the EU (Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, 2016). To address this challenge, the European Commission has created a list of CRMs. CRMs combine a high economic importance to the EU with a high risk associated with their supply.

Chancerel et al. (2015) estimated the quantities of several relevant metals (cobalt, gallium indium, rare earth elements (REE), tantalum, tin, gold, palladium, and silver) embedded in information and communications Technology (ICT) devices put on the market in Germany 2007 and 2012. Among all devices in scope, notebooks are important in terms of metals embedded in notebooks put on the market. Some of the findings by Chancerel et al. (2015) are illustrated in Figure 6, showing the content and distribution of cobalt over the ICT products sold in Germany in 2007 and 2012. In the single device, mass-wise cobalt, light rare earth elements and tin are of interest, whereas light and heavy REE, tantalum, cobalt and gold have the main value (Figure 7).

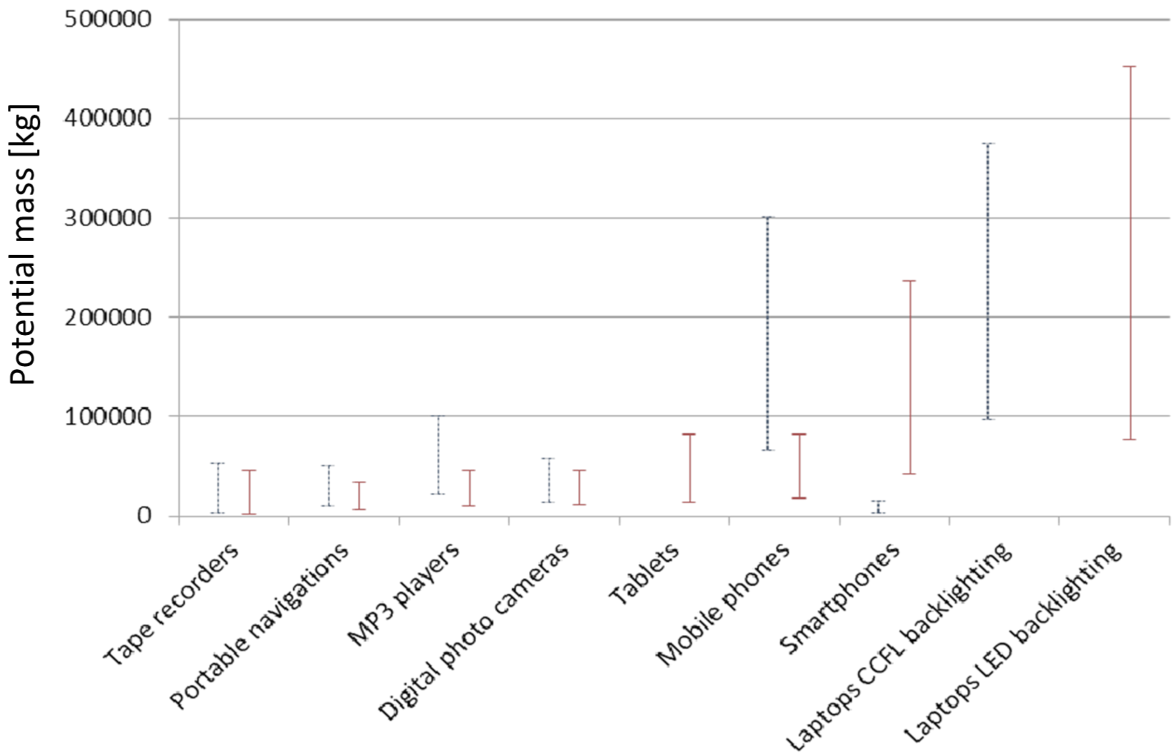


Figure 6 — Cobalt potential in kg and distribution over the products sold in Germany in 2007 (blue line) and 2012 (red line) (Chancerel et al., 2015)

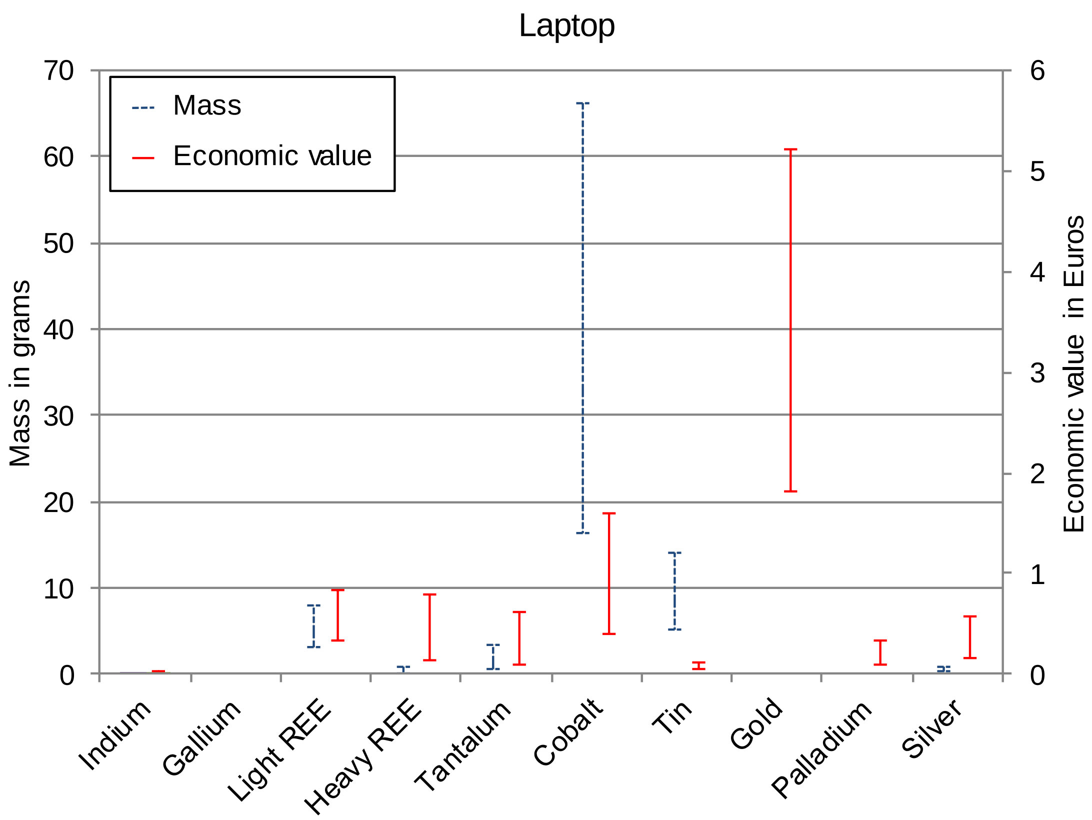


Figure 7 — CRMs and other relevant materials in notebooks (Chancerel et al., 2015)

2.4.1 Content of cobalt in batteries

Batteries have been identified as a fundamental source of cobalt in WEEE (Chancerel et al., 2013; European Commission, 2014a). LIB based on LCO which contain approximately 14 % cobalt (Sommer et al., 2015), account for the majority of cobalt consumption. Minor amounts of cobalt are contained in NiCd and NiMH batteries as well as in LIB based on NMC and NCA (Sommer et al., 2015).

Details of the cobalt content in batteries is provided in Figure 8. The data on cobalt content in LCO batteries in Figure 8 is markedly lower (14 %) compared to the data reported by Clemm et al. (2016) (22.8 %). The reason for this is assumed to be related to the battery type: the data by Clemm et al. (2016) refers to an integrated notebook pouch-type battery without heavy-duty casing (housing makes up less than 8 % of the battery pack by weight), while the data reported by Sommer et al. (2015) is based on literature on prismatic LCO batteries, published in the years between 2002 and 2012, where the reported housing mass percentage is between 24.5 % and up to 33.4 % of the total battery pack by weight.

Average REE and cobalt content in batteries in wt.%.

Battery type	Average cobalt content	Error	Average REE content	Error
Li-ion LCO	14.0	±2	0.0	–
Li-ion NCA	2.5	±1.5	0.0	–
Li-ion NMC	4.0	±2	0.0	–
Li-ion other types	0.0	–	0.0	–
NiCd	1.0	±0.5	0.0	–
NiMH AB5	3.0	±0.5	10.0	±2
NiMH other types	3.0	±0.5	0.0	–
Other batteries	0.0	–	0.0	–

Figure 8 — Detail of the content of cobalt for different batteries (Sommer et al., 2015)

2.4.2 Content of rare earths in HDDs

Even though the use of HDDs will decline in the future (see Figure 1, projections for 2018-2020), HDDs will keep playing a key role in computers thanks to their lower price and higher storage capacity than SSDs.

HDD magnets are the single largest application of rare earths, taking up 21 % of the total rare earth production by volume and generating 37 % of the total value of the rare earth market (Sprecher et al., 2014a). Although there are two types of rare earth permanent magnets (neodymium-iron-boron (NdFeB) and samarium-cobalt), neodymium-based magnets are more powerful (Sprecher et al., 2014a), and represent by far the most dominant of all current neodymium applications (Sprecher et al., 2014b). Typical elemental composition of NdFeB magnets includes (Prakash et al., 2014): neodymium (Nd) (23-25 %); dysprosium (Dy) (3.5-5 %); praseodymium (Pr) (0.05-5 %); Fe (62-69 %); B (1 %); Co (0-10 %); C (0-0.14 %); N (0-0.1 %); others (1-2 %). München and Veit (2017) reported a similar Nd content in NdFeB magnets (25.3 % by weight, adapted from Stuhlpfarrer et al. (2015), and 21.5 % by weight, directly measured on sintered magnets). HDDs will remain as the largest source of recycled neodymium until 2025, while magnets from wind turbines will become available for recycling mainly starting from 2030 (München and Veit, 2017). Recycling of rare earths from HDDs is technically feasible, once HDDs are extracted and separately sorted from other waste streams.

2.5 Interoperable external power supplies

EPS are frequently sold together with end-use appliances, such as notebooks, tablets and mobile phones. Especially for notebooks and tablets, they are usually personalised so as to be used only with the end-appliance with which they are sold (Dimitrova, 2012). This means that the EPS design is optimised for the device it is designed to power but is not generally usable with other devices (IEEE Std 1823, 2015). In that case, the 'active lifetime' of most of EPS is limited by the lifetime of the end-product that it serves (Bio Intelligence Service, 2007).

The concept of a common EPS aims to overcome this limitation, allowing the potential reuse of an EPS with other devices, thanks to interoperability, thus extending its useful service life.

A common EPS also plays a key role in terms of reduction of WEEE and residual waste. Because of their small size, the likelihood of EPS being discarded in the solid municipal waste fraction is high, while the correct practice would require them being orientated to a WEEE collection point for recycling (Bio Intelligence Service, 2007). Once an EPS enters the recycling plant the recycling process consists of mechanical shredding and material recovery (in particular ferrous metals and copper) with a similar efficiency to that of processing small household appliances ([16]).

This section provides an overview of the technical background and the existing specifications for common EPS in the ICT sector, as well as practical examples.

2.5.1 Common external power supplies for mobile phones

The European Commission has already addressed the problem of incompatibility of chargers for the mobile-phone product group, recognised to be a major inconvenience for users and also a cause of excessive material consumption and unnecessary waste.

Cucchietti et al. (2011) observed that more than a billion new devices are sold in the worldwide market every year and most of them represent a replacement of an older model. About 20 % of the volume of devices sold is represented by the EU market (Risk & Policy Analysts Limited, 2014). This implies that most of the associated old EPS are discarded even if still operational, as they are not compatible with the new devices. The GSM Association (GSMA) quantified this waste as about 51 000 t (the amount of redundant chargers manufactured and sold worldwide with mobile phones every year), which can potentially be eliminated (GSMA, 2009). However, potential savings in raw-material consumption related to common EPS do not appear to have materialised due to the very limited decoupling of mobile phones from their chargers, with only 0.02 % of EU handset shipments from 2011 to 2013 being supplied without an EPS. The associated reduction in the consumption of raw materials was estimated to be in the range 400-1 300 t (Risk & Policy Analysts Limited, 2014).

Therefore manufacturers agreed to harmonise chargers in the EU, with a voluntary commitment, and to provide charger compatibility on the basis of the micro-USB connector (European Commission, 2009). The European Committee for Electrotechnical Standardisation (FR: Comité européen de normalisation électrotechnique (Cenelec)) created a task force to develop the interoperability specifications of a common (universal) EPS, published as EN 62684:2010, and the IEC released its version of the common EPS Standard as IEC 62684:2011. Common EPS connect to the load with a micro-B USB connector and a cable, which may be detachable from the EPS thanks to a USB type-A connector (Figure 9).

([16]) Information based on interviews with WEEE recyclers.

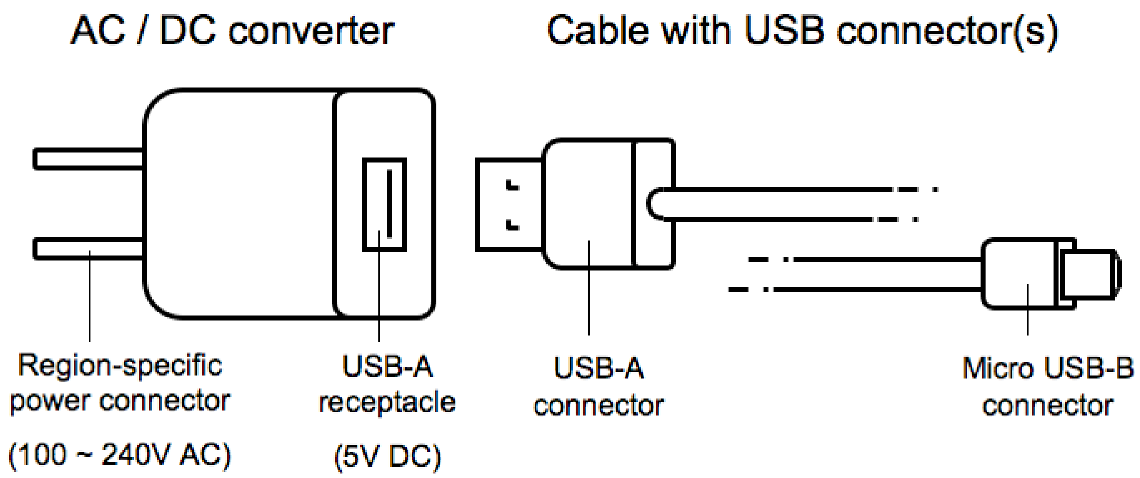


Figure 9 — Graphical representation of an EPS with micro-B connector, detachable cable with USB type-A connector and USB type-A receiver (image credits: ©Pugetbill 2011)

2.5.2 Common EPS for personal computers

As seen in Table 1, millions of mobile computers are shipped every year to Europe, with EPS that have the potential to be reused with other computers. Typically, each EPS is designed to optimally satisfy the requirements and specifications of the target notebook computer. The development of specifications for common EPS, however, can be based on the following three documents.

- IEC TS 62700:2014 (DC power supply for notebook computers).
- Standard IEEE Std 1823™-2015 (IEEE standard for universal power adapter for mobile devices).
- Recommendation ITU-T L.1002 (2016) (External universal power adapter solutions for portable ICT devices).

IEC TS 62700

This technical specification (TS) was issued by the IEC with the objective of supporting global interoperability of EPS for a specific range of products, so improving reusability and preventing waste generation (IEC/TS 62700, 2014).

IEC/TS 62700 (2014) states the minimum requirements for EPS for notebook computers. Specifically, it provides information about electrical specifications, such as DC output load conditions and voltage regulation, influences in the notebook computer market and suggestions on how to divide classes of devices according to power range (e.g. 65 W, 90 W, 120 W, but also other relevant classes depending on the expected power trends).

IEC/TS 62700 also provides specifications for connectors and plugs. According to the TS, the EPS may be provided with either a captive DC cable or with a detachable DC cable. As notebook computers have become slimmer and thinner, a 4.5 mm DC connector ([17]) would be appropriate for many slim computers, but may not have the current carrying capability for a 120 W EPS.

([17]) A connecting body used to connect and disconnect the electrical interface between an EPS and a device (IEC/TS 62700, 2014).

IEEE Std 1823-2015

The standard for common power supplies (or universal power supplies) ([18]) for mobile devices intended for portable computing and entertainment devices (notebooks and tablets) was issued by the IEEE in 2015 (IEEE Std 1823, 2015). The objective was to set out the features of a generic power-supply designed for reuse across brands, models and years. A compliant EPS will supply a nominal 21 V at up to 130 W and may negotiate voltages up to 60 V at power levels up to, but less than, 240 W. Each EPS will have one or more power ports to service load devices with control of each port via a serial communications link, an electrical variant of the CAN ([19]) bus standard. The power range delivered to the device by a compliant EPS should range from 10 to 240 W (IEEE Std 1823, 2015).

ITU-T L.1002

Recommendation ITU-T L.1002 (2016) sets out the TSs of common EPS ([20]), designed for use with portable ICT devices. The recommendation was issued by the Telecommunication Standardisation Sector of the International Telecommunication Union (ITU) ([21]). The goal of ITU-T L.1002 is to provide guidelines for energy efficiency and no-load power, but also to reduce greenhouse gas emissions, to optimise the use of scarce and raw materials and to enable a long product lifetime to reduce e-waste generation.

ITU-T L.1002 firstly describes basic configurations of EPS, consisting of a power adapter block with a detachable input cable and a detachable output cable to the ICT device. Then, it sets out different general recommendations for EPS and their interfaces, including cables, connectors, voltage, current, ripple noise, energy efficiency, no-load power, safety, electromagnetic compatibility, resistibility and eco-environmental specifications. All the recommendations have been set with the aim to increase interoperability of EPS and to reduce the number of duplicate portable power adapters.

The basic EPS configuration suggested by ITU-T L.1002 consists of an EPS with a detachable input cable ([22]) and a detachable output cable ([23]) to the ICT device. Nonetheless, adapters designed and tested with end-products may optionally use captive cables (if needed) to support system-level robustness and technical-performance requirements.

As improper combinations of EPS with ICT devices can result in incompatibility or reduced performance, ITU-T L.1002 also recommends EPS categories based on the output power interface (voltage, current and power) for different types of ICT products designed for portable use. Each category is defined with examples of the ICT-device types. Table 18 reflects the most common categories available on the market ([24]).

([18]) The product group is called Universal Power Adapter by the IEEE Computer Society.
([19]) Controller area network.
([20]) Recommendation ITU-T L.1002 uses a different terminology and refers to universal power adapter solutions (UPA).
([21]) ITU is the United Nations agency specialised in the field of telecommunications, information and communication technologies.
([22]) detachable alternating current (AC) cable: A detachable cable used to connect the power adapter to the AC mains for powering through two connectors, one on the universal power adapter side and the other on the AC mains side.
([23]) Detachable direct current (DC) cable: A detachable DC cable connects the power adapter to the ICT device for powering through two connectors, one on the universal power adapter side and the other on the ICT device side.
([24]) The trend of lower energy consumption in ICT devices is leading to lower EPS power requirements and, in view of this, a possible reduction of categories.

Table 18 — Recommended categories of EPS (ITU-T L.1002, 2016)

Category	Voltage [V]	Current [A]	Power [W]
Small 1	5	1.5 to 3	7.5 to 15
Small 2	12	2.5	30
Small 3	20	2.25	45
Medium	20	3	60
Big	20	4.25	85

2.5.3 USB cables and connectors

Micro-USB ([25]) connectors may represent a way to grant compatibility and interoperability of common EPS.

As mentioned in Section 2.5.1, a voluntary commitment to harmonise EPS in the EU was set among mobile-phone manufacturers and, as a result, it is now requiring EPS compatibility through micro-USB connectors. According to Risk & Policy Analysts Limited (2014), the market share of tablets with micro-USB charging solutions has increased over the period 2009-2013. For notebooks, however, very few micro-USB charging solutions are adopted and proprietary charging solutions are dominant.

- A model of the *tablet* market suggests that between 2008 and 2013, 69 % of models were supplied with a proprietary EPS but the micro-USB charger has become more commonplace, rising from 17 % of sales in 2011 to 47 % in 2013.
- The power requirements of *notebooks* can vary greatly depending on the size and internal components, with most charging in the range 40 W to 90 W, although this can be as low as 15 W and as high as 240 W. Therefore, micro-USB connectors are not suitable yet for charging many notebooks, having a limit at 60 W (3 A of current and 20 V of voltage) (USB Implementers Forum, 2016).

As found by Risk & Policy Analysts Limited (2014), 2013 was a turning point in terms of EPS, as the use of micro-USB EPS noticeably increased while proprietary EPS decreased. By looking at the tablets sampled by the authors (top 20 Amazon best sellers ([26]), sampled in September 2016), the use of micro-USB charging resulted the most common technology adopted.

Power delivery for portable information devices is continuously evolving and new USB technologies tend to combine data transport with high power delivery (IEC/TS 62700, 2014). Indeed, new USB technologies seem to target a higher range of power delivered to the device. However, this may not be sufficient to cover the specification of the Standard IEEE 1823 (2015), which specifies a power range of 10-240 W delivered to the device. One opportunity may be represented by the technology USB power delivery (USB PD), which supports up to 100 W of bidirectional power (sink/source) and up to 5 Gbit/s of data transport over USB (IEC/TS 62700, 2014), which became 10 Gbit/s with the release of the USB 3.1 Gen 2 specification (USB Implementers Forum, 2016). This technology is not covering the entire range proposed by the Standard IEEE 1823, but is a suitable solution for devices requiring 60-100 W (notebooks included).

While the common EPS described in the Standard IEC 62684:2011 (for mobile phones) adopted a micro-USB connector (as in Figure 9), another new USB specification for a small 24-pin reversible-plug connector was developed and named USB type C (Figure 10). USB type-C cables and connectors were developed to supply mobile devices, including notebooks and tablets, building on the new USB 3.1 Gen 2 standard for power and speed

([25]) Universal serial bus.
([26]) Nine different manufacturers were present in the tablet sample.

performance, which supports up to 100 W of bidirectional power (USB Implementers Forum, 2016). Among the main features it is possible to identify the reversible-plug orientation, the reversible cable direction and the scalable power. The Recommendation ITU-T L.1002 suggests implementing the USB type-C connector for the interface of EPS, in order to support broad reusability and interoperability (USB type-C receptacles as specified in IEC 63002, IEC 62680-1-2 and IEC 62680-1-3).

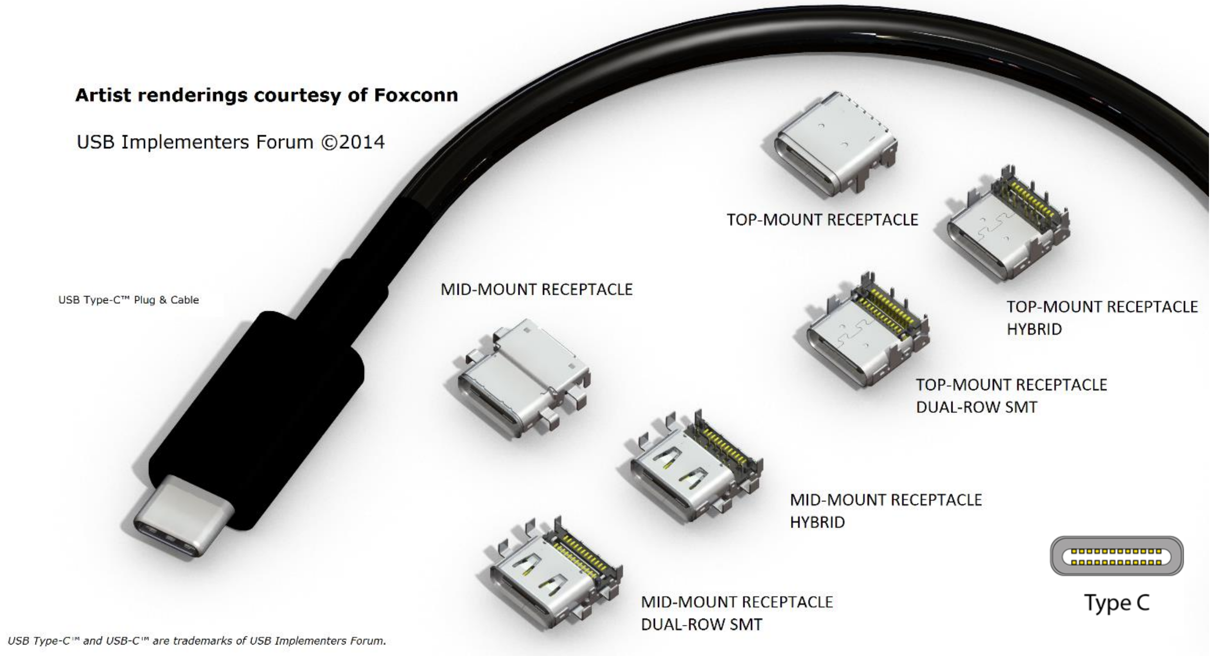


Figure 10 — USB type-C cable and connectors (image credits: ©USB Implementers Forum 2014)

2.6 Environmental impacts

Several studies focused on the environmental assessment of ICT devices are available in the literature. Several LCA studies have shown that the manufacturing phase of ICT products has a proportionally increasing environmental impacts as compared to the use phase (Prakash et al., 2016c). However, a main issue is represented by the representativeness of the product or system under analysis: as the technological progress in this sector is very fast, environmental results can be considered outdated after few years. Therefore, relying on dated studies might divert from the current state of play, and deep knowledge on the system under analysis is needed.

In this regard, Deng and Williams (2011) studied the question of how to measure technological progress at the product level, by using a 1997 desktop computer as a base case and a 2007 desktop computer as a replacing product. Generally, the production phase (which involves material extraction/processing and the manufacturing phase) and use phase have the highest impact in the life cycle of ICT products. The use phase seems to be predominant in energy consumption and global warming for some ICT products but for others, especially energy-efficient and low-weight products, manufacturing may dominate (Arushanyan et al., 2014). In the desktop-computer case study, on one hand the technological progress reduces the energy consumption of electronic devices (which was measured by the authors as the energy required by the transistors), on the other hand it might induce demand for more sophisticated components and for more powerful chips (which contain many more transistors), and therefore shift the highest impact to the other life-cycle phases (Deng and Williams, 2011).

Many studies focused on the initial stage of the ICT-device life cycle, using a 'cradle-to-gate'[27] approach, focusing mainly on the production phase. Teehan and Kandlikar (2013) estimated and compared the embodied CO_2 emissions of 11 ICT products, including desktop computers, notebook computers, a thin client device, an LCD monitor, small mobile devices (e.g. tablets and e-readers), a rack server and a network switch. The authors deviated from the conclusions drawn by Deng and Williams (2011), as they claimed that embodied CO_2 emissions for newer products are 50-60 % lower than corresponding older products with similar functionality, largely due to decreased material usage, especially reductions in integrated circuit content. Furthermore, the embodied CO_2 impact identified in the study was found to be linear with respect to mass, with a range of 27-39 kg CO_2 equivalent (eq) per kg of ICT product. This range, however, was judged to be very general and not totally appropriate for comparisons (Andrae, 2016). Also Malmodin et al. (2014) estimated the embodied impact of desktop computers (200-800 kg CO_2 eq/device) and notebook computers (100-400 kg CO_2 eq/device), with very wide ranges.

For the EoL phase, treatments have to be properly managed, as electronic waste may contain hazardous constituents that may negatively impact the environment and affect human health if not properly managed (Nnorom and Osibanjo, 2008). Also in this case it is possible to obtain data from the literature, but impacts of EoL processing deeply depends on the approach used to model impacts. Andrae (2016) recently published a review of methodological approaches used to conduct LCAs of consumer electronics. The author stated that LCA is the primary tool to study reuse, recycling and remanufacturing for an electronic product. However, external comparisons among LCAs are only meaningful if models from different companies (including functional unit and system boundaries) are technically comparable (Andrae and Vaija, 2014). Van Eygen et al. (2016) conducted an MFA devoted to the natural-material consumption of the recycling-chain system. Desktop and notebooks were the product groups analysed by the authors: collection, primary treatment and end-processing were the three phases of the EoL. The biggest impact for the primary-treatment step is caused by the use of chemicals, while the production of secondary metals represented the first cause of impacts for the end-processes. The treatment of the notebook batteries was found to be responsible for around 16 % of the impact.

Many studies have assessed the environmental impacts of LIB of electric vehicles in recent years, however, data on batteries powering mobile devices such as notebooks, tablets and smartphones is scarce. Clemm et al. (2016) calculated the environmental impact of the manufacturing phase (based on primary industry data), distribution and EoL phase of a notebook LIB. The consumption of energy during the use phase is not assessed, as it serves the purpose of powering the notebook and thus must be allocated to the notebook itself. It was found that the production phase dominates the life cycle in all impact categories (e.g. 95 % in terms of global warming potential (GWP)), while the recovery of cobalt and nickel lowers the overall impact by a few percentage points (e.g. 4.3 % GWP). A contribution analysis found that the cells have the largest impact (87 % GWP), followed by the battery-management system (12 % GWP) and finally the housing. As a subcomponent of the cells, the cathode material (LCO) has the highest impact, followed by the anode (graphite) and the electrolyte ($LiPF_6$). The consumption of auxiliaries also contributes up to 24 % of the impacts (acidification potential) to cell production.

The material composition of the notebook battery is comparable to batteries powering tablets and smartphones and thus can be used for those devices as well.

Finally, focusing on the external power supply, Cucchietti et al. (2011) calculated the environmental impact of the production phase of chargers for mobile phones, by using a 'cradle-to-gate approach. The considered impact categories were climate change (measured by means of the GWP indicator) and energy demand (measured by means of

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27

the gross energy requirement indicator) and for both of them the main contributor to results was represented by electronic components (75-80 % of the embodied impacts). The authors concluded that also in the case of the other impact categories, the contribution to the results of electronics remains higher than 70 %.

Table 19 — Relevant sources in the scientific literature

Authors and year	**Type of product**	**Scope — impacts**
Andrae & Andersen, 2010	LCA of desktop computers and notebook computers	Literature review — GWP, Energy demand
Benoit et al., 2012	Generic notebook computer	Cradle to grave — social impacts
Choi et al., 2006	Personal computer	Cradle to grave — several indicators
Ciroth & Franze, 2011	Specific notebook computer	Cradle to grave — several indicators + social impacts
Duan et al., 2009	Desktop computer	Cradle to grave — several indicators
Ekener-Petersen and Finnveden, 2013	Generic notebook computer	Cradle to grave — social impacts
Eugster et al., 2007	Desktop computer	Cradle to grave
Manhart and Griesshammer, 2006	Notebook computer	Cradle to gate — social impacts
James and Hopkinson, 2007	Personal computer	several indicators
PE International, 2008	Notebook computer	Global warming
Prakash et al., 2016	LCA of desktop computers, notebook computers and mini desktop computers	Cradle to grave — GWP
Teehan & Kandlikar, 2012	Desktop computer	Literature review — GWP, Energy demand
Williams, 2004	Personal computer	Use phase — energy use

2.6.1 Standards for environmental assessment of ICT products

The European Framework Initiative for Energy & Environmental Efficiency in the ICT Sector grouped a series of standards focused on the environmental analysis of ICT products. Narrowing the analysis to goods only, it is possible to list the following.

- ETSI 203 199/ITU 1410: Methodology for environmental LCA of ICT goods, networks and services.
- IEC 62921: Quantification methodology for greenhouse gas emissions for computers and monitors.
- IEC 62725: Analysis of quantification methodologies of greenhouse gas emissions for electrical and electronic products and systems.
- IEC 50600-4: Design of data centre facilities and infrastructures.
- Greenhouse gas (GHG) protocol ICT Hardware: *Product life-cycle accounting and reporting standard ICT Sector Guidance* (Chapter 6). Guide for assessing GHG emissions of hardware.
- GHG protocol ICT Software: *Product life-cycle accounting and reporting standard ICT sector guidance* (Chapter 7). Guide for assessing GHG emissions related to Software.

— GreenGrid Carbon-usage effectiveness: *A green grid data centre sustainability metric* (carbon-usage effectiveness (CUE)).
— EU energy star: *Labelling energy-efficient office equipment*.
— EPEAT: *Electronic product environmental assessment tool*, by US EPA.

3 Analysis of end-of-life practices for the product group

For the analysis of the material-efficiency aspects of computers the REAPro (resource-efficiency assessment of products) method (Ardente and Mathieux, 2014) was applied. The method starts from the analysis of current EoL practices and processes, to identify product-resource-efficiency 'hot spots'. 'Hot spots' are those product's aspects that are relevant for some observed EoL processes, as for example: components that are relevant for the product durability, content of hazardous substances or relevant materials (e.g. precious or CRMs), parts that difficult to be treated and recycled, etc.

As highlighted in Section 2, the greatest part of the market for the computer product group is represented by notebook computers, tablet/slate computers and desktop computers (97 % of the total number of computers, in 2030) therefore the next sections have a particular focus on these three subcategories.

Section 3.1 illustrates processes currently performed for the recycling and recovery of computers, representing the so-called EoL scenarios (Ardente and Mathieux, 2014). Section 3.2 discusses some potential alternative processes to the scrapping of a product, such as prolonging its lifetime through repair and reuse.

3.1 Analysis of recycling/recovery practices

The recycling of computers is regulated by the European WEEE directive (European Union, 2012). According to this directive, components in computers that require selective treatments include:

- batteries;
- PCB larger than 0.1 dm^2;
- LCDs panels larger than 1 dm^2;
- external electrical cables;
- mercury-containing components, such as switches or backlighting lamps;
- plastic-containing brominated FRs;
- electrolyte capacitors containing substances of concern (height > 25 mm, diameter > 25 mm or proportionately similar volume).

However, the treatment of these components (and, in general, treatment of computers) are variable according to their type. Peculiarities of computer recycling will be discussed in the following sections.

3.1.1 Recycling/recovery of desktop computers (without integrated display)

The recycling of desktop computers currently follows two main scenarios, combining optional and (to a certain degree) accurate dismantling and depollution of the computer, with the following shredding and material recovery.

The *first scenario* (manual dismantling as initial treatment) has the benefit of separating the components with high integrity and purity, which allows a higher recovery rate in their following recycling processes. The main disadvantage is related to the labour cost and to the higher level of time required (with consequently a lower amount of waste treated per hour). Inversely, the *second scenario* (shredding as initial treatment) presents better economic performance (in terms of costs of treatment per tonne), while the efficiency of the sorting of materials is lower. The balance between the two scenarios is therefore represented by the potential economic gain from the additional recovery of certain precious metals (e.g. palladium, gold and silver) and valuable materials (e.g. copper) due to the dedicated-manual dismantling compared to the labour costs. It is also highlighted that the content of steel and aluminium does not represent a discriminating factor between the two EoL scenarios, since these materials are generally recovered at high rates with mechanical treatments. On the other side, the separation of plastics does not create an economic gain, since they have low recyclability (due to the content of several additives as FRs and fillers) and limited value. Shredded plastics from computers are generally contaminated by various other fractions and suitable for the manufacture of lower quality products (downcycling) or incinerated.

Based on direct observations of the authors at some European recycling plants (in Belgium, Germany, Spain, Italy and France) within the current and previous projects (Ardente et al., 2013; Ardente and Mathieux, 2012 a; Talens Peiró et al., 2016; Talens Peiró and Ardente, 2015), manual disassembly is generally largely implemented for desktop computers, mainly because of the modular design and low efforts for the dismantling (all components are generally fastened with standard screws and full disassembly takes around 2-4 minutes) compared to the additional gains from the sorting and the dedicated recycling of certain components (e.g. SSD, HDD, ODD and PCBs — including the motherboard, CPU, RAM modules and graphic cards). However, this analysis was carried out on waste desktop computers at the recycling plants, concerning mainly devices produced some years before. This implies that future products could pose some dismantling problems especially for new devices which are of very small dimensions, sometimes commercially referred as 'mini' desktop computer. These computers are characterised by a very compact structure (similar to that of games consoles). Based on recent studies by Prakash et al., they have a lifetime of 5 years and lower-life-cycle GWP (959 kg CO_2 eq.) compared to notebooks and normal desktop computers. However, Prakash et al. did not provide specific detail on the recycling of 'mini' desktops, limiting to report the amount of greenhouse gas emissions for their disposal (estimated at 4.8 kg CO_2 eq. in comparison to the 9.6 kg CO_2 eq. of a normal desktop) (Prakash et al., 2016b).

From interviews with recyclers it was not possible to collect much information about the EoL of 'mini' desktop, since this type of computer had not yet reached the recycling facilities. Even the scientific literature is lacking for such information.

Only one manufacturer was found to be providing public information concerning EoL disassembly instructions for some mini desktop computers ([28]) ([29]), identifying the components that require selective treatments (such as PCBs, batteries, plastics containing brominated FRs, electrolytic capacitors (contained in the power supply) and external cables) (HP, 2016). This document also includes a detailed sequence of pictures that illustrate all the procedures and steps needed to disassemble all the main components of the product, including the frames, various PCBs (motherboard, memory, wireless LAN card), the storage systems (HDD and SSD), the fan and thermal units) (Figure 11).

