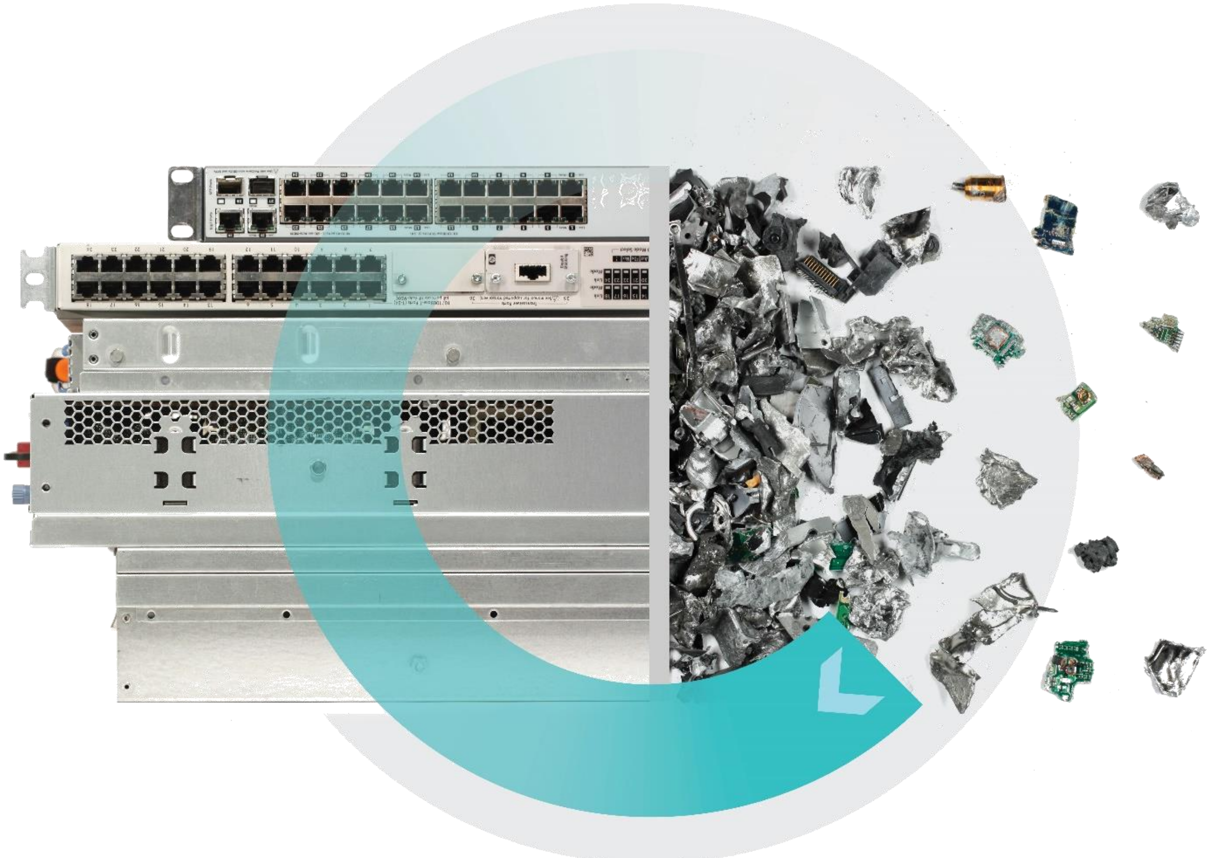
Circular Economy
for the Data Centre Industry

A SITUATIONAL ANALYSIS OF A CIRCULAR ECONOMY IN THE DATA CENTRE INDUSTRY



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ABSTRACT

The Data Centre Industry (DCI) is one of the most important pillars of current technological and economic developments. In 2017, DCs' global traffic data was 11.7 ZB and it is predicted to grow up to 20.6 ZB in 2021, from 1.1 ZB in 2010 [1]. In Europe, DCI is concentrated in North-West Europe, where more than 55% of DCs are located (Dodd et al., 2018, CloudScene, 2018).

DCs are buildings or rooms in buildings that house electronic and electrical equipment (EEE), a category of products that is reported to cause 1 to 4% of environmental impacts in Europe according to Labouze, Monier et Puyou. In this type of equipment, more than fifty different materials can be found per product, including ferrous, non-ferrous metals, precious metals (PM), platinum group metals (PGM), rare earth elements (REE), plastics and/or ceramics, and some are considered as Critical Raw Materials (CRMs) by the European Commission [5]. Currently, the CRMs recycling rate from Waste Electronic and Electrical Equipment (WEEE) is ~1% [6], in consequence, there is considerable room for improvement along the whole life cycle to increase the recovery of these materials.

This assessment aims to study the design and material composition of data centre equipment (specifically servers and switches (network equipment)), as well as to analyse their performance in a circular economy and their environmental performance to provide recommendations for ecodesign guidelines. First, the state of the art presents the current practices, trends and challenges in the DCI to achieve higher circularity. Then, end-of-life servers and switches were dismantled, and a motherboard was chemically characterised. A screening Life Cycle Assessment (LCA) including all the life cycle stages except the use phase is carried out to identify the environmental hotspots. Moreover, an economic assessment on a full dismantling business case has been done to assess the feasibility of the introduction of new stakeholders in charge of fully dismantling and distributing the waste streams to achieve higher material recoveries.

The assessment illustrates the urgent need to achieve higher material resource efficiency in DCI to ensure a secure supply chain of materials, especially CRMs. PCBs have been identified as the most environmentally impactful components of DC equipment and the ones with the highest economic and environmental benefits if recycled by take-back schemes. There is still large room for improvements in the design of equipment to allow higher material recoveries. Much more collaboration among stakeholders in DCI is needed to ease reuse, refurbishing and recycling of equipment. Given the high complexity of the electronics equipment supply chain, regulatory bodies should oversee encouraging best practices and banning actions that limit higher circularity.

Keywords: *Data Centre, Critical Raw Materials, Waste Electrical and Electronic Equipment, Dismantling, Life Cycle Assessment, Ecodesign.*

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INDEX OF ACRONYMS

Be	Beryllium
Co	Cobalt
CPU	Central Processing Unit
CRMs	Critical Raw Materials
DC	Data Centres
DCI	Data Centre Industry
ECM	Electronics Contract Manufacturers
EEE	Electronic and Electrical Equipment
EF	Environmental Footprint
EMS	Electronics Manufacturing Services
EU	European Union
FICT	Free ICT Europe Foundation
FLAP	Frankfurt London Amsterdam Paris
Ga	Gallium
GB	Gigabit
GDPR	General Data Protection Regulation
GPP	Green Public Procurement
GRI	Global Reporting Initiative
HDD	Hard Disk Drives
IaaS	Infrastructure as a Service
ICT	Information and Communication Technology
IED	Industrial Emissions Directive
In	Indium
IP	Internet Protocol
ISO	International Organization Standardization

ITU	International Telecommunication Union
JDM	Joint Design Manufacturer
JRC	Joint Researching Centre
LCA	Life Cycle Assessment
LCT	Life Cycle Thinking
Li	Lithium
LIB	Lithium-Ion Batteries
Mg	Magnesium
Mo	Molybdenum
MSP	Managed Service Providers
MW	Megawatt
Nb	Niobium
Ni	Nickel
NPIs	New Product Introductions
NPV	Net Present Value
NWE	North West Europe
OCP	Open Compute Project
ODD	Optical Disc Drives
ODM	Original Design Manufacturer
OEM	Original Equipment Manufacturers
PaaS	Platform as a Service
Pb	Palladium
PCB	Printed Circuit Board
PDU	Power Distribution Units
PEF	Product Environmental Footprint
PGE	platinum-group elements
PGM	Platinum Group Metals

PM	Precious Metals
Pt	Platinum
PSU	Power Generation Units
R&D	Research & Development
REE	Rare Earths
RoR	Rate of Return
SDD	Solid-State Drives
SaaS	Software as a service
Sb	Antimony
Si	Silicon metal
SV	Server
Ta	Tantalum
Te	Tellurium
UPS	Uninterruptible Power Supply
W	tungsten
WEEE	Waste Electronic and Electrical Equipment
ZB	Zettabit

INTRODUCTION NOTE

The Data Centre Industry (DCI) is one of the most important pillars of the current technological and economic developments. The activities of this sector started in the middle 1950s and it has experienced a large evolution during the last 70 years. In 2017, DCs' global traffic data was 11.7 ZB and it is predicted to grow up to 20.6 ZB in 2021, from 1.1 ZB in 2010 [1].

The optimization of DCI is a matter of high importance due to the fast evolution of the industry. These facilities consume large amounts of energy to provide uninterrupted service. To keep the business sustainable, stakeholders have tried to optimise their processes to save resources, energy and to minimise the costs. Although important improvements are implemented to optimise the energy consumption of DCs, resource efficiency, circular economy and resource sustainability are not considered in these current developments. Increase in resource demand raises concerns over their availability. In recent years, national and international institutions have targeted sustainable resource supply and new economy models (e.g. circular economy, etc.) as a goal of their short- and long-term strategies [7]. The role of stakeholders all along the value chain is crucial to implement these new concepts.

DCs are formed by EEE within the category of Information and Communication Technology (ICT). This category of products needs to be optimised in terms of sustainability, given that it is reported to cause 1 to 4% of environmental impacts in Europe according to Labouze, Monier et Puyou in 2003 [4]. In this type of equipment, more than fifty different materials can be found per product, including ferrous, non-ferrous metals, PM, PGM, REE, plastics and ceramics, and some are considered as CRMs by the European Commission [5].

Currently, the recovery of CRM from WEEE in Europe is less than 1% and the collection rate is estimated to be lower than 30% [6]. The complexity of these products makes the application of a circular economy more difficult. Given the high value and complex recovery of the CRM, a circular economy should involve adherence to the waste hierarchy (see Figure 1 below). When a product is no longer reusable, waste products should be used as a resource for future products. However, WEEE is one of the most complex groups of waste to be managed in this context.

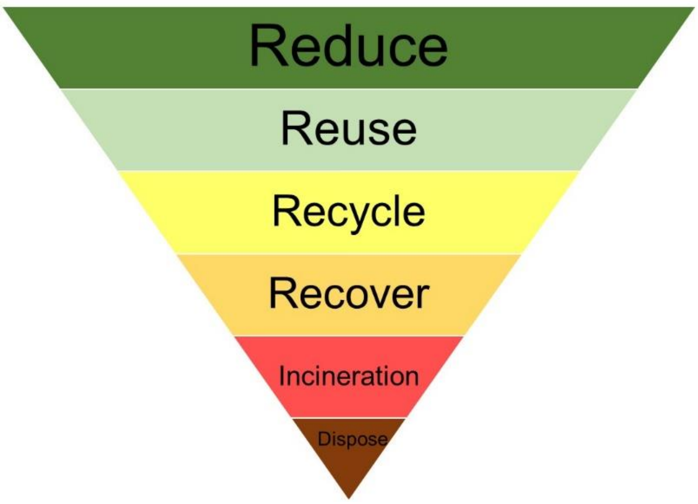

Figure 1: Waste Hierarchy Diagram

Municipal waste management systems are not suitable for handling WEEE which also contains toxic and hazardous materials. An appropriate management system based on a *Product-Centric* approach, instead of a *Material-Centric* approach, considering all the complexities of electronic products, would allow recovery of the valuable materials and avoid damage to the environment and people. Nowadays part of the materials in WEEE are lost at the end-of-life, including some valuable materials or CRM [8], which are defined as critical according to their economic importance and supply risk in a European perspective [5]. Other materials may be lost as products at the end-of-life do not enter an appropriate recycling chain. In consequence, a circular economy strategy for EEE considering a life cycle approach needs to be implemented and optimised [9]. The approach must start from the design phase, which presents 80-90% of the influence in end-of-life processes [10].