([28]) http://www.hp.com/hpinfo/globalcitizenship/environment/productdata/Countries/_MultiCountry/disassembly_deskto_201512319023191.pdf

([29]) http://www.hp.com/hpinfo/globalcitizenship/environment/productdata/Countries/_MultiCountry/disassembly_deskto_2014516234519169.pdf

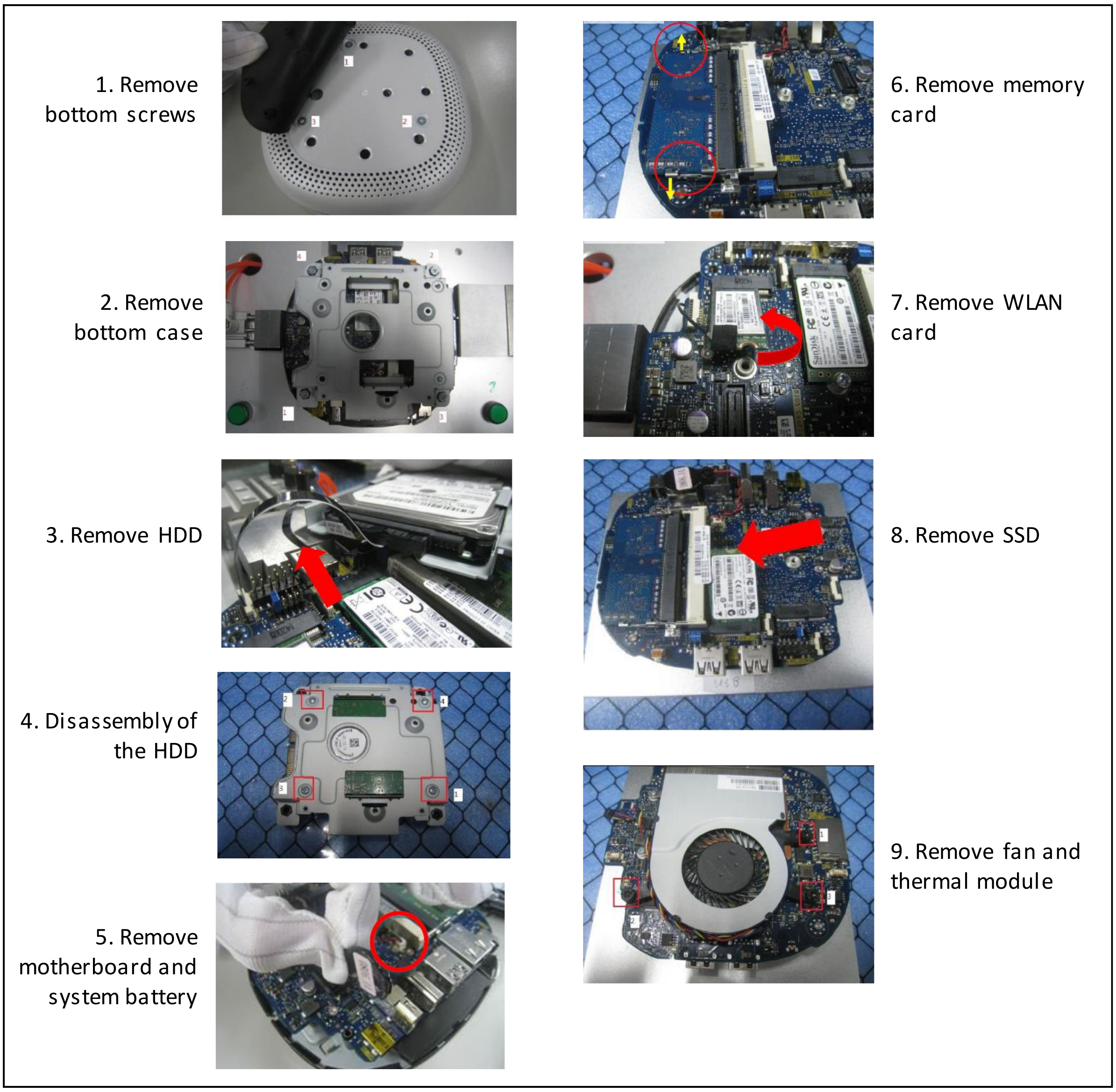

Figure 11 — Disassembly sequence of a mini desktop computer (HP, 2016)

Videos on the web are another available source of information concerning the disassembly of mini desktop, although they do not relate specifically to recycling activities but mainly to repair or illustrative purposes ([30]) ([31]) ([32]) ([33]). According to these videos, screws and snap fits are mostly used for the fastening. The disassembly appears generally straightforward, although some difficulties could arise because of the use of tiny screws, screws covered by footpads or rubber, and the position of snap fits and screws which are not always easily accessible. In one case the presence of a 1 000 mAh battery was also observed inside the mini desktop ([34]) (Figure 12).

(30) https://www.youtube.com/watch?v=18Q_-23f8Mw
([31]) https://www.youtube.com/watch?v=PTKKWTau-Pc
([32]) https://www.youtube.com/watch?v=O-CJxAF2XFc
([33]) https://www.youtube.com/watch?v=PrT2ycNjotI
([34]) Larger capacity batteries are intended for certain models, making them more similar to notebooks (http://www.digitaltrends.com/computing/the-voyo-v2-mini-pc-is-a-desktop-that-thinks-its-a-laptop/) or power bank (http://www.komu.it/prodotti/mini-pc/).

Figure 12 — Detail of the interior of a mini desktop computer containing a battery ([35]).

The compact structure of mini desktops could make their recycling similar to that of games consoles (mainly based on the manual disassembly to sort out PCBs and successive shredding of the remaining parts ([36]). With increasing miniaturisation of electronics such as 'system on chip', there is increased scope for reducing the size and weight of the devices, with associated reductions in material and transport. In addition, it is possible to design products for recycling, such as reducing the number of different types of plastics and simplifying disassembly. However, very compact products may be harder to disassemble and recycle, and lighter products may be weaker which could increase the amount of packaging required (AEA, 2010). Small dimension can also cause the product to be improperly disposed of, for example, into waste bins (Huisman et al., 2015).

Available EoL information on mini desktop is, anyway, still limited and will be complemented with experience from recyclers once this type of waste will reach the WEEE facilities.

Undifferentiated shredding of desktop computers was not directly observed, but it is discussed in the scientific literature especially concerning the potential losses of precious and valuable substances contained in PCBs (Chancerel et al., 2009; Rahimifard et al., 2009). EoL scenarios for desktop computers are following described in detail (Figure 13).

— Scenario 1: Manual dismantling, shredding and mechanical sorting.
  - The desktop computer is loaded on the dismantling table. Cables are extracted (when present) ([37]).
  - After opening the casing (metal lid, plastic frames), the operator dismantles all internal components, starting from cables and connectors, various PCBs (such as motherboard and graphic cards) and power supply. The dismantling proceeds with all the relevant components, including storage system (SSD or HDD), and ODD (when present).
  - Additional dismantling is undertaken on key components, especially on the motherboard, to separate the memory RAM, the CPUs (after the preventive extraction of the heat exchanger), and button-cell batteries, (when present). These components are separated because of their high values in terms of precious-metal content.

([35]) From: https://www.youtube.com/watch?v=JjddUXpkZf4
([36]) https://www.youtube.com/watch?v=Zs2SpbNYA0Y
([37]) Waste desktops generally arrive at the recycling plant already deprived of their external cables.

- Components separated are sorted out into differentiated boxes and successively addressed to external dedicated recycling plants ([38]) to optimise material recovery.
- Unsorted components are shredded and successively metal and plastic components are sorted via mechanical treatments (e.g. magnetic and eddy-current separators, densimetric separators).

Examples of video on this scenario are available on the web ([39]) ([40]).

— Scenario 2: Shredding and mechanical sorting.
  - The desktop computer is loaded onto a conveyor belt after extracting external cables ([41]).
  - Metals and plastic components are sorted by mechanical treatments (e.g. magnetic and eddy-current separators, densimetric separators).

Examples of videos on this scenario are available on the web ([42]) ([43]).

([38]) A large variability of the dedicated recycling processes was observed for components dismantled at the recycling plants. For example, PCBs are sent to metal smelters, other electronics to companies specialised in the concentration of valuable fractions, and large plastic parts to companies specialised in polymer sorting. Material fractions which are high concentrated thanks to deep manual dismantling or high-technology plants have generally a higher value but also, higher costs. The selection of the further processing of sorted components depends, therefore, on the balance between the costs for processing and their potential residual value.
([39]) https://www.youtube.com/watch?v=5BkgSEBIFjw (accessed September 2016).
([40]) https://www.youtube.com/watch?v=uSvfun8FC-c (accessed September 2016).
([41]) In some cases a pre-shredding phase is possible, where the desktops are partially shredded and opened, and afterwards recycling operators hand-pick and sort some parts for separate recycling (such as HDDs or pieces of PCBs).
([42]) https://www.youtube.com/watch?v=gDtj_Skhffg (accessed September 2016).
([43]) https://www.youtube.com/watch?v=RXZMM6_TRrE (accessed September 2016).

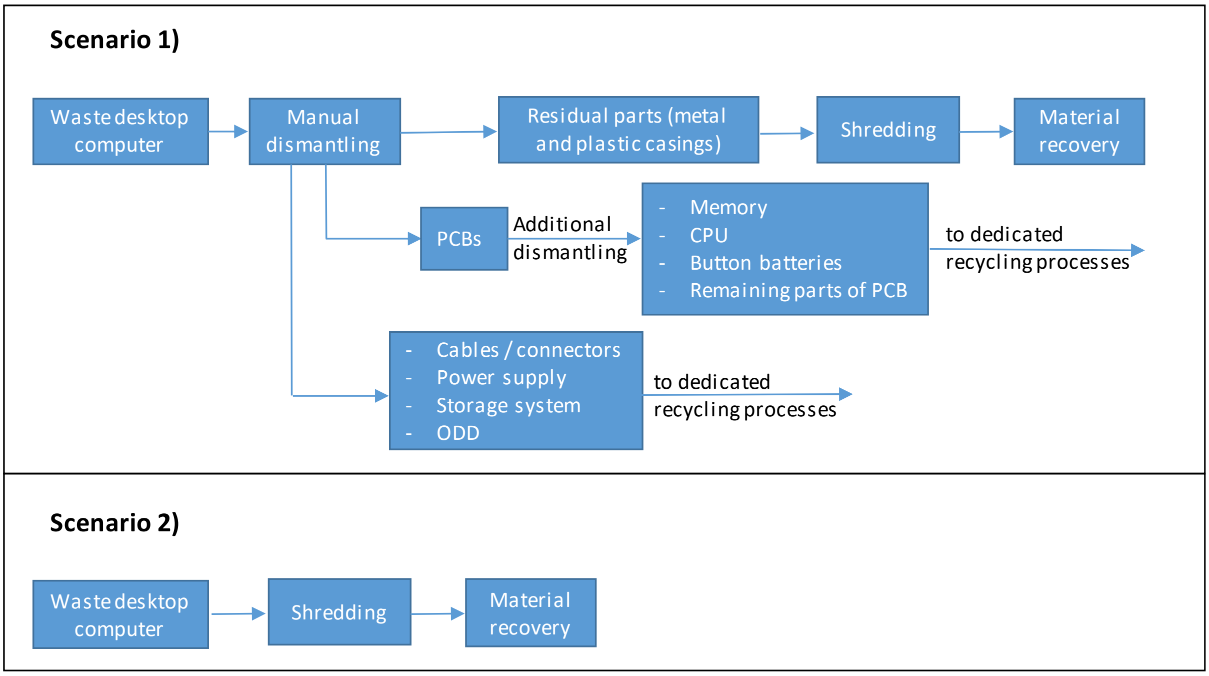

Figure 13 — Desktop computers EoL scenarios. Scenario 1 (Manual dismantling, shredding and mechanical sorting); Scenario 2 (Shredding and mechanical sorting)

3.1.2 Recycling/recovery of integrated desktop computers

Integrated desktop computers are a particular case of desktop computers that use an integrated display. A few examples have been found concerning the EoL disassembly of certain integrated desktops ([44]) ([45]), and suggest the disassembly of the following components for selective treatments: various PCBs, batteries, liquid-crystal displays (LCDs) and external cables. An example of the disassembly sequence for an integrated desktop computer is illustrated in Figure 15. Disassembly can be made with standard tools (screwdriver for screws type 'TORX T8'). No relevant differences are identified for the recycling processes for integrated desktop with or without touch screens.

Since this type of computer has only recently been introduced to the market, their market share is still little (Viegand Maagøe and VITO, 2017), therefore, the number of these products reaching EoL is still limited. Based on direct interviews of the authors of this present report with recyclers, it resulted that currently very few samples of integrated desktops have been treated so far, and this waste is generally recycled in the process line for the treatment of electronic displays (monitors and televisions). It is also recognised that recycling operators cannot easily distinguish integrated desktop computers from simple computer monitors based on a superficial look at the exterior.

Even the disassembly information suggested by the manufacturer for integrated desktops (as detailed in Figure 15) is very similar to that recommended for electronic displays, as can be observed by a comparison with similar EoL information provided for monitors ([46]).

([44]) http://www.hp.com/hpinfo/globalcitizenship/environment/productdata/Countries/_MultiCountry/disassembly_deskto_2016524202927.pdf

([45]) http://www.hp.com/hpinfo/globalcitizenship/environment/productdata/Countries/_MultiCountry/disassembly_deskto_201093204739.pdf

([46]) Various similarities can be observed between the disassembly of integrated desktops and the disassembly of monitors, as for example in:

Some minor differences are observed in the disassembly of certain electronic components (such as SSD, HDD or ODD) in use in the integrated desktop while generally missing in electronic displays.

Evidences currently collected (from recyclers and the little available documentation from manufacturers) suggest that the recycling of integrated desktops is analogous to that of standard monitors and other electronic displays. Therefore, potential material-efficiency requirements for integrated displays could be built analogously to those of electronic displays (promoting the ease of dismantling and the provision of information for recyclers).

Figure 14 — Example of an integrated desktop computer.

http://h22235.www2.hp.com/hpinfo/globalcitizenship/environment/productdata/Countries/_MultiCountry/disassembly_monito_200983185211.pdf

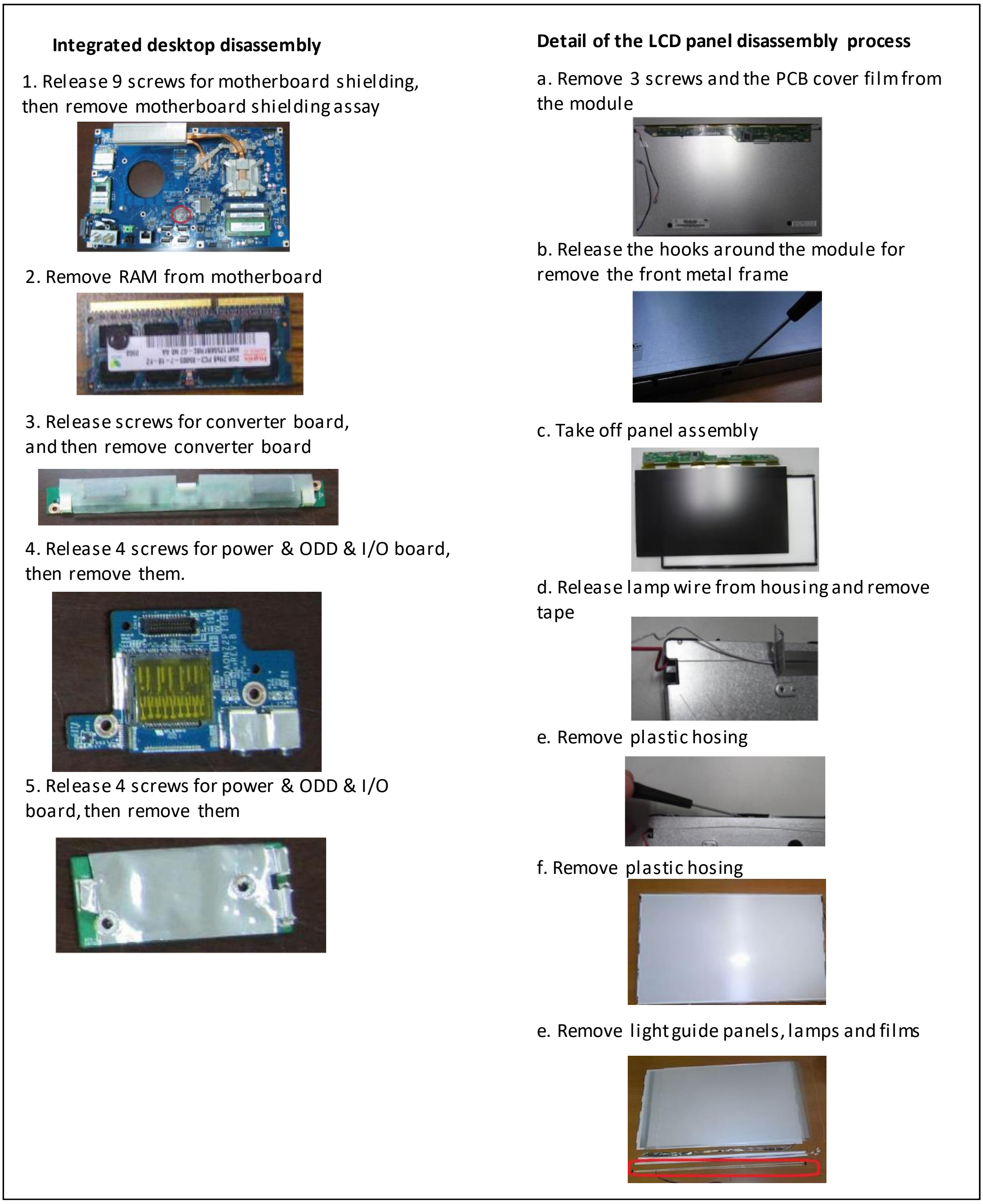

Figure 15 — Disassembly sequence for an integrated desktop computer ([47])

([47]) http://www.hp.com/hpinfo/globalcitizenship/environment/productdata/Countries/_MultiCountry/disassembly_deskto_201093204739.pdf

3.1.3 Recycling/recovery of notebooks

Recycling of notebooks assumes, after the extraction of the battery and the display panel (which is usually done manually), further manual sorting (e.g. removal of circuit boards, and capacitors ([48]), storage systems or optical drives) and/or mechanical liberation (shredding). Thereafter, further separation and sorting generates fractions, which are then forwarded to final treatment ([49]).

The display panel is usually further dismantled manually or semi-automatically ([50]) into fractions and components, e.g. iron and plastic fractions, and LCD panel and circuit board fractions ([51]). At present, LCD panels are either stored for future treatment or treated with technologies that are still in an early development stage or under development (usually, the polarisation foils are removed from the LCD panel, the LCD panel is mechanically broken down (e.g. crushed) and indium is mobilised through hydrometallurgical treatment (Rasenack and Goldmann, 2014; Rotter et al., 2012)). Other fractions are forwarded to be further processed using interim and final treatment technologies.

In principle, treatment operators combine different mechanical and manual dismantling and separation methods, depending on which components they target and whether they have acceptors for special parts that are difficult to process such as HDDs. In the following, two scenarios are presented: mechanical treatment after depollution (scenario 1), or medium-depth manual dismantling of the notebook (scenario 2).

- Scenario 1: Mechanical crushing and sorting. After the removal of the battery and display panel, the entire device is treated in a medium shredder for further separation of the different fractions (see Figure 16).
- Scenario 2: Manual medium-depth dismantling. After the removal of the battery and display panel, certain high value components are manually recovered from the device (Figure 17), such as;
  - the mainboard (including CPU and RAM) and other PCBs, directly forwarded to the copper smelter;
  - HDDs and ODDs, to be forwarded to a medium shredder for further separation of iron, aluminium, magnets and circuit board fractions.

The rest of the notebook's body goes then to a medium shredder for further separation of fractions (Gabriel, 2015; Vannieuwenhuyse, 2016).

(48) Currently large electrolyte capacitors containing substances of concern have to be separately removed, as described in Section 3.1. However, newer notebooks do not contain such capacitors, unless integrated into PCBs.
(49) The final treatment aims to produce secondary raw materials, reuse appliances and components, and to treat fractions by incineration and dispose of them e.g. at landfill sites.
(50) E.g. http://www.mrtsystem.com/products/flat-panel-processor/
(51) In line with requirements of WEEE Directive, display panels greater than 100 square centimetres are removed for depollution at the recycling plant, with the removal of the mercury-containing CCFL backlighting (when present). However, as it is assumed that more-recent devices feature LED backlighting, the mercury-containing fractions are not considered here.

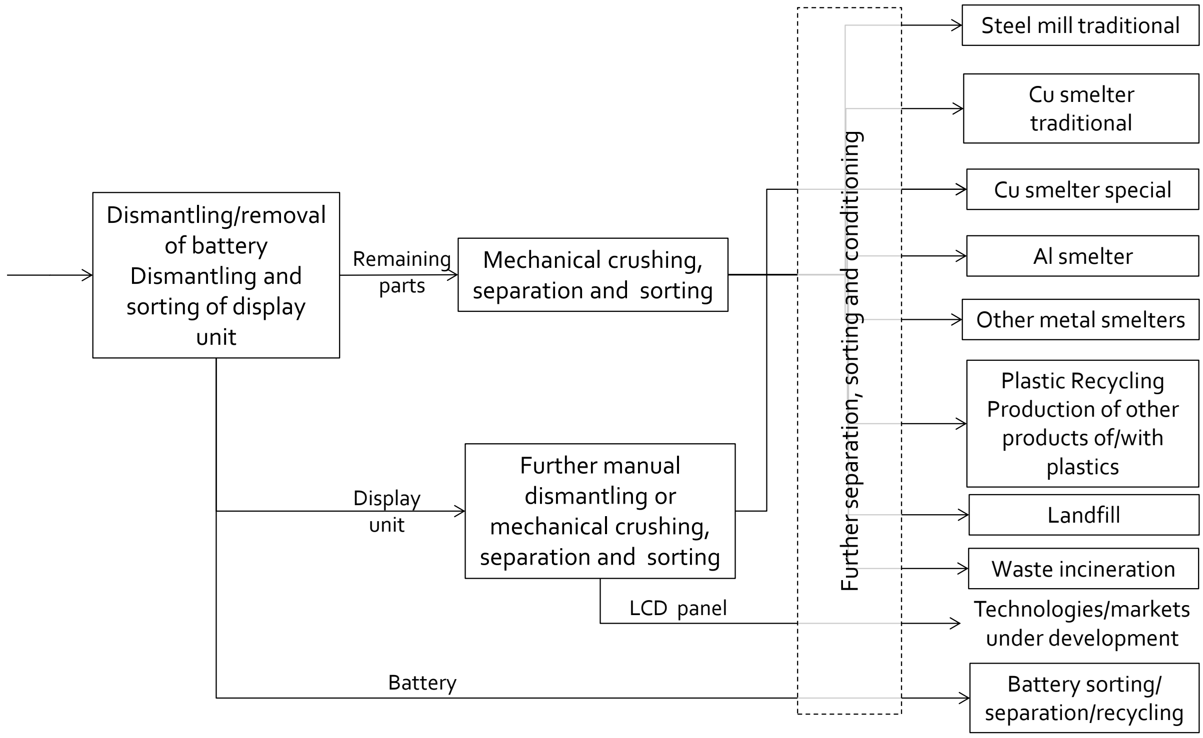

Figure 16 — Mechanical crushing, separation and sorting (Scenario 1). Cu = copper. Al = Aluminum.

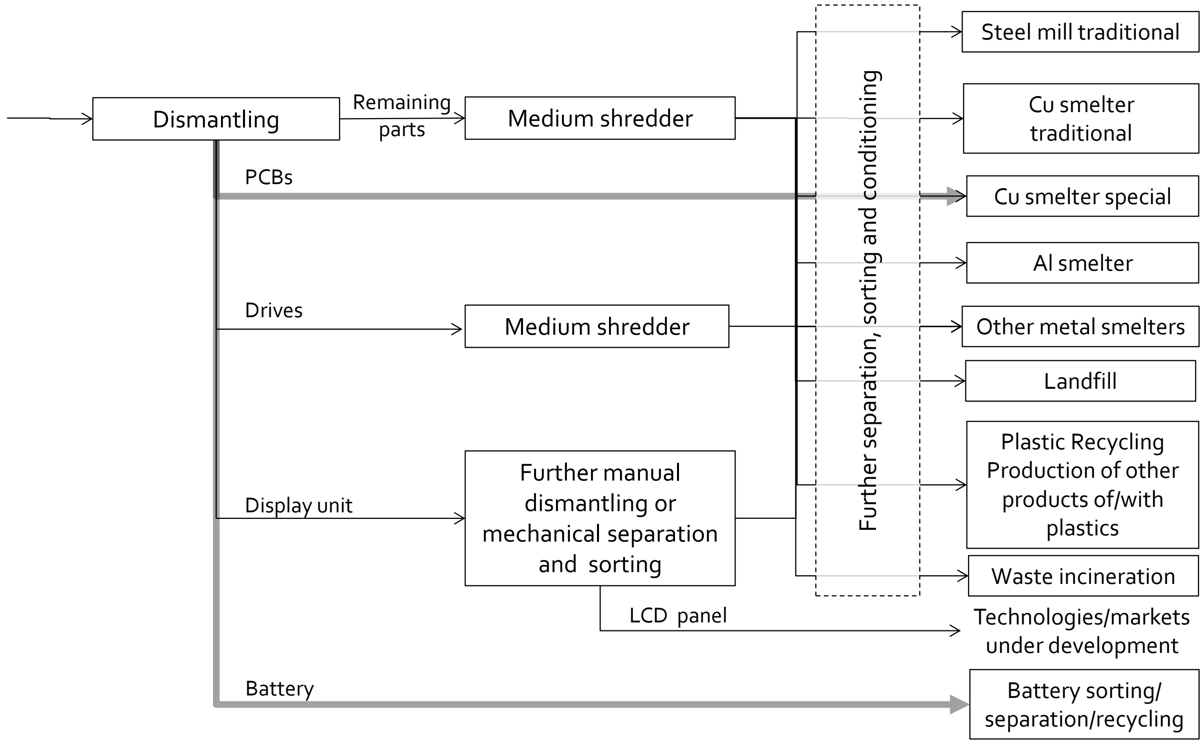

Figure 17 — Manual medium-depth recycling scenario for notebooks (Scenario 2). Cu = copper. Al = Aluminum.

3.1.4 Recycling/recovery of tablets

Currently, the number of discarded tablet computers reaching recycling facilities is still extremely limited; therefore EoL scenarios for these products can be only tentatively assessed. A first evaluation has been based on information provided by three recyclers of WEEE in Germany (ELPRO, Braunschweig; Adamec Recycling GmbH, Fürth and EGR Elektro-Geräte Recycling, Herten) (Schischke et al., 2014). Further interviews with some recyclers were made in 2016, but no additional conclusions can be drawn.

After battery removal, three possible pre-processing approaches are identified, depending on the facility and taking into account economic considerations.

- Scenario 1: shredding of the whole device via cross-flow shredder.
- Scenario 2: deep-level manual dismantling of the subassemblies (such as aluminium or plastic housing, mainboard, LCD, magnesium frame if present), using predominantly screw drivers (battery powered and hydraulic).
- Scenario 3: direct treatment in copper smelter after removal of the battery.

The representativeness of the second scenario is limited, since the likelihood that the labour cost for manual dismantling is not covered by the value of material disassembled for recycling is very high.

Such treatment chains are similar to the ones described in scenarios 1 and 2 for the notebook section.

Based on interviews and consultations with recycling operators about the deep-level manual dismantling scenario, the following materials and components were identified as potentially relevant:

Plastics

In general, plastics can be separated according to their colour: white (including light grey), black, and mixed colours. White plastics have a significantly higher value compared to black plastics. Black plastics contain carbon black, which complicates the proper identification and subsequent separation.

Aluminium

Aluminium housing is of high interest for material recycling and it can justify a slightly increased disassembly effort. Magnets (or other metal parts such as copper) attached to the aluminium housing can reduce the recovery value via mechanical processing.

Magnesium

Magnesium frames are found in most of the dismantled tablets with plastic back-covers. Currently, magnesium frames are not dismantled into separate fractions, but are rather processed together with the aluminium fraction. For high-quality magnesium recycling, it is necessary to achieve a high purity magnesium fraction, which is difficult via mechanical separation due to the similar physical properties of Al and Mg.

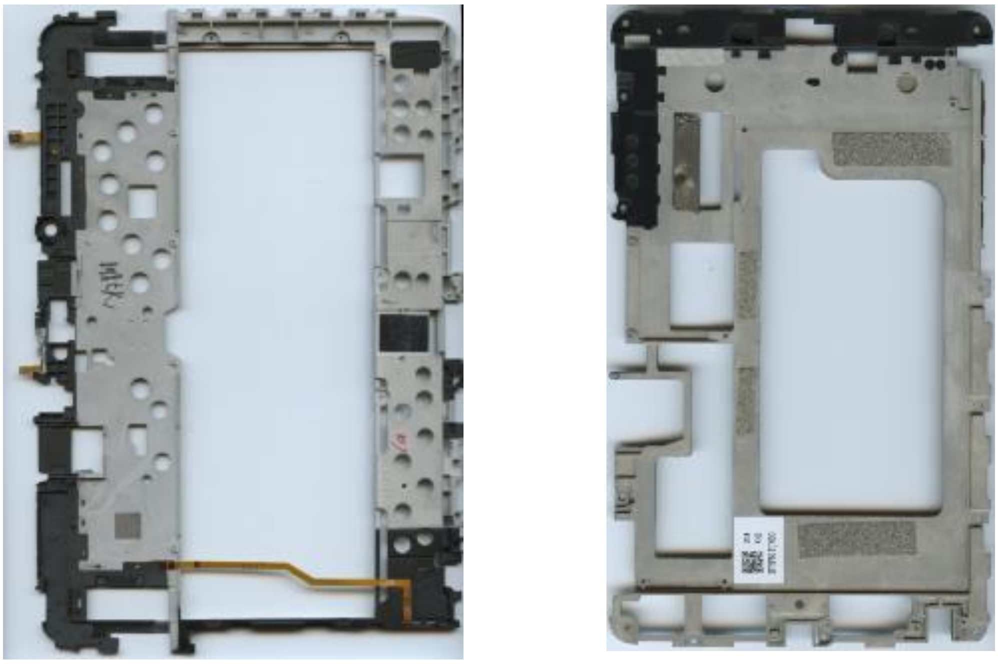

Figure 18 — Magnesium frames in tablets (Schischke et al., 2014)

Magnesium was also identified as a CRM for the EU and it could potentially become an interesting material for recyclers and justify manual-disassembly costs, taking into account increased flows of EoL tablets in the future.

Display panels

Display panels contain minuscule quantities of indium and REE as well as gold in minor amounts, which is used for interconnects and connectors of light-emitting diodes (LEDs) and for controlling ICs. However, recycling systems are not yet adjusted to recover them efficiently (Nissen et al., 2013). Evidence from interviews with recyclers indicates that currently only a limited number of tablets reach recycling facilities. Therefore, recyclers' statements are based on their experience with other electronic devices containing display panels. The time needed to separate the display panel from the rest of the device is critical. According to the recyclers, the display panel would be separated manually under the condition that it is easily accessed and removed. If the front glass is not fused to the rest of the LCD unit, it would be separated. However, as tablets do not contain mercury-containing backlights, separation of the display panels has a lower priority compared to e.g. the pre-processing of display panels from older notebooks and electronic displays.

PCB

Tablet mainboards are considered high-grade. After tablet opening, the PCB can be easily removed and sorted. No removal of electromagnetic interference (EMI) shields from PCBs is provided for as the amount of material is not worth the effort.

3.1.5 Focus on recycling/recovery of electronic PCBs

Due to the weight fraction of PCBs in notebooks (around 15 %), their recyclability has a strong influence on the overall recyclability rate for computers. It is therefore crucial to estimate the detail of the recyclability of elements (element groups) contained in PCBs because of the relevance of precious and trace metals from an economic, environmental and/or criticality perspective (Chancerel and Marwede, 2016).

A recent study by Chancerel and Marwede (2016) analysed the recyclability of PCBs, following the compiling of an exhaustive chemical composition based on several sources, and identifying the specific recycling rates per elements. Table 20 provides detail for the main recycled materials. It is noticed that 22-25 % of the mass of the PCB is recycled (and over 90 % of the material value), while around 60 % is recovered as other material, 16 % recovered as energy and 10-30 ppm is disposed of (Chancerel and Marwede, 2016).

Table 20 — Recycling rate of materials in PCB of notebook properly treated (Chancerel and Marwede, 2016)

Material in PCB	**Recycling rate [%]**
Ag	95 %
Au	95 %
Bi	80 %
Cu	95 %
Ni	90 %
Pb	80 %
Pd	95 %
Sn	75 %
Zn	50 %
Br	50 %
Sb	80 %

3.1.6 Focus on recycling/recovery of batteries contained in the product group

After collection, batteries are usually sorted according to their chemistries (lead acid, alkaline, NiCd, NiMH, Li-ion, etc.) before being conducted to recycling treatments (Accurec, 2016). The sorting of batteries is currently mostly done manually. Those who do the sorting attempt to identify the battery chemistry primarily via the labels on packaging/casing of the batteries. However, in practice labels are sometimes missing, making identification and sorting difficult. According to the interviews carried out with the German battery-recycling company Accurec, dismantling centres remove EoL batteries from the WEEE stream, nevertheless during removal, batteries are regularly damaged or the cells are removed from the battery pack. Because of the absence of a label at a cell level, cell batteries are classified as not identifiable and are sent to dedicated landfills, thus they are lost for appropriate recycling. This is due to a lack of requirements for battery labelling.

Currently, there are three different marks required by law worldwide which aim to highlight the presence of Ni, Cd or Pb (Figure 19). No labelling is mandatory to comprehensively identify the battery chemistry in Europe. However, according to Accurec, incorrect sorting of Pb or NiCd batteries with LIB complicates the recycling processes and potentially poses risks for the workers and for the environment. For example, in the case of missorting of NiCd batteries into LIB, the toxic Cd metal can be released in the off-gas because the treatment of LIB does not intend to treat Cd (Accurec, 2016). So, to avoid environmental pollution, a more expensive off-gas cleaning system must be applied.

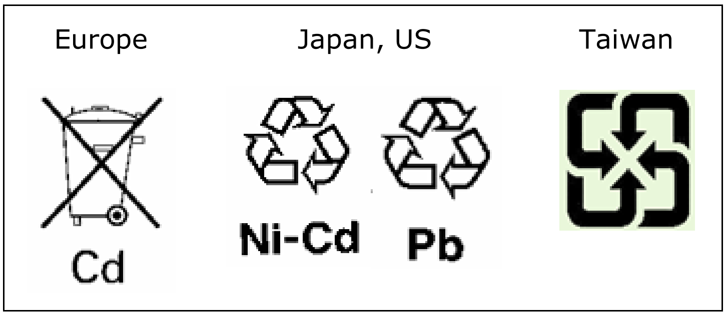

Figure 19 — Current legislative battery marks (source: BAJ)

In practice, manufacturers usually apply battery marks according to their chemistries, however not in a consistent manner (see examples in Figure 20).

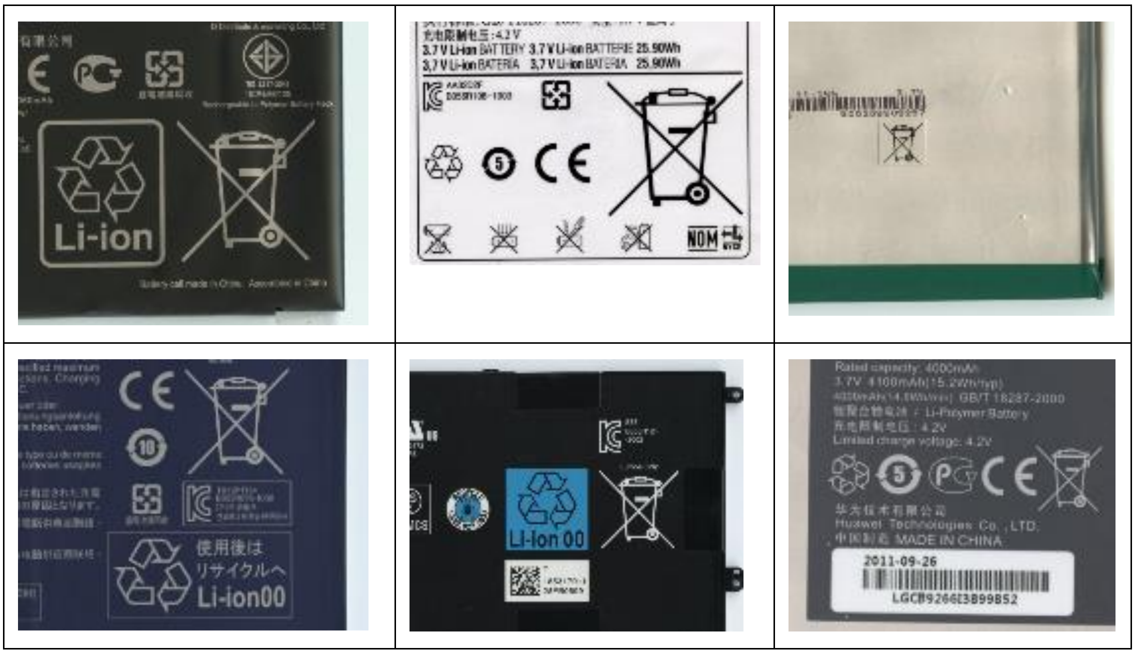

Figure 20 — Examples of battery marks in current practice (unreleased data from Slates D4R)

In addition, the different chemistries of LIB (LCO, NMC, LFP, etc.) are currently not indicated on battery packs or cells, leading to economic and material losses. Depending on the Li-ion chemistry, the content of cobalt varies from 0 to 15 % by weight. However, usually all Li-ion battery subtypes are co-processed, making the subsequent separation and extraction of metals more difficult and expensive. For example, in the extraction process of cobalt from high cobalt concentrates (LCO-type LIB), the iron and phosphorous from the mixed processing of LFP batteries become polluting elements and need to be removed. Such removal increases the cost of the process. Therefore, a batch-wise treatment allows for better concentration of the target metals than a diluted mixture and is more feasible from both a technical and economical point of view. In order to implement more precise sorting and dedicated treatment of batteries according to their sub-chemistry, a more-detailed indication on battery packs as well as at the cell level would be in need (Accurec, 2016).

In Japan, rechargeable batteries are often marked with the 'battery-recycle mark' (Figure 21), developed by the BAJ ([52]). Currently, battery manufacturers in Japan are required to display the Moebius loop mark on batteries (Figure 19) under the law for promotion on effective utilisation of resources ([53]). However, as there is currently no international standard for battery marking available, the BAJ promotes the internationally standardised use of one battery mark as shown in Figure 21. The logos identify four different types of battery chemistries by colour and abbreviation: NiCd, Ni-MH, Li-ion and Pb.

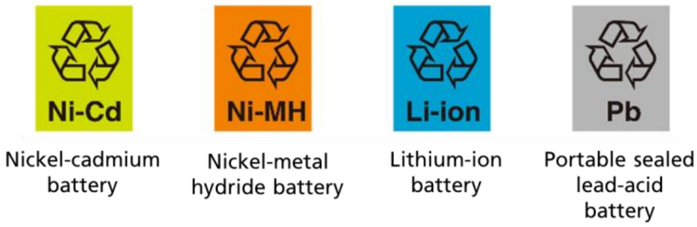

Figure 21 — Battery-recycle mark, developed by the BAJ and promoted to be used as an international standard, which indicates the four different battery types by colour and in text.

The BAJ points out the advantages of the use of an internationally standardised battery-recycle mark as follows.

- Meeting all the various marking standards globally on each battery can be challenging for manufacturers from a space and design perspective.
- The production of different labels, separate production runs for each destination, and separate inventories increases costs for manufacturers.
- The use of various marks on each battery leads to lower recognition by users, impeding efforts to raise the collection rate.

The BAJ believes that the international use of the battery-recycle mark will increase recognition, hence contributing to improved portable-battery recycling globally, as well as saving costs for battery manufacturers.

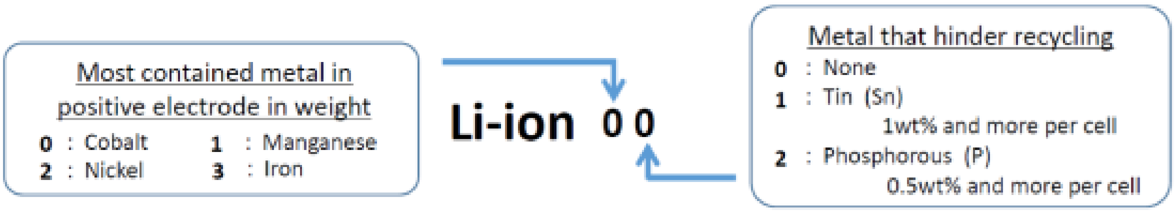

Figure 22 — The two-digit code, developed and recommended for use by BAJ, which is added to the logo for LIB to identify: the metal with the highest mass in the positive electrode (first digit); and the presence of a metal which hinders recycling (second digit).

Battery recyclers have requested that the marking should include an additional mark to identify Li-ion batteries containing over a certain amount of tin and phosphorous. Following the request, the BAJ recommends the industry also add a two-digit code to the logo for LIB to specify with the first digit the metal (such as Co, Mn, Ni, or Fe) predominantly found (by mass) in the cathode, and whether tin or phosphorous exceeding a specified threshold are contained in the battery (Figure 22). The battery-recycle mark is currently applied to battery packs by several manufacturers. Examples are shown in Figure 23.

([52]) http://www.baj.or.jp/e/
([53]) Global Environment Centre Foundation: Law for promotion on effective utilization of resources, 2016, http://nett21.gec.jp/Ecotowns/

Figure 23 — Application of the battery-recycle mark on a notebook battery (left) and a tablet battery (right) (sources: newbatteryshop.com and ifixit.com).

Similar to the processes in Japan, battery recyclers have requested that the IEC develop standard for battery marking to improve the recognition of battery chemistry. The reasons are provided as follows:

Many recycling processes are chemistry specific, undesired events may occur when a battery which is not of the appropriate chemistry enters a given recycling process. Therefore, in order to ensure safe handling during sorting and recycling processes, it is necessary to mark the battery so as to identify its chemistry. (IEC 62902 draft, 2017).

A draft standard was circulated March-June 2017, which specified the appearance, colour and size of the marking (Figure 24). The Mobius loop is to be included if not yet placed on the battery in a different position. It should be noted that the scope of the draft standard is currently limited to batteries with a volume of more than 900 cm^3 and hence does not apply to portable batteries for ICT devices. An expansion of the scope to also include portable batteries, as well as a process to create a European standard, is conceivable.

Figure 24 — Battery markings developed by IEC as published in the draft standard circulated in March 2017.

In interviews with several actors of the LIB-value chain, the benefits and potential problems of a uniform battery-marking system were investigated. While the approach was welcomed by some actors, the interviews pointed out contradictory views, in particular with regard to the information content and colour of such a marking. It was stated that in order to identify and verify the most relevant marking parameters, additional standardisation work has to be carried out. The interviewees recommended the consideration of the following aspects.

- The marking should lead to a positive value for the recyclers and the environment (by increasing the recycling rate) and be able to adapt towards the changing material composition of batteries due to novel battery technologies.

- For safety reasons, the marking should contain additional information, e.g. indicating the type of electrolyte used, together with an indication of whether or not it is flammable.
- Requirements need to be uniform on a global scale. For instance, the Mobius loop symbol indicates that a product is recyclable, however in the US there is no dedicated recycling of LIB in place.
- Having a colourful marking could complicate or mislead battery sorting, e.g. according to the US NFPA 704 Hazard Identification System ([54]), the blue colour indicates the level of health hazard. However, this hurdle seems to have been overcome in the efforts by the IEC mentioned above, as battery-recycling facilities strongly supported the colour coding.
- The marking should indicate the process compatibility (e.g. indicate the presence or absence of phosphorous).
- The letter size indicating the battery type needs to be standardised.

Concern was raised regarding the indication of the cobalt content in batteries. While this could lead to improved, batch-wise treatment of batteries according to their cobalt content, there is a risk of 'cherry picking' of LIB with high cobalt content, potentially leading to a lower economic incentive to recycle remaining batteries with little to no cobalt content, as cobalt typically remains the dominant economic driver for LIB recycling.

Additional remarks

- A certification system for battery recycling is needed ensuring that recycling on a global level follows the same standards and efficiency.
- In the future, technologies for LIB recycling have to adapt to the changing material composition. In the longer term, recyclers will have to develop recycling technologies according to the LIB subchemistries. In this respect, marking of LIB subchemistries seems useful.

The current main treatment processes for the recycling of batteries include thermal pre-treatment, mechanical treatment, pyrometallurgy and hydrometallurgy (Accurec, 2015). Table 21 summarizes a list of LIB recycling plants and the applied recycling processes.

([54]) http://www.nfpa.org/codes-and-standards/all-codes-and-standards/list-of-codes-and-standards?mode=code&code=704

Table 21 — Li-ion battery-recycling plants processes

Company	**Recovered Elements**	**Process**	**Country**
Glencore	Ni, Co, Cu	Thermal pre-treatment + pyrometallurgy + hydrometallurgy	Canada
Umicore	Ni, Co, Cu, Fe	Pyrometallurgy + hydrometallurgy	Belgium
Accurec	Ni, Co, Cu	Thermal pre-treatment + pyrometallurgy + hydrometallurgy	Germany
Kyoei Seiko	Ni, Co, Fe	Pyrometallurgy	Japan
JX Nippon	Ni, Co, Cu, Fe, Mn, Li	Thermal pre-treatment + mechanical treatment + hydrometallurgy	Japan
Dowa	Ni, Co, Cu	Thermal pre-treatment + pyrometallurgy + hydrometallurgy	Japan
GEM	Ni, Co, Cu, Fe, Mn, Li	Mechanical treatment + hydrometallurgy	China
Brunp	Ni, Co, Cu, Fe, Mn	Mechanical treatment + hydrometallurgy	China
Telerecycle	Ni, Co, Cu, Fe, Li	Mechanical treatment + hydrometallurgy	China
Kobar	Ni, Co, Cu, Fe	Mechanical treatment + hydrometallurgy	Korea
Recupyl	Ni, Co, Cu, Fe, Li	mechanical treatment + hydrometallurgy	France
Retriev	Ni, Co, Cu, Fe	Aqueous + mechanical treatment + hydrometallurgy	United States
SNAM	Ni, Co, Cu	Thermal pre-treatment	France
AkkuSer	Ni, Co, Cu, Fe	Mechanical treatment	Finland
EDI	Ni, Co, Cu	Mechanical treatment	France
Batrec	Ni, Co, Cu	Mechanical treatment	Switzerland

3.1.7 Future recycling scenario for notebooks

As the design of notebooks changes, the treatment processes can change in the near future. The compact, highly integrated design of (sub-)notebooks and desktop computers with integrated displays, the progressively miniaturisation of devices (as for mini desktop computers), the increased use of SSDs instead of HDDs and the reduction of the content of precious metals in PCBs (i.e. the declining of the economic gain potentially achievable from the recycling) (Bangs et al., 2016), together with the currently low commodity prices, will probably make it technically and economically less feasible to go for a medium-deep manual dismantling of valuable components. Therefore, operators could focus more and more on full shredding processes in which, after the removal of the battery, the whole device (including the display panel, when present) goes to a shredder. This trend for future EoL scenarios would, however, lead to less-pure separated fractions and higher losses of valuable materials (Vannieuwenhuyse, 2016).

Currently, the WEEE directive requests that 'liquid-crystal displays (together with their casing where appropriate) of a surface greater than 100 square centimetres and all those back-lighted with gas discharge lamps' have to be removed and treated selectively (European Union, 2012). The separate treatment of the display panels with LED backlighting (or OLED displays ([55])) does not necessarily require separate treatment for depollution. However, treatment operators might still separate the LCD from the rest in the future because liquid crystals contaminate the plastic fraction after shredding and sorting (Vannieuwenhuyse, 2016).

3.2 Analysis of repair/reuse practices

Even if manufacturers claim to design products to minimise the need for repair, by means of the selection of high-quality materials and components, as well as a durable, reliable structural design (Digitaleurope, 2017a), it was observed that failures in computers occur quite commonly. Digitaleurope (2014) stated that, every year, about 118 000 t of IT equipment and spare parts are worldwide shipped for original equipment manufacturer repair and remanufacturing, of which roughly 28 000 t in Europe. Nearly 59 % of the shipments take place under warranty, and about 6 % of the products shipped for repair turn out to be unrepairable.

A Eurobarometer survey observed that, when a main failure occurs, 77 % of EU citizens would rather repair their goods than buy new ones, but ultimately have to replace or discard them because they are discouraged by the cost of repairs and the level of service provided (European Commission, 2014b).

The following sections summarise information about current practices in terms of the repair and reuse of personal computers, notebooks and tablets in particular. Main failures, practices in design, user preferences regarding repair or upgrade and recommendations for ecodesign are provided.

3.2.1 Reuse and repair of notebooks

Main failures

A recent IDC study among 800 United States organisations showed that the average annual failure rate for notebooks is 18 % (average of company notebooks requiring repair of some kind, during a year). The rate of failure increases each year a device is in use, ranging from 11 % failing the first year to more than 20 % failing by year five. Moreover, by the end of year five, 61 % of notebooks had had a failure that required repair (IDC, 2016).

The IDC also reported the components most often damaged in notebooks, such as the screen, followed by the keyboard, then the data-storage drive (HDD or SSD) and the battery (Figure 25). Among the top ways end-users damage devices in their company, the overwhelming top reason across categories was simply dropping the device while carrying it. The number 2 issue was spilling liquid on the device, and the number 3 issue was the device falling off a desk. On average, workers lost about 5.8 working hours for notebook repairs (Figure 26).

([55]) Organic light-emitting diode.

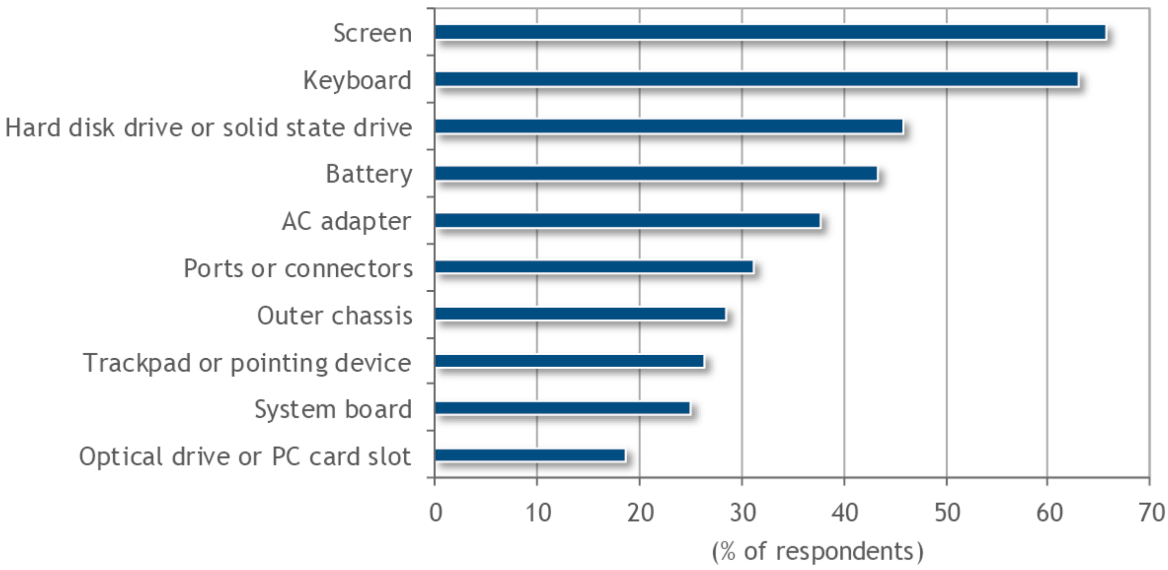

Figure 25 — Most common components in notebooks that suffered damage or breakage (IDC, 2016).

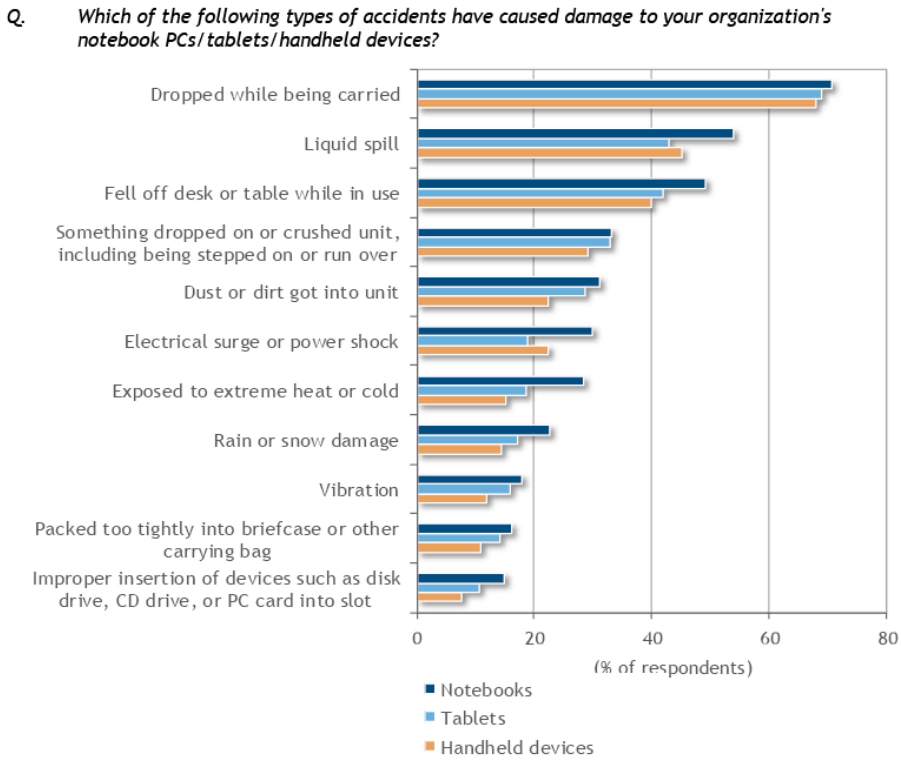

Figure 26 — Types of accidents causing notebook, tablet and handheld device damage, according to the IDC (2016).

Interviews with repair-and-reuse operators of professional business notebooks confirm these findings. According to them, the main frequent failures in notebooks involve: displays, keyboards, hard drives, batteries, EPS, memories, fans, connectors (USB, network) and optical plastic elements such as small covers and outer frames (Private communications, 2017).

These outcomes are also confirmed by a previous IDC study (2010) which shows that nearly 20 % of notebooks have to be repaired due to a physical failure (14.2 %) or due to damage from accidents (9.5 %) every year (IDC, 2010). In that survey the majority of respondents with damaged notebooks reported that the notebook had suffered a damaged keyboard, followed by notebooks which had suffered damage to the display screen. Non-exposed parts which are the most prone to damage include batteries and HDDs, both cited by over half of the respondents (IDC, 2010). The greatest source of damage was human error (Figure 27). When respondents were asked how their notebooks broke, the majority responded that the devices were dropped while being carried, followed by two other reasons, liquid spilled onto the devices, and the device fell off a desk or a table (IDC, 2010).

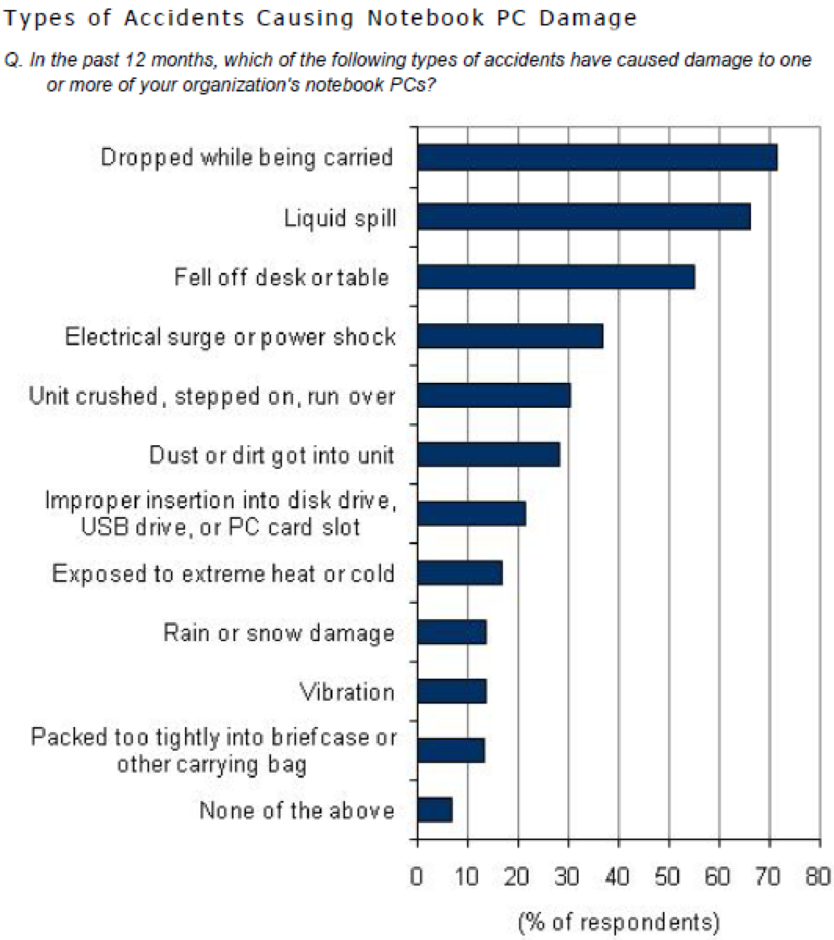

Figure 27 — Types of accidents causing notebook damage, according to the IDC (2010).

Other sources are available in literature. The insurance company SquareTrade, for instance, analysed failure rates for over 30 000 new notebook computers covered by notebook-warranty plans in 2009. Looking at the first 3 years of ownership, 31 % of notebook owners reported a failure to SquareTrade. Two thirds of these failures (20.4 %) came from hardware malfunctions, and one third (10.6 %) was reported as accidental damage (SquareTrade, 2009).

Repair-and-reuse operators report additional reasons for failures (Private communications, 2017).

- Handling through transport and storage.
- Wear and tear.

— Poor design or not enough testing creates inherent defects: palm rests cracking, hinges breaking, LCD screen pressure marks due to key caps sitting too proud on the keyboard etc.

Apart from this, repair-and-reuse operators identified other issues which hamper refurbishment.

— BIOS passwords or registration systems which hinder access to the device (costs to reset BIOS Passwords are EUR 30-120 which means that this is usually not economically viable or BIOS password (PWD) reset is not at all possible). Other systems such as the iCloud ([56]) or the device enrolment programme from Apple cannot be reset without the original PWD from the user. Therefore devices cannot be repaired if there was no factory reset by the user.
— BIOS settings hinder the replacement of components which are not the originals or the installation of a newer operating system. Repair-and-reuse operators argue that there is no technical reason not to allow for replacement with other parts.
— There are no standardised mechanical connections to fix hard disks, drives and other components to the chassis.
— There is no standardised layout of keyboards. Because keyboards are not available, repair-and-reuse operators imprint blank keys. A standardised layout of keyboards would facilitate (cross-European) sales of devices.

In a non-representative survey about the failure probability of components in consumer and business notebooks, four out of four repair services state that batteries and HDDs fail (very) frequently (Prakash et al., 2016a). The display, display-cover (including frame joints) and the casing of consumer notebooks break frequently according to three repair service companies for consumer notebooks, whereas for business notebooks this does not seem to be the case (Prakash et al., 2016 a; Private communications, 2016). Consumer products typically look more fashionable but are built to less-robust specifications than commercial-focused products. Conversely, commercial-focused products have traditionally been more staid in design, but they are built to endure slightly more robust use (IDC, 2016).

If the mainboard fails repair does not pay off as the cost for a new mainboard usually exceeds the price of a new notebook (or the residual value of the device). Similarly, the repair of tablets (of any component) for resale usually does not pay off, as the residual value of the tablet is too low. Such a repair reportedly makes sense only for high value brands (Krüger, 2016; Private communications, 2017).

The criteria to decide whether a device is to be refurbished is a quick cost-benefit analysis, i.e. the potential resale value versus the time (and cost) invested to refurbish the device. The cost-benefit analysis is usually done through a quick outer inspection and defect analysis of the device. The effort (time) to refurbish the devices is estimated based on experience.

The following components are frequently replaced in business devices by repair-and-reuse operators:

— batteries
— memories
— HDDs
— ODDs
— fan and cooling fins,
— keyboards and keys
— displays

([56]) One reuse operator mentioned, that 50 % of iPhones and iPads are discarded because of this issue, although they are fully functional.

— plastic covers.

Business-device-repair-and-reuse operators report that about one in five batteries in the devices are replaced. The experience is that the used batteries have 40-80 % of their original capacity left after 3 years' run time. Batteries are usually tested for run time (30 minutes as a benchmark, 60 % of original runtime). If the benchmark is not achieved, batteries are replaced. Other repair-and-reuse operators report the use of software tools (to access data on battery SoH stored by the battery-management system) to determine the remaining capacity of notebooks batteries. It is not the experience of repair-and-reuse operators that batteries outlast the lifetime of the device (Private communications, 2017).

Replacement parts come from the 'plundering' of other devices (stored for spare parts) or are bought from third parties, B-brands or other repair-and-reuse operators. The availability of affordable original spare parts (from original manufacturers) is cited as a problem. Especially small (plastic) parts, wear-and-tear parts, and parts of the chassis are not available on the market and have to be extracted from other devices. In the future, 3D printing might help to solve this problem. Grade A and A+ batteries are sold to original manufacturers, which re-sell them for three to five times the original price. Therefore, repair-and-reuse operators tend to buy grade A- to B batteries from battery manufacturers. EPS units are available and are usually used across different generations.

Mass-storage-unit (HDD and SSD) data need to be erased to facilitate reuse. Commercial data-erasure software is usually used to perform this process. Repair-and-reuse operators stated that this process does not always work satisfactorily. In these cases, the mass-storage units need to be physically destroyed in order to safeguard the client-data-security needs (Private communications, 2017).

The following information would facilitate repair and help the repair-and-reuse operators.

— Open access to data sheets with lists of components.
— Information about the ease of battery replacement (made available for consumers).
— Information about type of tools.
— Exploded diagrams.

The repair-and-reuse operators interviewed have divergent opinions on whether this information and spare parts should be available for the end-consumer. Some opt for the 'right to repair'. Others prefer a registration process for authorised repair-and-reuse operators (as long as this is not bound to the requirement to sell new devices) to ensure the quality and safety of repair (Private communications, 2017).

Currently, business devices are still easy to repair. However, consumer notebooks are not refurbished due to their design and low price. No current issues with snap fits in business notebooks were identified. However, there is no standardisation of the type of screws used and every manufacturer is using different screws.

According to repair services and repair-and-reuse operators, the following changes in the design of new notebook products (e.g. sub-notebooks and Ultrabooks™ ([57])) compared to 'regular' notebooks could limit the lifetime of the devices, i.e. limit the ability to repair or upgrade the devices (Bölling, 2016; Prakash et al., 2016a) (Private communications, 2017):

— built-in batteries;

([57]) Subnotebooks are a very thin and light version of a traditional notebook. They are generally less than 18-21 mm thick and 1.8 kg (Electronics Takeback Coalition 2012). Most types use SSD instead of HDD. Subnotebooks use low-power processors and feature fast boot times which return the device from standby mode in a few seconds. They use prismatic battery packs lasting from 5 to 11 hours. ODD and Ethernet ports are generally omitted due to their limited size. The Ultrabook™ was created as a specification and trademarked brand by Intel for a class of high-end subnotebooks designed to feature reduced bulk without compromising battery life [Wikipedia, https://en.wikipedia.org/wiki/Ultrabook accessed on 16.03.2017].

— soldered-in memory (RAM);
— built-in mass storage;
— built-in (wireless) network interface card (NIC);
— small connectors.

Waterproofing of devices is seen as rather critical for repair-and-reuse operators because the housing of devices is often glued to achieve this effect. Usually, business devices already have protecting design features for water spillage that work well (Private communications, 2017).

In some cases, neither HDD/SSD nor RAM are exchangeable against new components in sub-notebooks (Ultrabooks™); either Ultrabooks™ are secured with special screws or the RAM, and sometimes SSD flash storage, is soldered directly onto the mainboard ([58]). The slimmer and lighter the devices become, the more integrated they are and thus the harder it is to replace components (Private communications, 2016). It is expected that mass storage will not fail as frequently in the future, as HDDs are substituted by SSDs, which have no moving parts (Private communications, 2016). However, there is evidence that SSDs also degrade over time (Private communications, 2017).

From the industry point of view, the benefits of integrating components are; a more rigid and uniform design of their devices, slimmer form factor and lower manufacturing costs. For users, this means that components cannot be easily exchanged or upgraded by themselves or by professional repair services (for reasonable costs). This may lead a certain share of users to invest their money in a new device.

User preferences

Regarding end-users, the main inconveniences caused by a defective device are the loss of productivity and the loss data (IDC, 2016). Defects and failures are also the main motivations for buying a new notebook (Prakash et al., 2016b). A German-based internet survey assessed the main reasons for replacing a notebook after first use. It differentiated three main reasons:

- the old device was defective;
- the old device was malfunctioning or unreliable;
- the old device was still functioning, but the user wanted a better one.

Figure 28 shows that the percentage of notebooks being replaced because they were defective or malfunctioning increased over time whereas the percentage of still-functioning notebooks being replaced with a better one decreased (Prakash et al., 2016b).

([58]) https://www.heise.de/newsticker/meldung/Oeko-Logo-EPEAT-winkt-Ultrabooks-durch-1729666.html; http://www.com-magazin.de/praxis/hardware/20-fakten-zu-ultrabooks-7388.html

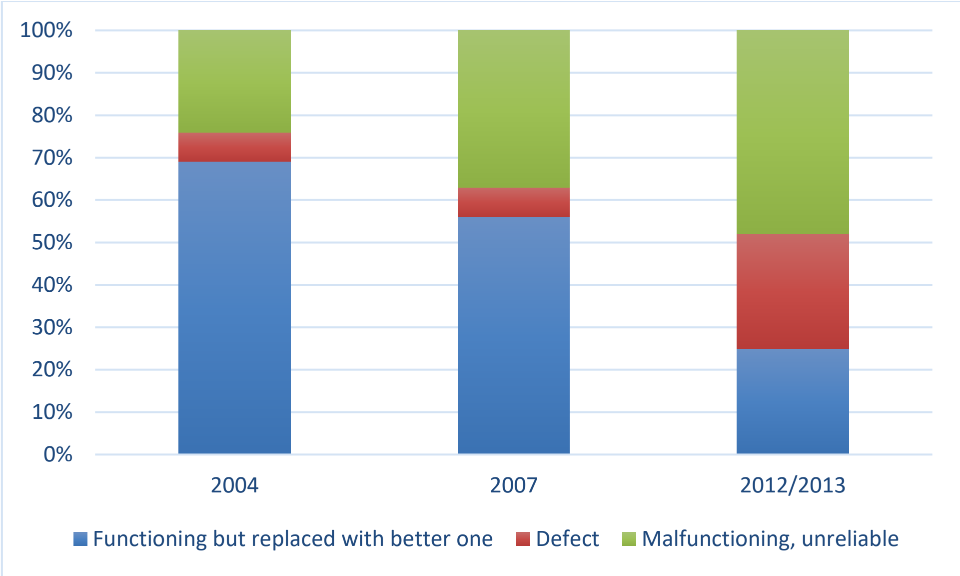

Figure 28 — Reasons for replacing a notebook after first use (Prakash et al., 2016b)

In a survey by Forsa (2013) in Germany half of the respondents judged it to be important that old computers can be upgraded with components with higher energy efficiency or with higher performance. In the same survey 61 % of the people interviewed stated that they would continue to use a notebook or tablet with a built-in battery even if the battery was to break or lose capacity as long as they could bring it to an electronic shop and have the battery replaced there directly on-site. Just 10 % of the survey participants would send it to a repair service to exchange the battery and then continue to use the device (Forsa, 2013).

Finally, Prakash et al. (2016b) surveyed the influence on the purchase decision of the information provided by the original manufacturer (i.e. the availability of spare parts, repair services, exchangeable parts and their lifetimes). Information about the lifetime was rated to be important or very important by 45 % of the interviewees. Consumers would even be willing to pay an additional price for a higher-quality product in the sense of extending the product life. If no lifetime-related product information is available, the majority of the interviewees chose the cheapest model (Prakash et al., 2016b). The survey shows also that the information on the exchangeability of the battery leads to a clear shift to buy a more expensive notebook, but also the ability to replace/repair the HDDs, graphics processing unit (GPU) or mainboard has an effect on the buying decision (i.e. shifting the decision from buying a cheaper notebook without exchangeable parts to buying a more expensive notebooks with exchangeable parts). The survey finally shows that the participants would prefer to buy a notebook with an exchangeable battery over a notebook with built-in batteries.

Recommendations to improve reparability

Talens Peiró et al. (2016) discussed some possible criteria on reparability for computers: 'computers should be designed such a way that key components (such as HDD/SSD, memory, screen assembly and LCD backlight, keyboard and track pad, and cooling fan) where used, are easily accessible and exchangeable by the use of universal tools' ([59]) (Talens Peiró et al., 2016). Suggestions provided by Dodd et al. (2014b) for Ecolabel requirements were aligned to the proposals by Talens Peiró et al. (2016b) as: 'All major repairable/replaceable components of computers, if applicable, such as hard drive, CD/DVD and Blue-ray drive, printed circuit board, memory, screen assembly, LCD

([59]) Defined by the study as: widely used commercially available tools such as screwdrivers, spatulas, pliers, or tweezers (Talens Peiró et al., 2016).

backlight, keyboard, track pad, rechargeable battery, cooling fan, catches and hinges shall be easily accessible and exchangeable by the use of universal tools (i.e. widely used commercially available tools)'. In order to prove compliance with the criteria above, manufacturers should provide clear disassembly and repair instructions (e.g. hard or electronic copy, video) and make them publicly available, to enable a non-destructive disassembly of products for the purpose of replacing key components or parts for upgrades or repairs (Talens Peiró et al., 2016). Additionally, a diagram showing the location of the abovementioned components and how these can be accessed and replaced can be made available in preinstalled user instructions and via the manufacturer website.

An additional suggestion could regard the distinction between components that can be repaired and those which need to be replaced (e.g. for upgrade) (Dodd et al., 2016, 2015); moreover repairs that can be carried out by consumers should be identified and clearly distinguished by those that necessitate professional work for safety reasons and in respect of warranty conditions (Dodd et al., 2016, 2015).

Initiatives

The Empowering Repair Co.Project (a collaboration between eBay, HP, and iFixit) aims to populate a portal with product information to enable more efficient disassembly and recycling of IT products (Ellen MacArthur Foundation, 2016). Other platforms are already available with guidelines on how to repair EEE or reviews of products and scores concerning their ease of repair. A method based on reparability scores has been developed (e.g. by iFixit) based on the difficulty of opening the device, the types of fasteners found inside and the complexity involved in replacing major components. Points are awarded for upgradability, the use of non-proprietary tools for servicing, and component modularity (Greenpeace, 2017).

Some manufacturers, such as HP, are committed to helping end-users extend the useful lifespan of products, by freely sharing service manuals and providing a wide range of service options and product warranties that enable people to repair their devices and maintain product quality (Ellen MacArthur Foundation, 2016). From a study conducted by Greenpeace (2017), 3 out of 17 brands assessed make the provision of spare parts and repair manuals easy to access.

Availability of spare parts is also crucial to allowing the reparability of computers. According to the Empowering Repair Co.Project, manufacturers should make spare parts available to all interested parties for a period after manufacturing that reflects the potential product life and for a price that reasonably reflects the part-production cost.

Summary

Surveys in Austria and Switzerland showed that the first-use time (products in use, time until a replacement is bought) of notebooks is significantly shorter than the desired lifetime (the time consumers desire the product to be functioning) (Thiébaud-Müller et al., 2017; Wieser and Tröger, 2016). The most important reason for buying a new notebook is due to defects or malfunctions — even more important than technical innovations or a lack of performance. The most frequent failures in notebooks are keyboards, displays, batteries and data storage. If those can be repaired or replaced easily many people would continue to use the same notebook. Increased reparability has the potential to bring more notebooks into a second or third life.

3.2.2 Reuse and repair of tablets

Main failures

According to repair inquiries on a German website ([60]) which compares repair prices and services (repeated inquiries possible) visitors mainly inquire about repairs for tablet-display defects. Display defects can include the following: an unresponsive touch screen, a black screen, pixel errors, broken glass or touchscreen (not in order of number reported). Other failures depend on the specific device (e.g. home button repair for some Apple tablets or repair of subscriber identification module (SIM) card reader for some Samsung tablets. Complementary findings can be retrieved from Knack (2016): the main common quality issues for tablets are: broken pixels (dots or lines on the display), dust or other dirt behind the screens, dust inside the camera, unresponsive touch screen and overheating batteries. Samsung for example recalled 2.5 million devices after reports of batteries exploding while charging (The New York Times, 2016).

Finally, as reported by the IDC (2016), the average annual failure rate observed in US organisations for tablets is 15.7 %. The most damaged component was the screen, followed by ports or connectors, the outer chassis and then the battery. On average, workers lost about 4.2 working hours for tablet repairs (Figure 29).