Energy efficiency in the use of the equipment will not be studied given that it has been the focus of designers and researchers for many years, and the optimisation of the energy use is already widely standardised by experts, for example, Yang Luo et al. 2019 [11] and Qingyuan Zhou et al. 2019 [12]. Subsequently, a screening LCA approach would be applied to identify hotspots and provide ecodesign recommendations for the reintroduction of CRM in the loop, trying to decrease the dependence on non-EU imports. Therefore, this study is devoted to improving the strategies recommended by the Joint Research Centre (JRC) [2] to develop the end-of-life and design for dismantling (regarding reuse, refurbishment, recycling).

Table 1. CRMs commonly used in IT equipment

CRM	Applications in IT equipment
Antimony	Micro capacitors
Beryllium	High power transistors
Cobalt	Lithium-ion batteries (LIBs)
Gallium	Integrated circuits
Germanium	LEDs
Indium	Semiconductors, Pb-free welding, screens
Magnesium	Aluminium alloys
Natural graphite	Heat transfer
Niobium	Micro capacitors
PGMs	Connectors, capacitors, HDDs
REE – including neodymium	Magnets
Silicon metal	Semiconductors
Tantalum	Micro capacitors
Tungsten	Integrated circuits

Life Cycle Thinking (LCT) approaches are used by stakeholders to study the environmental, societal and economic performance of products and services to minimize both cost and environmental footprint and increase social benefits. In this way, it is possible to identify hotspots and gaps in the processes and find solutions by implementing ecodesign methods. The main environmental hotspots in the value chain of DCs are related to the electricity consumed (the mix and the electricity used by the equipment) in the use phase of the data centre [13]. Several actions have been made to optimise DCs energy efficiency (e.g.: standards, eco-labels, JRC technical reports on Best Practice guidelines, Ecodesign Directive, etc.). On the other hand, efficient use of resources is a key step to achieving sustainability, especially regarding the high economic and societal aspects related to IT equipment and CRMs. Achieving an efficient circular economy in the DCI would help to minimise these impacts and create a secure supply chain for materials. Identifying the actors and the current practices along the supply chain is crucial to minimise the overall impacts. Although there are examples of screening LCAs of data centres, (e.g. Whitehead et al, 2015) exhaustive LCA of data centres are not yet available in literature due to the complexity of the equipment and the lack of data regarding some elements of what the materials are made of.

In the following sections, the state of the art of DCs is introduced, focusing on resource efficiency and CRMs. Subsequently, a report of dismantling and material characterisation of DC equipment and a screening LCA in DCI, with special focus on North West Europe (NEW) are presented.

1. STATE OF THE ART FOR DATA CENTRES' CIRCULAR ECONOMY

In the following sections, the state of the art of data centres sustainability is presented regarding further improvements and possibilities for closing the loop between designers and end-of-life actors to establish a more circular economy.

1.1. Data server's Life Cycle/stakeholders

Data server's life cycle can be schematized according to Figure 2. There is already an established circular thinking system, where the equipment is repaired and recycled, but there is a lack of efficiency due to different interests and approaches of stakeholders along the different life cycle stages. Besides, the waste generated in DCI is mainly electronic waste, which presents particular difficulties in the recycling process, resulting in large losses of some elements where concentration is not high enough to be economically interesting to develop a recycling process even though, many of these elements are considered as CRMs in Europe. In consequence, an effective and complete circular economy system is not being applied and further improvements must take place to ensure higher sustainability in DCs' supply chain. The first step to achieve this circular economy is to know the precise composition of the equipment and the availability (lifespan of equipment, location and amount) of end-of-life equipment generated by DCI. This information is not easily accessible to designers or manufacturers, but it is fundamental to know before establishing the best end-of-life strategy.

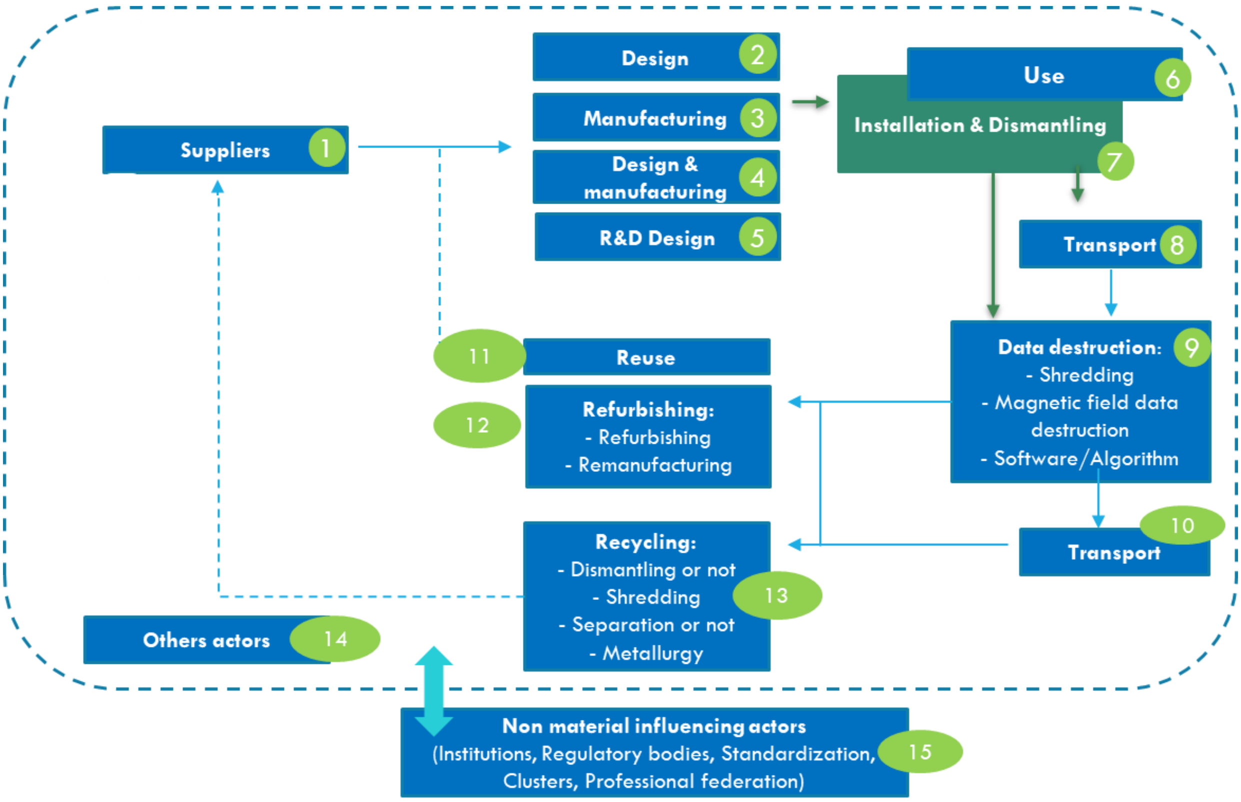

Figure 2. DC's life cycle

The DCI presents complexities and difficulties in tracing the supply chain. Some actors can carry out different activities and participate in different life cycle stages. Regarding materials sourcing and design of equipment, they can sub-contract multiple companies. In Figure 2, suppliers refers to the equipment suppliers (such as hard disk drives or servers). Manufacturing includes the assembly of components to obtain, for example, a data server or a switch. Non-material actors influencing the data centre supply chain must also be considered, and examples include regulatory bodies, associations or non-profit organisations.

1.1.1. Design and manufacturing

Design and manufacturing business models have been developed since the introduction of data centres to the point that nowadays, both stages are carried out by different companies.

The various established design and manufacturing business models are now described. There are two major groups of electronics hardware manufacturers – OEM (Original Equipment Manufacturers) and Contract Electronics Solutions Providers, who often subcontract with each other to provide solutions for the same OEM.

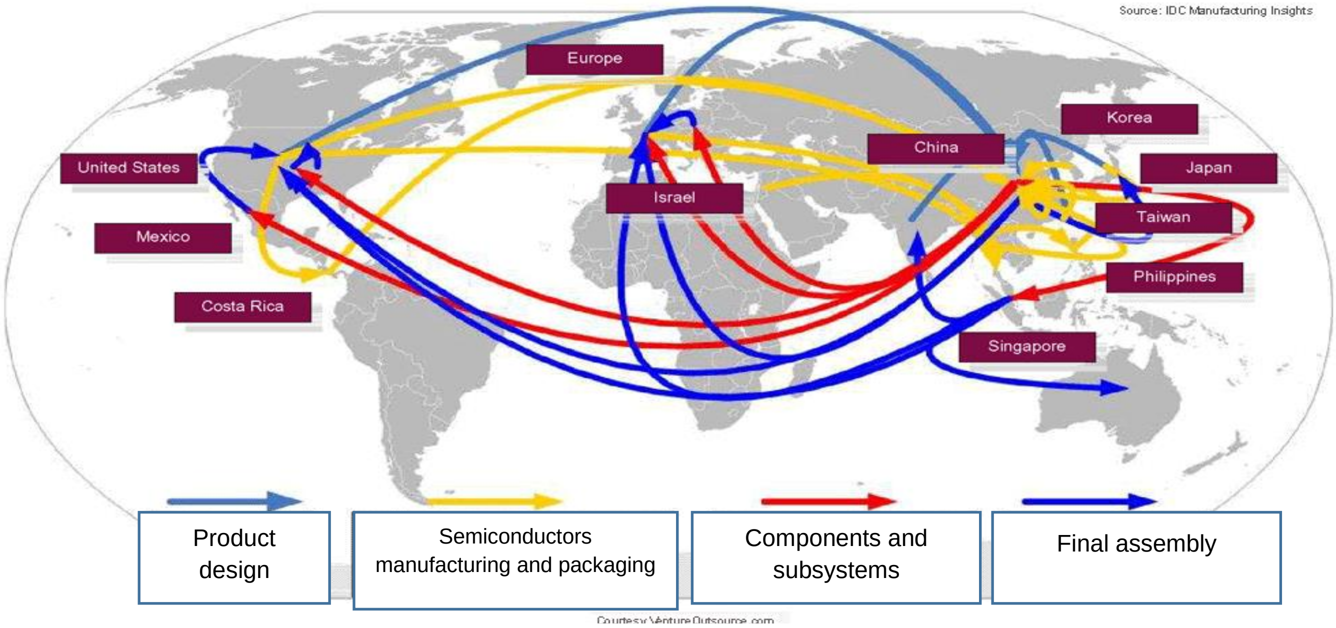

Figure 3. The global value chain for the electronics industry (source: ventureoutsource.com)

I. OEM – Original Equipment Manufacturer

OEM are companies that design and build a product according to their specifications. Their brands and logos are displayed on final products (e.g. Cisco, Dell or Lenovo.). Several OEM companies dominate the branded data centre equipment/server market, namely Dell, HPE, IBM, Cisco and Lenovo but there is increasing competition from unbranded 'white boxes' supplied by ODMs (original design manufacturers), that are comparable to branded products but less expensive. Some brands design their products in-house and others out-source this service; in the data centre electronics sector most brands sub-contract other services because it is more economical than paying for land and factory overheads, purchase and deployment of manufacturing and test equipment, staff hiring and training, etc. The services are coordinated in-house and by external Electronics Solutions Providers who manage component vendors and suppliers across the supply chain.

II. Contract Electronics Solutions Providers (CESP)

These companies (providers of solutions) contract their electronics services solutions to OEM customers (and other solutions providers) to bring OEM customer products to market. Some contract electronics solutions providers only offer their services to OEMs who have the product in certain end markets, such as medical and healthcare, industrial electronics, consumer wearables, automotive and data centres. Business models include:

III. <u>Design houses / Electronics design houses</u>

Focus on electronics design but some companies also offer electrical design services and/or hardware and firmware design services across a variety of product markets. Design houses generally offer R&D services, which may be specialist (e.g. embedded systems). Electronics design is profitable and competitive and is accelerating new product introductions (NPIs) as companies try to increase value to maintain relevance and competitiveness.

IV. <u>Electronics Manufacturing Services (EMS)</u>

They have evolved and include services in addition to core manufacturing. Some companies offer design manufacturing services; the various business models include:

a. Contract manufacturers

They present a generic term for manufacturers that formally outsource production manufacturing/buy-in components and/or products to complete their products.

b. Electronics contract manufacturers (ECM)

Mainly, they specialise in manufacturing electronics products.

c. Original Design Manufacturer (ODM)

A company that designs and manufactures a product as specified by another company. Until 2005 the term was only used for Taiwan-based companies, but it now applies to companies in many countries that offer EMS. An ODM will produce unbranded products for clients who rebrand them for local or export sale. The model has proved economically beneficial for big brands who can benefit from lower local labour and transport costs, proximity to markets and key mineral and metal resources. ‘Foreign’ companies/brands can also benefit from this model when local laws prohibit their direct ownership of assets. ODMs also innovate, develop and patent technologies which can contribute to and support (big) brand competitiveness. Compal Electronics is a very successful Taiwanese ODM that mass produces notebook computers and monitors for numerous branded companies. In 2011, for example, Compal Electronics and other Taiwanese ODMs produced 94% of all notebook computers.

ODM white label and private label: white label goods are non-label generic products designed, manufactured and distributed to various outlets/ retailers, who sell the products under their own logo/brand name. Private label goods are not generic and are produced for specific retailers.

d. Joint Design Manufacturer (JDM)

In this model OEM and contractors collaborate in the design process; ownership of internet protocol (IP) is shared although the percentage will vary according to the level of design, design feature/functionality contributed by each partner and the volume of products taken to market. Like ODM, JDM also offers manufacturing services.

1.1.2. Server design

Server design tends to focus on exterior casing, modularity of internal components and user interface while engineering design focuses on electronics. Changes in product design are often stylistic and incremental because rack servers are designed to fit into racks and blade servers are designed to fit into a chassis (and save space). Consequently, major changes would also require changes in the rack and/or chassis design and configuration, which is limited because rack and server design are inter-related. A rack may only match one type or brand of server and changes to server chassis (housing/casing) design tend to be incremental and stylistic rather than functional. Most mainstream R&D relates to electronics and computing technology.

1.1.3. Server producers

Anecdotal evidence shows that servers are produced in Europe. However, most companies assemble components produced by CEMs, ODMs or OEMs in Asia. Consequently, server manufacturers are better described as 'vendors' or as 'configuration' businesses (i.e. they assemble components to meet clients' requirements) and/or they assemble stock items.

1.1.4. Server manufacturers/vendors

These actors develop the assembly, installation of software and run tests. Table 2 shows the market share of the various server manufacturers/vendors in 2018 and the end of 2017. Figure 4 shows ODM Direct and Others (approx. 57%) contribution to the market was greater than the combined share of the branded producers (Dell, IBM, HPE, Inspur and Lenovo). The percentage of servers sold by branded producers has decreased since 2010, in favour of ODMs. This fact leads to an increasingly difficult to track and audit supply chains. In consequence, the influence on the design is also lower.

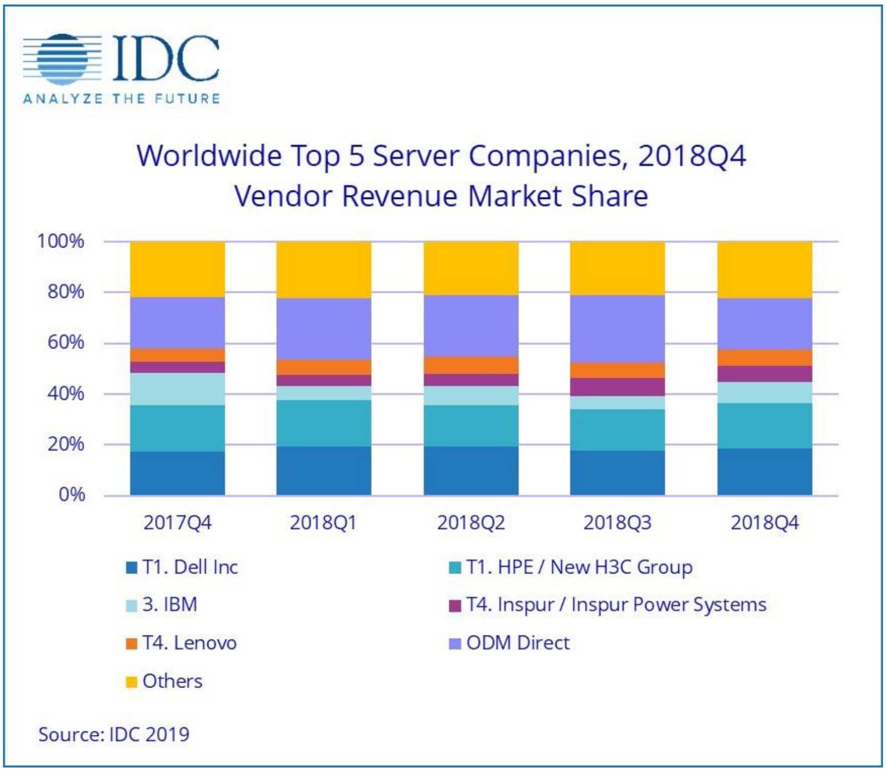

Figure 4. Market share for enterprise servers in 2018 and Q4 2017 [14]

Table 2. Revenue and growth of server vendors in 2018 (IDC Worldwide Quarterly Server Tracker, March 6, 2019).

Top 5 Companies, Worldwide Server Vendor Revenue, Market Share, and Growth, Fourth Quarter of 2018 *(Revenues are in US$ Millions)*					
Company	**4Q18 Revenue**	**4Q18 Market Share**	**4Q17 Revenue**	**4Q17 Market Share**	**4Q18/4Q17 Revenue Growth**
T1. Dell Inc.[1]	$4,426.2	18.7%	$3,677.2	17.5%	20.4%
T1. HPE/New H3C Group[4,2]	$4,199.8	17.8%	$3,801.9	18.1%	10.5%
3. IBM[3]	$1,951.0	8.3%	$2,652.9	12.8%	-27.6%
T4. Inspur/ Inspur Power Systems[4,4]	$1,548.8	6.6%	$907.2	4.3%	70.7%
T4. Lenovo	$1,458.7	6.2%	$1,090.0	5.2%	33.8%
ODM Direct	$4,736.2	20.1%	$4,245.4	20.2%	11.6%
Rest of Market	$5,294.3	22.4%	$4,566.1	21.8%	15.9%
Total	**$23,615.0**	**100%**	**$20,980.7**	**100%**	**12.6%**

The following chart shows the evolution of the market share in 2018 compared to the end of 2017 in terms of unit shipments.

Table 3. Server unit shipments and growth in 2018 (IDC Worldwide Quarterly Server Tracker, March 6, 2019)

Top 5 Companies, Worldwide Server Unit Shipments, Market Share, and Growth, Fourth Quarter of 2018 *(Shipments in thousands)*					
Company	**4Q18 Unit Shipments**	**4Q18 Market Share**	**4Q17 Unit Shipments**	**4Q17 Market Share**	**4Q18/4Q17 Unit Growth**
1. Dell Inc.	580.6	19.4%	582.5	20.4%	-0.3%
2. HPE/New H3C	473.8	15.8%	483.7	17.0%	-2.0%
3. Inspur/ Inspur Power Systems	247.6	8.3%	182.4	6.4%	35.7%

[1] IDC declares a statistical tie in the worldwide server market when there is a difference of one percent or less in the share of revenues or shipments among two or more vendors.

[2] Due to the existing joint venture between HPE and the New H3C Group, IDC will be reporting external market share on a global level for HPE and New H3C Group as "HPE/New H3C Group" starting from Q2 2016.

[3] IBM server revenue excludes sales of Power Systems generated through Inspur Power Systems in China starting from Q3 2018.

[4] Due to the existing joint venture between HPE and the New H3C Group, IDC will be reporting external market share on a global level for HPE and New H3C Group as "HPE/New H3C Group" starting from Q2 2016.

T4. Huawei	211.6	7.1%	166.4	5.8%	27.2%
T4. Lenovo	190.7	6.4%	181.6	6.4%	5.0%
ODM Direct	695.9	23.3%	653.0	22.9%	6.6%
Rest of the market	592.8	19.8%	602.1	21.1%	-1.5%
Total	**2,993.0**	**100%**	**2,851.6**	**100%**	**5.0%**

1.1.5. Installation and dismantling

This phase has been optimised where a modular approach was adopted by manufacturers of DC equipment. DCs are used in critical applications such as healthcare, finance, governments or the army. Installing and removing rapidly the equipment in case of failure is demanded by operators. Servers, switches, storage equipment and batteries (from power generation) present high modularity and the ease of dismantling and installing these components are well developed, given their short lifespan (see Table 11).

The Open Compute Project (OCP) illustrates this modularity with the Modular Data Centre Sub-Project. This sub-project aims to design and use modular solutions optimised for OCP hardware, as well as to improve the speed of data centre deployment, to reduce the environmental impact in data centre construction and to improve data centre efficiency in both power and cooling.

1.1.6. Refurbishing and Reuse

Once removed, DC equipment is tested to identify whether it still functions. Products can be directly reused as “equivalent to new” or they can be dismantled, and the up-to-date parts are ‘harvested’ and sold to spare parts providers or reused internally. They can be used to build equipment of equal or lower technological profile. Non-operating components can be refurbished or remanufactured (see section 1.6.1) if it is required or/and profitable. Unusable parts are sent to recyclers, where they are treated to recover the metals, incinerated with or without energy recovery, or landfilled.

Some electronic components from data centres are frequently reused; these include Hard Disk Drives (HDD) and memory cards where reuse rates are >40%, while Central Processing Units (CPU) (5.2%), motherboards (2.7%) and Power Supply Units (PSU) are reused less frequently due to the fast development of new technologies, which often optimises energy efficiency and increases the storage capacity. After each reuse cycle, HDDs and memory cards must go through the data sanitation phase [15].