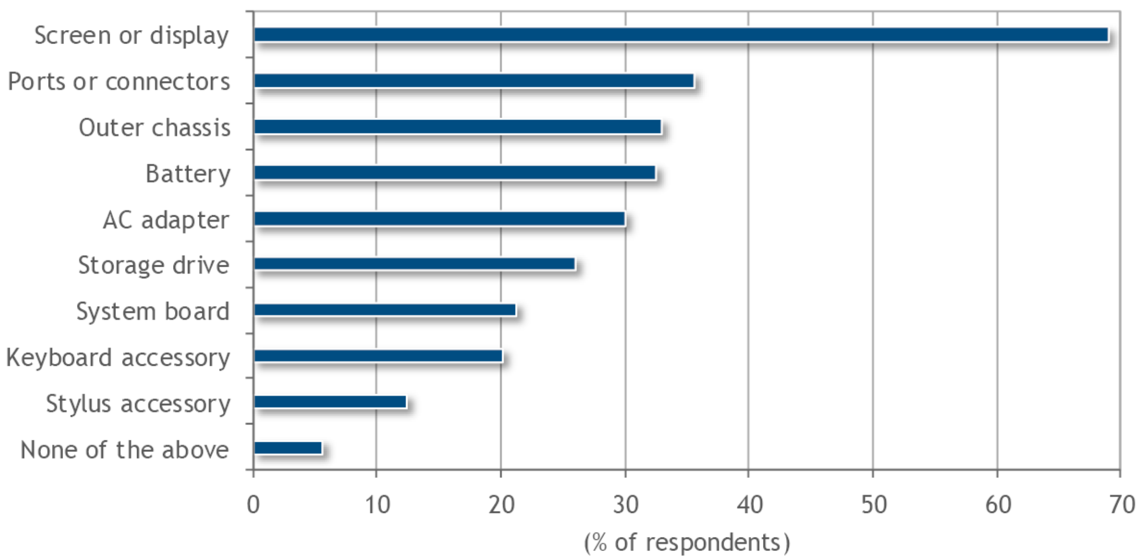

Figure 29 — Most common components in tablets that suffered damage or breakage (IDC, 2016).

Design approaches and reparability

A non-destructive step-by-step disassembly analysis performed by Fraunhofer IZM showed that among 21 analysed tablet computers, huge differences in the design approaches of the various manufacturers can be found. These differences lead to a significant variety of process steps required for opening the device, dealing with the types of connections used, and the removal of the main components (such as the battery, mainboard and display panel) as well as subassemblies (Nissen et al., 2013; Schischke et al., 2014, 2013).

Tablets feature four main mechanisms to fasten the device, components and subassemblies. The choice of fastener has significant influence on the time and difficulty of the disassembly, component removal and reassembly, in particular those listed below.

([60]) https://www.handyreparaturvergleich.de

- Screws are a good option in terms of opening, removal of parts and reversibility. However, the number of screws and the variety of screws (different sizes and heads) influence the disassembly time. Evidence from the disassembly trials show that axially accessible screws are typically easier to remove than the one radially accessible.
- Clips are considered a good option. However, the strength and the accessibility influence the easy-and-damage-free opening of the device.
- Connectors are used for the electrical connections, e.g. to connect the display or the battery to the mainboard. Connectors should be detachable as sometimes disconnecting small connectors can be delicate work and lead to damage.
- Adhesives are a suboptimal solution for fastening the device housing as well as for the main parts, in particular to attach the battery.

With respect to device opening, tablets feature three main principles — clips, screws, and adhesives. Evidence from the interviews with two repair companies (iFixit, San Luis Obispo, California and w-Support, Hartmannsdorf, Germany) indicates that screws are the preferred option in terms of damage-free opening. If clips are used, the reversibility depends mainly on their construction, robustness and their ability to disengage simultaneously. The use of adhesives is suboptimal as it requires heating tools, which could cause damage to temperature-sensitive components, e.g. the battery and some ICs.

In order to open the device without damage, multiple covers need to be separated such as camera or speaker covers. In most cases device opening starts from the backside, thus to reach the components on the opposite side — mainboard, battery and the display (last), the disassembly has to proceed through the whole device (Nissen et al., 2013).

Two main design principles are used to fasten the battery. In the first case, the battery is placed in a metal or plastic tray, which is attached (with an average of four screws) to the device. In the second case, the battery is directly glued into the device. The disassembly analysis of 21 tablets has shown that it is only after the tablet opening that the battery can be located. In 17 out of 21 tablets a combination of screws and adhesives were used to fix the battery in place. In 3 out of 21 tablets the battery wires were even soldered onto the mainboard. In order to remove the battery, multiple disassembly steps are required (between 3 and 10) (Nissen et al., 2013; Schischke et al., 2013).

With respect to repair, the glued option is suboptimal in terms of reversibility and safety as it requires a careful approach in order to not damage the battery cells. Access to the battery without the need to remove the mainboard is advantageous in terms of repair; it increases the reversibility and speeds up the process of battery replacement. Batteries with a connector cable to the mainboard are easier to replace than those with soldered wires (Nissen et al., 2013).

With regard to mainboard removal, the disassembly study indicates that the use of connectors allows for non-destructive removal of the mainboard. Easy access to connectors (on the upper side of the boards) and screws (not hidden under tapes, access from above) facilitate repair practice.

Moreover, tablets are particularly prone to being dropped, which makes the display a particularly sensitive part. According to iFixit, breakage of the display is one of the most frequent reasons for tablet repair (Schischke et al., 2014). An interesting finding is that the damage can affect only the front glass and not the whole unit. Therefore, non-fusion of the front glass with the display panel is a precondition for repair.

Therefore, easy access, dismantling and replacement of the display is of particular relevance. The considerable amount of steps required to access the display complicates the non-destructive part removal. In addition, working through the entire device increases the risk of damaging other device subassemblies.

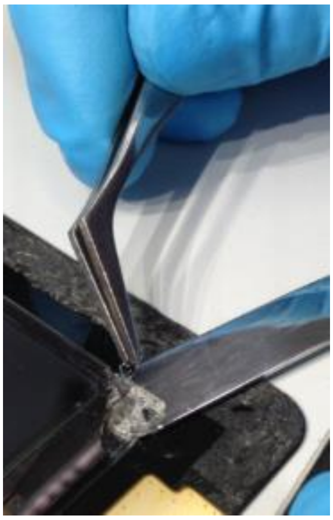

Figure 30 — Failed attempted to separate the front glass from the display panel (Schischke et al., 2014)

A study of the literature formulated some general recommendations to facilitate the repair of tablets, based on the analysis of product disassembly and interviews with iFixit and w-Support (Schischke et al., 2014).

- Easy-to-open and reversible closing mechanism, optimal via several screws. Clips might be used under the condition that they are robust and easy to disengage.
- A modular design, allowing for an easy-and-damage-free removal, as well as substitution of subassemblies, especially the ones that are prone to accidental damage. In general, all broken parts could be repaired under the condition that they are easily disassembled from each other.
- Colour-coded screws and labelled cables inside the device.
- Non-fusion of front glass with the LCD unit.
- Absence of proprietary screws or fasteners.
- Application of zero-insertion-force (ZIF) connectors for the connection of the battery and display with the mainboard; ribbon cables are also a possible alternative.
- Mainboard fixing to the housing via three to a maximum of seven screws.

iFixit also reveals that, due to absence of available information about tablet opening, usually the very first repair trial of a device just launched on the market causes unnecessary damage, degrading the product's value (Schischke et al., 2014). Thus, information concerning tablet opening and repair is considered highly relevant (e.g. as the repair Standard IEEE 18741 or oManual[61] – an open XML-based standard for semantic, multimedia-rich procedural manuals). In addition, repair makes no sense if spare parts are not made available from the manufacturers.

The same study identified that the following design features in tablets are suboptimal for repair (Schischke et al., 2014).

- Attachment of numerous subcomponents to a damage-prone part: in that case, all of the subcomponents have to be removed before the replacement of the respective part.
- Adhering of housing, battery, mainboard or display.

[61] See section 6.2.1 for further details.

— Multi-adhering of components, for instance when front glass, backlights and digitisers are fused together. Breaking any of these parts will require the replacement of the entire display panel.

4 Discussion and identification of hot spots and of improvement opportunities

Sections 2 and 3 aimed to introduce the technical background and current situation of the product group, concerning, in particular, market data, BoMs and also an analysis of current and potential future practices concerning recycling and repair/reuse.

During this analysis, several *hot spots*, i.e. aspects of the product group that are relevant from a material-efficiency perspective, were identified. Hot spots consist of, for example, problems potentially encountered by EoL operators during the treatment of computers, or design features of the products that facilitate (or hamper) disassembly or repair. Identified hot spots are summarised in Table 22 for each product sub-group and organised among three main material-efficiency aspects: recyclability, repairability/reusability and material savings.

Some hot spots (for example the unknown content of indium in notebook and tablet displays) or potential obstacles for the dismantling of integrated desktop computers, were identified during the analysis of similar product groups (e.g. 'electronic display'). With this purpose a draft regulation for ecodesign implementing measures for electronic displays is currently in preparation and it addresses some the aspects identified in Table 22. Therefore, these aspects have been not elaborated further in the present study. Aspects detailed in Table 22 are judged as relevant and these will be further explored in the following sections. The table also clarifies which aspects are relevant for the product sub-groups.

The following three sections are as follows.

- Proposals of actions to improve waste prevention (Section 5)
- Proposals of actions to enhance repair/reuse (Section 6)
- Proposals of actions to enhance recyclability (Section 7)

Each proposal is supported by a short introduction on the state of play and motivations (Rationale), and is then discussed in terms of the feasibility of the action, focusing in particular on the availability of standardised procedures or on the need for standardisation work. Some of the authors observed that the absence of appropriate metrics and standards has been a key barrier to material efficiency, and that specific standardisation needs can be systematically identified, developing adequate metrics for performance measurements, reliable and repeatable tests, and calculation procedures (Tecchio et al., 2017).

Finally an initial assessment of benefits/impacts for specific actions is presented. The initial assessment has been developed considering the potential material savings and additional flows of recycled materials obtainable thanks to material-efficiency measures that aim to facilitate dematerialisation and a circular economy. We recall that *material efficiency* does not directly regard resources used to produce energy, nor energy used during the lifecycle of products (Tecchio et al, 2017).

Raw materials are crucial to Europe's economy and essential to maintaining and improving our quality of life. Securing reliable and unhindered access to certain raw materials is a growing concern within the EU and across the globe. Examples of critical raw materials include REE, indium and cobalt (Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, 2016).

Table 22 — Summary of 'hot spots' of computer sub-product groups (as identified during the analysis of Sections 2 and 3)

Material-efficiency aspects and sub-aspects		**Identified hot spots (divided by sub-product groups)**	
		Non-mobile personal computers	**Mobile personal computers**
		Desktop computers and Integrated desktop computers	**Notebooks and Tablets**
Waste prevention	Lifetime of product and components.		Limited lifetime of batteries.
			Failure problems observed on computer components (e.g. display panel, keyboard, data storage, battery, ports or connectors, outer chassis).
	Prevention of material consumption.		Presence of unnecessary external power supplies (EPS) in new computers sold.
Repairability/reusability			Need for detailed information about the disassembly of certain components, such as batteries, memories, data storage, display panels.
		Lack of information crucial for repair Privacy issues due to data content (and needs for secure data deletion).	
Recyclability	Ability to remove components containing valuable and hazardous materials	For integrated desktop: Difficulties for the dismantling of the display panel. For compact desktop (mini desktops): possible dismantling problems for the batteries (when present).	Difficulties for the dismantling of certain components, such as batteries, display panels, PCBs in various parts.
	Recyclability of plastics	High diversity of plastic with additives (including flame retardants (FRs)) in the whole product group makes difficult to sort and recycle polymer at a sufficient quality.	
	Recyclability of batteries		Identification and composition of batteries is not always clear by recyclers hence creating inefficiency in the treatments and material losses.
	CRM content	Additional information on the content and location of certain CRMs could incentivise research and investments of new technologies and process for their recycling.	

4.1 EU Ecolabel and EU green public procurement criteria

Reports by Dodd et al. (2016, 2015) and Talens Peiró et al. (2016) were consulted to understand which options were suggested for the revision of the EU Ecolabel and the EU green public procurement (GPP) criteria of the product group. Talens Peiró et al. (2016), in particular, developed specific criteria for the reparability and design for dismantling of computers and electronic displays. Criteria for the EU Ecolabel were released officially through the Commission Decision (EU) 2016/1371 of 10 August 2016, establishing the ecological criteria for the award of the EU Ecolabel for personal, notebook and tablet computers (European Commission, 2016).

This further analysis was done to understand which options could potentially be adopted to address the hot spots of Table 22, even though mandatory requirements related to the Ecodesign directive typically take into consideration verification methods which are different from the ones applied for voluntary schemes.

A summary of the interested criteria of the Commission Decision (EU) 2016/1371 is given hereinafter. These criteria, as well as findings from Dodd et al. (2016, 2015) and Talens Peiró et al. (2016) were used to develop possible improvements under the ecodesign directive, in Sections 5, 6 and 7.

Lifetime extension: durability testing of personal computers

Notebook computers must pass certain durability tests for the award of the EU Ecolabel. Each device must be verified to function as specified and to meet the stipulated performance requirements after performing some mandatory tests (specified in IEC 60068, e.g. resistance to shock tests, resistance to vibration, drop tests) and additional durability tests (temperature stress, screen resilience, water-spill ingress, etc.).

Lifetime extension: upgradability and reparability

Key components of personal computers (memories, mass-storage systems, screen assembly and LCD backlight, keyboards, track pads and cooling fans) should be easily accessible and exchangeable with the use of universal tools. Furthermore, rechargeable batteries in mobile computers should be manually extractable, with no need of tools, and information on how to separate the battery pack should be marked on the base cover of the chassis. Exceptions were proposed for tablets, for which the extraction of the battery would be allowed with a maximum of four steps (three for sub-notebooks and Ultrabooks™) and the use of commercially available tools. The applicant is also asked to provide clear disassembly and repair instructions.

End-of-life management: plastic components

Plastic components with a mass greater than 25 g for tablets and 100 g for all other computers should be properly marked, including the presence of FRs. The polymer composition can be identified by means of ISO 11469 and ISO 1043 markings.

End-of-life management: design for disassembly

Furthermore, key components (PCBs, internal power supplies, HDDs, batteries, etc.) should be easily extracted from the product. A disassembly test must be carried out according to the test procedure detailed in the Appendix of the Commission Decision (EU) 2016/1371. The test must record the number of steps required and the associated tools and actions required to extract the key components.

5 Possible actions to improve waste prevention

According to the waste hierarchy set out by the European Commission (Directive 2008/98/EC, (European Union, 2008)), waste prevention has the first priority, before preparing for reuse or recycling. Among the strategies to close (and slow) material loops, design for reliability and durability and design for standardisation and compatibility are key aspects (Bocken et al., 2016). As such, opportunities to eliminate or postpone factors potentially leading to premature obsolescence of personal computers have a high priority in legislation implementation.

5.1 Battery durability

5.1.1 Rationale

End-users want durable goods, such as notebooks, to last considerably longer than they are currently used (Wieser and Tröger, 2016). Prakash et al. (2016b) surveyed the influence of information provided by original manufacturers about the availability of spare parts, repair services, exchangeable parts and *lifetime* on the purchase decision. Information about the lifetime was rated as *important* or *very important* by 45 % of the interviewees. Battery durability is considered by users to be a key feature: in a survey conducted by the IDC (2010), 68 % of respondents confirmed that the battery lifetime on their notebook computer was not sufficient for their business needs. Respondents also indicated that 22 % of notebook computers required the purchase of a replacement battery during its lifetime.

Therefore, increased battery durability becomes important considering the current trend towards more-integrated devices, leading manufacturers to integrate batteries within devices and abandoning the previously widespread slide-lock removal mechanisms. Examples for this development were provided in Section 3.2 of this report. Manufacturers design integrated batteries to improve the robustness of the whole device and to make devices thinner, however end-users may face potential difficulties in replacing an exhausted battery by themselves. Hence, battery durability is a more meaningful factor than ever.

Information about battery durability

LIB inevitably lose a fraction of their full-charge capacity with every charge/discharge cycle they go through (see Section 2.2.2). It has been shown that the capacity of some batteries fades quicker than others (Clemm et al., 2016). To guarantee a minimum level of durability and hence prevent premature waste generation, battery-cycle tests may be used to determine the number of charging cycles a battery can withstand before its capacity fades to a certain threshold.

Current legislation requires manufacturers of notebooks to provide data on the expected cycle life of batteries in notebooks (Commission Regulation (EU) No 617/2013) ([62]). In a non-exhaustive survey of the websites of notebook manufacturers it was found that only two manufacturers provided such information (Apple ([63]) and HP ([64])), only one of which refers to specific notebook models. Furthermore, without a set of complementing information on the methodology applied to determine the minimum number of charging

([62]) 7.1 From 1 July 2014
'7.1.1 Manufacturers shall provide in the technical documentation and make publicly available on free-access websites the following information:
[…] (o) the minimum number of loading cycles that the batteries can withstand (applies only to notebook computers)' (Commission Regulation (EU) No 617/2013).

([63]) https://support.apple.com/en-us/HT201585

([64]) http://support.hp.com/us-en/document/c00596784 cycles, data cannot be considered meaningful. At the very least the following information is required to put the number of charging cycles provided by the manufacturer in context:

- the definition of a charging cycle;
- the capacity threshold at which the battery is considered exhausted;
- the measurement methodology (e.g. a testing standard).

A cycle is defined as 'an amount of discharge approximately equal to the value of design capacity' (SBS-IF, 1998), with design capacity referring to the theoretical capacity of a new battery (pack) (also: 'rated capacity' during a 5-hour discharge, as declared by the manufacturer). In practice, a charging cycle is often defined as discharging (possibly in several partial-discharge events) and consequently recharging it to 100 % (e.g. Apple).

Information on the methodology and capacity threshold would allow for transparency as well as a certain degree of comparability between the different cycle numbers manufacturers provide for their devices. Ideally, a standardised methodology would be stipulated to allow for greater transparency and comparability.

Battery durability in stationary use

A common use pattern for notebooks is stationary use, in particular in office environments. Stationary use means non-mobile use, e.g. on a desk, and in grid operation, i.e. directly plugged into a power outlet or using a docking station. As the battery is constantly connected to the grid, the battery SoC is permanently close to 100 %. High SoC is known to accelerate the ageing of LIB (Section 2.2.2). A study on the lifetime of notebook batteries in the field found that 50 % of the notebook batteries in the offices of companies or public administrations were cycled up to 30 times per year. Despite the low charging frequency, a large share of the batteries had lost significant portions of their initial capacity (Clemm et al., 2016). This is partly attributed to the high SoC during notebook use in grid operation as well as other factors, such as increased temperatures when working in grid operation and using a docking station in particular, among other factors. In conclusion, the user should have the means to increase the durability of device batteries by preventing a constantly high SoC when using their notebook in grid operation.

It is technically feasible to limit the SoC to which a notebooks battery is charged when plugged into a power outlet via software tools. Several of the large notebook manufacturers ship their devices with such software preinstalled ([65]). One of the features of this software is the option to use battery-optimising modes. A software button (on/off switch) allows the user to enable and disable a mode in which the battery is charged up to a pre-defined or user-defined state of charge, commonly in the range of 50-70 % SoC. Thus, a high SoC is prevented while using the notebook in grid operation, potentially increasing battery durability at relatively low cost to the manufacturer.

When battery-optimising mode is not enabled, the software tool of one manufacturer will recommend the user (via a pop-up message) enable battery-conservation mode, if the device is used in grid operation (and 100 % SoC) for a predefined period (e.g. 2 hours). The user can switch off battery-conservation mode and fully charge the battery if needed, e.g. before using the device in mobile, battery-powered mode. The disabling of battery-conservation mode can further be triggered at a certain time as defined by the user (e.g. with a timer coupled to a calendar application). Battery-conservation mode is further recommended when the device will not be used for a period of time, to decrease calendar ageing of the battery.

([65]) Examples are the Lenovo battery conservation mode, Dell battery meter, Sony battery care.

5.1.2 Possible improvements

Information about battery-cycle life

A minimum level of battery durability could be potentially established when information about battery-cycle life are made available to end-users (e.g. in the user documentation), with common testing rules. In a durability test for batteries, two main parameters consist in the number of charge/discharge cycles and the remaining full-charge capacity compared to the initial-charge capacity (SoH). So, the two possible ways to identify battery durability are as follows.

- Declaring the number of charging cycles device batteries can withstand before the capacity fades to a set threshold.
- Declaring the SoH of the battery (the remaining full-charge capacity compared to the initial-charge capacity) after a predefined number of charging cycles.

The second option seems more practical, as the first option would disadvantage products with higher durability, as more charging cycles are needed to reach the desired threshold. The availability of information on battery-cycle life would help end-users to get an indication on how long the battery in a specific device may last. This piece of information may potentially be complemented with the manufacturing date of the battery. Moreover, such a declaration on the cycle stability of the battery allows the comparability among products of different manufacturers, and potentially pushing the market towards higher-quality battery cells.

Therefore, batteries could be tested in accordance with the most recent version of the Standard EN 61960 ([66]), and results could be communicated as the remaining full-charge capacity of the battery compared to the initial-charge capacity, after a predefined number of charge/discharge cycles (e.g. 300 and/or 500 cycles).

Standard EN 61960 defines secondary ([67]) (rechargeable) batteries (battery packs) and cells as follows.

- Secondary lithium battery: 'unit which incorporates one or more secondary lithium cells and which is ready for use. It incorporates adequate housing and a terminal arrangement and may have electronic-control devices'.
- Secondary lithium cell: 'secondary single cell whose electrical energy is derived from the oxidation and the reduction of lithium. It is not ready for use in an application because it is not yet fitted in its final housing, terminal arrangement and electronic-control device'.

According to Section 2.2.2, a remaining charge capacity of 80 % of the initial charge is typically reached between 300-500 charge/discharge cycles, for consumer products (Battery University, 2016a). Taking into consideration this evidence and the technological progress (declarations of batteries that can be considered consumed after 1 000 cycles are available ([68])), it is reasonable to consider 300 and 500 charge/discharge cycles for the declaration of the remaining charge capacity according to EN 61960 tests, and the remaining charge capacity after 500 cycles as a possible parameter to be directly communicated to users. Voluntary declarations about the SoH after a higher number of cycles (e.g. 750 and/or 1 000 cycles) can be encouraged as well.

Battery manufacturers have a number of possible tests to evaluate battery-cycle life following the Standard EN 61960. The test on battery life can be applied either at the battery-cell level or at battery-pack level. Furthermore, non-accelerated or accelerated-

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([66]) IEC 61960:2011 Secondary cells and batteries containing alkaline or other non-acid electrolytes — Secondary lithium cells and batteries for portable applications.

([67]) IEC definition of a primary cell: 'cell which is not designed to be electrically recharged'; IEC definition of a secondary cell: 'cell which is designed to be electrically recharged' by way of a reversible chemical reaction (IEC, 2017).

([68]) https://support.apple.com/en-us/HT201585 test procedures are available. Specifically, Section 7.6.3. 'Endurance in cycles at a rate of 0.5 I_t A (accelerated-test procedure)' is pointed out in order to reduce the burden of the test requirements (as compared to the regular test procedure set out in Section 7.6.2.); however, with this approach, batteries are subject to overstressed conditions and capacity may fade quicker.

Tests conducted at the battery-pack level are closer to reality, considering that notebook batteries are often composed of four or more cells. However, manufacturers may use the same battery cells in different pack combinations, so testing a specific cell would give a good indication of how all packs incorporating that cell behave. It is therefore recommended to refer to the test for cells rather than for battery packs since single-cell design may be used in multiple battery-pack designs.

Using the accelerated-test procedure, and assuming that battery charging takes 3.5 hours, the test procedure for 500 cycles is estimated to result in the following time investments:

- charging: 3.5 hours
- idle time: 0.5 hours
- discharge: 2 hours
- time investment per cycle (sum): 6 hours
- time investment for 500 cycles: **125 days**.

However, the non-accelerated-testing procedure can more realistically reproduce use patterns of notebook and tablet computers, as the prescribed discharge rate of 0.2 C [69] (discharge within 5 hours) is much closer to the power consumption of such devices compared to the discharge rate of 0.5 C in the accelerated-testing procedure. Furthermore, private communications with manufacturers confirmed that non-accelerated-testing procedures are commonly applied to batteries at the manufacturing plant.

Under the assumption that battery charging takes 3.5 hours, the test procedure for 500 cycles is estimated to result in the following time investments:

- charging: 3.5 hours
- idle time: 0.5 hours
- discharge: 5 hours
- time investment per cycle (sum): 9 hours
- time investment for 500 cycles: **188 days**.

It can be assumed that cell testing of cycle life takes place at the cell manufacturer rather than the device manufacturer. It can further be assumed that cell manufacturers test their cells before mass production, in part to provide specifications to their customers. Hence, it can be assumed that certain testing data on cell cycle life and the applied methodology is already available to the cell manufacturer and the additional burdens of a legislative requirement in this context would be limited.

The information about battery durability, to be provided in the user documentation, can be complemented by the following features of the battery:

- design capacity;
- voltage;
- date of manufacture;
- the capacity threshold at which the battery is considered exhausted;
- the definition of charge/discharge cycle and the measurement methodology used for testing;
- explanation on how ambient temperature and battery SoC can impact the battery lifetime;

[69] Coulomb: it is the electric charge transported by a constant current of one ampere in one second.

— battery manufacturer.

Finally, this possible improvement was also based on and compared to what was proposed for the revision of the EU Ecolabel criteria and EU GPP criteria for personal computers. The authors of the background studies proposed that points be awarded for durable batteries. Points were supposed to be achieved at different thresholds (including the here-proposed threshold of 500 charge/discharge cycles), depending on when the battery reaches 80 % of the initial full-charge capacity. For verification, the applicant must provide a test report for the battery cells or packs showing compliance according to the EN 61960 (Dodd et al., 2016). For the scope of the Ecodesign directive, instead, such a test report could be done by a third-party laboratory to verify the compliance with what was declared by the manufacturers.

Future developments may also consider establishing efficiency classes for the SoH of batteries, using an 'A-G grading system', or similar. The collection of more extensive data about batteries in the market (e.g. through a dedicated database) could help in building such a grading system.

Battery lifetime optimisation

The durability of notebook batteries could be further improved by implementing a preinstalled functionality which prevents battery-cell capacity to fade because of being kept for a long time at a high SoC (see Section 2.2.2: between 90 and 100 %). This may occur when the device is used stationary (i.e. in grid operation).

Manufacturers can develop in-house solutions (e.g. functionalities, or battery-charging algorithms) for this problem, even if the literature review highlighted that a practical option could be to limit the SoC of the battery to a specified value (e.g. 70 % or less compared to the available full-charge capacity) whenever the device is used stationary (i.e. in grid operation). In any case, the effectiveness of such a lifetime optimisation function can be guaranteed if 1) manufacturers take action to inform the users of its existence and the benefits, 2) end-users can have the option to temporarily disable the limit on SoC ([70]), but cannot have the option of setting limits on the SoC that potentially reduce the battery lifetime, decided by manufacturers.

Such a function could also be used to provide information about the battery features to end-users, such as:

- current SoC;
- current SoH (as the current full-charge capacity compared to the design capacity);
- number of charge/discharge cycles the battery has already gone through;
- battery temperature;
- battery chemistry;
- other features of the battery (see the list of complementary information to be provided in the user documentation for battery durability).

5.1.3 Initial assessments of benefits/impacts (battery lifetime optimisation)

Increased battery durability potentially increases the time the battery can be used in a notebook (or tablet) before losing as much capacity as to be considered as having reached its EoL. Thus, either the replacement of the device battery is delayed, or even the disposal of the entire device is delayed. This may prevent the waste-and-environmental impacts associated with recycling as well as the manufacturing of a replacement battery.

([70]) For a limited amount of time (e.g. until the next restart of the computer).

As can be derived from Figure 3, the lower the SoC of a battery when in storage (without cycling), the higher its durability will be. Depending on the SoC, the capacity of the tested cells fades to 80 % full-charge capacity after varying times:

- SoC of 95 % after less than 300 days,
- SoC of 80 % after around 300 days,
- SoC of 70 % after around 400 days,
- SoC of 50 % after more than 500 days.

The testing by Schmalstieg et al. (2014) has been carried out under conditions of elevated temperature (50 °C) to speed up the observable effects of calendar ageing at varying SoC. However, by deriving a factor which describes how much capacity fade is prevented by capping the SoC, the actual number of days in the accelerated test can be ignored to establish the following simplified scenarios.

Scenario A: A notebook computer is permanently used in grid operation. Assuming that a software to limit the SoC in grid operation limits the SoC, the battery durability may be increased as follows.

- SoC limit at 70 % may increase battery durability by factor [400 days/300 days =] 1.34.
- SoC limit at 50 % may increase battery durability by factor [500 days/300 days =] 1.67.

Scenario B: A notebook computer is used 75 % of the time in grid operation and 25 % mobile on battery power. The effect of SoC limit would only account for the share of grid operation. Hence, if the SoC is capped at 70 % during grid operation, the durability is increased by factor 1.26 (calculation below). If SoC is capped at 50 %, the factor is 1.50.

- SoC limit at 70 % may increase battery durability by factor [(0.75 * 1.34) + (0.25 * 1) =] 1.26
- SoC limit at 50 % may increase battery durability by factor [(0.75 * 1.67) + (0.25 * 1) =] 1.50

Scenario C: A notebook computer is used 50 % in grid operation and 50 % mobile on battery power. The effect of SoC limit will only account for the share of grid operation. Hence, if the SoC is capped at 70 % during grid operation, the durability is increased by factor 1.17 (calculation below). If SoC is capped at 50 %, the factor is 1.34.

- SoC limit at 70 % may increase battery durability by factor [(0.5 * 1.34) + (0.5 * 1) =] 1.17
- SoC limit at 50 % may increase battery durability by factor [(0.5 * 1.67) + (0.5 * 1) =] 1.34

Prakash et al. (2016c) investigated the effect of extending the lifetime of notebooks used in public administration for a total useful life of 6 years instead of 3 years. In their assumptions, the authors estimated that battery replacement is necessary in 50 % of notebook computers to allow such a lifetime extension. This assumption can be converted into a value of 1.5 batteries/mobile computer, and was here adopted to build a base-case scenario in which the lifetime of notebooks, according to Table 2, is considered to be 5 years on average. The average mass of a notebook battery was assumed to be 259.6 g (according to Table 14) while its average composition was derived from Table 17.

In our assessment, we considered the projection of shipments of notebooks in 2020 (about 41.7 million of products), and that the average mass and the average composition of batteries are kept constant over time. The market projection for notebooks was gathered from Table 1.

We estimated the benefit of battery-optimisation software with the following parameters.

- Base-case scenario: no use of battery-optimisation software and need for batteries for each notebook computer set to 1.5 batteries.

— Scenario B: notebooks working in grid operation 75 % of the time, SoC limits 70 % and 50 %.
— Scenario C: notebooks working in grid operation 50 % of the time, SoC limits 70 % and 50 %.

Scenario A (notebooks working in grid operation 100 % of the time) was not considered realistic. With these assumptions, it was possible to estimate the material saving achievable thanks to the adoption of scenarios B and C instead of the base-case scenario, where no battery-conservation software is used. Results are presented in Table 23. Table 23 provides the total mass of materials that can potentially be saved, as well as specific savings of cobalt (Co), lithium (Li), nickel (Ni) and copper (Cu), compared to the base-case scenario.

Table 23 — Material savings (batteries in million units/year, materials in t/year) achievable when a battery-optimisation software is implemented in notebooks.

Future scenarios	**Scenario B**		**Scenario C**	
	cap 70 %	**cap 50 %**	**cap 70 %**	**cap 50 %**
Notebook batteries (million units/year)	12.9	20.8	9.1	15.9
Cobalt, Co (t/year)	281	454	198	346
Lithium, Li (t/year)	60	97	42	74
Nickel, Ni (t/year)	131	211	92	161
Copper, Cu (t/year)	452	730	318	556
Other (t/year)	2 424	3 915	1 707	2 980
Total (t/year)	3 347	5 407	2 357	4 116

The yearly rate of material saving ([71]) estimable with these hypotheses ranges between 2 357 t and 5 407 t. In the best conditions (Scenario B and SoC limit set to 50 %), about 454 t of cobalt, 97 t of lithium, 211 t of nickel and 730 t of copper can be saved every year.

A SoC limit set to 50 % would bring the highest material savings, however would also limit the autonomy of the notebook battery once it is not used in grid operation. A SoC limit set to 70 %, instead, would allow a higher autonomy in case the notebook battery is not used in grid operation, but implying reduced material savings. Manufacturers could actively develop more developed in-house functionalities to prevent the battery to remain at full charge when the notebook is in grid operation, and to enable one or more limits on the battery state of charge (SoC) when the notebooks is in grid operation.

5.1.4 Other potential benefits (information about battery-cycle life)

The assessment of the potential benefits related to the communication of the remaining full-charge capacity of the battery compared to the initial-charge capacity, after a predefined number of charge/discharge cycles, is characterised by higher uncertainty, for both notebooks and tablets. As reported in Section 2.2.2, a battery is considered exhausted when its capacity reaches 80 % of original capacity. However, batteries can continue to be used even below 80 % capacity, although the runtime of the device will be decreased. This can be reached after 1 000 charge/discharge cycles, for high-quality products, but typically it is reached between 300-500 charge/discharge cycles. It is

([71]) Scenarios do not consider the amount of materials lost through refining, processing and manufacturing.

assumed that declaring the performance of the battery would boost the competition among battery manufacturers, resulting in more durable products.

An average value of 1.5 batteries/mobile computer (notebooks and tablets) was again assumed as base case, and two hypothetical scenarios in which the value is decreased to 1.4 and 1.3 batteries/mobile computers. With these hypotheses, and considering notebooks and tablets sold in 2020, 2025 and 2030, as in Table 1, the replacement of 4.1-8.1 million batteries/year for notebooks and 3.8-7.5 million batteries/year for tablets can potentially be avoided. The total saving of materials can be estimated in the range 1 560-3 050 t/year. Nonetheless, we highlight that further work is needed to estimate the potential improvement in battery durability.

5.2 Decoupling external power supplies from personal computers

5.2.1 Rationale

EPS represent a very significant percentage of the whole weight and materials used for ICT (estimated to be in the range 10-20 %), thus it is important to set specifications for materials and EoL compatibility, in order to minimise their impact on the environment (ITU-T L.1002, 2016).

The rationale for this section is to promote the reuse of EPS by means of the following.

- The adoption of *interoperable* and *common EPS* (as described in Section 2.5), which makes the service life of an EPS independent from the product's useful life.
- The progressive *decoupling* of products and EPS, which intends to promote the reuse of EPS already available by the end-users.

Material savings can be achieved thanks to the reduced production and delivery of new EPS and the consequent reduction in electronic waste. As reported in Section 2.3.4, an EPS supplies power to notebooks, tablets, and other devices that do not contain internal components to derive the required voltage and power directly from the grid. The function carried out by EPS is to transfer power to the device by converting voltage and current characteristics from the grid to the desired load levels. Therefore, reuse of EPS is possible, when the power output and other main features (e.g. interfaces, connectors, energy efficiency, no-load power or safety) are compatible with multiple ICT devices.

An example of EPS reusability thanks to compatible specifications is represented by the mobile-phone sector. A memorandum of understanding (MoU) was recently signed between the European Commission and 14 electronics manufacturers. The agreement is for the harmonisation for all EPS for data-enabled telephones and hence enables the reusability of the EPS. As reported by Cucchietti et al. (2011), a common EPS would bring benefits to manufacturers, vendors and customers; the latter category, in particular, would be able to share just one charger for more than one device. Manufacturers and vendors would be able to ship and sell their devices without the charger in the package, with potential material savings due to the reduced use of materials and impacts for transport and distribution (about 90 % of EPS are manufactured in Asia (Risk & Policy Analysts Limited, 2014)) and the box containing a new mobile phone can be around 25 % lighter when an EPS is not included.

Back to the computer product group, as little as 10 years ago, it was observed that efficient EPS are getting smaller, lighter in weight, and more convenient to store and transport (Bio Intelligence Service, 2007). PCBs used in EPS were characterised as low-grade (< 200 ppm gold), the classification used for low mass of valuable materials (Dimitrova, 2012; Goosey and Kellner, 2002). Nowadays, efficient EPS operate at cooler temperatures, contain fewer parts, and are likely to result in greater product reliability (Bio Intelligence Service, 2007); it is also possible to find EPS for notebooks with a weight of 85 g, and an output power of 65 W (FINsix®, 2016) on the market. Moreover, new EPS would not have large transformers or capacitors (EPS based on the switching-mode technology do not require such components), and would be characterised by smaller size and weight, thanks to technological innovation and to more integrated and miniaturised components (Dimitrova, 2012). The PCBs of EPS could potentially be processed by dedicated recycling processes to optimise the recycling output, but due to the complex dismantling required and the small quantity of valuable materials, this becomes not viable economically (Sarkis, 2001).

With these preconditions, it seems reasonable to promote the reuse of EPS for personal computers in order to extend the lifetime and therefore to enhance material savings. According to the Risk & Policy Analysts Limited (2014) study, the harmonisation of EPS for portable electronic devices would affect manufacturers in different ways.

— There would not be significant costs on the manufacturers of portable electronic devices.
— Significant impacts on competition, competitiveness, trade and investment flows are not expected.
— Harmonisation might slow down innovation, according to some stakeholders consulted by the authors.
— Manufacturers of chargers and cables could potentially benefit from the use of more expensive components, but are also likely to incur revenue losses due to increased decoupling.