Table 4. Reuse rate and reusability index of data server components [15]***.***

Component	Reuse rate (%)	Reusability in mass (%)	Component	Reuse rate (%)	Reusability in mass (%)
HDD	47.7	6.3	**Motherboard**	2.7	6.0
Memory cards	40.1	0.5	**Raid card**	2.1	0.02
CPUs	5.2	0.2	**Chassis**	1.4	48.4
PSUs	5.0	12.3	**Expansion cards**	0.7	1.3

1.1.7. End-of-life of DC equipment

When servers, network equipment and storage devices, reach the end-of-life phase, they are classified in the category of IT (information and telecommunications equipment) according to the WEEE Directive 2012. Since 2018, the equipment is classified as category 4 (Large equipment: any dimension larger than 50cm) or 6 (Small IT and telecommunication equipment) in the case of switches or data storage equipment, depending on the size.

Data centres are one of the main providers of IT e-waste due to their interrupted activity and the high rates of equipment replacement. The availability and volume of e-waste mean that there is potential for ambitious and profitable business models and practice to reduce waste and recycle and reclaim materials.

Data at European level and member state level regarding category III waste (from WEEE Directive 2012) in 2016 are shown in Table 5 below. They cannot be considered as a proxy for data server waste, but it can be assumed that they follow the same or similar trends. In consequence, these data, together with the number of data centres in each region, can give an approximate idea of whether specific recycling strategies for data centres could be managed in NWE or not.

Table 5: 2016 WEEE category III statistics in France, UK, Germany Netherlands and Europe-28[16]

	WEEE category III, IT & telecommunications equipment in 2016					
	Collected		Reused and recycled		Waste treatment	
Country	**Quantity (kt)**	**Europe share**	**Quantity (kt)**	**Europe share**	**Quantity (kt)**	**Europe share**
UK	159	23.77%	132	23.70%	147	23.71%
France	94	14.05%	77	13.82%	94	15.16%
Germany	115	17.19%	100	17.9%	115	18.55%
Netherlands	28	4.19%	22	3.95%	27	4.35%
EU-28	669		557		620	

Countries from FLAP (Frankfurt, London, Amsterdam and Paris) market collect more than 55% of category III e-waste in Europe, more than 300kt per year (expected to increase).

Specific data for DCI in the Netherlands is available in GreenIT Report: *Circular Data Servers,* where it is estimated that more than 184k server units are scrapped every year in Amsterdam alone and only 11% are refurbished, 24% recycled and the remaining portion is exported out of Netherlands. From the recycled fraction, it was estimated that 81% of the materials are recovered, while 15% is valorised (incineration with energy recovery or using residues as insulation) and only 4% is lost in the process. The export of data servers for reuse is estimated to be >50%.

1.1.8. Other non-material influencing actors

Some influential stakeholders in the data centre's life cycle are non-material influencing actors. They are responsible for developing the regulations and standards used by the rest of the stakeholders. The entities involved in standardisation include government organisations (Codex, IMO, UN/ECE), international and national standardisation bodies (e.g. ISO and AFNOR), industry consortia (The Green Grid, Ecova Plug Load Solutions) and European standardisation organisations, such as CEN and CENELEC.

I. CEN and CENELEC

These organisations develop standards in Europe regarding telecommunications and electrotechnical. Their international equivalents are ISO and IEC.

In March 2019, CEN and CENELEC developed two standards to facilitate communication of CRMs content in energy-related products.

II. International Telecommunication Union (ITU)

This international organisation aims to standardise practices regarding IT equipment. Several standards consider the circular economy and e-waste to achieve long-term sustainability ambitions. The ITU-T L1XXX standards are focused on e-waste management and recycling of rare metals products, providing guidelines to communicate the rare metals content and general recommendations and suggestions on the management of end-of-life products to increase the efficiency of the circular economy.

1.1.9. Case study: Dell supply chain

A Dell case study was chosen to assess the data servers supply chain. Their providers can be found online [17] together with the sustainability report [18], which complies with GRI (Global Reporting Initiative) sustainability standards. It can be found the final assembly locations, ODMs and other direct material suppliers.

Dell-branded servers are produced by ODMs / assembled in India, Poland, Malaysia and China by Dell; in China and Mexico by Foxconn; and in China by Mitac and Wistron. PCBs are made in China by Dell (see Annex 1). However, it is not possible to identify server component suppliers from this list. It is likely to find numerous subcontracted suppliers of the different components.

1.2. Policy in Europe

The main policies regarding data centres in Europe affect specific stakeholders in the DC supply chain. The most extensive efforts to include waste electronic and electrical equipment (WEEE) (including IT equipment from DCs) management in policies have been made in Europe and these regulations are used as examples for other regions. In consequence, manufacturers located in Asia or America also need to fulfil the European regulations if their products are imported in Europe. Official non-European institutions also develop standards and regulations that conform to the European examples;

Table 6: Regulation in Europe regarding sustainability in DCs

EU regulation / directive	Year of the last update	Influenced actors in DCI	Main considerations
WEEE Directive	2018	Suppliers, Manufacturers, Waste managers	Producer responsibility. Eco-design. Collection, sorting and preparation for treatment.
RoHS Directive	2011	Suppliers, Designers,	Prevention of risks, manufacturing obligations, management of hazardous substances containing components.
Battery Directive	2006	Suppliers, Manufacturers, Waste managers	Management of all type of batteries

Regulation (EC) No 1013/2006 and Commission Regulation (EC) No 1418/2007 of 29 November 2007	2007	Transport	Export of waste across EU members borders.
GDPR	2018	Users	GDPR replaces member states regulations homogenising regulation of personal data in Europe. Data security must be reported. It covers all data centres storing data from European citizens.
ETS Phase III	2013	Suppliers, Designers, R&D, Manufacturers and Users	Reduce carbon emissions of data centres with a capacity above 7MW.
Ecodesign Directive: LOT 9	2016	Suppliers, Designers, R&D, Manufacturers and Users	Requirements at the design stage to set minimum efficiency standards. Compilation of standards.
MCPD: Medium Combustion Plant Directive	2015	Suppliers, Designers, R&D, Manufacturers and Users	Air quality requirement for generators >1MWth and <50MWth
IED – Industrial Emissions Directive	2010	Suppliers, Designers, R&D, Manufacturers and Users	Industrial emissions to air, water and land for operators with generating capacity above 15 MW
NIS - Network and Information Security Directive	2015	Users	Management of cyber incidents
BEMP – Best Environmental Management Practices	2015	Manufacturers, Designers, Waste managers	Guideline to complement EconoManagement and Audit Scheme.

I. WEEE Directive (2012/19/EU) & RoHS

These directives consider electrical and electronic equipment to minimize the impacts of these products in all their life cycle stages, avoiding and limiting the number of toxic elements (RoHS).

The extended producer responsibility is introduced in WEEE Directive to create the link between manufacture and the end-of-life of electronic products and allocate the responsibility among different stakeholders (mainly producers, importers and end-of-life managers). The extended producer responsibility is included in the final price to cover the costs of end-of-life management.

The WEEE Directive sets the end-of-life management targets and obligations. Depollution of the waste is mandatory. Different components must be removed before treatment, including external cables, printed circuit boards (PCB) and batteries. E-waste is classified in different categories (until August 2018 there were 10, currently there are 6) to harmonise the data collection and tracing of the waste. DC end-of-life equipment is included in category IV (large equipment with any external dimension more than 50 cm), V (small equipment with no external dimension more than 50 cm) or VI (small IT and telecommunication equipment with external dimensions under 50 cm).

II. Report on Critical Raw Materials and the Circular Economy

The European Union defined 27 materials as CRMs under the economic importance and supply risk criteria [19]. These materials are particularly important for high-tech products and emerging innovations relevant for the energy transition and our zero-carbon economies such as solar panels, electric vehicles and their batteries or wind turbines. CRMs present crucial functions in EEE, and, in consequence, in DCs (see Table 14).

Table 7 CRMs defined by EU in 2018.

Critical Raw Materials (CRMs)			
Antimony	Fluorspar	LREEs*	Phosphorus
Baryte	Gallium	Magnesium	Scandium
Beryllium	Germanium	Natural graphite	Silicon metal
Bismuth	Hafnium	Natural rubber	Tantalum
Borate	Helium	Niobium	Tungsten
Cobalt	HREEs	PGMs	Vanadium
Coking coal	Indium	Phosphate rock	

* Light Rare Earth Elements

Given that EU DC industry is dominated, creating a secure supply chain for these materials is crucial for the wealth of European Industries [5].

III. General Data Protection Regulation (GDPR)

The new EU General Data Protection Regulation [20] was implemented in May 2018. It replaces the previous Directive to harmonise data privacy regulations across Europe and protect EU citizens' data privacy. The regulation is applied to all the personal data of EU citizens regardless of the company location, including data stored in DCs. It is mandatory to document all the data processing activities, including data leaks. The data subject has the right to ask the controller and third parties' processors to erase his/her personal data, defining personal data as any information relating to an identifiable person who can be directly or indirectly identified by reference to an identifier. Also, the privacy of data must be addressed from the design stage of the systems and facilities.

The data sanitisation life cycle stage is affected by this regulation given that companies must report carefully where the data are found. Besides, the penalties due to failure under the GDPR can get up to 4% of the annual turnover or 20M€ maximum.

IV. Other regulations in Europe

Other regulations support the optimisation of energy efficiency for the data centre to minimise emissions (MCPD: Medium Combustion Plant Directive, 2015 or IED – Industrial Emissions Directive, 2010) or recommending the extension of the lifetime for products (European Parliament resolution of 4 July 2017 on a longer lifetime for products: benefits for consumers and companies (2016/2272(INI)).

1.2.1. Standards

The Data centre industry follows standards regarding the sustainability and the efficiency of the system. Most standards are expensive for small and medium companies, limiting their access and use.

All the phases of the life cycle are considered by different standards. The use of firmware and CRMs are the main gaps not covered by standards used in the industry which makes the end-of-life strategy and the circular economy system more difficult to develop.

The standards concerning DCI compiled by JRC are shown in Table 8. The consideration of circular economy aspects and material resource efficiency is included in the International Electrotechnical Commission technical report IEC TR 62635:2012 and the UK's first standard for the treatment process of WEEE and reuse of EEE.

I. PAS 141:2011

This British standard was developed by industry experts. It aims to provide guidelines to manage WEEE. In this way, the generation of waste can be reduced by reuse and the waste can be properly treated by recycling and recovery, decreasing the amount of waste sent to landfill. It also aims to fight illegal exports and encourage job creation in organisations involved in preparing WEEE for reuse.

II. IEC TR 62635:2012

This standard provides a methodology for information exchange among manufacturers and recyclers, specifically to calculate recyclability and recoverability rates. It also provides conditions to identify parts to dismantle, to reuse, recycle them or to mitigate environmental hazards. It also helps to select the end-of-life scenario.

The recyclability and the recoverability are calculated in terms of the recycling and recovery rates of each part and the mass ratio.

$$\text{Rcyc} = \frac{\text{sum of recyclable masses of each parts}}{\text{total product mass}} \text{x}100\% = \Sigma\,(\text{m(i) x RCR (i) MEEE x}100\%$$

- m(i): the mass of part i
- RCR: Recycling rate of the i^{th} part in corresponding EoL treatment scenario
- M_{EEE}: Total product mass

The standard also provides a list of recycling and recovery rates from 2012.

III. BS EN 45559:2019 Methods for providing information relating to material efficiency aspects of energy-related products

This standard provided by CEN and CENELEC in March 2019 provides methods and templates to communicate material efficiency aspects of energy-related products, such as EEE. It can be used to develop a communication strategy in horizontal, generic, product-specific or product-group. It is based on EU Regulation No. 666/2013 to establish the product requirements, and ease communication from manufacturers and end-of-life management. As well, the WEEE Directive is referenced to provide recommendations in the end-of-life phase.

The main technologies used to track EEE and communicate a large amount of data with the purpose of Ecodesign are described in the standard:

- Optical technologies: bar code and QR code
- Electromagnetic:
  - Radio-frequency identification device (RFID) can be useful when large amounts of goods are managed. The disadvantages of these methods are the cost, the need for

specific tools to manufacture and read the tags and they do not usually present high data density. There are two types of RFID:

    - Active RFID tags: have their power supply and include a read range of 100m
    - Passive RFID tags: they are powered by the electromagnetic energy transmitted by the reader. Reading is only possible from near contact (up to 25m). The main advantage is the ability to track items enclosed within an assembly.
- NFC: This technology enables the communication between devices when they are touched together or brought within a few centimetres of each other [21].

IV. NSF/ANSI 426-2017: Environmental Leadership and Corporate Social Responsibility Assessment of Servers

This standard developed by NSF and approved by American National Standard Institute (ANSI) in 2017, provides a set of performance objectives considering the energy and material efficiencies to minimise the overall environmental impact of servers.

It is focused on:

- Replacement of components
- Takeback service by manufacturers
- End-of-life management
- Environmental management system
- Supply chain reporting
- Responsible mineral sourcing
- Compliance with occupational health and safety and social responsibility performance standards
- Product LCA

At the release data, NSF recognised that only 25-35% of the products would have obtained a bronze certification and, even fewer silver and gold certifications.

It requires a minimum content of recycled plastic (10% for external enclosures) as well as the elimination of heavy metals from the packaging.

It also states that servers should be designed to facilitate repair, reuse, recycling and safe handling. For example, components (such as cards, CPUs, memories, cables, power supply units or PCBs) must be dismantled according to WEEE Directive and that they should be removable by hand or with commonly available tools.

The recyclability of the product is set at a minimum 90%, which means that 90% of the mass of the server must be recycled with the technology available at the date that the product is declared. When plastic is valorised in smelters with energy recovery, it is considered as recyclable.

It also recommends conducting a cradle-to-grave LCA following ISO 14040/14044 or European Union Product Environmental Footprint Guide (PEF) to declare the environmental performance of the product [22].

V. ITU-T Standards

The International Telecommunications Union provide standards to improve the circular economy of ICT equipment. These standards are free.

ITU-T L.1xxx standards are focused on power supply series, e-waste management and recycling of rare metals in ICT products, which could be also adopted in DCI:

- ITU-T L.1100 (2012): focused on the recycling of rare metals from ICT products. It provides basic information about the content of the metals in ICT products, the recycling processes and communication methods of metal composition [23].
- ITU-T L.1021 (2018): Focused on Extended Producer Responsibility (EPR). The benefits and challenges of adopting a take-back scheme are briefly highlighted[24].

ITU is currently developing standards regarding the environmental impacts of end-of-life and circular economy structures, potential effects of selling services instead of equipment on waste generation and environmental impacts.

Table 8. Standards for DCs (JRC Intertek PLC, 2016).

Parameter	Published standard in use by industry
Server active state and idle state power	ESTAR servers v2.0 Sert V1.1.0
Server overall energy performance (TEC)	ESTAR servers v2.0 Sert V1.1.0
Energy proportional operation	Sert V1.1.0
Data storage active state and idle state power; overall energy performance	ESTAR servers v2.0 Sert V1.1.0
Energy proportional operation	Sert V1.1.0
Data storage COMs	ESTAR servers v2.0 SNIA Emerald V 2.x
Power supply efficiency	EPRI protocol v 6.7
Power supply power factor	EPRI protocol v 6.7
Firmware availability	/
Operating temperature and humidity	ASHRAE guidelines 4th edition table 2.3
Acoustic noise	ISO 779:2010 ECMA 74
Removability of external enclosures, PCBs, processors, data storage devices and batteries with common tools	IEC TR 62635:2012 PAS 141:2011
Ease of dismantling, reuse and recycling at the end-of-life	IEC TR 62635:2012 PAS 141:2011
Data sanitisation	NIST 800-88 rev1 CESG various
Material composition	
CRM content	/

In Europe, the standards EN 50600 are also used; these include building construction, power distribution, physical security, management and operational information, energy efficiency, use of renewable energy and IT equipment efficiency.

Concerning the end-of-life, WEEELABEX is a European label of excellence which implements CENELEC standards (EN 50625-1 Collection, logistics & treatment requirements for WEEE. General treatment requirements). This standard establishes that the waste cannot be resold from broker to broker. It is only acceptable to sell WEEE to authorized WEEE treatment businesses.

1.3. Analysis of the DC market in North Western Europe (NWE)

In 2017, DCs' global traffic data was 11.7 ZB and it is predicted to grow up to 20.6 ZB in 2021. North America and Pacific Asia present the highest cloud traffic (2.1 ZB and 2.3 ZB in 2018) followed by North Western Europe (NWE) with approximately 1 ZB in 2018. Traditionally, DCs were installed in the same location where data were used - physical DC model - but, since the implementation of the Internet, the paradigm has shifted to the virtualization of data and the use of Cloud DCs, where data are stored at and used from different locations. In global terms, only 17% of DCs are physical DCs and, by 2021 it is expected that Cloud DCs will be responsible for 94% of the workload. NWE market is led by the FLAP markets [1].

DCI is growing every year in Europe. The increase of the demand, the shift in the design phase from high-density servers to minimum consumption data centres and the shift to virtualization of DCs lead to an increase in their size and number. More than half of the data centres[5] in Europe are located in North Western Europe (Dodd et al., 2018, CloudScene, 2018):

Table 9. Number of DCs in the UK, France, Germany and the Netherlands (Dodd et al., 2018, CloudScene, 2018)

Number of Data Centres						
Country	Enterprise	Share in Europe	Colocation	Share in Europe	Managed Service Providers	Share in Europe
UK	11500	19.10%	450	20.32%	25	16.45%
France	8700	14.45%	270	12.19%	20	13.16%
Germany	13200	21.92%	410	18.51%	30	19.74%
Netherlands	5600	9.30%	250	11.29%	15	9.87%

In the Netherlands, the estimated number of data servers in 2016 was 4.3 million units, and 1.5 million were located in Amsterdam metropolis [25].

In terms of power take-up, FLAP markets reached 1256 MW, where London is the leading provider with almost 600 MW, followed by Frankfurt (240 MW), Amsterdam (240MW) and Paris (156 MW). Power take-up values have experienced a rapid increase during the last decade, and they are expected to continue to increase; for example in Frankfurt. 17.6 MW new Data Centres are already being constructed. Besides, the industry is developing all around Europe including minority markets

5 The number of total data centres in Europe was extracted from CloudScene.com. It only includes big commercialised data centres, composed by IT equipment, cooling system, network equipment, building structure, security and power generation.

such as Dublin, Iceland, Norway, Sweden, Finland, Denmark, Madrid and Milan which are experiencing rapid development with the construction of hyper-scale data centres [26].

Concerning the amount of equipment currently in data centres, estimated values are difficult to obtain given the heterogeneous distribution of data servers. They can be found in large quantities in colocation DCs, and it is supposed that numerous data servers are used by independent users or in small data storage facilities. It is also assumed that the number of servers will increase significantly with the growth of hyper-scale DCs, which allow easy and rapid increments in storage capacity. It is also expected that the number of private small DCs[6], connected to big commercialised DCs, will also increase with a lower rate than big public DCs[7] [1].

1.4. Business models in DCI

DCs business models have not stopped evolving since their appearance in the economic system. The rapid embrace of the internet and the development of storage equipment have led to significant changes in the use of DCs.

- Physical data centres:

  There are two types of Physical data centres. The definitions are extracted from the JRC technical report “*Development of the EU Green Public Procurement (GPP) Criteria for Data Centres and Server Rooms*” [2]:

  - Enterprise data centres: their sole purpose is the delivery and management of services to the employees and customers of the enterprise that operates them.
  - Colocation DCs: data centre facilities in which multiple customers locate their network(s), servers and storage equipment.

- Cloud computing or Managed Service Providers (MSP): Data are stored in big DCs located in a different place from the user. These can be based in large facilities known as hyper-scale data centres, which allow for a rapid increase in the storage capacity. Hyperscale data centres are expected to account for 53% of data servers by 2021 in the world -double of nowadays share(~27%)- [1]. In this business model, the flow of end-of-life products is more concentrated than in the previous model, and therefore the specific End-of-Life strategies (reuse - recycling) for DCI equipment could become more economical.

- Cloud computing DCs: offer different services, showing more flexibility than physical data centres for companies. In general terms, there are three types of activities:
  - Software as a service (SaaS) (71% by 2021)

    SaaS represents the largest cloud market and it is expected to continue growing. Applications, data, middleware, operating system, virtualisation, servers, storage and networking are controlled by the cloud provider managers.

  - Infrastructure as a Service (IaaS) (21 % by 2021)

6 DCs composed by private IT equipment connected to big commercialised DCs by cloud services to create back-ups.
7 Public data centres assets lie on the service provider (Cisco, 2018).

In this case, users manage applications, data, middleware and operating systems while providers still manage virtualization, servers, storage and networking.

- Platform as a Service (PaaS) (8% by 2021)

Customers manage their data and applications, but everything else depends on the cloud provider, including the operating system, servers, networking and middleware.

➢ Hybrid computing (physical + cloud services):

Nowadays, hybrid computing is a very common practice, especially among small and medium-sized organisations. The aim of this business model is the optimisation of the resources and the costs, especially in terms of CAPEX (see Table 10). In this environment, some of the cloud resources are managed in-house and others by an external provider. As an example, data servers can be installed in-house to store and manage the data, while the cloud services can be used for back-up purposes. In this way, the company only manages the maintenance of the data centre equipment, avoiding expenses and complications related to cooling systems or power generation units. Data are transferred to big data centres a limited number of times a day using the cloud. In this way, the large data centre facility is running and consuming high amounts of electricity while data is being transferred, and the rest of the time, it is dedicated to storing information in standby mode, which minimises energy consumption. It is difficult to estimate the number of pieces of equipment used with hybrid computing purposes given that there is no specific data available.

Table 10. Cost for owners and customers of DCs for different business models [2]

Cost category	**Cost range for DC owners (% breakdown of total life cycle cost)**				**Cost range for DC customers (% breakdown of total life cycle cost)**			
	Server rooms	Enterprise	Colocation	MSP	Server rooms	Enterprise	Colocation	MSP
Capex facilities	1-5%	15-20%	60-80%	15-20%	1-5%	15-20%	1-5%	0%
CAPEX IT	30-60%	30-40%	10-20%	30-40%	30-60%	30-40%	40-50%	0%
OPEX facilities	10-30%	10-15%	1-10%	10-15%	10-30%	10-15%	5-15%	35-50%
OPEX IT	20-40%	25-35%	1-5%	25-35%	20-40%	25-35%	30-40%	50-70%
Decommissioning	5-10%	5-10%	1-5%	1-5%	5-10%	5-10%	1-5%	0%
Facilities end-of-life	1-5%	1-%	1-2%	1-2%	1-5%	1-5%	N/A	N/A

1.5. Data Centres' composition from literature

The circular economy and resource efficiency strategies in DCI depend on the material composition of the equipment. Manufacturers do not provide information about the components inside the servers given that these components are most of the time manufactured (sometimes even designed) by actors outside their operational control.