5.2.2 Possible improvements

The provision of information on the EPS specifications and the presence/absence of the EPS in the packaging of notebooks and tablets could potentially enhance the reuse of available EPS, and hence result in a significant reduction in material consumption for the production of unnecessary power supplies and for the treatment of electronic waste. This information provided to end-users could promote the use of common EPS across different devices. Material savings can potentially be achieved thanks to reductions in production, packaging, transport and distribution.

Such information can be conveyed to end-users through the user documentation and a logo (e.g. on the packaging). For personal computers that use an EPS the information could include the required power-supply specifications, namely voltage, current and rated output power.

The main goal of the logo could be to indicate the presence or absence of the EPS within the packaging. If it is present the end-user can be informed through the user documentation about the possibility to use the contained EPS with other devices and compatibly with the EPS specifications. Vice versa; if the EPS is absent the user documentation can notify the user about the possibility to use an alternative suitable EPS which meets the device specifications. The user documentation should also inform about the type of connector required to interface the EPS with the device.

Labelling schemes can be based on standards and recommendations. In particular, the specifications of the common EPS should include the following.

— The recommended types of device that can be connected (e.g. notebooks, tablets).
— Input voltage type, input voltage range, frequency range and maximum input current.
— Output voltage, current and power ranges, with efficiency of power conversion.

Standards can be used and can be further developed to illustrate the interoperability of common EPS for use with notebooks and/or tablets.

IEC/TS 62700 (2014) (DC power supply for notebook computers), Standard IEEE Std 1823 (2015) (Standard for universal power adapter for mobile devices) and Recommendation ITU-T L.1002 (External universal power adapter solutions for portable ICT devices) represent relevant sources to illustrate the common charging capability and interface requirements for the EPS, as in the case of IEC 62684 (2011) developed for data-enabled mobile telephones.

5.2.3 Initial assessments of benefits/impacts

The initial assessment was based on future scenarios in which electronic devices (notebooks and tablets) and EPS are gradually decoupled, meaning that a certain percentage of products put on the market will not include an EPS in the packaging. Future scenarios were estimated by the authors of this report.

The same EPS may be used by different types of products which are compatible with the power-supply specifications (e.g. notebooks and tablets, but also smartphones and other electronic devices). In order to assess potential benefits related to the decoupling of EPS from personal computers, two scenarios have been developed, one related to EPS in notebooks and another for EPS in tablets. In this context, these scenarios do not take into account that the harmonisation of power specifications could bring about the common use of the same EPS for tablets and notebooks. These devices used to have different power requirements (lower for tablets and higher for notebooks), and assessment concerning these products have also been considered separately in previous research (Risk & Policy Analysts Limited, 2014). Nowadays however, many notebooks can work with a power requirement of less than 100 W, and the USB type-C specifications allow scalable power up to 100 W ([72]). However, due to the lack of input data, it was not possible to estimate the number of notebooks and tablets that can potentially share the same EPS. Thus, this section does not consider the possibility of using the same common EPS for both notebooks and tablets and assumes that the technology of the common EPS would be based on micro-USB connectors, although notebooks and tablets could also rely on standard-USB connectors.

Risk & Policy Analysts Limited (2014) focused on the harmonisation of EPS for portable electronic devices and found that micro-USB was barely used for charging devices, as it would be subject to power output limitations. Harmonisation would be more feasible given the release of IEC/TS 62700 (2014), the Standard IEEE 1823 (IEEE, 2015) and the Recommendation ITU-T L.1002 (2016).

Scenarios used in previous studies for mobile phones

According to the Risk & Policy Analysts Limited (2014) report, two scenarios were drawn in order to study the product group of mobile phones, differentiating between possible action taken by the European Commission. In the first one (namely 'Scenario 2 %'), the European Commission was supposed only to encourage discussions among manufacturers of the relevant devices, with the goal of facilitating a consensus on the use of a common EPS; as a result, 2 % of devices were supposed to be sold without a charger, based on an extrapolation of the current decoupling trend (device and EPS) for mobile phones. In the second one (namely 'Scenario 50 %'), the European Commission was supposed to propose legislation requiring that devices use the common EPS; in this case 50 % of mobile phones were supposed to be sold without a charger. 50 % represents the highest possible decoupling rate, basing the estimates on the current levels of ownership of mobile phones and expected charging behaviour of consumers.

Scenarios developed for notebooks and tablets

The assessment of potential benefits related to the proposed action was built considering the European market projections for notebooks and tablets of Table 1, Section 2.1. Average masses of 114 g and 440 g were considered for EPS used by tablets and notebooks respectively, according to Risk & Policy Analysts Limited (2014). The composition of the two power supplies was retrieved from Table 13, taking into account the '60 W notebook' for the tablet EPS composition, and the '90 W notebook' for the notebook EPS composition (Bio Intelligence Service, 2007; Dimitrova, 2012). The average composition of electronics in EPS for tablets and notebooks has been retrieved from the values of Table 11.

The assessment was developed on different scenarios for years 2020, 2025 and 2030. Compared to the study of Risk & Policy Analysts Limited (2014), where only the two 'Scenario 2 %' and 'Scenario 50 %' were considered as extreme situations (the first representative of the state of play and the second representative of the best result

([72]) The USB power delivery is capable of delivering up to 100 W with the standard USB connector and up to 60 W with the micro-USB connector.

obtainable thanks to direct legislative action from the European Commission), the current assessment also developed some intermediate scenarios.

— Scenario 10 % and Scenario 20 %: expected range of decoupling of products and EPS potentially obtainable thanks to EPS labelling.
— Scenario 30 % and Scenario 40 %: optimistic range of decoupling obtainable thanks to a more stringent actions.

For each decoupling percentage, material saving is calculated, as the total mass of EPS not produced and not shipped with the given volume of notebooks and tablets. Assessments do not take into consideration the environmental impact/benefit of transport, packaging, use phase and EoL. Inefficiencies occurring during the production phase (e.g. generated scraps) were not taken into consideration.

Results are shown in Figure 31. Histograms were built for the 3 years considered (2020, 2025 and 2030), representing the estimation of the amount of materials saved (annual reduction) thanks to the decoupling of devices (tablets and notebooks) and EPS. When considering the expected range of decoupling potentially obtainable thanks to the proposed labelling (Scenarios 10 % and 20 %), about 2 300-4 500 t of materials could be saved every year, considering the estimated sales of tablets and notebooks. We highlight a slight difference in values in 2020, 2025, 2030, as according to the source of data for market projections, shipment and sales will be stable for the two product categories over the considered time horizon (Viegand Maagøe and VITO, 2017). Indeed, looking at the chart for the year 2030, and considering Scenarios 10 % and 20 %, the estimated potential savings of materials are in the range of 2 295-4 591 t/year (80 % allocated to the notebook product group, 20 % allocated to the tablet product group). This result is 4-6 times higher than the associated reduction in the consumption of raw materials calculated by Risk & Policy Analysts Limited (2014) for the decoupling of mobile phones from their chargers, in the EU market from 2011 to 2013.

Table 24 and Table 25 provide an overview of the specific material saving divided by material category (we identified four main material categories, according to the study conducted by Bio Intelligence Service, namely plastics, ferrous metals, non-ferrous metals and electronics). Table 26 and Table 27 were built using the information from Table 11 (Section 2.3.2) and the results of Table 24 and Table 25, in which only the category 'electronics' was considered. Taking into consideration these assumptions, it was possible to estimate the specific material saving due to the avoided production of electronics, highlighting some precious metals and CRMs (e.g. silver, gold, beryllium, cobalt, chromium, copper, gallium, palladium and antimony).

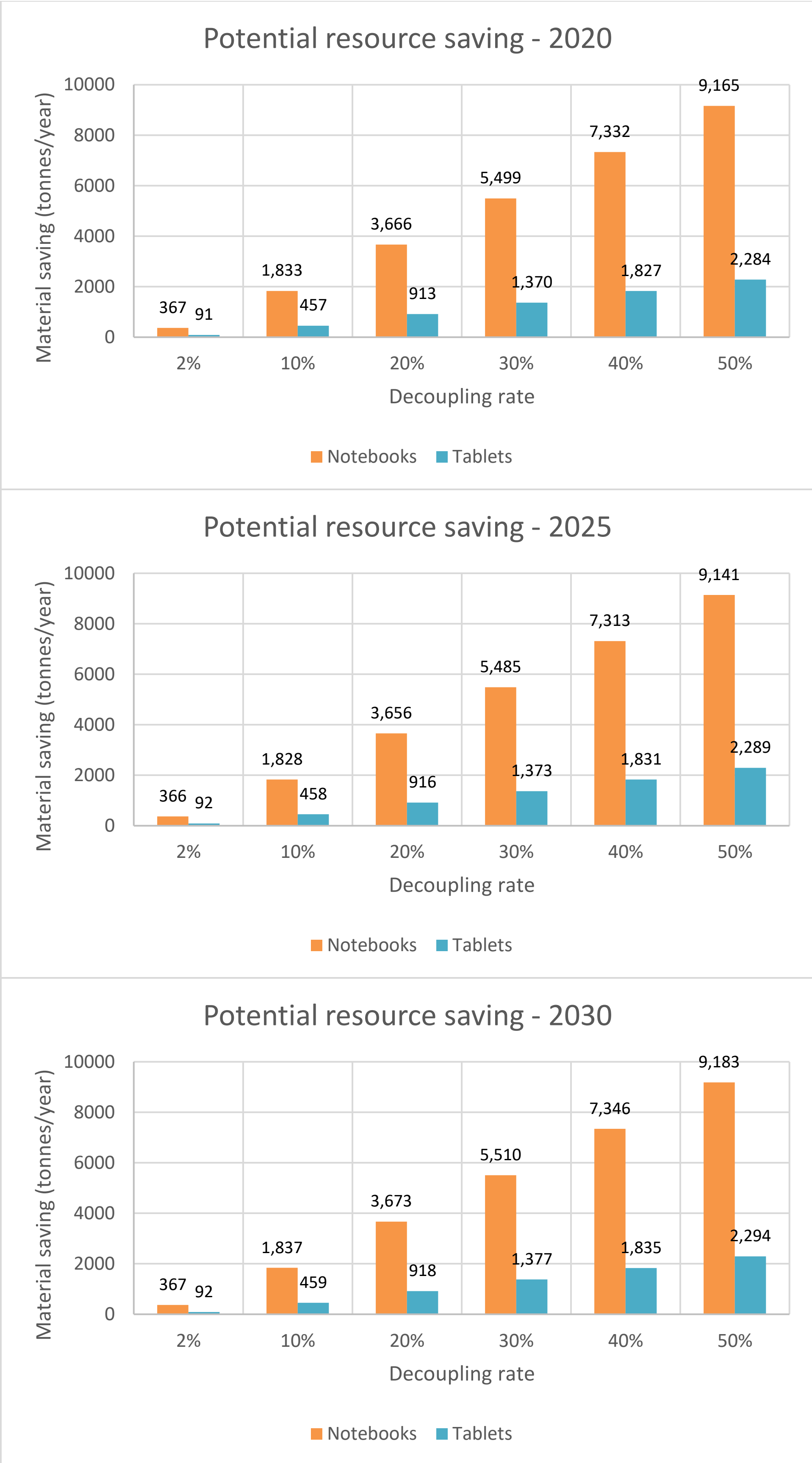

Figure 31 — Potential material saving (t/year) in 2020, 2025 and 2030, divided by product categories: notebooks and tablets.

Table 24 — Material savings [t/year] divided by category (plastics, ferrous metals, non-ferrous metals, electronics). **Notebooks**.

Notebooks — Material savings divided by category [t/year]						
Decoupling scenario	**2 %**	**10 %**	**20 %**	**30 %**	**40 %**	**50 %**
2020						
Plastics	115	574	1 148	1 722	2 296	2 870
Ferrous metals	3	14	28	42	56	70
Non-ferrous metals	86	430	861	1 291	1 722	2 152
Electronics	163	815	1 629	2 444	3 258	4 073
2025						
Plastics	114	572	1 145	1 717	2 290	2 862
Ferrous metals	3	14	28	42	56	69
Non-ferrous metals	86	429	859	1 288	1 717	2 146
Electronics	162	812	1 625	2 437	3 250	4 062
2030						
Plastics	115	575	1 150	1 725	2 300	2 875
Ferrous metals	3	14	28	42	56	70
Non-ferrous metals	86	431	862	1 294	1 725	2 156
Electronics	163	816	1 632	2 449	3 265	4 081

Table 25 — Material savings [t/year] divided by category (plastics, ferrous metals, non-ferrous metals, electronics). **Tablets**.

Tablets — Material savings divided by category [t/year]						
Decoupling scenario	**2 %**	**10 %**	**20 %**	**30 %**	**40 %**	**50 %**
2020						
Plastics	30	148	295	443	590	738
Ferrous metals	1	3	7	10	14	17
Non-ferrous metals	28	139	278	417	556	695
Electronics	33	167	333	500	667	834
2025						
Plastics	30	148	296	444	592	740
Ferrous metals	1	3	7	10	14	17
Non-ferrous metals	28	139	279	418	557	696
Electronics	33	167	334	501	668	835
2030						
Plastics	30	148	297	445	593	742
Ferrous metals	1	3	7	10	14	17
Non-ferrous metals	28	140	279	419	558	698
Electronics	33	167	335	502	670	837

Table 26 — Material savings divided by substance [t/year]. **Notebooks** (only the mass of electronics was considered for this assessment).

Notebook electronics — Material savings divided by substance [t/year]						
Decoupling scenario	**2 %**	**10 %**	**20 %**	**30 %**	**40 %**	**50 %**
2020						
Ag	0.18	0.90	1.79	2.69	3.58	4.48
Au	0.03	0.16	0.33	0.49	0.65	0.81
Be	0.02	0.08	0.16	0.24	0.33	0.41
Co	0.02	0.08	0.16	0.24	0.33	0.41
Cr	0.57	2.85	5.70	8.55	11.40	14.26
Cu	30.95	154.77	309.55	464.32	619.10	773.87
Ga	0.00	0.01	0.02	0.02	0.03	0.04
Pd	0.03	0.16	0.33	0.49	0.65	0.81
Sb	0.49	2.44	4.89	7.33	9.78	12.22
2025						
Ag	0.18	0.89	1.79	2.68	3.57	4.47
Au	0.03	0.16	0.32	0.49	0.65	0.81
Be	0.02	0.08	0.16	0.24	0.32	0.41
Co	0.02	0.08	0.16	0.24	0.32	0.41
Cr	0.57	2.84	5.69	8.53	11.37	14.22
Cu	30.87	154.37	308.73	463.10	617.46	771.83
Ga	0.00	0.01	0.02	0.02	0.03	0.04
Pd	0.03	0.16	0.32	0.49	0.65	0.81
Sb	0.49	2.44	4.87	7.31	9.75	12.19
2030						
Ag	0.18	0.90	1.80	2.69	3.59	4.49
Au	0.03	0.16	0.33	0.49	0.65	0.82
Be	0.02	0.08	0.16	0.24	0.33	0.41
Co	0.02	0.08	0.16	0.24	0.33	0.41
Cr	0.57	2.86	5.71	8.57	11.43	14.28
Cu	31.01	155.07	310.14	465.22	620.29	775.36
Ga	0.00	0.01	0.02	0.02	0.03	0.04
Pd	0.03	0.16	0.33	0.49	0.65	0.82
Sb	0.49	2.45	4.90	7.35	9.79	12.24

Table 27 — Material savings divided by substance [t/year]. **Tablets** (only the mass of electronics was considered for this assessment).

Tablet electronics — Material savings divided by substance [t/year]						
Decoupling scenario	**2 %**	**10 %**	**20 %**	**30 %**	**40 %**	**50 %**
2020						
Ag	0.04	0.18	0.37	0.55	0.73	0.92
Au	0.01	0.03	0.07	0.10	0.13	0.17
Be	0.00	0.02	0.03	0.05	0.07	0.08
Co	0.00	0.02	0.03	0.05	0.07	0.08
Cr	0.12	0.58	1.17	1.75	2.33	2.92
Cu	6.33	31.67	63.35	95.02	126.69	158.37
Ga	0.00	0.00	0.00	0.01	0.01	0.01
Pd	0.01	0.03	0.07	0.10	0.13	0.17
Sb	0.10	0.50	1.00	1.50	2.00	2.50
2025						
Ag	0.04	0.18	0.37	0.55	0.74	0.92
Au	0.01	0.03	0.07	0.10	0.13	0.17
Be	0.00	0.02	0.03	0.05	0.07	0.08
Co	0.00	0.02	0.03	0.05	0.07	0.08
Cr	0.12	0.58	1.17	1.75	2.34	2.92
Cu	6.35	31.75	63.50	95.24	126.99	158.74
Ga	0.00	0.00	0.00	0.01	0.01	0.01
Pd	0.01	0.03	0.07	0.10	0.13	0.17
Sb	0.10	0.50	1.00	1.50	2.01	2.51
2030						
Ag	0.04	0.18	0.37	0.55	0.74	0.92
Au	0.01	0.03	0.07	0.10	0.13	0.17
Be	0.00	0.02	0.03	0.05	0.07	0.08
Co	0.00	0.02	0.03	0.05	0.07	0.08
Cr	0.12	0.59	1.17	1.76	2.34	2.93
Cu	6.36	31.82	63.64	95.47	127.29	159.11
Ga	0.00	0.00	0.00	0.01	0.01	0.01
Pd	0.01	0.03	0.07	0.10	0.13	0.17
Sb	0.10	0.50	1.00	1.51	2.01	2.51

5.3 Durability testing for personal computers

5.3.1 Rationale

Broadly, there are often differences between traditional and commercial notebooks, tablets, and handheld devices. Consumer products typically look more fashionable but are built to less-robust specifications than commercial-focused products. Conversely, commercial-focused products have traditionally been more staid in design, but they are built to endure slightly more robust use (IDC, 2016).

As mentioned in Section 3, the two most recurring accidents for both notebooks and tablets occur because of the following.

- The computer was dropped while being carried or fell off desk or table while in use.
- Liquid was spilled on the computer.

Possible options to improve the durability performance of personal computers may be related to resistance to falls (or other mechanical shocks) and resistance to water. This section provides examples of testing methods for ruggedness and robustness of notebooks and standardised methods to test resistance to water.

Resistance to drops/falls and shocks

Notebook manufacturers developed testing methods for ruggedness and robustness of notebooks partially based on the US Military Standard 810 G ([73]). The MIL-STD-810 G test method standard is intended to help organisations in preparing tests to evaluate how well a particular piece of equipment can perform in the field. The standard outlines dozens of test methods, each associated with a source of environment stress, such as vibration, moisture, dust, extreme temperatures, or humidity. While there is no one recommended (or required) list of tests for device categories, most major computer vendors generally perform between 5 and 8 tests (HP, 2015).

For the durability of the screen for example, the manufacturers mainly perform the following tests which partially go beyond or differ from the tests set in the military standard and for which they have developed their own testing equipment and facilities (ASUS, 2016; HP, 2015; Lenovo, 2016; Samsung, 2015): (corner) drop test; torsion (twist) test; impact (weight drop) test; compression test; hinge-cycling test.

Manufacturers use those test routines to improve the design of notebooks and thus make them more durable. This can include more robust components, better layouts and improved junctions between components. Furthermore, notebook computers must pass certain durability tests for the award of the EU Ecolabel (European Commission, 2016), and similar requirements were also developed in the context of the EU GPP scheme, where points are awarded for products that have passed durability tests carried out according to IEC 60068, US MIL810G or equivalent (Dodd et al., 2016).

Another group of standards is the EN 60068 series for testing of environmental stress on electronic components and products. Table 28 shows some of the testing procedures which could be used to assess the robustness of computers.

([73]) http://everyspec.com/MIL-STD/MIL-STD-0800-0899/MIL-STD-810G_CHG-1_50560/

Table 28 — Testing procedures of the EN 60068 series.

Standard	**Title**	**Test description**
EN 60068-2-6	Environmental testing — Part 2-6: Tests — Tests Fc: Vibration (sinusoidal) (IEC 60068-2-6:2007)	This part of IEC 60068 gives a method of test which provides a standard procedure to determine the ability of components, equipment and other articles, hereinafter referred to as 'specimens', to withstand specified severities of sinusoidal vibration. If an item is to be tested unpackaged it is referred to as a test specimen. However if the item is packaged then the item itself is referred to as a product and the item and its packaging together are referred to as a test specimen.
EN 60068-2-7	Basic environmental testing procedures — Part 2: Tests; test Ga and guidance: Acceleration, steady state (IEC 60068-2-7:1983 + A1:1986)	To prove the structural suitability and the satisfactory performance of components, equipment and other electrotechnical products, hereinafter referred to as 'specimens', when subjected to forces produced by steady acceleration environments (other than gravity) such as occur in moving vehicles, especially flying vehicles, rotating parts and projectiles, and to provide a test of structural integrity for certain components.
EN 60068-2-27	Environmental testing — Part 2-27: Tests — Test Ea and guidance: Shock (IEC 60068-2-27:2008)	This part of IEC 60068 provides a standard procedure for determining the ability of a specimen to withstand specified severities of non-repetitive or repetitive shocks.
EN 60068-2-31	Environmental testing — Part 2-31: Tests — Test Ec: Rough handling shocks, primarily for equipment-type specimens (IEC 60068-2-31:2008)	This part of IEC 60068 deals with a test procedure for simulating the effects of rough handling shocks, primarily in equipment-type specimens, the effects of knocks, jolts and falls, which may be received during repair work or rough handling in operational use.
EN 60068-2-75	Environmental testing — Part 2-75: Tests — Test Eh: Hammer tests (IEC 60068-2-75:2014); German version EN 60068-2-75:2014	This part -2-75 of IEC 60068 provides three standardised and coordinated test methods for determining the ability of a specimen to withstand specified severities of impact.

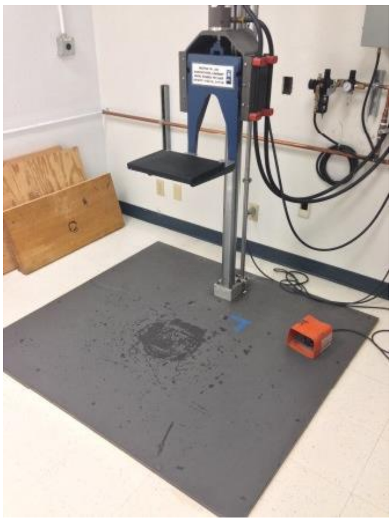

Figure 32 — Picture of a drop test applied to a notebook (Westpak, 2013).

Resistance to water

The keyboard, the display, the display-cover (including frame joints) and the casing of consumer notebooks are the components most prone to fail due to falls/drops or liquid spillage.

Regarding damage due to liquid spillage, manufacturers have the possibility to adopt waterproof solutions for certain personal computers, and test their IP according to the Standard IEC 60529 — Degrees of protection provided by enclosures (ingress protection (IP) code). The standard classifies and rates the degree of protection provided against, dust, water, accidental contact, and intrusion through mechanical casings and electrical enclosures. A device tested according to IEC 60529 is classified using an IP code, according to the results obtained. The IP code is typically followed by two digits, indicating the solid-particle-protection class and the liquid-IP class. As an example, an electronic device classified as IP-22 is protected against insertion of fingers (Solid-particle protection) and against vertically or nearly vertically dripping water (liquid IP). When no data are available to specify one of the two protection ratings, the digit is replaced with the letter X (e.g. IP-X2).

Thus, the second digit specifies the liquid IP that the enclosure provides against harmful ingress of water, and ranges from 0 to 9. An overview of the types of test set out by IEC 60529 is provided in Table 29.

An additional durability test was introduced by the decision on EU Ecolabel criteria for notebook computers (European Commission, 2016), and is focused on water-spill ingress. The test has the following characteristics.

- The test must be carried out twice.
- A minimum of 30 ml of liquid should be poured evenly over the keyboard of the notebook or onto three specific, separated locations, then actively drained away after a maximum of 5 seconds, and the computer then tested for functionality after 3 minutes.
- The test should be carried for a hot and a cold liquid.
- The notebook should remain switched on during and after the test.

The notebook must then be dismantled and visually inspected so as to ensure it passes the IEC 60529 acceptance conditions for water ingress.

Table 29 — Examples of IEC 60529 test levels and short descriptions. The level number specifies the second digit of the IP code (BS EN 60529:1192+A2:2013).

Level	Degree of protection	Short description of the test
0	None	—
1	Protected against vertically falling water drops	Vertically falling drops. Test duration: 10 minutes. Water flow rate 1 mm/min.
2	Protected against vertically falling water drops when enclosure tilted up to 15°	Vertically falling drops and object tilted at an angle of 15° from its normal position. Test duration: 2.5 minutes for every direction of tilt (10 minutes total). Water flow rate 3 mm/min.
3	Protected against spraying water	Water falling as a spray at any angle up to 60° from the vertical, using either a spray nozzle or an oscillating fixture. Spray nozzle. Test duration: 5 minutes minimum. Water flow rate 10 l/min. Oscillating tube. Test duration: 10 minutes. Water flow rate 0.07 l/min per hole.
4	Protected against splashing water	Water falling as a spray at any angle up to 180° from the vertical, using either a spray nozzle or an oscillating fixture. Spray nozzle. Test duration: 5 minutes minimum. Water flow rate 10 l/min. Oscillating tube. Test duration: 10 minutes. Water flow rate 0.07 l/min per hole.
5	Protected against water jets	Water projected by a nozzle (6.3 mm diameter) against enclosure from any direction. Test duration: 1 minute per square metre for at least 3 minutes. Water flow rate 12.5 l/min.
6	Protected against powerful water jets	Water projected in powerful jets (12.5 mm nozzle diameter) against the enclosure from any direction. Test duration: 1 minute per square meter for at least 3 minutes. Water flow rate 100 l/min.
7	Protected against the effects of temporary immersion in water	The enclosure is immersed in water under specified conditions of pressure and time (up to 1 m of submersion). Test duration: 30 minutes.
8	Protected against the effects of continuous immersion in water	The enclosure is immersed in water under specified conditions of pressure and time (depth specified by manufacturer). Test duration: by agreement.
9	Protected against high pressure and temperature water jets	Water projected by a fan jet nozzle against the enclosure from any direction. Test duration: 30 seconds in each position for a minimum of 3 minutes. Water flow rate 15 l/min. Water temperature: 80 °C.

5.3.2 Possible improvements

The standards IEC 60529 can be used to test the liquid-IP class for personal computers.

The provision of information on the liquid-IP class for personal computers (in particular notebooks and tablets) to end-users would inform them about the product characteristics. The users, according to their needs, could be more conscious about the purchase and contribute in this way to reducing the amount of personal computers repaired or discarded because of liquid spillage yearly.

Such information can be reported through the technical documentation and conveyed to end-users through the user documentation and through dedicated pictograms. The main goal of the pictograms would be to indicate the level of protection against dripping water, spraying water and water jets.

5.3.3 Future improvements: development of additional standards on endurance testing

Although the durability of notebooks and of some of their functions is a relevant material-efficiency aspect both for consumers and for manufacturers (who do communicate on this) the setting of specific requirements would require some additional standardisation work. Although some endurance-testing procedures are available, there are no generally agreed testing parameters, performance benchmarks, critical values and routines specified for notebooks (Ripperger, 2016). Furthermore, the number of samples of models to be tested and the verification specifications (pass or fail criteria) have to be detailed further (Dodd et al., 2015). Thus, more work is necessary to set requirements for the testing of notebooks against physical stress in order to improve the robustness and ruggedness of the devices (both notebooks and tablets).

A good start for this set of tests is the recommendation proposed by Dodd et al. (2015) for the 'Durability testing of notebooks for the EU Ecolabel' (Table 30). The drop/fall test, for instance, is described according to the MIL-STD-810 G, 516.6, Procedure IV. The final European Commission decision (2016) establishing the ecological criteria for the award of the EU Ecolabel for personal, notebook and tablet computers, instead, refers to the Standard series EC 60068. Specifically, IEC 60068-2-31 describes three possible tests.

(a) Drop and topple (a simple test intended to assess the effects of knocks or jolts likely to be received primarily by equipment-type specimens during repair work or rough handling on a table or bench).
(b) Freefall procedure 1 (a simple test to assess the effects of falls likely to be experienced due to rough handling. It is also suitable to demonstrate a degree of robustness).
(c) Freefall procedure 2 (a test that additionally simulates repetitive shocks likely to be received by certain component-type specimens, for example connectors in service).

Among the mandatory durability tests for notebook computers described by the EU Ecolabel for personal, notebook and tablet computers, it is specified that the notebook must be dropped from a height of 76 cm onto a non-yielding surface covered with a minimum of 30 mm of wood. One drop must be made on each of the following: top, bottom, right, left, front and rear side, as well as each bottom corner. The notebook must be switched off during the test and must successfully boot up following each drop. The casing must remain integral and the screen undamaged following each test (test method IEC 60068 Part 2-31: EC — Freefall, procedure 1). The same procedure is applied for tablets.

In addition to the tests described in Table 30, the durability of the hinges should be tested through hinge-cycling tests. For instance, one of the additional tests described by the Commission decision on EU Ecolabel of notebook computers (European Commission, 2016) specifies that the screen must be fully opened and then closed 20 000 times. The screen must then be inspected for any loss of stability and hinge integrity.

Table 30 — Durability testing for notebook computers proposed by Dodd et al. (2015).

Durability Test	**Test conditions and performance benchmark**	**Reference for test method**
Drop	122 cm drop height onto a 5.0 cm of plywood surface on concrete, 4-6 drops per sample to a total of 26 drops covering each face, edge and corner. The notebook is non-operational during the test but must function following the test.	MIL-STD-810 G, 516.6, Procedure IV
Shock	40 g for 18 tests each applied to Bottom, Left and Back side. The notebook is non-operational during the test but must function following the test.	MIL-STD-810 G, 516.5, Procedure I For further review of equivalence: IEC 60068
Vibration	20-2000 Hz, 1.04 Grms*, 1 hour applied to bottom, left and back side. The notebook is to be operational during and after the test. * root mean square acceleration	MIL-STD-810 G, 514.6, Category 24 For further review of equivalence: IEC 60068
Temperature	Three 24 hour exposure cycles for each extreme in a test chamber – 29 °C and 63 °C. The test to be repeated for an operational and non-operational notebook. The notebook must be checked that it functions following each routine.	MIL-STD-810 G, 501.5, Procedure II For further review of equivalence: IEC 60068
Water ingress	0.2 litres of water is to be poured evenly over the main body of the open keyboard face of the notebook, drained after 3 seconds, inverted on its side for 45 seconds and then tested after 2 minutes. The notebook is to be operational during and after the test.	MIL-STD-810 G, 506.5, Procedure III For further review of equivalence: IEC 60529
Screen pressure	25 kg loading to be applied to the centre of the screen lid with the notebook placed on a flat surface. The screen to then be inspected for lines, spots and cracks.	*No formal reference: stakeholder input required. Potential to refer to panel pressure test methods.*
Keyboard accelerated live	10 million random keystrokes simulation for *(to be specified)* product samples. The keys to then be inspected for their integrity.	*No formal reference: stakeholder input required.*

6 Possible actions to enhance repair/reuse

6.1 Disassemblability of key components for personal computers to enhance repairability

6.1.1 Rationale

For mobile personal computers, display panels, batteries, keyboards and data storage are the components most prone to fail or to be damaged (see Section 3.2, statistics by the IDC (2010, 2016) and interviews with stakeholders). Furthermore, battery performance is one of the key features for consumer choice (Dodd et al. 2016, 2015) but degrades over time and can influence the service life of the device. Also, mass storage and memory significantly determine the performance of both mobile and non-mobile personal computers (i.e. the used capacity can limit the usability of the device).

Manufacturers' designs aim to minimise the need for repair, through the selection of high-quality materials and components, together with a durable, reliable structural design (Digitaleurope, 2017a). However both the average annual failure rates of computers (IDC (2016) estimated 18 % for notebooks and 15.7 % for tablets) and the reparability rates (every year, about 6 % of the products shipped for repair or remanufacturing to manufacturers turn out to be unrepairable (Digitaleurope, 2014)) are not negligible.

According to a 2014 Eurobarometer survey, 77 % of EU citizens would rather repair their goods than buy new ones, but ultimately have to replace or discard them because they are discouraged by the cost of repairs and the level of service provided (European Commission, 2014b). For end-users, the availability of repair options to fix day-to-day problems with the devices at reasonable costs is an important factor for a substantial prolongation of the product lifetime (Dodd et al. 2016, 2015). However, the trend to build and sell more-integrated devices such as sub-notebooks or tablets (see Section 2.1), makes an easy repair or upgrade more difficult (see Section 3.2), i.e. components such as track pads, keyboards, or network interface card (NIC) cannot be easily disassembled, repaired/replaced and reassembled. Although a repair might be feasible, the difficulty and the cost may lead a certain share of users to rather purchase a new device.

Overall, the ease of repair, or upgrade, becomes more and more important in order to:

- prolong the operational life of the device (by enhancing repair and refurbishing), and
- avoid environmental impacts due to the manufacturing of a new device and the disposal of electronic waste (by enhancing preparation for reuse).

Design for ease of maintenance and repair, design for upgradability and adaptability, design for standardisation and compatibility, design for disassembly and reassembly are recognised to be key strategies to improve product life extension (Bocken et al., 2016)

6.1.2 Possible improvements

According to the Ellen MacArthur Foundation (2016), products should be entirely assembled by reversible means such as screws instead of glue, rivets or non-reversible snap locks. The use of proprietary fasteners should be avoided. Batteries should be easily replaceable, preferably without the use of any tools, and should not be glued or soldered to a product. Components should not be integrated to such a degree as to make individual replacement of functional components impossible. Finally, manufacturers should make repair information available: as soon as a product is launched; to all interested parties, including non-profit repair initiatives; free of charge (Ellen MacArthur Foundation, 2016).

The reversible disassembly of relevant components (such as batteries, internal power-supply units, displays, mass-storage systems, memories, keyboard, track pad, network-interface card (NIC), wireless local-area-network (LAN) card and cooling fan assemblies) plays a key role in enhancing reuse of personal computers.

Possible actions to enhance repair and refurbishing, but also preparation for reuse, can be listed, considering different levels.

- Professional repair operators can be provided with information about the disassembly, replacement and reassembly operations needed for each relevant component of computers.
- Users can be provided with clear and easily accessible information about the disassembly and replacement of the batteries used in computers.

Such documentation could be useful not only to enhance repair and refurbishing of EEE, but also for preparation for reuse of WEEE. It has been recognised that repair (and upgrade) of components should not be limited only to the manufacturer's authorised service providers during the warranty period, but generally to professional repairers (BIO by Deloitte, 2015; RREUSE, 2013), in order to reduce safety risks (e.g. due to improper repairs or incorrect components). End-users or non-professionals should be allowed to replace components, which are easy exchangeable; in any case where only official repair services are available, this will limit competition and may not help to reduce repair costs (Dodd et al., 2015). On the other hand, manufacturers are reluctant to disclose proprietary information and would prefer to limit the availability of disassembly instructions for authorised repair services only.

Key components were already identified by Talens Peiró et al. (2016) and proposed by Dodd et al. (2016) for the revision of the EU GPP criteria of personal computers. As proposed by these two studies, the verification of this criterion is done with a manual, provided by the applicant, which includes an exploded diagram of the device illustrating the parts that can be accessed and replaced.

In the context of the Ecodesign directive, however, documentation on the sequence of disassembly, replacement and reassembly operations could be provided for key components (highlighted by literature reviews on frequent failures, damages, and interviews with repair operators), when present in the product.

- Notebooks (and desktop computers): batteries (including stand-by button cells on the motherboard), internal power-supply units, display ([74]), data storage (HDD, SSD and eMMC), memories, keyboards.
- Tablets: batteries and displays.

Other relevant notebook components cited by repair operators were: network-interface cards, wireless LAN card, track pads, ports and connectors, cooling fan assemblies, audio connectors and cameras.

Relevant information for professional repair operators can include: exploded diagrams ([75]) of the product (showing the location of components); disassembly sequences; type and number of fastening technique(s) to be unlocked; tool(s) required; warnings if delicate disassembly operations are involved (risk of damage). Diagrams, photos or videos showing the disassembly steps could be used to accompany and better communicate this information. A comprehensive set of information should also include information about the safety requirements and risks (if any) related to the disassembly, replacement and reassembly operations. Such documentation could be available to professional repairers, and to users (for repair operations that they can safely perform).

The Open Manual Format (oManual) could be used to make the abovementioned information available. oManual is an open XML-based standard for semantic, multimedia-rich procedural manuals. It can be used to store and present e.g. service manuals, 'how

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([74]) Listed by Greenpeace (2017) as the most problematic component for design for repairability of mobile devices (notebooks, tablets and mobile phones). The display is often designed in a way that makes replacement very costly. Two-thirds of the devices (30 out of the 44) that were tested had displays that were designed to be difficult or costly to replace (Greenpeace, 2017).

([75]) Information such as exploded diagrams is especially useful for preparation for reuse and remanufacturing purposes, where it is economical to consult such information online (EERA, 2016).

to' guides, assembly instruction and user manuals (IEEE 1874, 2013). The oManual structure is suitable for describing/documenting the steps (disassembly, dismantling) for specific products. It provides the necessary structure to describe the steps in words and pictures/videos. Ongoing European standardisation work could elaborate on this standardised format and could help to more precisely specify the information to be provided.

Nevertheless, when software ([76]) or firmware ([77]) is required by the repaired/reused device to function, the software or firmware should be used as recommended by the original equipment manufacturer (prEN 50614, 2016).

Future developments to assess the ease of disassembly could focus on the standardisation of tools needed to disassemble a device (see Recchioni et al. (2016)), and on the number and types of disassembly steps ([78]) needed for certain repairs (Vanegas et al., 2017, 2016). The use of the Maynard operation sequence technique (MOST) is a more elaborate way to illustrate a step. MOST is based on fundamental activities called standard sequences, which are a set of basic motions, which include horizontal actions over a distance, physical move in the vertical direction, the action of gaining control, the action of placement and the action of loosening. The application of the MOST would require the establishing of how to describe/list each (dis)assembly step in a consistent and comprehensive way, for example by using a standardised structure (including the abovementioned oManual).

A 'step' can then be defined as a sequence of certain activities (Vanegas et al., 2016). Vanegas et al. (2016), for example, identified six basic tasks (sequence of basic motions) for the disassembly of a household appliance (electronic display): tool change, identifying connectors, manipulation of the product, positioning, disconnection, and removing. For each task, they specified a sequence of activities. For repair activities, the reverse tasks to assemble the product also need to be specified. The method was recently updated by Peeters et al. (2018) who enlarged the database of disassembly sequences (i.e. adding new types of connectors, such as cable connectors, cable plugs and glues requiring wedge/pry and peel actions to be released) and the scope of the analysis (i.e. including the calculation of reassembly operations). Peeters et al. (2018) tested the updated method on two case studies represented by notebook computers. The updated method allows now to evaluate both the ease of disassembly ($eDIM_D$) and the ease of reassembly ($eDIM_R$) metrics. The sum of the two metrics ($eDIM_D$ and $eDIM_R$) estimates the overall effort needed for disassembling and reassembling one or more components.

Upgradability of personal computers

Especially for tablets and Ultrabooks™, the upgrade of components such as the main memory (RAM) or data storage is currently technically limited due to the high integration and the small form factor of the devices. An extension of the mass storage for example is in some devices feasible (e.g. through extra slots for secure digital (SD) cards), but not for all models of computers. Technical possibilities and limits of replacement and upgrade have to be discussed with stakeholders.

In a survey by Forsa (2013), in Germany, half of the respondents judged it to be important that computers can be upgraded with components with higher energy efficiency or with higher performance. In the same survey, 61 % of the people interviewed stated that they would continue to use a notebook or tablet with a built-in battery in a case where the battery breaks or loses capacity if they can bring it to an electronic shop and the battery is replaced there directly on-site.

([76]) An ordered set of instructions and associated data, which controls and protects the operation of equipment (prEN 50614, 2016).

([77]) A computer program or data that cannot be easily changed by the user (prEN 50614, 2016).

([78]) A possible definition of disassembly 'step' (or disassembly task) is 'a basic disassembly action that cannot be further disaggregated'. A simple definition is to say that one-step finishes with the removal of a part or a change of a tool.

In the context of the revision of the EU GPP criteria, for instance, Dodd et al. (2016) proposed points that can be awarded to devices with the potential to replace and upgrade the RAM (socketed design) and the potential to expand the storage by using slots supporting mass-storage media.

Batteries

As mentioned at the beginning of Sections 5.1.1 and 6.1.1, battery performance represents one of the key features for consumer choice. However, batteries degrade over time, and replacements may be necessary to re-establish the initial performance of the whole product. In a survey conducted by the IDC (2010), over half of respondents stated that battery failures caused problems for their business. Respondents also indicated that 22 % of notebook computers required the purchase of a replacement battery during their lifetime. Consumentenbond (2015) reported that 77 % of consumers were able to replace the battery of their notebooks themselves, in 2012, while this percentage fell to 42 % in 2015 ([79]). Participants of a recent German survey preferred to buy a notebook with an exchangeable battery over a notebook with a built-in battery (Prakash et al., 2016b). The ease of access and replacement of the battery of a personal computer becomes therefore relevant, especially when this operation has to be done by end-users or by professional repair operators. Nevertheless, removable batteries instead of built-in batteries are also welcomed by recyclers, in order to dismantle easier (EuRIC, 2016a). This piece of information can be provided for end-users before the moment of purchase through the use of different logos.

For the revision of the EU GPP criteria for personal computers, Dodd et al. (2016) proposed a comprehensive criterion on ease of replacement for rechargeable batteries. In their proposal, rechargeable batteries must not be glued or soldered into portable products (as a core criterion). Furthermore, Talens Peiró et al. (2016) and Dodd et al. (2016) identified three different requirements for batteries with a performance of less than 800 charge/discharge cycles (when tested according to IEC EN 61960): manually exchangeable, without tools, for notebooks and portable all-in-one computers; exchangeable with a screwdriver in a maximum of three steps for sub-notebooks; and exchangeable with a screwdriver and spudger in a maximum of four steps for tablets and two-in-one notebooks. We elaborated further on these options, to avoid differentiations among mobile computer subcategories, and we thought about possible logos to be used to identify different levels of difficulty in replacing the battery of a personal computer.

- Logo 1: identifies that the batteries of the portable computer can be disassembled and replaced by the user, with or without the need of tools.
- Logo 2: identifies that the batteries of the portable computer cannot be disassembled and replaced by the user: this task requires assistance.

The disassembly operations in logo 1 should be performed using manual or power-driven standard tools. The list of the tools to be considered can be drawn from Annex B of Recchioni et al. (2016). Assistance is required for disassembly operations of logo 2, because of the complexity of the disassembly, or because of the use of glues and adhesives, or because the disassembly operation may damage the product or compromise the safety of the end-user.
Definitions and possible symbols to identify logo 1 and logo 2 (Table 31) should be targeted by standardisation activities.

([79]) 612 notebook computers were analysed.

Table 31 — Proposed logos and correlation with the ease of disassembly of batteries.

Logo 1	Logo 2
Battery can be removed and replaced by the user, with or without the need of tools.	Battery replacement requires assistance (*). (*) The battery contained in the product cannot be replaced by the end-user, but by professionals. The user manual could provide detail and information about the customer service to be contacted.

This classification concerning logo 1 could be potentially split into two categories.

- Logo 1.1: identifies that the batteries of the portable computer can be removed and replaced by the user, without the use of manual or power-driven tools.
- Logo 1.2: identifies that the batteries of the portable computer can be removed and replaced by the user, with the use of manual or power-driven tools.

As proposed for the revision of the EU GPP criteria, manufacturers could illustrate how the battery is installed in the product, the steps required to remove and cover markings, and provide comprehensive instructions in the user manuals.

In the future, more ambitious actions could be proposed about the ease of disassembly of the product. Indeed, the repair operators interviewed confirmed that firmly glued computer components may represent an obstacle to the product repair. Nevertheless, adhesive tapes used to fasten two or more parts may reduce the ease of disassembly of a product, even though they also seal out water and dust.

The adhesive strength of the adhesive tapes used in electronics is generally specified in N/cm, representing the amount of force required to peel up a cm-wide strip of tape at a constant rate. However, the configuration and amount of tape used can vary significantly, drastically changing the difficulty in separating adhered components. For these reasons, setting a limit to the adhesive strength of adhesive tapes used in computers would not help in improving their ease of disassembly. A more verifiable measure could be the pull-off force required to separate adhered components, measured as a pressure, in N/cm^2. However, further standardisation work is needed to identify a reliable procedure to test adhesive strength, environment conditions (temperature) and reference values.

Future actions

Considering the ease of disassembly of computers, a metric/index on disassembly of products can be developed, where quantitative parameters for disassembly are either Boolean (e.g. 'Are only reversible disassembly operations necessary to open the device?' (yes/no) or integer values (e.g. number of steps X to remove the battery). A threshold on the number of disassembly steps to access, replace and reassemble a particular component of a device could be established to ensure fast and safe repairs. 'Reversible disassembly', in this context, means that all of the following are true.

(a) The sequence of disassembly steps can be reversed to assemble the product.
(b) The parts to be (dis)assembled have not broken in any case of professional handling.
(c) The device is fully functioning after the assembly.

Further standardisation work might be necessary to set out unambiguously what 'disassembly steps' are. Moreover, further research would be needed to establish the target value for the threshold on the number of steps. Standards under the development of European Mandate M/543 for material-efficiency aspects of energy-related products (European Commission, 2015b) could serve the purpose, as those relate to the development of methods to assess ability to access or remove components from products to facilitate the repair, remanufacture or reuse.

Regarding the ease of disassembly of batteries in personal computers, future actions could consider asking manufacturers to design computers in such a way that the battery can be always be replaced by end-users, with or without tools, and with instructions provided in the user documentation. Fixed batteries could still be used in cases where there are safety issues, documented by manufacturers.

6.1.3 Initial assessments of benefits/impacts

Because notebook and tablet computers are so mobile, they are much more susceptible than desktop computers to potential risks such as travel wear and tear, airport security, and everyday accidents such as bumps or spills. Recent IDC studies focused on the US business sector found nearly 20 % of notebook computers break or require repair at some point in their lifetime. In their 2010 survey, each year 9.5 % of notebook computers in business organisations were damaged due to an accident, and 14.2 % of notebooks reported other kinds of physical problems (i.e. hardware malfunction) (IDC, 2010). According to the 2016 survey, instead, the percentage of notebook computers in business organisations damaged due to an accident slightly increased (11 % each year), while the other reported physical problems decreased (about 12 % each year). Overall, about 18.5 % of notebooks and 14.5 % of tablets needed repair of any kind (IDC, 2016).

Another source, SquareTrade, analysed failure rates for over 30 000 new notebook computers covered by warranty plans and found that one third of all notebooks will fail within 3 years. As mentioned in Section 3.2.1, two thirds of these failures came from hardware malfunctions, and one third was reported as accidental damage (SquareTrade, 2009).

Upgradability is also a key element to extend the lifetime of a computer. According to the survey conducted by Prakash et al. (2016a), the main reasons for buying a new notebook was that the old one was faulty (46 %), followed by 'the old one didn't have enough functions' (25 %). From another survey, half of the respondents judged relevant that old computers or notebooks can be upgraded with components with higher energy efficiency or with higher performance (Forsa, 2013).

In our analysis we focused on possible scenarios with improved reparability only, trying to understand the amount of notebook and tablet computers that risk being discarded because repair is not feasible. Possible improvements in terms of reparability aim to reduce this amount and to extend the lifetime of devices that were damaged or which reported malfunctions.

A summary of failure rates due to malfunctions and accidents is provided in Table 32 for notebooks. The total failure rate for notebook computers within the first year of use is 7.2 %, 19.7 % in the first 2 years of use and 31 % within the first 3 years, according to SquareTrade. On the other hand, the most recent average failure rate was reported to be 18.5 % by the IDC and this average value was used to develop a scenario for the reparability of notebook computers. On the other hand, the average failure rate of 14.5 % (again reported by the IDC) was used to develop a scenario for the reparability of tablet computers.

Table 32 — Notebook failure rates due to hardware malfunction and accident, according to two sources of data: the IDC (2010, 2016) and SquareTrade (2009).

Failure rates	(IDC, 2010)	(IDC, 2016)	(SquareTrade, 2009)		
			First year of use	2 years of use	3 years of use
Hardware malfunction	14.2 %	12.3 %	4.7 %	12.7 %	20.4 %
Accident	9.5 %	11.0 %	2.5 %	7.0 %	10.6 %
Total	([80]) 19.6 %	18.5 %	7.2 %	19.7 %	31.0 %

Considering the estimated annual sales of personal computers (years 2020, 2025 and 2030, Section 2.1), it was possible to estimate the number of mobile computers (notebooks and tablets) sold in a certain year that are likely to report a failure. However, it was not possible to estimate the uncertainty associated with these projections, and alternative scenarios were analysed. Table 33 provides detail about the number (millions of units per year) and the mass (t per year) of computers that are expected to report a failure, considering the average yearly failure rate of 18.5 % for notebooks and 14.5 % for tablets. This evaluation was done on the estimated sales of personal computers, and is expected to be greater when considering the stock volume.

Table 33 — Computers expected to report failures (failure rate of 18.5 % for notebooks and 14.5 % for tablets). Estimations based on the sales expected for 2020, 2025 and 2030.

Year		**2020**	**2025**	**2030**
Notebooks	million units/year	7.71	7.69	7.72
Tablets	million units/year	5.57	5.58	5.59
Total	million units/year	13.27	13.26	13.31
Notebooks	t/year	14 875	14 835	14 903
Tablets	t/year	2 942	2 949	2 956
Total	t/year	17 817	17 785	17 859

In our scenario we considered that some of the computers reporting a failure are not repaired and are discarded as WEEE. The percentage of computers that are repaired, instead, is represented by the *repair rate*. As no data on repair rates are available, to the knowledge of the authors, estimations were developed thanks to expert judgments. Repair rates depend on several factors, such as the type of failure, the type of repair needed, the initial cost of the computer, the age of the device or warranty plans. In our hypothesis we considered two main scenarios.

— Computers in the first 2 years of use, with warranty plans. Repair rate 80 %.
— Computers older than 2 years, with no warranty plans. Repair rate 20 %.

Results are reported in Table 34, as the number (millions of units per year) and the mass (t per year) of notebooks and tablets that are expected to be discarded as WEEE and therefore directed to EoL processes.

([80]) Notebook computers needing repair of any kind.

Table 34 — Notebooks and tablets expected to be discarded as WEEE (repair rate 80 % for mobile computers in the first 2 years of use, with warranty plans; repair rate 20 % for mobile computers older than 2 years of use, with no warranty plans; average failure rate of 18.5 % for notebooks and 14.5 % for tablets).

Year		**2020**		**2025**		**2030**	
Age of the computer	years	≤ 2	> 2	≤ 2	> 2	≤ 2	> 2
Notebooks	million units/year	1.54	6.17	1.54	6.15	1.54	6.18
Tablets	million units/year	1.11	4.45	1.12	4.46	1.12	4.47
Total	million units/year	2.65	10.62	2.65	10.61	2.66	10.65
Notebooks	t/year	2 975	11 900	2 967	11 868	2 981	11 923
Tablets	t/year	588	2 354	590	2 359	591	2 365
Total	t/year	3 563	14 254	3 557	14 228	3 572	14 287

We then observed what could be the situation when the percentages of computers discarded as WEEE are decreased by 5-20 %, thanks to improved reparability. The two scenarios in any case of enhanced reparability can be then summarised as follows.

— Notebooks and tablets in the first 2 years of use, with warranty plans. Repair rates hypothesised to be 81-84 %.
— Notebooks and tablets older than 2 years, with no warranty plans. Repair rates hypothesised to be 24-36 %.

Results are reported in Table 35 (computers in the first 2 years of use, with warranty plans) and Table 36 (computers older than 2 years, without warranty plans), expressed as material savings. Repairs were simulated considering an average repair service with replacement of the components more prone to fail according to the IDC, namely the display, the battery, the HDD and the motherboard.

Table 35 — Products (million units/year) and material (t/year) savings thanks to enhanced reparability (repair rate 81-84 % for computers in the first 2 years of use, with warranty plans, average failure rate of 18.5 % for notebooks and 14.5 % for tablets).

Year		**2020**	**2025**	**2030**
Notebooks	million units/year	0.077 - 0.308	0.077 - 0.307	0.077 - 0.309
Tablets	million units/year	0.056 - 0.223	0.056 - 0.223	0.056 - 0.224
Total	million units/year	0.133 - 0.531	0.133 - 0.531	0.133 - 0.533
Notebooks	t/year	135 - 542	135 - 540	136 - 543
Tablets	t/year	18 - 72	18 - 72	18 - 72
Total	t/year	153 - 613	153 - 612	154 - 615

Considering the first 2 years of use, between 0.13 and 0.53 million units of notebooks and tablets, expected to be discarded as WEEE, are now considered as potentially repaired devices. With this hypothesis between 150 and 620 t of materials can be saved every year.

When notebooks and tablets older than 2 years and without warranty plans are considered, repair rates and therefore material savings can be potentially increased, with material savings ranging from 610 to 2 460 t per year (Table 36).

The values of Table 35 and Table 36 take into consideration the amount of resources required to produce the spare parts necessary for the repair.

Table 36 — Products (million units/year) and material (t/year) savings thanks to enhanced reparability (repair rate 24-36 % for computers older than 2 years, with no warranty plans, average failure rate of 18.5 % for notebooks and 14.5 % for tablets).

Year		**2020**	**2025**	**2030**
Notebooks	million units/year	0.308 - 1.233	0.307 - 1.230	0.309 - 1.236
Tablets	million units/year	0.223 - 0.890	0.223 - 0.893	0.224 - 0.895
Total	million units/year	0.531 - 2.124	0.531 - 2.122	0.533 - 2.130
Notebooks	t/year	542 - 2 166	540 - 2 161	543 - 2 170
Tablets	t/year	72 - 287	72 - 288	72 - 288
Total	t/year	613 - 2 453	612 - 2 448	615 - 2 459

6.1.4 Potential benefits for other product categories

The assessment of the potential benefits related to enhanced reparability of desktop computers is characterised by higher degrees of uncertainty. To the knowledge of the authors, there is no statistical analysis reporting figures for yearly failure rates of desktop computers, so a hypothetical failure rate of 16.5 % (as an average of 18.5 % for notebooks and 14.5 % for tablets) was assumed.

In the case of desktop computers, however, it a very high repair rate of 90 % (the percentage of devices which reported a failure and were repaired) was assumed, independent of the age of the desktop computer. It was also assumed that enhanced-reparability strategies would bring smaller benefits in terms of repair-rate increase (in the range of 0.5-1 %).

With these hypotheses, and considering estimated market data for years 2020, 2025 and 2030 (as in Table 1) 2-2.24 million desktop computers will report failures, and without enhanced-reparability strategies 0.20-0.22 million computers will be discarded. Taking into consideration the hypotheses on enhanced-reparability strategies, 96-216 t of materials are saved every year instead.

However, we remark that future work is needed to collect data about the repair services of desktop computers in order to strengthen the estimates.

6.2 Secure data deletion for personal computers

6.2.1 Rationale

One major barrier to the reuse, repair and recycling of computers is data-privacy issues. A recent article by Polverini et al. (2017) investigated the relationships between resource efficiency aspects in electronics and data protection and cybersecurity issues. This article identified that users are generally not keen in reusing computer because not ensured about the properness of data erasure after first use.

Desktop computers, notebooks and tablets regularly store sensitive and confidential data pertaining to users and organisations, including (but not limited to) documents, photos, videos, location and contact data, stored on various media such as HDD, SSD, flash, SIM and memory cards. The major operating systems usually include an option to 'factory reset' the device, bringing the device into its original factory state ([81]). However, this does not necessarily guarantee that all the personal data of the user are deleted comprehensively and permanently. Hence, it is believed that data-privacy issue is one of the major factors that discourage users from making their obsolete but functional devices available to the reuse market or to the appropriate recycling paths in the case of dysfunctional devices.

Data sanitisation is the process of deliberately, permanently and irreversibly removing or destroying the data stored on a memory device (prEN 50614, 2016). Other techniques of data eradication do not allow the reuse of the device (e.g. degaussing magnetic media, drilling HDD platters). Besides data sanitisation, it may be viable to encrypt user data and so permanently delete the key required for decryption so as to ensure third parties cannot access the user data thereafter. This means that the data are still physically present on the storage media, but permanently inaccessible.

It should be noted that depending on the effort invested, it cannot necessarily be fully guaranteed, that user data cannot be recovered using highly sophisticated technical tools. Hence, users would mainly benefit from reasonably-safe data sanitisation, without taking into account data recovery methods that require large amount of temporal and financial investments.

6.2.2 Possible improvements

Personal computers could have tools available (or preinstalled ([82])) to permanently delete any personal data contained in data-storage systems without compromising the functionality of the whole device for further reuse. Secure ([83]) data deletion could be ensured by means of a dedicated functionality or software. If data deletion cannot be ensured, personal computers could have tools available to encrypt personal data in storage systems and to permanently delete the key required for decryption.

A study on computer severs (Talens Peiró and Ardente, 2015) compiled a list of available standards by country, based on data from Hintermann and Fassnacht (2008) and Fisher (2015). Talens Peiró and Ardente (2015) also provided a list of possible methods available for data deletion, as detailed in Table 37.

According to the US Department of Defense Standard 5220.22-M for clearing and sanitisation for different types of media, data clearing is defined as 'a method of

([81]) At the time of writing this feature is available in some form at least on Windows 10, macOS X, Android and iOS.

([82]) A built-in functionality can be defined as a functionality that does not require the installation or usage of additional software or hardware components not already present in the provided system.

([83]) Secure data deletion means the effective erasure of all traces of existing data from storage media, overwriting the data completely in such a way that access to the original data, or parts of them, becomes unfeasible for a given level of effort.

sanitisation by applying logical techniques to sanitise data in all user-addressable storage locations for protection against simple non-invasive data recovery techniques using the same interface available to the user; typically applied through the standard read and write commands to the storage device, such as by rewriting with a new value or using a menu option to reset the device to the factory state (where rewriting is not supported)'.

Hence, standards on data sanitisation are particularly relevant to enable the reuse of devices. The draft Standard prEN 50614 (2016) provides some examples of nationally approved data-sanitisation standards, such as HMG IS Standard No 5 (UK), DIN 66399 (Germany), NIST 800-88r1 (US). Other initiatives in support of data deletion are the CPA security characteristics for data sanitisation — flash based storage, the CPA security characteristic overwriting tools for magnetic media version 2.1, and the CAS sanitisation requirements version 2.0 Nov 2014.

While the user-addressable storage in desktop computers can oftentimes be disassembled with reasonable effort, storage solutions in more-integrated devices, such as notebooks and tablets, are less easily accessed. This emphasises the importance of tools that allow the users to delete their data, without having to rely on third parties, before the devices are passed on for reuse or recycling.

The German environment label Blue Angel has a set of criteria for mobile phone (RAL GmbH, 2013). Section 3.3.3 of the document describes the requirements in terms of data-deletion issues:

To allow a second use of a mobile phone the device shall be designed so as to allow the user to completely and safely delete all personal data on his own without the help of pay software. This can be achieved by either physically removing the memory card or with the help of software provided by the manufacturer free of charge. When using a software, the deletion process shall at least include an 'overwrite' of all the data stored with a random pattern, or, in the case of flash storage with zero values.

Table 37 — Methods for secure data deletion (Talens Peiró and Ardente, 2015)

Data-deletion method	**Overwriting (number)**	**Description of overwriting cycles**
Bruce-Schneier algorithm	7	first: zero second: one third to seventh: random character
Peter-Gutmann algorithm	35	random character
Pfitzner (created by Roy Pfitzner)	33	random character
Random data	customised	random character
Secure Erase (Parallel ATA (PATA) and Serial ATA (SATA) based hard drives)	1	first: writes a binary one or zero
Write zero (used by Windows Vista and following windows versions)	1	zero

6.2.3 Potential benefits for the product group

The need to take action on secure data deletion is in line with the principles of privacy and protection of personal data as set by the General Data Protection Regulation (EU) 2016/679 and in particular its Article 25 on 'data protection by design and by default'. If the ambitious objectives concerning reuse contained in the circular economy package are to be implemented, special care should be taken for the protection of personal data contained in electronic products and components. Secure data deletion is also becoming a day-to-day activity of EoL operators (EGG 2016+, 2016).

Secure data deletion is therefore considered as a necessary prerequisite to allow reuse of computers, complying with principles on privacy and protection of personal data.

The assessment of the potential benefits related to secure data deletion is however characterised by certain degrees of uncertainty. To the knowledge of the authors, there is no statistical analysis reporting figures for computers discarded (or not repaired/reused) due to data-deletion issues, nor robust surveys.

It was assumed that currently 5 % of the volume of desktop, notebook and tablet computers of Table 1 is reused after the first useful lifetime, without repair activities or component replacement, but only thanks to cleaning and data deletion. It was then assumed that *secure* data deletion would bring additional benefits in terms of reuse rates (6-10 % of the volume of desktop, notebook and tablet computers of Table 1).

With these assumptions, and considering estimated products sold for 2020, 2025 and 2030, as in Table 1, 0.9-4.7 million computers would be reused and therefore a significant amount of materials would benefit from an extended lifetime. The lifetime extension depends on a case-by-case basis. Considering these hypotheses, however, it is possible to estimate a lifetime extension for 2 300-12 200 t of materials every year (59 % for desktop computers, 33 % for notebooks and 8 % for tablet).

Also in this case we remark that future work is needed to strengthen the estimates.

7 Possible actions to enhance recyclability

The design for dismantling of computers is a necessary precondition for their efficient and swift depollution and recycling. The following sections aim to provide proposals to support the ease of dismantling.

7.1 Dismantlability of key components for personal computers

7.1.1 Rationale

According to the analysis in Section 3, notebooks and tablets at EoL, after depollution with the extraction of the battery, can follow two main processing routes: a first one based on the full mechanical crushing (shredding) and sorting of the waste; and a second one including some additional pre-treatments (medium-depth manual dismantling) before subsequent shredding and mechanical sorting.

Article 15 of the WEEE directive (European Union, 2012) also calls for 'Member States to take necessary measures to ensure that producers provide information free of charge about preparation for reuse and treatment in respect of each type of new EEE placed for the first time on the European Union market within 1 year after the equipment is placed on the market'. Relevant information about EEE placed on the market is crucial for WEEE treatment operators. Indeed, the rapid evolution in product design, the miniaturisation of EEE, components and materials used for their manufacturing some of which are critical make their repair and recycling increasingly challenging (EuRIC, 2016b). However, according to the association of reuse-and-recycling industries this article remained so far largely neither implemented nor enforced (EuRIC, 2016b).

These considerations have also been confirmed by the recyclers interviewed, who reiterated that, for the safe and efficient recycling of computers, products should be designed so that the access and removal of batteries ([84]) (including button batteries contained in the mainboard), display panels and PCBs (contained in several components, including motherboard, memory RAM, CPUs, graphic cards, and mass-storage systems) is facilitated. In particular, there is the risk that certain components of computers (e.g. batteries and display panels) which are difficult to extract would be shredded together with other waste, with the consequent dispersion of pollutants and contamination of other recyclable fractions (DEFRA, 2006), the risk of explosion in the shredders (Hand, 2013; Powel, 2002), and the irreversible loss of valuable materials (Van Eygen et al., 2016). Improper battery treatments can be associated with risks in terms of worker and facility safety (Section 3.1.6), including accidental fires in the WEEE treatment plants.

For the safe and efficient recycling, information on dismantling process and location of battery and other valuable components is essential (EERA, 2016). Information could concern the following.

- Extra information on materials that are recyclable if certain technology is used (for example for certain plastic components containing additives).
- Content of dangerous components/substances used (as a minimum the ones mentioned in Annex VII of the WEEE directive, see Section 3.1): provision of a short description and photo, and the location where these are usually found in the appliance.

([84]) Measures to improve the design for disassembly of batteries from computers are also in lines with the principles of the Batteries Directive 2006/66/EC, which state in article 11 that appliances should be designed in such a way 'that waste batteries and accumulators can be readily removed. Appliances into which batteries and accumulators are incorporated shall be accompanied by instructions showing how they can be removed safely and, where appropriate, informing the end-user of the type of the incorporated batteries and accumulators'.

— Dismantling instructions: these could include exploded diagrams of the computer model, indicating the opening mechanism and required tools; in the case of clips, this should include information related to the direction in which the housing should be opened.
— How to recognise special models and specific dismantling instructions for them.
— Advice on collection (separate/mixed) and on logistics.

Additional relevant information could also include the following (EERA, 2016).

— Extra information on materials that are recyclable if certain technology is used (e.g. poly-methyl methacrylate (PMMA) plates from displays to be dismantled manually).
— Information on those batteries which cannot be removed without (advanced) tools (providing then information on what tools should be used and where to find them).
— Description of the component/substance and its different types, e.g. whether substance is dangerous.
— Personal-protection equipment needed for handling.
— Risks for workers when the waste is not properly dismantled.
— Advice on possibilities to sort the components or substances (when different treatment is possible for different types).
— Advice on available treatment techniques.

It is also highlighted that such information, should be provided in a standardised manner to maximise its operational utility (EuRIC, 2016a).

Apart from all this information (to be provided e.g. via digital platforms), recyclers stressed the importance of labelling, provided that the information fulfils the following conditions (EERA, 2016): it is uniform; it is adopted early and by all; and it is visible and easily recognisable (big logos or letters, colours). The labelling should be applied to (EERA, 2016):

— provide information on hazardous components and substances;
— give instructions for logistics and/or treatment.

It is also recognised that up to one third of total WEEE produced in the EU, including computers, is not correctly disposed of and treated (Huisman et al., 2015). In particular, there is a risk that the small dimensions of IT equipment would facilitate the incorrect sorting by users into the waste bin. Economic incentives for a proper waste collection and treatment are crucial, as for example, establishing deposit/refund systems for computers, in order to incentivise users for a proper disposal of the waste and improve material recovery (Huisman et al., 2015; Zhong and Schiller, 2011).

7.1.2 Possible improvements

Computer designs could be developed so that components that are crucial for material-efficiency aspects can be easily located, extracted and addressed to specific recycling treatments. Measures to ease the disassembly have been proposed and analysed for various EEE (Ardente et al., 2013; Ardente and Mathieux, 2012b; Talens Peiró et al., 2016; Talens Peiró and Ardente, 2015).

In order to facilitate the ease of dismantling of key components (such us batteries, PCB assemblies larger than 0.1 dm^2, display panels larger than 1 dm^2, any mercury-containing component or capacitors containing electrolyte) specific joining or sealing techniques can be used. In particular, large number of different fastenings and/or certain types of fastening which are difficult to be dismantled can represent an obstacle for recyclers for the efficient recovery of key components. According to EERA (2016) and EuRIC (2016a), in order to improve the recycling, it is absolutely useful that components of different material composition (such as plastics and metals or batteries and PCB) are not soldered, glued or permanently fixed together. Recyclers experience many difficulties when these material groups are fixed together, resulting in higher material losses ([85]).

Key components for this and other product groups were also identified by Talens Peiró et al. (2016) (computer and electronic displays) and Dodd et al. (2016, 2015), who suggested thresholds on the maximum time required to extract them from the device. Such an approach, proposed for the revision of the EU Ecolabel and EU GPP criteria, however, poses some problems for verification, and its application in the context of the ecodesign directive would require standardised procedures to measure or calculate the time required for the extraction.

Ease of dismantling can be proved and enhanced thanks to a comprehensive documentation on the sequence of operations needed to access the key components, describing the type and number of fastening technique(s) to be unlocked, and tool(s) required. As for the disassembly, in this case the exploded diagram of the product showing the location of the components to be dismantled can also be useful. The recycling industry welcomes making the information available electronically/on digital platform(s), which is the main format easily accessible by relevant stakeholders (EuRIC, 2016a). The period of 15 years is considered by the recycling industry to be an possible time frame with regard to the duration for which the document should be kept available (EuRIC, 2017).

It is important to remark that evidence collected so far indicate that the design of desktop computers is generally not posing dismantling problems during recycling (see Section 3.1.1). The design of the new models of desktops (e.g. 'mini desktop') could be the source of some problems in the future, since their compact structure makes their design similar to that of games consoles ([86]). However, a limited number of these computer models have reached EoL, and therefore EoL processes can only be estimated through analogies with similar product groups (such as games consoles or notebook computers). Based on the very limited information available from a manufacturer (see Section 3.1.1), mini desktop computers should not cause high levels of difficulty for their recycling. However, based on the comments received from a stakeholder, the compact structure of mini desktops could hamper the dismantling of these computers and the removal of batteries and other valuable components as CPU and SSDs.

For desktop computers with integrated displays, their EoL treatments are affected by problems similar to those of electronic displays (see Section 3.1.2). Furthermore, they could be specifically labelled in order to allow recycling operators to identify them as computers already at the early stages of the recycling process.

Some components, such as tablet frames containing magnesium, although shown as relevant for dismantling in the analysis of recycling practices (see Section 3.1.4), have been excluded from the list of targeted components. This is due to the fact that frames can take various form and shapes and that the requirement could hence be difficult to be verified. It is however argued that ensuring an easier dismantling of the abovementioned components should also enhance facilitated dismantling of frames.

According to a European recycler association, information relevant for dismantling should be made accessible to recyclers and market-surveillance authorities, ideally through dedicated digital platforms ([87]), as for paper documentation there is the risk that it is static and becomes outdated if not revised in time (EERA, 2016).

([85]) The consequence is that, if this is not regulated in some way, recycling and recovery rates as given in Annex V of the WEEE directive cannot be met (EERA, 2016).

([86]) In the case of games consoles, industries proposed a 'self-regulatory initiative', addressing also some EoL issues (Sony, Microsoft, Nintendo, 2015). This documents states that 'to improve both recycling and reuse at end-of-life, maintenance and refurbishment is possible by non-destructive disassembly' and 'To improve recycling at end-of-life, console plastics parts > 25g are marked indicating their material composition (using ISO conforming marks)'.

([87]) There are ongoing projects about how to develop and communicate relevant information for recyclers. For

A standardised format for the documentation to support the verification of the requirement have to be established. For example, the format published by the Austrian ministry of environment ([88]) can represent a basis. Moreover, this standardised format should be based on the horizontal standardisation work under European Mandate M/543 on material-efficiency aspects of energy-related products (European Commission, 2015b), which requires 'documentation and/or marking regarding information relating to material efficiency of the product taking into account the intended audience (consumers, professionals or market-surveillance authorities)' to be developed.

Additional work is also necessary to unambiguously set out what is a *high adhesion* two-sided adhesive tape. Future options could improve the design for the dismantling of the products (based, for example, on the development of metrics to assess the ease of dismantling ([89])). Again, standardisation work under Mandate M/543 (European Commission, 2015b) could be initiated, for the specific development of methods to assess the ability to access or remove certain components or assemblies from products, and to facilitate their extraction at EoL for ease of treatment and recycling.

7.2 Marking of plastic components

7.2.1 Rationale

New EEE use more and more quantities and different types of plastics (WEEE forum, 2017). The EEE industry accounts for 5-7 % of the total European plastic demand, and the polymers used are highly engineered with the inclusion of additives. Although in theory plastics are all perfectly recyclable, in practice the recyclability of plastics is generally very low (EN TS 16524, 2013). 'Products consisting mainly of plastic have a very low recyclability rate in practice and it is all the lower when different plastics are combined in the same product' (EN TS 16524, 2013). Moreover, the European Commission in 2013 observed that only a small fraction of plastic waste is at present recycled (European Commission, 2013). Appropriate measures to enhance the recycling of plastics could also improve competitiveness and create new economic activities and jobs (European Commission, 2013).

Plastic recycling poses various problems (Elo et al., 2009; Peeters et al., 2014).

- The lack of process capable of performing plastic sorting and separation.
- Plastic can be recycled roughly a limited number of times; then the plastic is worn out and of poor quality.
- Complexity of the plastic mix, which makes it both difficult to separate plastics from each other and generally expensive to recycle.
- Plastics can contain several additives which degrade the virgin plastic.
- Plastic can be reinforced or mixed with metals and other non-plastics, which degrade the plastic when recycled.
- Most plastics type are only present in relatively small flow amounts, which makes it difficult to achieve the required economies of scale for advanced recycling operations.

example, the EU Horizon 2020 project 'CloseWEEE' (http://closeweee.eu/) aims to develop processes for separation and recovery of materials (including plastics, CRMs, and other valuable metals) from WEEE streams, and to improve the flow of information to recyclers through a dedicated digital platform (named 'recycler information centre' — http://www.werecycle.eu/) in order to make recycling procedures quicker and safer

([88]) 'Leitfaden für die Behandlung von Elektro- und Elektronikgeräte' (EERA, 2016).

([89]) For examples of metrics to assess the ease of disassembly, see: Vanegas P., Peeters J.R., Cattrysse D., Duflou J.R., Tecchio P., Mathieux F., Ardente F., 2016. Study for a method to assess the ease of disassembly of electrical and electronic equipment — Method development and application in a flat panel display case study. EUR 27921 EN. doi:10.2788/130925 (Available: https://ec.europa.eu/jrc/en/publication/study-method-assess-ease-disassembly-electrical-and-electronic-equipment-method-development-and?search)

Density sorting of plastic (via sink-float techniques) is currently the easiest and still most adopted sorting systems for shredded plastics (Peeters et al., 2014). Different plastics are separated according to their different densities thanks to water or air separators. Some advanced processes for the separation of plastics are currently under development (e.g. near infra-red (NIR) analysis spectroscopy, x-ray fluorescence (XRF) spectroscopy, Visible light optical separation), although their efficiency of separation and their applicability to the sorting of shredded plastics are still under investigation (Elo et al., 2009; Peeters et al., 2014). Sorting of different plastics is also performed based on manual dismantling. This technique can be technically and economically viable for high-quality technical plastics used in EEE, including computers (Mathieux et al., 2008; Peeters et al., 2014).