The efficiency of the circular economy, especially the recycling process, depends on the amount, characteristics and assembly of the materials which form the equipment. However, there are not enough studies concerning CRM from data centres to make a comparison of products, technologies or configurations. Two different sources are used to collect data about the composition of the data server: Garnier, 2012 and Peiró & Ardente, 2015. Additional sources were also used where cited. These are however older servers and do not represent the range of equipment that is already in use in many SME and hyper-scale DCs; models include blade servers and equipment designed via the Open Compute Project where components are minimised to create 'stripped out 'or bare-bones products that facilitate hot-swapping of malfunctioning components. Specific exhaustive analyses of a wider range and larger number of items of data centre equipment and materials composition needs to be done to design the appropriate circular economy strategy.
Technological developments led to more efficient use of resources and a higher number of CRMs in electronic equipment than before. Therefore, the material composition in DCI changes rapidly. It is needed to assess the material composition of all types of technologies to determine the most efficient end-of-life strategy for DC equipment.

It's important to highlight that available literature data is based on old equipment and the need to include new / blade and OCP type servers is crucial to understand the evolution of this equipment.

1.5.1. DC components and materials

The most critical components regarding the circular economy of DCs are those which have a shorter operational life. Data servers, storage equipment, network equipment and batteries from Power Distribution Units (PDUs) present the shortest lifespan in a DC facility, in consequence, refurbishment, remanufacturing or recycling are required more frequently. The presence of CRMs makes these components of high interest regarding European sustainability. For example, batteries need CRMs such as cobalt to function. In consequence, they also need to follow the best end-of-life scenario route to avoid the use of primary CRMs and reintroduce them back in the value chain.

Table 11. Main components of a data centre facility (Garnier, 2012).

	Data centre equipment	Lifespan (Years)
Power generation	Uninterruptible power supply (UPS)	20
	Transformers	20
	Switchgear	20
	Backup generators	20
	Power distribution units (PDUs)	20
	Batteries	3-5
	Power cables	20
IT	Servers	3-8
	Storage equipment	3-5
	Network equipment (switches, routers, etc.)	3-5

	Chassis	20
	Network cables	10
Cooling system	Chillers	20
	Computer room air conditioning units (CRACs)	20
	The direct expansion air handler	20
	Pumps	20
	Cooling towers	20
	Heat exchange systems	20
	Reservoir storages for collecting rainwater	20
Security system	Fire-suppression system	20
	Video-cameras	20
Building structure	Lighting, infrastructure, etc.	20

I. Critical components in DCs

a. Servers

In the specific case of data servers, two different types of products are identified: rack servers and blades. The rack servers or rack-mounted servers are designed to fit into bays in cabinets, tend to be general-purpose machines that support a wide range of requirements. On other hand, blades are thin modular units, several of which slide into or are housed in a chassis to save space, cabling and power; typically have built-in CPUs, memory, integrated network controllers and sometimes storage drives or video cards will be housed in the chassis. They have the high processing power and can be 'hot-swapped' (easily removed from the chassis and replaced to avoid redundancy).
Inside the data servers, the most valuable components for recycling are the PCBs. Some of them are classified as high-value PCBs, with >400 ppm of gold concentration, while the rest are classified as poor PCBs (low value), with a low concentration of gold. They are formed by layers of copper and non-conducting material (resin epoxy reinforced with glass fibre or phenolic resin and paper fibre) and components mounted on the substrate, which, usually are composed by:

- semiconductor components (33%)
- capacitors (24%)
- unpopulated circuit boards (23%)
- electrical resistances (12%)
- switches and other materials (8%) [15]

PCBs can be found in servers as well as in drives (HDD and solid-state drives (SSD)), optical disc drives (ODDs) and power supply units (PSUs).

Blade type servers:

Blade and rack servers are both networking servers. Blade servers introduce modularity into the compute architecture. Typically, they run a single application and work together with other blades, whilst rack servers can run multiple applications in a stand-alone state. The thinner, stripped-down blades - with their CPU, RAM and storage - are slotted into a chassis containing centralised components – such as cables and memory – for each blade to share. This chassis of blades then sits within a rack. A single rack, therefore, has the physical capacity to provide a higher compute density, but with a lower energy consumption because of the shared power source. Each blade is also hot-swappable meaning a single blade can be removed and replaced without taking them offline.

b. *Storage equipment in DCI*

HDDs and SSDs store all the data. Every 3-5 years (knowing that SDDs are supposed to last longer than this), these drives are substituted due to failures in their functioning. Then, data sanitisation is the next step to carry out to protect the information previously stored. Afterwards, the end-of-life stage takes place. Reuse or recycling are the most likely scenarios, depending on the destruction of the data method chosen, the technology and the age of the device. HDDs contain REE such as Nd and Dy and SSDs contain PGM and silicon metal as CRMs.

Currently, the most common equipment to store data is HDD. The main alternative is SSD technology which presents several advantages such as faster performance and energy savings.

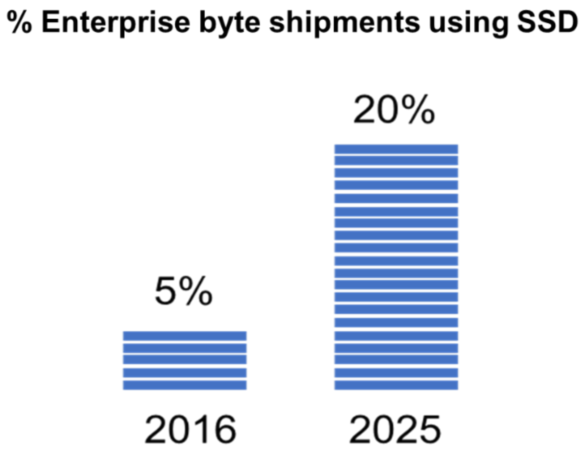

Figure 5. Enterprise byte shipments estimation using SSD (the remaining percentage corresponds to HDD) [27]

The difference in price between both technologies is limiting the mainstreaming of SSD in DCI. Recent developments are helping to reduce the price of SSDs and increase the competitiveness of these devices. The expected trend is that SSDs will be adopted by DCI when the price difference between HDD and SSD allows an economically viable change without any risk to the operator.

This shift would result in a decrease of use of REE, one category of CRMs, given that SSD is not composed of magnets. On the other hand, SSD is constituted by flash memories made of high purity silicon metal. Silicon metal and magnets are not currently recycled from old scrap[8] even though the number of waste HDDs could make a viable recycling scenario.

[8] Old scraps can be defined as scrap from products that goes to the end-of-life phase after its use phase, which means it needs processes to obtain recycled materials.

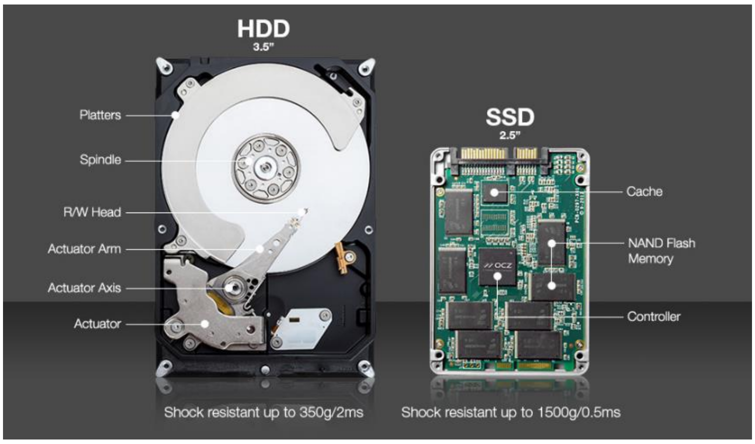

Figure 6. HDD and SSD [27].

- Hard Disk Drives

HDDs use the magnetism of materials on a rotating platter to store data. Permanent magnets (NdFeB) are used; they also contain other REE, such as Dy. Other metals and plastics complete the composition, and there is a high concentration of aluminium [28]. The R/W head permits the reading and writing of data. It is situated in an actuator which, with the help of the rotation of the platters, selects the right magnetic domain to read or write. The rotation speed is around 7000 RPM, though in some servers can run at higher speeds. The mechanism of writing and reading uses the binary code and the direction of the magnetic pole points up or down, creating a code of 1 or a 0. The traditional technology for recording was longitudinal recording, where the magnetic poles were pointing in the same direction as the movement of the head. With perpendicular recording technology, the surface density increases drastically and enables storage of 100 GB per square inch (15.5 GB per square cm). Other important developments have been achieved to increase the storage density of HDD including heat-assisted devices (HAMR) or microwave-assisted (MAMR) which are expected to store 20 TB data in the standard HDDs of 3.5". Further developments are expected to be commercialised with competitive prices in the next decade, which means that HDD will be still mainstreamed to store data due to the lower price compared to SSD.

- Solid State Drives

SSDs are based on semiconductor engineering materials. High purity silicon is the main material found in flash memories, made of floating-gate transistors. The most interesting property is the higher read and write speed compared to HDDs. In HDDs, the speed depends on the rotational speed of the platters. The absence of mechanical parts in SSD makes the reading process faster, given that fragmentation of data does not affect the speed of the process. The heat and the noise produced are also much lower than those from HDDs, so the energy savings in cooling are also an advantage of this technology.

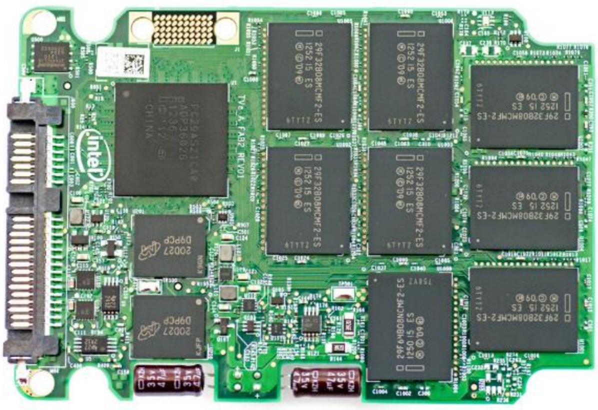

Figure 7. Solid-state drive without chassis [27]***.***

c. *Network equipment*

Network equipment is fundamental in the architecture of DCs, especially in cloud computing. Routers, switches or modems connect devices inside and outside the DC and allow the transfer of data. These devices have a high refresh rate at 3-5 years and the number of devices found in DC is significant. There may be 1 or more switches per rack. The optimisation of the architecture also allows the optimisation of physical resources.

- Routers

Routers are used for networking which forwards data between networks. They act as distributors of the information, choosing the fastest route possible.

These devices are usually composed of a fan, cables, chassis, power supply unit and a motherboard with components. The most common components are the processors, flash memories and capacitors.