The efficiency of manual sorting of plastics is, however, dependent on the properness of plastic marking, values of recyclates and labour cost. Marking of plastic should follow standardised approach, as that proposed by ISO 11469 (ISO 11469, 2000), and standards of the series ISO 1043 (EN ISO 1043-1, 2002; EN ISO 1043-4+A1:2016, 1999). Nevertheless, EERA (2016) observed that markings on plastics in use nowadays are not fully reliable in some cases. Moreover, codification of WEEE plastics is often ambiguous and not harmonised at EU level (WEEE forum, 2017). Tests carried out at the premises of an EERA member showed that markings on the back-covers of flat panel displays were not reliable, and the polymer type often did not match with the marking. Recyclers who follow the markings can therefore end up separating materials incorrectly and this could potentially lead to them having contaminants (such as brominated flame retardants (BFRs) in materials where BFRs should not be present) (EERA, 2016). Audits should be enforced to ensure that the marking and the plastic type match.

7.2.2 Possible improvements

Associations of WEEE recyclers suggested that the proper marking of plastics (and their additives and FRs) would be beneficial for recycling companies, especially for recyclers that dismantle plastic parts manually (EERA, 2016). WEEE Forum (2017) recommends developing best-practice guidelines for plastics sorting, characterisation of plastic fractions as well as monitoring and tracing of the destination of sorted outputs.

In order to improve the manual separation of valuable plastic parts, the marking of plastic parts above a certain weight (e.g. 50 g) could be systematically applied.

The marking of plastic parts, as said, should follow a standardised approach (see Section 7.2.1), with specific exemptions ([90]) as for example, the following.

- PCB assemblies.
- PMMAs, and other optical plastic parts.
- Wiring and cables.
- Packaging, tape and stretch wraps.
- Labels.
- Electrostatic discharge components and, electromagnetic interference components.
- Acoustics module.
- Plastics where marking is not possible because of the shape or size of the part, or when the marking would impact on the performance or functionality of the part, or where marking is technically not possible because of the moulding method.

As reported in Ardente et al. (2016), plastic components containing FRs can be recognised through standardised symbols. Both the document establishing EU Ecolabel criteria (European Commission, 2016), and the study supporting the revision of the EU GPP criteria

([90]) These exemplary exemptions are derived from comments received from industries related to the marking of plastics in other products (electronic displays).

of personal computers (Dodd et al., 2016) include the marking of plastic components and plastic components with FRs, by means of ISO 11469 and ISO 1043 markings.

An example of comprehensive plastic marking is shown in Figure 24. Among the different information in the marking, polymer type and FRs are probably the most relevant for recyclers.

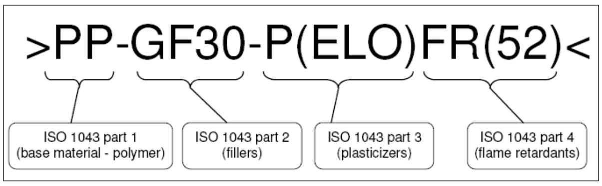

Figure 33 — Plastic marking according to ISO11469 (adapted from Bombardier (2010)).

It is also highlighted that aspects not specified by the Standard ISO 11469 are (Ardente et al., 2016):

- components to be marked,
- dimensions of marking,
- font to be used,
- location and visibility,
- additional quality characteristics (e.g. being legible, visible, durable and indelible).

7.3 Declaration of flame-retardant content

7.3.1 Rationale

As mentioned in Section 7.2, recycling of plastics can pose various problems during the recycling, especially due to the content of additives as FRs. According to all the recyclers interviewed, FRs (including BFRs) are the major barrier to plastic recycling (WEEE Forum, 2017). Current mechanical-sorting processes of plastics with additives are characterised by low efficiency, while innovative sorting systems are still at the pilot stage and revealed to be effective only in specific cases (Ardente et al., 2016).

FRs are chemical additives added to plastics to avoid potential internally and externally initiated ignitions. FR are used for EEE and, in particular, computers. For example, the analysis of the bill of material of notebooks revealed the presence of two large plastic parts (mass around 100 g) in polycarbonate with halogen-free phosphorous compound (code FR 40, according to ISO 1043-4).

However, FRs can reduce the recyclability of plastic parts. The presence of additives can reduce the mechanical properties of the materials, requiring additional treatments and additives to compensate for the degradation of such properties, as well as reduce the value of the materials in the market, and consequently the economic feasibility of recycling (Dawson and Landry, 2005). For such a purpose, the (IEC/TR 62635, 2015) suggests in the annexes that a 0 % recycling rate should be considered for polymers with FRs that are not properly separated from the other materials before the shredding.

Moreover, some FRs (such as certain BFRs) have high toxicity and for this reason they have been regulated, for instance by the Directive 2011/65/EU on the restriction of the use of certain hazardous substances in electrical and electronic products (RoHS). This directive established that Member States must ensure that new electrical and electronic equipment put on the market does not contain substances such as polybrominated biphenyls (PBB) or polybrominated diphenyl ethers (PBDE) (European Union, 2011). In addition, the directive on WEEE states in Annex VII that plastic-containing BFRs have to be removed from any separately collected WEEE (European Union, 2012).

7.3.2 Possible improvements

The provision of information on the content of FRs in plastic parts is a first step to contribute to the improvement of plastic recycling. Plastic marking (as discussed in previous sections) can contribute to the separation of plastics with FRs during the manual dismantling, allowing their recycling at higher rates (in line with prescription of IEC/TR 62635, 2015). However, more-detailed information about the composition of the product (including detail of plastic composition) can be beneficial for recyclers and it is also in line with the principles of the WEEE directive ([91]).

The provision of information on the FRs content could be structured and communicated in a systematised way through specific indexes. These indexes could support recyclers to check the use of FRs in computers and to develop processes and technologies suitable for plastic recycling in future. Moreover, these indexes could allow policymakers to monitor the use of FRs in the products and, in the medium-long term, to promote products that use smaller quantities of FRs.

As an example, the 'Flame retardant in plastic components' index, as specified by Ardente et al. (2016), aims to do the following.

- Detail plastic components that contains FRs (including mass and type of plastic components; mass and type of FRs).
- Provide, in a very synthetic way, an overview of the content of FRs.

To simplify the calculation and communication of this index, the scope of the index could be restricted to plastic components larger than a certain mass (e.g. larger than 50 g). In addition, some plastic components could be excluded from this calculation (e.g. PCB assemblies and cables, which always contain FRs). Exemptions could be also planned for information that is confidential (e.g. the type of certain FRs). In this case, it could be sufficient to declare that a certain part contains FRs, without specifying the types of FR. Exemptions need to be also adequately documented.

An example of a calculation table for the 'Flame retardant in plastic components' index is provided in Table 38. All masses are approximated at the gram.

([91]) The WEEE directive, in Article 4, states that appropriate measures should be encouraged 'so that the ecodesign requirements facilitating reuse and treatment of WEEE established in the framework of Directive 2009/125/EC are applied'.

Table 38 — Table for the calculation of the index on 'Flame retardant in plastic components' for computers (modified from (Ardente et al., 2016)).

Brand name and Product family: **A) Total mass of the computer [g]:**			
***i.* Plastic part** **(with flame retardants)** (*)	***ii.* Mass [g]**	***iii.* Polymer(s)** (**)	***iv.* Flame retardant(s)** (***)
Part *(1)*	…	…	…
Part *(2)*	…	…	…
…	…	…	…
Part *(j)*	…	…	…
B) Total [g]			
***v.* Plastic part** **(without flame retardants)** (****)	***vi.* Mass [g]**	***vii.* Polymer(s)** (**)	
Part *(1)*	…	…	
Part *(2)*	…	…	
…	…	…	
Part *(k)*	…	…	
C) Total [g]			
B) Total mass of plastic parts in the computer with flame retardants [g] (sum of masses in column *ii*)			
C) Overall mass of plastic parts in the computer without flame retardants [g] (sum of masses in column *vi*)			
			Index [%]
Ratio (in percentage) of plastic parts containing flame retardants on the total mass of the computer ($\frac{B}{A}$)			
Ratio (in percentage) of plastic parts containing flame retardants on the total mass of plastic parts ($\frac{B}{B+C}$)			

(*) plastic parts containing flame retardants, larger than 50 g
(**) standard abbreviated term for the polymer(s) in the plastic part, according to EN ISO 1043 series
(***) standard code number of the flame retardant(s) in the plastic part, according to EN ISO 1043 series
(****) plastic parts not containing flame retardants, larger than 50 g

7.4 Identifiability of batteries

7.4.1 Rationale

According to the analysis in Section 2.3.5, the market for rechargeable lithium-ion batteries is growing rapidly, accelerated through the demand increase in portable electronics, such as tablet and notebook computers. After collection, batteries at the EoL mostly appear as mixtures and are subject to manual sorting according to their chemistries. The identification of the chemistry type is based on the logo placed on the battery packaging/casing. In practice, however, when the batteries reach the recycling facility, the logos are sometimes missing, making identification and sorting difficult. In order to release manual labour force, raise the sorting speed as well as accuracy, better marking/identification with improved readability is required in order to implement efficient identification and sorting.

According to interviews with German battery recyclers, battery marking will facilitate the separation of mixed batteries and therefore increase the recycling rates of Li-ion batteries. Furthermore, interviews revealed that the cobalt content in LIB varies between 0 and 15 % based on the battery sub-chemistry. A more-detailed logo indicating the sub-chemistry system will be beneficial for more precise sorting and dedicated batch-wise treatment.

7.4.2 Possible improvements

According to EERA (2016), colouring at the component level is good for recyclers to create awareness and traceability of these components and/or materials and substances that need to be removed. This principle can be specifically applied to batteries to identify the battery chemistry.

Battery packs and cells (including those incorporated into battery packs) can be identified with the 'battery-recycle mark', or a similar marking symbol. Indeed, the 'battery-recycle mark' and the IEC draft standard represent a good basis for colour-based logos, even though additional standardisation activities should be initiated in order to adapt it to the EU legislation. The battery logo would reduce the limits of current marking practices if properly applied (visible, durable, legible and indelible). The identifiability of battery chemistry would be enhanced by the use of different colours.

Standardisation activities are currently ongoing to approve a draft international standard titled *Secondary batteries: Marking symbols for identification of their chemistry* (IEC 62902 draft, 2017). The draft document specifies methods for the clear identification of secondary cells, batteries, battery modules and monoblocs according to their chemistry (electrochemical storage technology), by using the battery-recycle mark. The draft standard concerns secondary cells, batteries, battery modules and monoblocs with a volume of more than 900 cm^3. The marking is applicable for secondary cell and batteries of following chemistries only:

— lead acid (Pb) (colour: grey)
— nickel cadmium (NiCd) (colour: green)
— nickel-metal hydride (NiMH) (colour: orange)
— lithium-ion (Li-ion) (colour: blue)
— secondary lithium metal (Li metal) (colour: blue).

The draft standard also specifies the dimensions of the marking symbols (with and without the recycling symbol), how the markings can be fixed to the battery (either by printing or labelling) and which procedure can be performed to test durability of marking to chemical agents.

If approved, this draft document may be the starting point for batteries with a volume of less than 900 cm^3, as is the case for personal computers.

Beside of the content of the draft IEC standard, for lithium-ion batteries, a two-digit code may be added to indicate the content of specific metals as well as substances hindering recycling.

To improve automated battery sorting solutions, future schemes could go beyond the proposed colour-coded 'battery-recycling mark'. One option suggested by a large German battery-recycling company is to add a QR (quick response) code to both battery cell and pack. QR codes were initially designed by the automotive industry for its assembly lines and would well-suited to the need of treatment operators (EuRIC, 2016a). The QR code could provide more precise information related to the battery subtype, concentration of cobalt and other REEs as well as a link to material safety sheets. Access to the information can be limited only to dedicated treatment operators part of the official compliance schemes to mitigate concerns over innovations in battery technologies.

7.5 Provision of information on the content of critical raw materials

7.5.1 Rationale

Within the 'raw materials initiative', the European Commission identified a list of CRMs that are crucial for the EU economy ([92]). The criticality associated with these materials is, in many cases, compounded by low substitutability and low recycling rates. Therefore, boosting material efficiency and increasing the recyclability of these materials has been identified as one pillar to reduce the risks associated with their supply.

Several CRMs are contained in computers such as cobalt in the batteries, neodymium and other REE in the HDD magnets, indium in the display panels, magnesium in some metal frames, and various CRMs (including palladium, REE, antimony, beryllium, cobalt, gallium, chromium, silicon) in the PCBs.

The knowledge of computer components containing CRMs (with details on the composition) would facilitate their identification by operators during EoL processing. Together with requirements on the design to ease the dismantling, this type of labelling of CRMs could increase the efficiency in the sorting of relevant components, addressing them to the proper treatments and, ultimately, increase their recycling rates (Ardente and Mathieux, 2014).

A detailed analysis of all the CRMs used in computers remains a challenge, because of the large variety of CRMs present in several components. Manufacturers have difficulties in collecting this information from suppliers, as typically the chemical composition of a component or alloy is not specified to suppliers (Digitaleurope, 2017b). However, industry already demonstrated the willingness to voluntarily provide information about some CRMs ([93]) in an aggregated format (Digitaleurope, 2013). The next sections will focus on two main CRMs that have been identified as relevant during the analysis of composition of computers and EoL scenarios (Sections 2 and 3).

7.5.1.1 Recovery of cobalt

To implement more precise sorting and dedicated treatment of LIB according to their sub-chemistry, an indication of the cobalt concentration in batteries is needed. For example, elements such as iron and phosphorous from LFP batteries represent an obstacle for the recovery of cobalt from high cobalt concentrates (LCO-type LIB). Thus, such polluting elements need to be removed. However the removal process for such polluting elements can increase the cost of the whole process. Therefore, the sorting of batteries according to their sub-chemistry, as a preliminarily to further treatment, makes it possible to have batches of waste which are richer in the concentration of the target metals (e.g. cobalt). Compared to the treatment of diluted mixtures of different battery types, the treatment of these concentrated batches is more feasible from both a technical and an economical point of view. As hydrometallurgical processing focuses on selected materials, for instance either cobalt and copper in the case of LCO batteries or copper and manganese for LMO batteries, the loss of material groups can be minimised when batch-wise processing per battery type is facilitated by labelling. The mass concentration allows for a better assessment of the economic viability of the treatment, i.e. improves the precision of the estimate of cobalt content and the material matrix (Accurec, 2016).

7.5.1.2 Recovery of rare earth elements

HDDs represent one of the main electronic components for containing certain rare earths. As detailed in Section 2.4.2, HDDs contains NdFeB magnets which mainly contain

([92]) The list of CRM is provided in:
http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52014DC0297&from=EN
([93]) Indium volumes by display technology type.

neodymium (23-25 % in mass) and a few percentages of other rare earths (such as dysprosium and praseodymium).

Compared to the total NdFeB production capacity, the recovery potential from HDDs is in the 1-3 % range, however the recycling could be potentially increased if neodymium could be traced from mine to material, product, and finally to waste (Sprecher et al., 2014a). It is estimated that neodymium in magnets will be the largest source of recycled neodymium until 2025 (München and Veit, 2017). The recycling of rare earths from HDDs is technically feasible, if these components are properly extracted and sorted from other waste streams.

HDD from different computer types (notebook and desktop) can take the same recycling route (München and Veit, 2017). In addition, Sprecher et al. (2014a) highlighted that NdFeB magnets should be treated relatively close to the waste-collection and treatment points, as shipping and handling large volumes of NdFeB magnets may be problematic because of the very high magnetic strength.

The separation of HDDs and NdFeB magnets occurs either after waste shredding or manual dismantling (Sprecher et al., 2014a). The former option, namely recycling through shredding, results in a very significant (> 90 %) loss of NdFeB, which is mainly lost in the ferrous fraction; after shredding, the neodymium must be leached out of the material and then be reprocessed in almost the same manner as virgin material is processed (Sprecher et al., 2014a). Neodymium liberated through shredding may also contaminate other recyclable fractions (Sprecher et al., 2014a). This option is therefore regarded as less efficient in terms of material recovery.

Vice versa, manual dismantling of HDDs proved to be much more efficient and have a lower environmental impact (Sprecher et al., 2014a). Experimental measurement of the efficiency of manual extraction of HDD from waste computers under current processes resulted in around 35 % (Sprecher et al., 2014a). This percentage could be further increased thanks to improved design of the product for the dismantling of the HDDs (as in requirement of Section 6.1) or provision of information on the content and location of neodymium (see e.g. Talens Peiró and Ardente (2015) for the enterprise-servers product group). Neodymium from magnets can be then further recycled through 'hydrogen decrepitation' process (Zakotnik et al., 2006) or by raising the temperature of the material above its Curie temperature (312 °C) in order for it to lose its magnetic properties (Dupont and Binnemans, 2015). The recycling of neodymium following these techniques can reach values of efficiency of 90 % (Sprecher et al., 2014a), and significantly lower environmental impacts (from 60 % to 90 % lower) compared to primary production (Sprecher et al., 2014b).

7.5.2 Possible improvements

Measures to improve the recycling of neodymium and other rare earths from magnets include the following.

- The declaration of the content of rare earths (e.g. the proposal for ecodesign requirements for fans ([94])).
- The provision of instructions for the dismantling (e.g. the requirement for the dismantling of magnets in ventilation units ([95])).

([94]) According to the preparatory study of ventilation fans, it is proposed that manufacturers declare the weight (if any) of the permanent magnets containing rare earths, in kg with 2 digits (e.g. 'permanent magnets 2.12 kg'), on the nameplate and in the technical document (VHK, 2015).

([95]) 'The manufacturer's free access website shall make available detailed instructions, inter alia, identifying the required tools for the manual disassembly of permanent magnet motors, […] for the purpose of efficient materials recycling […]' (European Union, 2014).

- The potential labelling/marking of the components (e.g. the proposal for a QR code on REE content developed by NSF (2015) for the environmental labelling enterprise servers ([96])).

Information about the presence of CRMs in computers could include: the content of cobalt in batteries; the content and location of components containing rare earths (e.g. neodymium, dysprosium, praseodymium in HDD magnets); the content and locations of palladium in PCBs.

This information could be as follows.

- Voluntarily provided by manufacturers in an aggregated format to be agreed with the recycling industry.
- Provided by manufacturers in the technical documentation needed to support the ease of dismantling of key components (Section 7.1).
- Provided by manufacturers through specific optical label (e.g. QR codes), to be developed in the future to report the content of CRMs. These optical labels could be placed directly onto the component or, alternatively, on the computer back-cover.

However, it is recognised that, to be effective and easily verifiable, the provision of information on the presence of CRMs in computers requires a standardised format for such communication, including for example, dedicated labelling. Standards under the development within the European Mandate M/543 (European Commission, 2015b) could serve the purpose, as those related to the 'use and recyclability of CRMs to the EU' and the development of 'documentation and/or marking regarding information relating to material efficiency of the product'.

([96]) 'The manufacturer shall indicate the type of actuator/voice coil and spindle magnets in the product's hard disk drive on the external enclosure of the hard disk drive by means of a QR code. The QR code shall link directly to the magnet type and location information on a publicly available database or the manufacturer's website in at least English. The QR code shall be printed in black on a white background if one or more of the magnets contain neodymium. The QR code shall include a non-machine readable chemical symbol (Nd)' (NSF, 2015).

7.6 Initial assessments of benefits/impacts

This section aims to present scenarios and impact assessments developed to enhance the recyclability of notebooks. This section refers to all of the improvements proposed in this chapter (Sections 7.1, 7.2, 7.3, 0 and 7.5), since these are produced as a result of combined action dedicated to promoting more material-efficient treatments and are therefore assessed together.

The potential benefits have been assessed based on the comparison of some reference scenarios (Figure 34). In particular, it is assumed that without any specific product measure on recyclability, waste notebooks will be treated in future analogously to the current situation and following the processes described in Section 3.1.3 (defined as 'business as usual — BaU' scenarios). On the other hand, it is assumed that the proposed actions will improve the economic viability of treatments which are more focused on medium-depth manual dismantling compared to treatments based only on 'mechanical crushing and sorting' after depollution. Moreover, a better design for recycling of notebooks could increase the separation of valuable components and the recycling rates of materials within these 'improved scenarios'. These two parameters (i.e. the flow of waste treated in the different scenarios and the efficiency of the different recycling treatments) are assumed to be affected by recycling improvements and this is reflected in the modelling of the following assessment.

In particular, the considered reference scenarios are as follows.

— Business as Usual (BaU) scenario: this reflects the base-case EoL treatments for notebooks, as described in Section 3.1.3. In particular, it is assumed that these scenarios are equally representative of EU treatments, with 50 % of the waste flows processed with depollution and mechanical crushing and sorting (BaU1), while another 50 % is processed according to "depollution, medium-depth dismantling and subsequent mechanical crushing and sorting" (BaU2). Compared to BaU1, the BaU2 scenario is characterised by higher recycling rates of batteries, PCB ([97]), storage systems and ODD, thanks to the more careful manual dismantling during the depollution and the following dedicated recycling.

— Improved scenario: moderate (named as scenario I.1 in Figure 34). These scenarios assume that, thanks to the proposed improvement actions, the flow of waste notebooks processed through "depollution, medium-depth manual dismantling and mechanical crushing" would increase compared to the BaU scenario. This can be justified with the reduction in effort to locate and dismantle relevant components and the consequent reduction in labour costs. The investigated actions would grant an increased battery separation for waste flow entering the different treatments (i.e. I.1.1 and I.1.2 in Figure 34), and higher recycling rates for the waste flows treated by "depollution, medium-depth manual dismantling and mechanical crushing" (I.1.2 in Figure 34).

— Improved scenario: high (I.2 in Figure 34). This scenario is analogous to the previous one (I.1) with the difference that material-efficiency actions are expected to produce higher benefits, in terms both of higher flows of waste treated by "depollution, medium-depth manual dismantling and mechanical crushing" (I.2.2 in Figure 34) and higher separation and recycling rates of components and materials. In addition, it is also expected that the waste treated through "depollution, mechanical crushing & sorting" (I.2.1 in Figure 34) would achieve a higher extraction rate of the batteries.

For the assessment it is considered that there will be 41.7 million notebook sold in 2020 (Section 2.1) that will reach their EoL in 2025. Assumptions about the composition of the notebooks are as follows.

— BoM of notebook components as detailed in Section 2.3.2.

([97]) Button cell batteries are considered to be further separated from PCBs manually dismantled.

— Average composition of batteries as detailed in Section 2.3.5 (Table 17).
— Storage systems are assumed to be constituted 50 % by SSD and 50 % by HDD (as discussed in Section 2.1, market projections to 2020). The content of neodymium and other rare earths is 30 % of the magnets in HDD (Prakash et al., 2014).

Table 39 illustrates the average recycling rates of different metals from notebook PCBs separated for dedicated treatments (derived from Chancerel and Marwede (2016)). The same recycling rates of Table 39 are assumed for SSD ([98]).

The assumed recycling rates of metals from batteries extracted and separately treated are: cobalt 90 % (Chancerel and Marwede, 2016); nickel 62 % and copper 90 % (Wang et al., 2014); lithium 50 % ([99]). Recycling rate of rare earths (neodymium and dysprosium) from HDD magnets extracted and separately treated is assumed 90 % (Sprecher et al., 2014a). ODDs that are separated are assumed to be dismantled to extract the PCB, while the remaining parts are treated by mechanical crushing and sorting. Recycling rates of other components materials are derived from IEC (2012). All the assumptions on waste flows and recycling rates are summarised in Figure 34.

Table 39 — Average recycling rates of different materials from PCBs separated for recycling (source: Chancerel and Marwede, 2016)

Materials in PCB	Recycling rate	Materials in PCB	Recycling rate
Ag	95 %	**Pb**	80 %
Al	0 %	**Pd**	95 %
As	0 %	**Sn**	75 %
Au	95 %	**Sr**	0 %
Ba	0 %	**Ta**	0 %
Be	0 %	**Zn**	50 %
Bi	80 %	**SiO_2**	0 %
Cd	0 %	**B_2O_3**	0 %
Cl	0 %	**K_2O**	0 %
Co	0 %	**CaO**	0 %
Cr	0 %	**MgO**	0 %
Cu	95 %	**NaO**	0 %
Fe	0 %	**C**	0 %
Ga	0 %	**Br**	50 %
Mn	0 %	**Sb**	80 %
Ni	90 %		

([98]) SSD have a structure similar to that of PCB and are assumed to be collected together with PCBs and recycled in the same facilities.
([99]) The recycling of lithium, although technically feasible with high efficiency (50-90 %) (Kushnir, 2015; Wang et al., 2014), is still not largely developed in the EU. Currently, a plant for the recycling of lithium has been established in France. Similar plants could be set in the EU, especially assuming in the next future a large growth of the amount of waste batteries sorted for recycling.

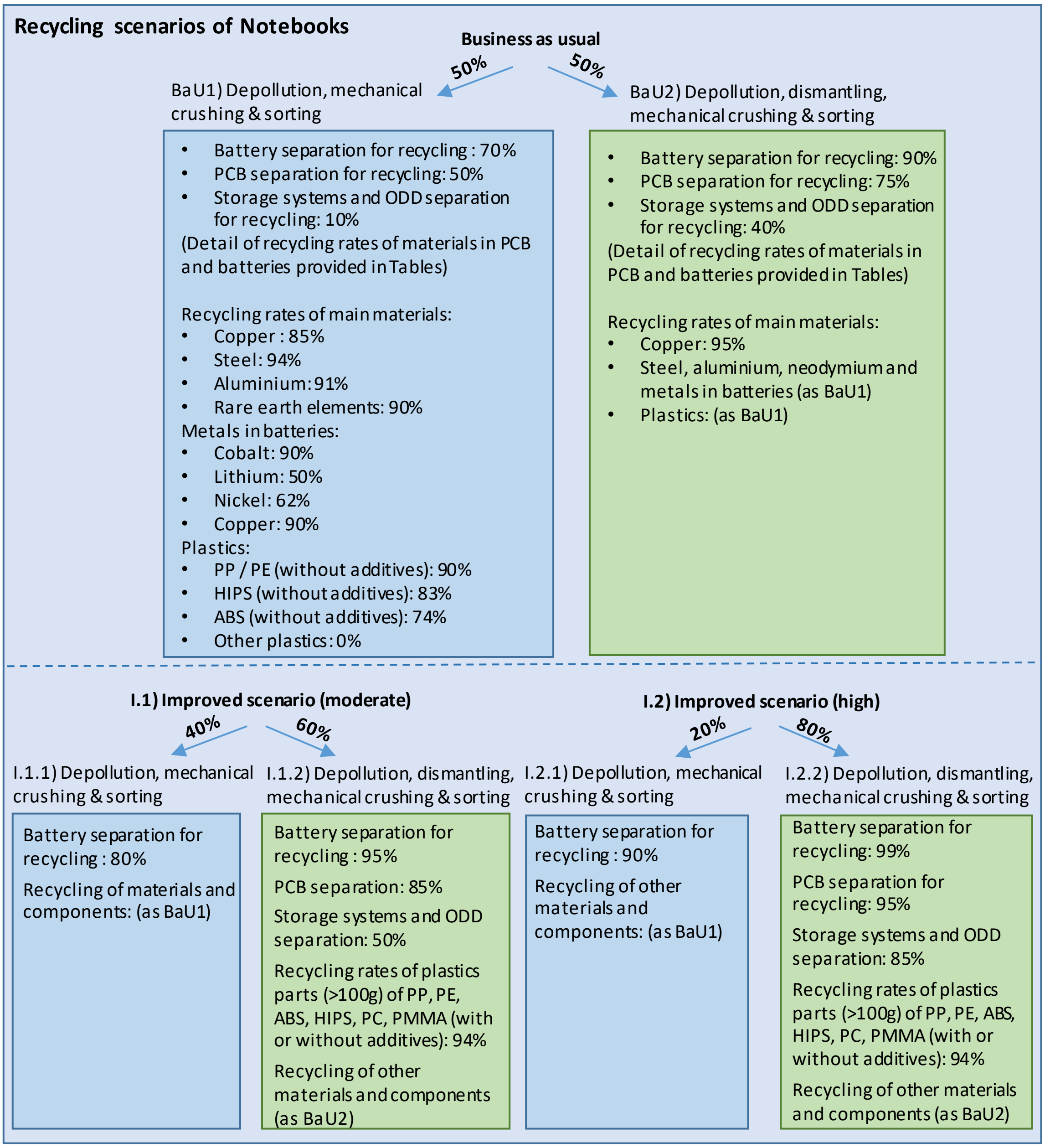

Figure 34 — References scenarios for the calculation of the benefits related to material-efficiency actions to enhance the recyclability of notebooks.

The results of the assessment are illustrated in Table 40. In particular, benefits have been estimated in terms of additional recycled materials obtained by moving from the BaU scenarios through the moderately improved scenario "I.1" and the highly improved scenario "I.2" respectively.

Table 40 — Estimated benefits thanks to enhanced recyclability of notebooks.

Materials	Amount of additional recycled materials [tonne]	
	Moderate improved scenario (I.1)	High improved scenario (I.2)
Plastics (from various components)	8 066.9	10 755.9
Copper (from various components)	318.3	763.0
Silver (from PCBs)	2.6	8.5
Gold (from PCBs)	0.2	0.5
Bismuth (from PCBs)	0.1	0.3
Nickel (from PCBs)	9.7	22.2
Lead (from PCBs)	8.0	21.1
Palladium (from PCBs)	0.2	0.5
Tin (from PCBs)	12.3	32.3
Zinc (from PCBs)	8.5	22.6
Bromine (from PCBs)	18.0	47.2
Antimony (from PCBs)	2.5	6.5
Neodymium (from HDDs magnets)	1.9	7.0
Cobalt (from batteries)	74.8	144.5
Lithium (from batteries)	8.7	16.8
Nickel (from batteries)	23.8	46.0

Comparing the estimated benefits in Table 40 with current amounts of recycling materials it is observed that:

- In 2012, 10.9 t of palladium was recycled in the EU28 (BIO by Deloitte, 2015). The analysed scenario would grant an additional recycling of about 0.2 t of palladium (scenario I.1) in the future, equivalent to 1.8 % of the current recycling amount, and achieve up to 0.5 t of additional recycled palladium (scenario I.2) equivalent to 4.7 % of the current recycling amount.
- In 2012, 6.3 kt of cobalt was recycled in the EU28 (BIO by Deloitte, 2015). The analysed scenario would grant an additional recycling of 74.8 t of cobalt (scenario I.1) in the future, equivalent to 1.2 % of the current recycling, and achieve up to 144.5 t of additional recycled cobalt (scenario I.2) equivalent to 2.3 % of the current recycling amount.
- In 2013, 14 t of neodymium was recycled in the EU28 (BIO by Deloitte, 2015). This implies that a large share of neodymium in WEEE is currently lost. The analysed scenario would grant an additional recycling of 1.9 t of neodymium (scenario I.1) in the future, equivalent to 13.5 % of the current recycling, and to achieve optimistically up to 7 t of additional recycled neodymium (scenario I.2), equivalent to about 49.7 % of the currently recycled amount.
- Lithium from batteries is largely not recycled. According to BIO by Deloitte (2015), the lithium currently recycled amounts to 16 t. The analysed scenario would improve the battery extraction in the future, and would promote the recovery of lithium as well. The amount of additional lithium potentially recycled ranges from

8.7 t (scenario I.1) up to 16.8 t (scenario I.2). These amounts are equivalent to around 50-100 % of the current recycled masses.

— Compared to the current recycling of antimony in the EU (9.7 kt (BIO by Deloitte, 2015)) the improvements would also allow moderate minor benefit in terms of additional antimony recycled (up to 6.5 t, equivalent to 0.1 % of the current recycling).

Finally, the proposed requirements will also contribute to increase the amounts of recycled plastics (8-10 kt of additional plastics), copper (318-763 t) and precious metals (0.2-0.5 t of gold; 0.2-0.5 t of palladium; 2.6-8.5 t of silver).

The previous estimated benefits are based on the assumption that all the waste notebooks will be properly collected and treated in the EU at EoL. However, there is evidence of large amounts of waste electronics that are illegally exported or improperly collected and treated (e.g. disposed of into trash bins) (Huisman et al., 2015). Assuming a loss of 26 % of the flow of waste notebooks, potential reduced benefits have been estimated (Table 41).

Table 41 — Revised benefits due to the potential strategies to enhance the recyclability of notebooks (based on a reduced amount of waste properly collected).

Materials	**Amount of additional recycled materials [t]**	
	Moderate improved scenario (I.1)	**High improved scenario (I.2)**
Plastics (from various components)	5 969.5	7 959.4
Copper (from various components)	239.7	609.3
Silver (from PCBs)	2.0	6.6
Gold (from PCBs)	0.1	0.4
Bismuth (from PCBs)	0.1	0.2
Nickel (from PCBs)	7.3	17.7
Lead (from PCBs)	6.1	17.5
Palladium (from PCBs)	0.1	0.4
Tin (from PCBs)	9.4	26.8
Zinc (from PCBs)	6.5	18.6
Bromine (from PCBs)	13.7	39.1
Antimony (from PCBs)	1.9	5.4
Neodymium (from HDDs magnets)	1.4	5.1
Cobalt (from batteries)	55.6	107.8
Lithium (from batteries)	6.5	12.5
Nickel (from batteries)	17.7	34.3

7.6.1 Potential benefits for other product categories

The assessment of the potential benefits related to design for dismantling strategies is more difficult and uncertain for computers other than notebooks.

In the case of tablets, a small amount of waste currently reaches recycling facilities. Still the dismantling process for tablets is under development and refinement by recyclers. However, Section 3.1.4 analysed some criticalities during the processing of waste tablets, mainly related to the extraction of the batteries and PCBs. Design for recycling strategies as proposed in this section could contribute to simplifying the pre-processing of tablets and increase the material efficiency of the recycling processes overall, in terms of higher quantity/quality of materials separated for recycling.

For the assessment of the benefits of design for dismantling strategies for tablets it is roughly assumed to achieve similar improvements as discussed for notebooks. This implies that the efficiency of sorting and processing of PCBs and batteries could increase by around 10-20 %. Considering the average BoM of tablet (as in Table 12), the average composition of batteries (as in Table 11) and the average composition of batteries as for notebooks (as in Table 17), and assuming the same recycling rates as in Figure 32, it is roughly estimated that the additional amounts of recycled materials are: 30-60 t of cobalt, 4-7 t of lithium, 80-170 t of copper and 0.2-0.6 of various precious metals.

The process of dismantling and depolluting traditional desktop computers is instead well established and no criticalities have been identified in our analysis. However, the market of traditional desktop computers is estimated to continue declining, while the market shares of new types of desktops (e.g. mini desktops) are expected to grow in the next future. These new desktops can pose some problems during recycling, especially due to the very compact structure and the difficulties in extracting PCBs and batteries potentially contained in the computer. Designing for recycling strategies as proposed in this section could contribute to keeping the attention of manufacturers focused on the EoL aspects of these desktops and to promote designing computers for recycling solutions that facilitate their processing. However, due to the lack of information about the flows of mini desktops sold and their BoM, it is not possible to quantify such benefits.

8 Conclusions

The research findings of this technical report can be grouped into two levels. We firstly identified the so-called hot spots, namely the aspects of the personal-computer product group that are relevant from a material-efficiency perspective. *Hot spots* include the problems currently encountered by users (e.g. design features of the products that may hinder reuse, disassembly or repair) and by EoL operators (e.g. during the collection and treatment of computers). We then provided an analysis of potential actions aimed at overcoming the current *hot spots* and at improving the material efficiency of the product group, in particular enhancing durability, reusability, reparability and recyclability. Such analysis aimed to identify material-efficiency aspects which can be relevant for the current revision of the Ecodesign Regulation (EU) No 617/2013. This work has been carried out in the period June 2016-September 2017, in parallel with the development of *The preparatory study on the review of Regulation No 617/2013*.

Possible actions to improve material efficiency of personal computers were classified into three levels and also according to the waste hierarchy set out by the European Commission (Directive 2008/98/EC), in which waste prevention has the first priority, before preparing for reuse and finally recycling. Among the strategies to close material loops, durability and reusability are key material-efficiency aspects. As such, opportunities to eliminate or reduce factors potentially leading to breakages or loss of performance of personal computers have a high priority. A special focus was given to the content of raw materials (including EU CRMs) in computers and how to increase the efficient use of these materials, including material savings thanks to waste prevention and increased reuse and repair, and strategies to improve material recycling at the EoL of the products.

Possible actions to improve waste prevention

Among the possible actions to improve waste prevention we discussed two strategies to improve battery durability for mobile personal computers, one strategy for reducing the need for unnecessary EPS, and one strategy to raise awareness about the durability of computers, in particular the resistance to liquid ingress.

Battery durability resulted to be a key feature for users. A key indicator is represented by the remaining charge capacity of the battery compared to the initial-charge capacity, measured after a predefined number of charge/discharge cycles (e.g. 300 and 500 cycles). This information could be provided to users to raise awareness of an important aspect influencing the performance of the product. The assessment of this indicator can be based on the existing procedures set out in Standard EN 61960. This strategy could also represent a potential trigger for competition, as the performance of the battery could be evaluated with common tests and conditions. It will also help to gather data for future improvements (e.g. drawing up performance classes for grading battery performance). For battery durability, it was also proposed to promote the use of algorithms to manage the SoC of batteries while notebooks are in grid operation, a condition that may recur in office environments, for example. This would prevent the battery remaining at a SoC of 100 % for long time, a condition that accelerates the ageing of the battery. In this case, standards to support the development, implementation and verification of such algorithms have to be developed.