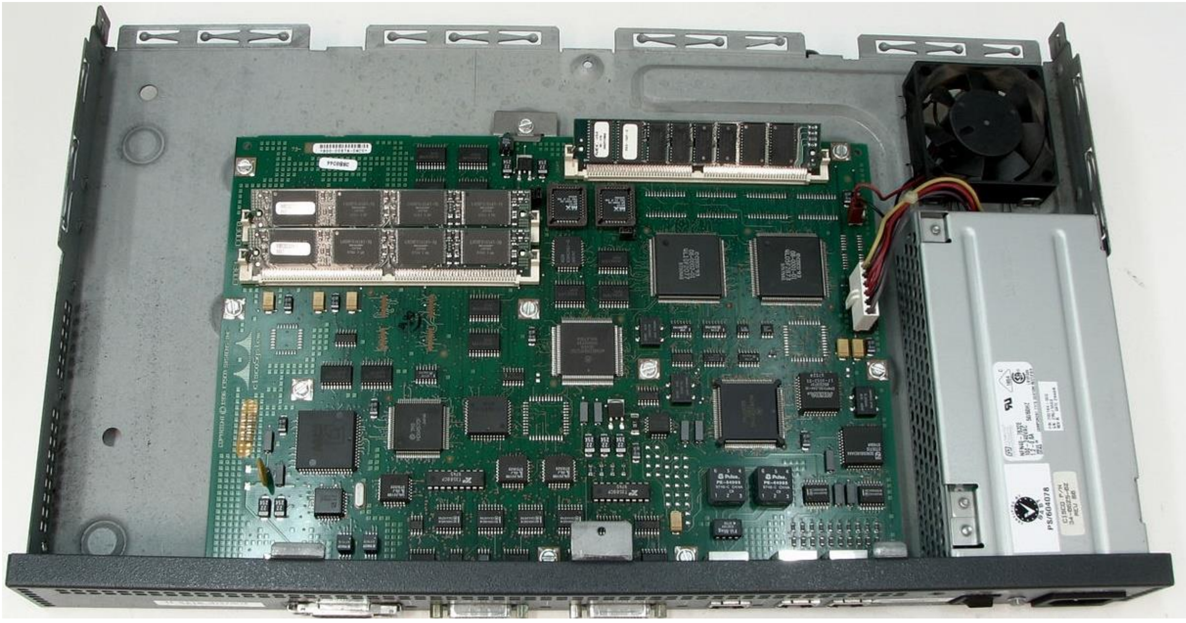

Figure 8. Cisco 2503 Router (source: en.wikipedia.org)

➢ Switches

Switches connect devices from the same network inside a building. The network connects servers and computers; it also acts as a controller, allowing the different devices to share information and communicate with each other. The components found in switches are similar to those found in routers.

d. Batteries

In DCI, two kinds of batteries are used in the power distribution unit: mainly valve-regulated lead-acid batteries (VRLA) and lithium-ion batteries (LIB). Due to their higher energy efficiency, recharging rates and higher reliability, VRLA is being substituted by LIB, which also has a higher power and energy density and a longer expected lifetime. VRLA is known for its low price and low reliability, and they are often the initial cause of unplanned data centre outage [29]. In DCI, LIBs and nickel-metal hybrid batteries (NiMH) can also be found inside the serves in the form of coin or prismatic batteries.

LIBs contain fewer toxic materials than VRLA or nickel-cadmium batteries (Ni-Cd) but managing the waste of all batteries is a priority to preserve the environment and, besides, to recover CRMs.

DCI demand for LIBs is increasing every year (see Figure 9) for UPS and inside the electronics (coin and prismatic batteries). The European LIB industry is expected to be developed in the coming years due to the adoption of electric vehicles.

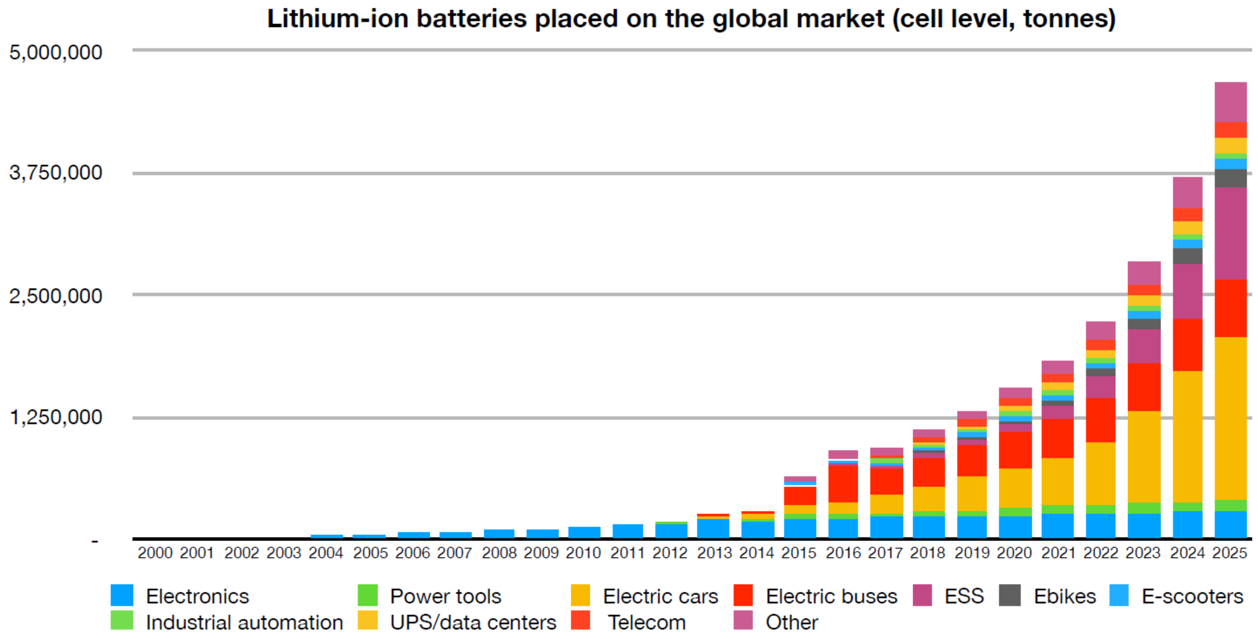

Figure 9. LIBs placed on the global market (2000-2025) [30]

II. Data servers' materials composition

The European Commission JRC estimated the composition of a 'basic building brick' data server, after assessing the design for Ecodesign Regulation Lot 9 for enterprise servers. They used manufacturers' materials declaration and their results are presented in Table 12 and Table 14. CRM in data servers (Peiró & Ardente, 2015).

Table 12. Bill of materials of enterprise server [15].

Component	Material	Mass (kg)	Component	Material	Mass (kg)
Chassis	Steel	12.265	**Mainboard**	Controller board	1.667
	ABS	0.348	**2 PSUs**	Steel	1.346
	PC	0.282		Aluminium	0.226
	Aluminium	0.249		Fan	0.154
	Copper	0.179		Plastic (EVA)	0.075
	PCB	0.131		Plastic (PCFR40)	0.051
4 Fans	Steel	0.386		PCB	1.542
	Copper	0.078		Cables	0.031
	Ferrous based	0.055	**Cables**	Brass	0.007
	PBT-GF30	0.206		Copper	0.081
	PCABSFR40	0.021		Zinc	0.096
	Plastic undefined	0.200		HDPE	0.104
4 HDDs	Aluminium	0.787		PVC	0.145
	Steel	0.547		PUR	0.002
	Ferrous based	0.152		Synthetic rubber	0.035
	Copper	0.007			
	Magnet	0.068	**ODD**	Low alloyed steel	0.115
	PCB	0.068		Copper	0.007
	PCABS	0.068		Aluminium	0.001
	PCGF	0.052		HDPE	0.028
2 CPUs		0.054		ABS	0.012
Batteries	Coin cell LIB	0.002		PC	0.007
	Prismatic LIB	0.043		PCB	0.019
Memory	PCB	0.135	**Packaging**	Cardboard	3.629
Heat Pipes for CPUs	Low alloyed steel	0.14		HDPE	0.078
	Copper	0.442		GPPS/Styrofoam	1.026
Total: 27.799 kg					

a. *Critical Raw Materials in data servers*

Electronic products and IT equipment present CRMs for their functioning, therefore, numerous CRMs are used in data servers. The characterisation of the data servers is taken from the literature.

Table 13. European list of 2017 CRMs. Highlighted the materials found in data servers [5].

Critical Raw Materials (CRMs)			
Antimony	Fluorspar	LREEs	Phosphorus
Baryte	Gallium	Magnesium	Scandium
Beryllium	Germanium	Natural graphite	Silicon metal
Bismuth	Hafnium	Natural rubber	Tantalum
Borate	Helium	Niobium	Tungsten
Cobalt	HREEs	PGMs	Vanadium
Coking coal	Indium	Phosphate rock	

Table 14. CRM in data servers (Peiró & Ardente, 2015).

Component	CRM
Lithium-Ion Batteries	Co
HDD	Dy
	Nd
SSD	Si
	(CRM found in PCB)
PCB	Pd
	Pt
	Sb
	Si
	Ga
	Ge
	Ta
	Co
Connectors	Sb
	Be
	Co
	Pd
	Si metal

CRMs are mainly found in batteries, drives (HDD and SSD), PCBs and connectors. Neodymium (Nd) has the highest mass and is used in magnets in HDDs, followed by cobalt from batteries and silicon metal from the integrated circuits in PCBs (see Table 15). The silicon (glass fibres used to reinforce the PCB) in servers is not a CRM given that only the silicon in form of metal is considered as CRM. These materials are of high economic importance and the risk to supply is also high. 100% of supplies are imported to the European Union except for cobalt (32% is imported) and silicon metal (64% is imported). Moreover, recycling rates for most of these materials are not high and many are dispersed throughout products: e.g. antimony (Sb) as a flame retardant in PCB plastics. The low concentrations of the materials in products lead to higher losses and, in consequence, lower recycling rates.

Table 15. Amount of CRM found in data server [15].

Material	Quantity in the server (g)	Material	Quantity in the server (g)
Sb	4.44		
Be	0.03	**REEs**	
Co	9.27	**Dy**	3.60
Mg	0.004	**Nd**	14.63
Pd	0.40	**Pr**	3.60
Si	11.23	**Tb**	0.75

Table 15 shows the CRM characterisation results from the data server studied by Peiró & Ardente. Some CRMs are missing due to their presence in components that are not included in their reference studies and/or because some of the components studied were manufactured more than a decade ago.

1.6. Data Centres End-of-Life scenarios

Some data centres have already implemented a circular economy system in terms of reuse, expanding the lifespan of the components by refurbishing and remanufacturing before being sent to the recycling plant. Even so, the circularity of data servers is still underestimated in DCI [31]. The market already offers refurbishment and remanufacturing services although some problems related to compatibility (e.g. firmware uploads) limit higher efficiency of resources [32]. In consequence, further improvements need to be implemented to increase the reusability and the circularity of ITC products.

When the lifespan cannot be prolonged anymore by refurbishment or remanufacturing, products should be sent to the recycling facility in different streams (after dismantling and physical separation processes). The recycling strategy of the different components differs and must be studied independently given the differences in composition and valuable materials content. In the case of storage equipment from DCI, a mandatory step is the sanitisation of data before the storage equipment changes proprietor (e.g. from data centre operator to refurbishment or recycling company). This step directly affects the circularity of the storage equipment, influencing in the aggregation state of the feed material sent to the recycler (shredded or non-shredded), therefore influencing the recovery efficiency of valuable materials (e.g. PGM).

CRMs deserve special attention due to their economic and societal considerations. They are fundamental to the composition of IT products, so circular economy approaches must be pursued to avoid importation and use of primary CRMs. The CRM recycling rate from WEEE is ~1% [6], in consequence, there is a large room for improvement throughout the whole life cycle to increase the recovery of these materials.