EPS were addressed as they represent a significant percentage of the whole weight and materials used for ICT (10-20 %), thus it is important to minimise the need for materials and the impact on the environment. The action proposed is to declare, in a standardised way, the presence/absence of the EPS within the packaging of the product, and the compatibility with other devices. Such a proposal has the potential to trigger the decoupling of EPS and devices and to inform users about how and when an EPS can be reused. IEC TS 62700, Standard IEEE 1823 and Recommendation ITU-T L.1002 can be used to develop standards for connectors and power specifications.

The last strategy aims to address the problem of products damaged by drops/falls or liquid spillage. Components such as the keyboard, the display, display-cover (including frame joints) and the casing of consumer notebooks are the components most prone to fail due to drops/falls or liquid spillage. Manufacturers have the possibility to test waterproof solutions for certain personal computers, and test their ingress protection (IP) according to the Standard IEC 60529 — Degrees of protection provided by enclosures (IP code). The action proposed, also in this case, is to declare in a standardised way the IP class. Standardisation activities may be needed to further define existing (but not standardised) tests, specifically relevant for the personal-computer product group. As an example, the EU Ecolabel criteria for computers include a test on durability against water-spill ingress ([100]). Such a test relies on the Standard IEC 60529 to establish the acceptance conditions only and, therefore, standardisation activities are needed to univocally set out testing conditions.

Possible actions to enhance repair and reuse

Among the possible actions to enhance repair and reuse we identified two strategies related to the ease of disassembly of personal computers, and one option related to the deletion of personal data in mass-storage systems.

Ease of disassembly is a crucial feature to improve the reusability of products, but also to extend their lifetime. EU citizens would rather repair their goods than buy new ones, but ultimately have to replace or discard their goods because they are discouraged by the cost of repairs and the level of service provided. We proposed that ad hoc documentation could be prepared not only to provide useful information to enhance repair and refurbishing of EEE, but also for preparation for reuse of WEEE. Two levels of information were considered. The first level involves professional repair operators, who can be provided with information about the disassembly, replacement and reassembly operations needed for a set of relevant components of personal computers (batteries, internal power-supply units, display, data-storage memories, keyboards, etc.). The second level involves users, who can be provided with clear and easy accessible information about the ease of disassembly and replacement of batteries used in personal computers. In particular, users can be informed on whether the replacement of the battery can be done by them, or by a professional repair operator. In both cases, standards have to be developed to ensure that the information is provided using a common format.

One major barrier to the reuse, repair and recycling of computers is data-privacy issues. Desktop computers, notebooks and tablets regularly store sensitive and confidential data for users and organisations. As a number of operating systems already include the option to 'factory reset' the device, bringing the device into its original factory state, we propose to preinstall a built-in functionality to ensure secure data deletion. Secure data deletion means the effective erasure of all traces of existing data from storage media, overwriting the data completely in such a way that access to the original data, or parts of them, becomes unfeasible for a given level of effort. A number of existing national standards (HMG IS Standard No 5 (UK), DIN 66399 (Germany), NIST 800-88r1 (US)) can be used as basis to develop international standards on secure data deletion. The protection of personal data contained in electronic product and components should be treated with special care, and the need to take action on secure data deletion is also in line with the principles of privacy and protection of personal data as set by the General Data Protection Regulation (EU) 2016/679.

([100]) The test shall be carried out two times. A minimum of 30 ml of liquid shall be poured evenly over the keyboard of the notebook or onto three specific, separated locations, then actively drained away after a maximum of 5 seconds, and the computer then tested for functionality after 3 minutes. The test shall be carried for a hot and a cold liquid (European Commission, 2016).

Possible actions to improve recyclability

Finally, among the possible actions to enhance recyclability, we discussed five possible strategies to improve the ease of dismantling of personal computers which are aiming to facilitate the extraction and the identification of different components and materials.

The design for the dismantling of computers is a necessary condition to efficiently depollute and recycle them. As such, computer components that are crucial for material-efficiency aspects should be easily located and extracted, in order to be properly and efficiently addressed in specific recycling treatments. Thus, the first strategy proposed targets for the ease of dismantling of products, which can be proved and enhanced thanks to comprehensive documentation provided by manufacturers. This documentation may include the sequence of operations needed to access the key components, namely the ones listed in the Annex VII of the WEEE directive. Such documentation would serve as guidance for recyclers and as proof that key components can be accessed and dismantled. At the time being, as stated for the actions to enhance repair and reuse, standards have to be developed to ensure that the information is provided using a common format.

Another related strategy to promote recyclability of computers is to mark plastic parts in order to recognise the type of plastic used and sort them correctly. Marking of plastic should follow a standardised approach, such as that proposed by ISO 11469, and standards of the series ISO 1043. Plastic marking can contribute to separation of plastics with FRs during the manual dismantling, allowing their recycling at higher rates, however, more-detailed information about the composition of the product (including detail of plastic composition) can be beneficial for recyclers and it is also in line with the principles of the WEEE directive. On such purpose, a third strategy is proposed, as regards the declaration of flame-retardant content in plastics. The provision of information on the content of FRs in plastic parts is a first step to contribute to the improvement of plastic recycling. Detailed information about FRs content could be given in a more systematised way, for example through the development of specific indexes. These indexes could support recyclers in checking the use of FRs in computers and in developing future processes and technologies suitable for plastics recycling. Moreover, these indexes could support policymakers in monitoring the use of FRs in the products and, in the medium-long term, to promote products that use smaller quantities of FRs.

In order to properly sort batteries by battery chemistry, a further action proposed is to adopt a battery-recycle mark, which reduces the limits of current marking practices if properly applied (visible, durable, legible and indelible). The identifiability of battery chemistry would be enhanced by the use of different colours. Standardisation activities are needed, even though they are currently ongoing for batteries of big dimensions. The draft international Standard IEC 62902, titled '*Secondary batteries: Marking symbols for identification of their chemistry*', is currently being discussed. If approved, this draft document may be the starting point for batteries with a volume of less than 900 cm^3, as in the case of personal computers.

Finally, we also discussed which type of information on the content of CRMs could be helpful to improve the recycling efficiency. The provision of information could include: the content of cobalt in batteries, the content and location of components containing rare earths (e.g. neodymium, dysprosium, praseodymium in HDD magnets), and the content and locations of palladium in PCBs. Having the knowledge of computer components containing CRMs (with detail of the composition) would facilitate their identification by operators during EoL processing. The provision of information on the content of CRMs could increase the efficiency in sorting relevant components, addressing them with proper recycling treatments and, ultimately, increase their recycling rates. It was recognised that, to be effective and easily verifiable, this provision of information requires a standardised format for such communication. Standards under development within the European Mandate M/543 could serve the purpose, such as the ones related to the 'use and recyclability of CRMs to the EU' and to the development of 'documentation and/or marking regarding information relating to material efficiency of the product'.

Concluding remark

Overall, this analysis identified precise possible actions for improving material-efficiency performances of the product group. Furthermore, it also aimed at further stimulating the discussions between industry and policymakers about industrial practices that will enable a circular economy, focusing in particular on waste prevention, durability, reuse, repair and recycling. Furthermore, already-available or under-development international standards relevant for material-efficiency practices were identified and discussed. Further discussions will set out whether and how these material-efficiency strategies can be implemented in practice, also considering their verifiability by third parties (e.g. market-surveillance authorities).

References

Accurec, 2016. Accurec — Interviews.

Accurec, 2015. 'Comparative study on li-ion battery recycling technologies', H2020 CloseWEEE project, unpublished.

AEA, 2010. Building on the eco-design directive, EuP group analysis (I) ENTR Lot 3 Sound and imaging equipment. Task 1-7 report, AEA/ED45386/Issue 1.

Aladeojebi, T. K., 2013. 'Planned obsolescence', International Journal of Scientific & Engineering Research, Vol. 4, pp. 1504-1508.

Andrae, A. S. G., 2016. 'Life-cycle assessment of consumer electronics: A review of methodological approaches', IEEE consumer electronics magazine, Vol. 5, pp. 51-60. (doi:10.1109/MCE.2015.2484639)

Andrae, A. S. G., Vaija, M. S., 2014. 'To which degree does sector specific standardization make life cycle assessments comparable? — The case of global warming potential of smartphones', Challenges, Vol. 5(2), pp. 409-429. (doi:10.3390/challe5020409)

Apple, 2016. Maximizing battery life and lifespan (http://www.apple.com/batteries/maximizing-performance/).

Ardente, F., Mathieux, F., 2014. 'Identification and assessment of product's measures to improve resource efficiency: the case-study of an energy using product', Journal of cleaner production, Vol. 83, pp. 126-141. (doi:10.1016/j.jclepro.2014.07.058)

Ardente, F., Mathieux, F., 2012a. Integration of resource efficiency and waste management criteria in European product policies - Second phase. Report n° 2: Application of the project's methods to three product groups. (doi:10.2788/75910)

Ardente, F., Mathieux, F., 2012b. Integration of resource efficiency and waste management criteria in European product policies — Second phase. Report n° 1. Analysis of durability. (doi:10.2788/72577)

Ardente, F., Mathieux, F., Talens Peiró, L., 2016. Revision of methods to assess material efficiency of energy related products and potential requirements. (doi:10.2788/517101)

Ardente, F., Mathieux, F., Talens Peirò, L., 2013. Environmental footprint and material efficiency support for product policy. Report on benefits and impacts/costs of options for different potential material efficiency requirements for electronic displays. (doi:10.2788/28569)

Arushanyan, Y., Ekener-Petersen, E., Finnveden, G., 2014. 'Lessons learned — Review of LCAs for ICT products and services'. Computers in industry, Vol. 65, pp. 211-234. (doi:10.1016/j.compind.2013.10.003)

ASUS, 2016. Progressive from every angle, touch and user experience (https://www.asus.com/Microsite/commercial/ASUSPRO/progressive.html).

Bangs, C., Meskers, C., Van Kerckhoven, T., 2016. 'Trends in electronic products — the canary in the urban mine?', Electronics Goes Green 2016+, IEEE.

Battery University, 2016 a. How to prolong lithium-based batteries (http://batteryuniversity.com/learn/article/how_to_prolong_lithium_based_batteries).

Battery University, 2016b. BU-205: Types of lithium-ion (http://batteryuniversity.com/learn/article/types_of_lithium_ion).

Berger, R., 2012. 'The lithium-ion battery value chain' International conference on energy and automotive technologies, Istanbul.

BIO by Deloitte, ICF-GHK and SERI 2015. Study on socioeconomic impacts of increased reparability.

Bio Intelligence Service, 2007. Preparatory studies for eco-design requirements of EuPs.

Bocken, N. M. P., de Pauw, I., Bakker, C., Grinten, B. van der, 2016. 'Product design and business model strategies for a circular economy', Journal of industrial and production engineering, Vol. 33, Iss. 5. (doi:10.1080/21681015.2016.1172124)

Bölling, K., 2016. Personal communication on 06.11.2016.

Bombardier, 2010. Marking of plastics, rubbers and thermoplastic elastomers.

Broussely, M., Biensan, P., Bonhomme, F., Blanchard, P., Herreyre, S., Nechev, K., Staniewicz, R.J., 2005. 'Main aging mechanisms in Li ion batteries', Journal of power sources, Vol. 146, Iss. 1-2, pp. 90-96. (doi:10.1016/j.jpowsour.2005.03.172)

Chancerel, P., Mahlitz, P., Chanson, C., Binnemans, P., Huisman, J., Guzman Brechu, M., Rotter, V.S., Nissen, N.F., Lang, K.-D., 2016. 'Stocks and flows of critical materials in batteries: data collection and data uses', Electronics Goes Green 2016+, IEEE.

Chancerel, P., Marwede, M., 2016. Feasibility study for setting-up reference values to support the calculation of recyclability/recoverability rates of electr(on)ic products. (doi:10.2788/901715)

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, Vol. 98, pp. 9-18.

Chancerel, P., Meskers, C. E. M., Hagelüken, C., Rotter, V. S., 2009. 'Assessment of precious metal flows during preprocessing of waste electrical and electronic equipment', Journal of industrial ecology, Vol. 13, pp. 791-810. (doi:10.1111/j.1530-9290.2009.00171.x)

Chancerel, P., Rotter, V. S., Ueberschaar, M., Marwede, M., Nissen, N. F., Lang, K. -D., 2013. 'Data availability and the need for research to localize, quantify and recycle critical metals in information technology, telecommunication and consumer equipment', Waste management and research, Vol. 31, pp. 3-16. (doi:10.1177/0734242X13499814)

Clemm, C., Mählitz, P., Schlösser, A., Rotter, V. S., Lang, K. -D., 2016. 'Umweltwirkungen von wiederaufladbaren Lithium-Batterien für den Einsatz in mobilen Endgeräten der Informations- und Kommunikationstechnik (IKT)', UBA, Texte 52/2016.

Consumentenbond, 2015. Laptopaccu's steeds lastiger zelf te vervangen (https://www.consumentenbond.nl/laptop/laptopaccu-steeds-lastiger-zelf-te-vervangen) (accessed 19.04.17).

Cucchietti, F., Giacomello, L., Griffa, G., Vaccarone, P., Tecchio, P., Bolla, R., Bruschi, R., D'Agostino, L., 2011. 'Environmental benefits of a universal mobile charger and energy-aware survey on current products' 2011 IEEE 33rd International telecommunications energy conference (INTELEC). IEEE, pp. 1-9. (doi:10.1109/INTLEC.2011.6099888)

Daoud, D., 2010. The business case for ruggedized PCs.

Dawson, R. B., Landry, S. D., 2005. 'Recyclability of flame retardant HIPSs, PC/ABS, and PPO/HIPS used in electrical and electronic equipment', Proceedings of the 2005 IEEE international symposium on electronics and the environment, 2005. IEEE, pp. 77-82. (doi:10.1109/ISEE.2005.1436998)

Defra, 2006. Battery waste management life cycle assessment, Department for Environment, Food and Rural affairs (Defra) (UK).

Deng, L., Williams, E.D., 2011. 'Functionality versus 'typical product' measures of technological progress', Journal of industrial ecology, Vol. 15, pp. 108-121. (doi:10.1111/j.1530-9290.2010.00306.x)

Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, 2016. Critical raw materials (https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en) (accessed 18.10.16).

Digitaleurope, 2017 a. The contribution of the digital industry to repair, refurbishment and remanufacturing in a circular economy.

Digitaleurope, 2017b. Industry reaction on CRM information requirements following the Dutch and German comments on the consultation forum on servers (LOT 9).

Digitaleurope, 2014. Trans-boundary movements of waste vs used goods 4.

Digitaleurope, 2013. Position paper on dismantling, indium declaration and recyclability for TVs and displays.

Dimitrova, G., 2012. Impact of innovations in electronic equipment and components on their reuse and recycling. University of Natural Resources and Life Sciences, Vienna.

Dodd, N., Vidal-Abarca Garrido, C., Gama Caldas, M., Graulich, K., Bunke, D., Groß, R., Liu, R., Manhart, A., Prakash, S., 2016. Revision of the EU green public procurement (GPP) criteria for computers and monitors — technical report — final criteria. (doi:10.2791/027791)

Dodd, N., Vidal-Abarca Garrido, C., Wolf, O., Graulich, K., Bunke, D., Groß, R., Liu, R., Manhart, A., Prakash, S., 2015. Revision of the European ecolabel criteria for personal, notebook and tablet computers. (doi:10.2791/780423)

Dodd, N., Wolf, O., Graulich, K., Groß, R., Liu, R., Manhart, A., Prakash, S., 2014. Development of European ecolabel and green public procurement criteria for personal and notebook computers, technical report task 1, scope and definitions.

Dupont, D., Binnemans, K., 2015. 'Recycling of rare earths from NdFeB magnets using a combined leaching/extraction system based on the acidity and thermomorphism of the ionic liquid [Hbet][Tf2N]', Green chemistry, Vol. 17, pp. 2150-2163. doi:10.1039/C5GC00155B

Dwivedy, M., Mittal, R.K., 2010. 'Future trends in computer waste generation in India', Waste Management, Vol. 30, pp. 2265-2277. (doi:10.1016/j.wasman.2010.06.025)

Ecoinvent, 2013. Ecoinvent database (http://www.ecoinvent.ch/) (accessed 23.4.15).

EERA, 2016. EERA position paper. Netherlands.

EGG 2016+, 2016. Electronics Goes Green 2016+ Closing session.

Ellen MacArthur Foundation, 2016. Empowering repair.

Elo, K., Karlsson, J., Lydebrant, K., Sundin, E., 2009. Automation of plastic recycling — A case study. Sapporo (Japan).

EN ISO 1043-1, 2002. Plastics. Symbols and abbreviated terms. Basic polymers and their special characteristics.

EN ISO 1043-4+A1:2016, 1999. Plastics. Symbols and abbreviated terms. Flame retardants.

EN TS 16524, 2013. Mechanical products. Methodology for reduction of environmental impacts in product design and development.

EuRIC, 2017. Position on eco-design for displays: resource efficiency requirements.

EuRIC, 2016 a. EuRIC concrete proposals ecodesign for WEEE.

EuRIC, 2016b. Call for concrete actions to implement Article 15 of the WEEE directive on information for treatment facilities.

European Commission, 2016. Commission Decision (EU) 2016/1371 of 10 August 2016 establishing the ecological criteria for the award of the EU Ecolabel for personal, notebook and tablet computers.

European Commission, 2015 a. COM(2015) 614 final. Communication from the Commission to the European Parliament, the Council, The European Economic and Social

Committee and the Committee of the Regions. Closing the loop — An EU action plan for the circular economy.

European Commission, 2015b. M/543 C(2015) 9096 Commission implementing decision of 17.12.2015 on a standardisation request to the European standardisation organisations as regards ecodesign requirements on material-efficiency aspects for energy-related products in support of the imp. doi:10.1017/CBO9781107415324.004

European Commission, 2014 a. Critical raw materials profiles. Report of the ad hoc working group on defining critical raw materials. http://bookshop.europa.eu/ No 388. doi:10.2779/1 482

European Commission, 2013. COM(2013) 123 final — Green paper on a European strategy on plastic waste in the environment. doi:COM(2013) 123 final.

European Commission, 2009. Press release IP/09/1049: Commission welcomes industry's commitment to provide a common charger for mobile phones (http://europa.eu/rapid/press-release_IP-09-1049_en.htm?locale=en) (accessed 29.07.16).

European Union, 2014. Commission Regulation (EU) No 1253/2014 of 7 July 2014 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for ventilation units. Official Journal of the European Union.

European Union, 2012. Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE).

European Union, 2011. Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011 — RoHS. Official Journal of the European Union. (doi:10.1017/CBO9781107415324.004)

European Union, 2008. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain directives. LexUriServ. (doi:2008/98/EC.; 32008L0098)

FINsix®, 2016. DARTTM The world's smallest laptop charger® (https://finsix.com/shop/dart/) (accessed 9.12.16).

Fisher, T., 2015. Data sanitization methods. A list of software based data sanitization methods.

Forsa, 2013. Meinungen zu Umweltaspekten bei Computern.

Gabriel, R., 2015. End-of-life scenarios created in WF-RepTool.

Goosey, M., Kellner, R., 2002. A scoping study end-of-life printed circuit boards.

Greenpeace, 2017. How repairable is your mobile device? A product guide to best-selling smartphones, tablets and laptops.

Grzesik-Wojtysiak, K., Kukliński, G., 2013. 'Screening life cycle assessment of a laptop used in Poland'. Environment protection engineering, Vol. 39 (3).

GSMA, 2009. Mobile's green manifesto.

Hand, C., 2013. Dealing with waste lithium batteries | Croner-i (https://app.croneri.co.uk/feature-articles/dealing-waste-lithium-batteries-0) (accessed 13.9.16).

Hennies, L., Stamminger, R., 2016. An empirical survey on the obsolescence of appliances in German households. Resources, conservation and recycling, Vol. 112, pp. 73-82. (doi:10.1016/j.resconrec.2016.04.013)

Hintermann, R., Fassnacht, C., 2008. Leitfaden zum Sicheren Datenlöschen.

Hischier, R., Wäger, P. A., 2015. 'The Transition from desktop computers to tablets: a model for increasing resource efficiency?' ICT Innovations for Sustainability.

Houlihan, K., 2013. A streamlined life cycle assessment of Mobile computing (laptop/slate). Report 20/11/2013.

HP, 2016. Product end-of-life disassembly instructions. HP ProDesk 600 G1 Desktop Mini PC. (http://www.hp.com/hpinfo/globalcitizenship/environment/productdata/Countries/_MultiCountry/disassembly_deskto_2014516234519169.pdf)

HP, 2015. Technical white paper testing the business ruggedness and reliability of HP business PCs.

HP Inc., n.d. HP notebook PCs — understanding lithium-ion and smart battery technology | HP® customer support (http://support.hp.com/us-en/document/c00596784#c00596784_warranty) (accessed 13.9.16).

Huisman, J., Botezatu, I., Herreras, L., Liddane, M., Hintsa, J., Luda di Cortemiglia, V., Leroy, P., Vermeersch, E., Mohanty, S., van den Brink, S., Ghenciu, B., Dimitrova, D., Nash, E., Shryane, T., Wieting, M., Kehoe, J., Baldé, C. P., Magalini, F., Zanasi, A., Ruini, F., Bonzio, A., 2015. Countering WEEE illegal trade summary report, market assessment, legal analysis, crime analysis and recommendations roadmap, Unu. Lyon, France. (doi:978-92-808-4560-0)

Huisman, J., van der Maesen, M., Eijsbouts, R. J. J., Baldé, C. P., Wielenga, C. A., 2012. The Dutch WEEE flows. Bonn, Germany.

IDC, 2016. Pay Now, save Later: The business case for rugged devices.

IDC, 2010. White paper — The business case for ruggedised PCs.

IEC, 2017. Area: 482: Primary and secondary cells and batteries (http://www.electropedia.org/iev/iev.nsf/index?openform&part=482).

IEC/TR 62635, 2015. IEC/TR 62635:2015 Guidelines for end-of-life information provided by manufacturers and recyclers and for recyclability rate calculation of electrical and electronic equipment.

IEC/TS 62700, 2014. IEC/TS 62700:2014 DC power supply for notebook computers.

IEC 62902 draft, 2017. International Electrotechnical Commission (2017) — 62902 Ed.1.0: Secondary batteries: Marking symbols for identification of their chemistry.

IEEE 1874, 2013. IEEE Standard for documentation schema for repair and assembly of electronic devices. (doi:10.1109/IEEESTD.2014.6712032)

IEEE Std 1823, 2015. IEEE Standard for universal power adapter for mobile devices.

Investing News, 2016. 6 types of lithium-ion batteries (http://investingnews.com/daily/resource-investing/energy-investing/lithium-investing/6-types-of-lithium-ion-batteries/)

ISO 11469, 2000. Plastics — Generic identification and marking of plastics products.

ITU-T L.1002, 2016. Recommendation ITU-T L.1002 External universal power adapter solutions for portable information and communication technology devices.

Kahhat, R., Poduri, S., Williams, E., 2011. Bill of Attributes (BOA) in life cycle modeling of laptop computers. White Paper #103.

Kasulaitis, B. V., Babbitt, C. W., Kahhat, R., Williams, E., Ryen, E. G., 2015. 'Evolving materials, attributes, and functionality in consumer electronics: Case study of laptop computers', Resources, conservation and recycling, Vol. 100, pp. 1-10. (doi:10.1016/j.resconrec.2015.03.014)

Knack, O., 2016. 5 common tablet PC defects and how to address them (http://www.globalsources.com/NEWS/SIC-5-common-tablet-pc-defects-and-how-to-address-them.htm) (accessed 16.9.16).

Krüger, A., 2016. Personal communication on 14.11.2016.

Kushnir, D., 2015. Lithium-ion battery recycling technology 2015 current state and future prospects. Gothenburg, Sweden.

Lenovo, 2016. Beyond mil-spec [WWW Document].

Malmodin, J., Lundén, D., Moberg, Å., Andersson, G., Nilsson, M., 2014. 'Life cycle assessment of ICT', Journal of industrial ecology, Vol. 18, pp. 829-845. (doi:10.1111/jiec.12145)

Mathieux, F., Froelich, D., Moszkowicz, P., 2008. 'ReSICLED: a new recovery-conscious design method for complex products based on a multicriteria assessment of the recoverability', Journal of cleaner production, Vol. 16, pp. 277-298. doi:10.1016/j.jclepro.2006.07.026

München, D.D., Veit, H.M., 2017. 'Neodymium as the main feature of permanent magnets from hard disk drives (HDDs)', Waste management, Vol. 61, pp. 372-376. (doi:10.1016/j.wasman.2017.01.032)

Nissen, N. F., Stobbe, L., Oerter, M., Scheiber, S., Schlösser, A., Schischke, K., Lang, K.-D., 2013. 'Design features of current tablet computers to facilitate disassembly and repair', Proceedings of the 8th Ecodesign 2013, Jeju, Korea.

Nnorom, I. C., Osibanjo, O., 2008. 'Overview of electronic waste (e-waste) management practices and legislations, and their poor applications in the developing countries', Resources, conservation and recycling, Vol. 52, pp. 843-858. (doi:10.1016/j.resconrec.2008.01.004)

Peeters, J. R., Vanegas, P., Tange, L., Van Houwelingen, J., Duflou, J. R., 2014. 'Closed loop recycling of plastics containing flame retardants'. Resources, conservation and recycling, Vol. 84, pp. 35-43. (doi:10.1016/j.resconrec.2013.12.006)

Peeters J. R., Tecchio P., Ardente F., Vanegas P., Coughlan D., Duflou J. 2018. eDIM: further development of the method to assess the ease of disassembly and reassembly of products - Application to notebook computers; EUR 28758 EN; doi:10.2760/864982

Polverini D., Ardente F., Sanchez I., Mathieux F., Tecchio P., Beslay L. Resource efficiency, privacy and security by design: a first experience on enterprise servers and data storage products triggered by a policy process. Computer and Security, 2017 (doi: https://doi.org/10.1016/j.cose.2017.12.001)

Powel, J., 2002. Large volumes of electronics scrap are shredded before recycling, and this booming trend has many new twists and turns.

Prakash, S., Dehoust, G., Gsell, M., Schleicher, T., Stamminger, R., 2016 a. Einfluss der Nutzungsdauer von Produkten auf ihre Umweltwirkung: Schaffung einer Informationsgrundlage und Entwicklung von Strategien gegen „Obsoleszenz', Öko-Institut eV. (doi:10.1017/CBO9781107415324.004)

Prakash, S., Dehoust, G., Gsell, M., Schleicher, T., Stamminger, R., 2016b. Einfluss der Nutzungsdauer von Produkten auf ihre Umweltwirkung: Schaffung einer Informationsgrundlage und Entwicklung von Strategien gegen „Obsoleszenz' (unpublished annex).

Prakash, S., Köhler, A., Liu, R., Stobbe, L., Proske, M., Schischke, K., 2016c. 'Paradigm shift in green IT — Extending the life — Times of computers in the public authorities in Germany', Electronics Goes Green 2016+, pp. 1-7.

Prakash, V., Sun, Z.H.., Sietsma, J., Yang, Y., 2014. 'Electrochemical recovery of rare earth elements from magnet scraps - a theoretical analysis', ERES2014: 1st European Rare Earth Resources Conference|Milos|04- 07/09/2014.

prEN 50614, 2016. Draft standard for comments (general, techncial, editorial) — draft developed by CLC/TC 111X-WK07 — Requirements for the preparation for reuse of waste electrical and electronic equipment.

Private communications, 2017. Private communications and interviews with repair operators, refurbishers and stakeholders.

Private communications, 2016. Private communications with stakeholders.

Rahimifard, S., Abu Bakar, M.S., Williams, D.J., 2009. 'Recycling process planning for the end-of-life management of waste from electrical and electronic equipment', CIRP Annals — Manufacturing technology. pp. 5-8. (doi:10.1016/j.cirp.2009.03.080)

RAL GmbH, 2013. Basic criteria for award of the environmental label, mobile phones, RAL-UZ 106.

Rasenack, K., Goldmann, D., 2014. 'Herausforderungen des Indium-Recyclings aus LCD-Bildschirmen und Lösungsansätze', Thomé-Kozmiensky, K.J., Goldmann, D. (Eds.), Recycling Und Rohstoffe, Band 7. VIVIS Verlag.

Recchioni, M., Ardente, F., Mathieux, F., 2016. Environmental footprint and material-efficiency support for product policy. Feasibility study for a standardised method to measure the time taken to extract certain parts from electrical and electronic equipment. European Commission, JRC, Institute for Environment and Sustainability, Ispra. (doi:10.2788/29866)

Ripperger, J., 2016. Personal communication on 28.10.2016.

Risk & Policy Analysts Limited, 2014. Study on the impact of the memorandum of understanding (mou) on harmonisation of chargers for mobile telephones and to assess possible future options.

Rotter, V. S., Flamme, S., Götze, R., Ueberschaar, M., 2012. 'Thermodynamische Herausforderung bei Recycling von Nebenmetallen', Thomé-Kozmiensky, K. J., Goldmann, D. (Eds.), Recycling Und Rohstoffe, Band 5. TK Verlag, Neuruppin.

RREUSE, 2013. Investigation into the repairability of domestic washing machines, dishwashers and fridges.

Samsung, 2015. Light, but Durable: Reliability Testing of Samsung Notebooks [WWW Document].

Sarkis, J., 2001. Greener manufacturing and operations. Greenleaf Publishing.

Sarre, G., Blanchard, P., Broussely, M., 2004. 'Ageing of lithium-ion batteries', Journal of power sources, Vol. 127, pp. 65-71. (doi:10.1016/j.jpowsour.2003.09.008)

SBS-IF, 1998. 'Smart battery specifications implementers forum: smart battery system specifications', Smart battery data specifications revision 1.1.

Schischke, K., Stobbe, L., Dimitrova, G., Scheiber, S., Oerter, M., Nowak, T., Schlösser, A., Riedel, H., Nissen, N. F., 2014. Disassembly analysis of slates: design for repair and recycling evaluation. Berlin, Germany.

Schischke, K., Stobbe, L., Scheiber, S., Oerter, M., Nowak, T., Schlösser, A., Riedel, H., Nissen, N. F., 2013. Disassembly analysis of slates: design for repair and recycling evaluation. Berlin, Germany.

Schmalstieg, J., Käbitz, S., Ecker, M., Sauer, D. U., 2014. 'A holistic ageing model for Li(NiMnCo)O2 based 18 650 lithium-ion batteries', Journal of power sources, Vol. 257, pp. 325-334. (doi:10.1016/j.jpowsour.2014.02.012)

Seagate, 2016. Seagate life cycle analyses & corporate sustainability (http://www.seagate.com/gb/en/global-citizenship/life-cycle-assessment/) (accessed 8.16.16).

Sommer, P., Rotter, V. S., Ueberschaar, M., 2015. 'Battery related cobalt and REE flows in WEEE treatment', Waste management. (doi:10.1016/j.wasman.2015.05.009)

Song, Q., Wang, Z., Li, J., Yuan, W., 2013. 'Life cycle assessment of desktop PCs in Macau', International journal of life cycle assessment, Vol. 18, pp. 553-566. (doi:10.1007/s11367-012-0515-7)

Sprecher, B., Kleijn, R., Kramer, G.J., 2014 a. 'Recycling potential of neodymium: the case of computer hard disk drives', Environmental science and technology, Vol. 48, pp. 9506-9513. (doi:10.1021/es501572z)

Sprecher, B., Xiao, Y., Walton, A., Speight, J., Harris, R., Kleijn, R., Visser, G., Kramer, G.J., 2014b. 'Life cycle inventory of the production of rare earths and the subsequent production of NdFeB rare earth permanent magnets', Environmental science and technology, Vol. 48, pp. 3951-3958. (doi:10.1021/es404596q)

SquareTrade, 2009. 1 in 3 Laptops fail over 3 years: Netbooks fail 20 % more than laptops; ASUS & Toshiba the most reliable [WWW Document].

Statista, 2016. Shipment forecast of laptops, desktop PCs and tablets worldwide from 2010 to 2019 (in million units) (http://www.statista.com/statistics/272595/global-shipments-forecast-for-tablets-laptops-and-desktop-pcs/) (accessed 16.8.16).

Stuhlpfarrer, P., Luidold, S., Antrekowitsch, H., 2015. 'Recycling of Nd2Fe14B-magnets', Proceedings of EMC 2015.

Talens Peiró, L., Ardente, F., 2015. Environmental footprint and material-efficiency support for product policy — Analysis of material-efficiency requirements of enterprise servers. (doi:10.2788/409022)

Talens Peiró, L., Ardente, F., Mathieux, F., 2016. Analysis of material-efficiency aspects of Energy-related Product for the development of EU Ecolabel criteria — Analysis of product groups: personal computers and electronic displays. (doi:10.2788/642541)

Tecchio, P., McAlister, C., Mathieux, F., Ardente, F., 2017. In search of standards to support circularity in product policies: a systematic approach. Journal of cleaner production, doi:http://dx.doi.org/10.1016/j.jclepro.2017.05.198

Teehan, P., Kandlikar, M., 2013. Comparing Embodied Greenhouse Gas Emissions of Modern Computing and Electronics Products. Environ. Sci. Technol. 47, 3997-4003. doi:10.1021/es303012r

The New York Times, 2016. Samsung to recall 2.5 million Galaxy Note 7 s over battery fires (http://www.nytimes.com/2016/09/03/business/samsung-galaxy-note-battery.html?_r=0)

Thiébaud -Müller, E., Hilty, L. M., Schluep, M., Widmer, R., Faulstich, M., 2017. 'Service lifetime, storage time, and disposal pathways of electronic equipment: a Swiss case study', Journal of industrial ecology. (doi:10.1111/jiec.12551)

USB Implementers Forum, 2016. Universal Serial Bus — USB type-CTM Cable and Connector Specification [WWW Document]. URL http://www.usb.org/developers/usbtypec/ (accessed 7.29.16).

Van Eygen, E., De Meester, S., Tran, H. P., Dewulf, J., 2016. 'Resource savings by urban mining: The case of desktop and laptop computers in Belgium', Resources, conservation and recycling, Vol. 107, pp. 53-64. (doi:10.1016/j.resconrec.2015.10.032)

Vanegas, P., Peeters, J., Cattrysse, D., Duflou, J., Tecchio, P., Mathieux, F., Ardente, F., 2016. Study for a method to assess the ease of disassembly of electrical and electronic equipment. Method development and application to a flat panel display case study. EUR 27921 EN. doi:10.2788/130925

Vanegas, P., Peeters, J.R., Cattrysse, D., Tecchio, P., Ardente, F., Mathieux, F., Dewulf, W., Duflou, J.R., 2017. 'Method to assess ease of disassembly for ecodesign and treatment cost evaluation', Resources, conservation and recycling. (doi:https://doi.org/10.1016/j.resconrec.2017.06.022)

Vannieuwenhuyse, T., 2016. Oral communication on 15.9.2016.

Vetter, J., Novák, P., Wagner, M. R., Veit, C., Möller, K.-C., Besenhard, J. O., Winter, M., Wohlfahrt-Mehrens, M., Vogler, C., Hammouche, A., 2005. 'Ageing mechanisms in lithium-ion batteries', Journal of power sources, Vol. 147, pp. 269-281. (doi:10.1016/j.jpowsour.2005.01.006)

Viegand Maagøe and VITO, 2017. Preparatory study on the Review of Regulation 617/2013 (Lot 3) — Computers and Computer Servers (draft report).

von Geibler, J., Ritthoff, M., Kuhndt, M., 2003. The environmental impacts of mobile computing — A case study with HP — Final report.

Wang, F., Huisman, J., Stevels, A., Baldé, C. P., 2013. 'Enhancing e-waste estimates: Improving data quality by multivariate input-output Analysis', Waste management Vol. 33, pp. 2397-2407. (doi:10.1016/j.wasman.2013.07.005)

Wang, X., Gaustad, G., Babbitt, C.W., Richa, K., 2014. 'Economies of scale for future lithium-ion battery recycling infrastructure', Resources, conservation and recycling Vol. 83, pp. 53-62. (doi:10.1016/j.resconrec.2013.11.009)

WEEE Forum, 2017. WEEE plastics and chemical, product and waste legislation. 5 July 2017 Draft.

Westpak, I., 2013. Slides used during a webinar on 'Product Reliability Testing: Environmental and Mechanical Requirements';

Wieser, H., Tröger, N., 2016. The use time and obsolescence of durable goods in the age of acceleration. An empirical investigation among Austrian households. AK Wien.

Yang, J., Lu, B., Xu, C., 2008. 'WEEE flow and mitigating measures in China', Waste management, Vol. 28, pp. 1589-1597. (doi:10.1016/j.wasman.2007.08.019)

Zakotnik, M., Devlin, E., Harris, I.R., Williams, A.J., 2006. 'Hydrogen decrepitation and recycling of NdFeB-type sintered magnets', Journal of iron and steel research, international, Vol. 13, pp. 289-295. (doi:10.1016/S1006-706X(08)60197-1)

Zhong, H., Schiller, S., 2011. 'Design of the expense allocation mechanism in e-waste recycling deposit system under EPR framework', ICSSSM11, pp. 1-6, IEEE. (doi:10.1109/ICSSSM.2011.5959352)

LB-NA-28394-EN-N

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Publications Office

doi:10.2788/89220

ISBN 978-92-79-64943-1