Table 16. CRM in servers recycling

CRM in data servers	**EU Import reliance Primary material** [33]	**EOL-RIR** [5]	**EOL-RR** [34]	**Use in DCs**	**Recycling**
Sb	100%	28%	1-10%	Flame retardant in PCBs	Mainly recovered from lead-acid batteries. Sb from PCBs goes to the slag in pyro routes
Be	100%	0%	0.00%	as an alloying element in Cu alloys	Not recycled from old scrap, only from new scrap*
Co	32%	35%	68.00%	The cathode in LIB (PSU and PCB)	LIB can be recycled, and Co recovered.
Mg	100%	13%	39.00%	An alloying element for Al alloys	It is recycled in the aluminium recycling process
PGM	100%	11%	0-10%	Found in capacitors, HDD and coatings to enhance conductivity	Pt, Pd and Rh have well-developed recycling processes
REE	100%	6-7%	<1%	Nd and Dy in magnets of HDD	Recovery of REE is not currently economic. Lots of research projects in the field
Si metal	64%	0%	-	Connectors and Transistors (Flash memories in SSD and PCBs)	It is not currently recovered from old scrap
Ta	100%	1%	10-25%	Capacitors in PCBs	It is not currently recovered from old scrap

* new scrap is produced during manufacturing processes and it stays in the manufacturing facility, being recycled or returning directly to the production processes.

In Europe, recycling of PGMs and Co from LIB processes is being implemented. But the rest of the materials are not usually recovered from old scrap. In contrast, reintroducing waste materials from manufacturing stages into the production processes is an economic practice which has been applied for several decades. Recycling from old scraps, such as end-of-life servers needs more complex processes. PGMs are the most valuable materials to be recovered, therefore, the WEEE recycling processes are economically viable when these metals are targeted.

1.6.1. Reuse and refurbishment

Reuse and refurbishment allow the extension of the product lifespan. They are considered as priorities at the end of life scenarios before recycling. By reusing and refurbishing, products and materials can be reintroduced in the life cycle with low energy and resource consumption (e.g. as a deriving from transport, replacement of damaged components etc.). Conversely, recycling requires more energy for heat and recovers a fraction of the materials due to losses during the various processes. The three scenarios are beneficial; for example, they control the toxicity embodied in WEEE and preserve primary resources. The ease of reuse and refurbishment is directly linked to the ease of dismantling the equipment and this consideration is already included in some European standards (see Table 8).

The secondary market for refurbished equipment is quite developed in Europe and involves different actors (e.g. brokers, spare parts providers or remanufacturers). IT equipment is reused after being traded by brokers and in NWE, it is estimated that 133 brokers are dealing with data servers: in the UK there are 64, Germany - 29, Netherlands -24 and in France - 16 [35]. Remanufacturing in Europe generates a significant turnover of $6,900million, compared to $2,700million in the US. Spare parts providers get complete equipment, dismantle it and sell the components (under the requirements for spare parts) to third party maintainers who service and upgrade existing equipment. There are various business models based on secondary market equipment, e.g. ITRenew (USA), works with hyper-scale centres while Cistor (UK) specialises in Cisco equipment and iNet (UK) and Aliter Networks (NL) refurbish products from a range of brands

To facilitate reuse, remanufacturing and refurbishing are two possible processes:

1. Remanufacturing is another step in the value chain for data servers, which is included inside the refurbishment category in this report. The objective of this process is to provide "as new" products using end-of-life servers. It usually includes the following steps [36]:
   - Selection and decommissioning of incoming used product
   - Disassembly and cleaning
   - Data destruction
   - Rebuild of the product based on the latest technical specifications
   - Implementation of latest engineering changes and hardware/software/firmware uploads
   - Quality checks and verification of performance, electrical, safety and environmental standards
   - Packaging and shipping with "as new" warranty and services
2. Refurbishing is the improvement of a product which may involve making it look like new, with limited functionality improvements.

Free ICT Europe (F-ICT) is a non-profitable organisation that was created to support the utilisation of refurbished ICT. to extend the lifespan of the components and minimise the global impacts of the products. Regarding DCs, F-ICT highlighted in their Ecodesign Directive Lot 9 review that a high percentage of end-of-life components could be re-used if compatibility of assemblies and components could be more easily achieved. As the different pieces of equipment are interconnected, a fundamental requirement for a component is to have compatibility with the rest of the components. There are three compatibility layers:

1. Sub-assemblies: All sub-assemblies of one unit (e.g. server) must be compatible.

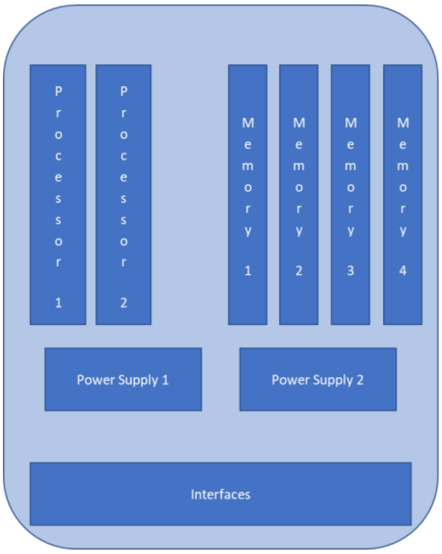

Figure 10. Server sub-assemblies (processors, memories, power supply, interfaces) [32].

2. IT Architecture: all equipment and components of the clusters of enterprise servers must be compatible.

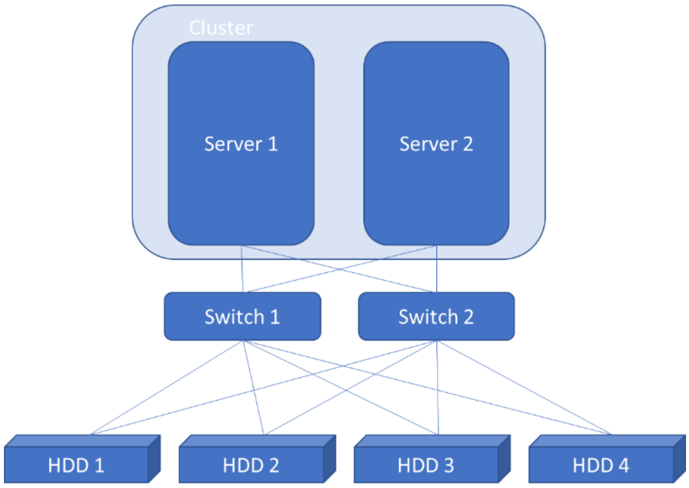

Figure 11. Simplified architecture of data centres [32].

3. Software: the software must also be compatible with all the equipment integrated into the system.

   To achieve this compatibility, OEMs create and install the firmware. This can be a system, hardware, component or peripheral programming with instructions to use all the programming and hardware. These instructions are subject to Intellectual Property Rights and the products usually present bugs so periodic updates are necessary. Using the same level of the update is also a requirement for compatibility. In consequence, if a second-hand server does not have the latest level of firmware it would not be of interest to end-users who will have to obtain a new component/server. In conclusion, the possibility to update the firmware to make different generation components compatible is the key to creating an efficient secondary market in the framework of the circular economy [32].

In other reports concerning the circular economy of data centres in the Netherlands, it is stated that closer collaboration among stakeholders is also required for a successful circular economy.[31]

1.6.2. Sanitisation or destruction of data

Storage devices from DCI need a sanitisation step before carrying out the end-of-life strategy.

Destruction of data is included in the new GDPR, where it is stated that a data breach will be penalised with 4% of turnover or up to 20M €; consequently = data destruction must be well-reported and ensured by the companies responsible for the process

The European Security Standard DIN EN 66399 distinguishes three classes of data:

- Class 1: low-security status data. Devices containing this type of data can be sanitised by any method: shredding, crushing, degaussing, data wiping, etc.
- Class 2: Higher protection for confidential data where disclosure would have a detrimental impact on a business or organisation. Devices containing this type of data are usually shredded on-site.
- Class 3: Higher protection for confidential data where disclosure would have a detrimental impact on the company or government/public sector entity. Devices containing this type of data are also shredded on-site.

The destruction process can either be carried out in the same facility where the drives are used or off-site, by in-house and out-sourced services. In the latter case, the transport of the devices needs high-security measurements. In every case, the data destruction manager reports the process carried out.

The technology of the drive is an important factor in the selection of the destruction method. SSDs cannot be drilled or degaussed, given that they are comprised of numerous memory chips which need to be destroyed individually and the fact that magnetic fields do not affect their storage properties.

The method to erase the data determines subsequent recycling processes given that it can lead to different agglomeration states of the waste (i.e. shredded or not). It is also determinant of the circular economy, allowing or not the possibility for reuse or repair.

The sanitisation process is usually followed by a verification process where equipment, personal competencies and results are verified.

The different methods are described in the table below:

Table 17. Data sanitisation methods.

Data sanitisation method	Route	Reusable	Security / Certainty of destruction	Capacity	HDDs	SSDs	Scrap value after data sanitisation (€/kg)	Additional comments
Shredding	Physical	No	Very High	45-2400 drives per hour	Yes	Yes	0.25-0.5	Essential for high-security data.
Crusher	Physical	No	Low	50-150 drives per hour	Yes	No	0.5-0.75	SSD are formed by multiple memories that need to be individually destroyed.
Degaussing	Magnetic	No	High	50-80	Yes	No	0.75 – 1	Degaussing also deletes start-up files and limits reuse. Old degaussers do not work with new drives (they require higher demagnetisation)
Overwrite	Software	Yes	Depends on the method		Yes	Yes	0.75 - 1	The overwriting process follows different standards depending on the country or organisation.

Degaussing makes the hard drive inoperable. Moreover, it is only useful for hard disk drives, because they are based on magnetic technology. Solid-state drives, which are expected to dominate the data storage market soon, are based in semiconductors and are not suitable for degaussers. Besides, the magnetic coercivity of new HDDs is higher than that in earlier drives and traditional degaussers have not the capacity to produce sufficiently high magnetic fields to erase the data.

I. <u>Shredding</u>

Drives are fragmented using a shredder, obtaining a stream rich in metals and PCB content. The regular particle sizes usually vary from 1cm to 2 cm. Shredding is the most cost-effective method of data destruction. The main drawback regarding the circular economy is that the drive and its components are no longer reusable. Some shredders are equipped with a magnetic separator to separate ferrous metals, but the separation of the various materials is still challenging.

Figure 12. Shredder of drives (source: ameri-shred.com)

Figure 13. Shredded drives (source: CEDaCI dismantling and characterisation)

II. <u>Crushing</u>

The crusher destroys the drive without fragmentation, applying high pressure until the mechanical failure of the driver. Other technologies drill holes on the device instead of applying pressure. This method is only suitable for magnetic drives, i.e. HDDs.

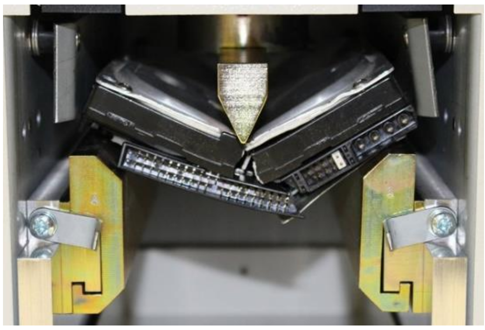

Figure 14. Crushing of drives (source: www.veritysystems.com)

III. Degaussing

A magnetic field (around 3000 Oe) is applied to erase the information by demagnetizing hard drives manufactured before 2006. After this year, hard drives presented an important increase of coercivity (>5000 Oe) which make the drives unsuitable for traditional degaussers [37]. This data destruction method does not allow the reuse of the drives given that all the information is removed, including the start-up files.

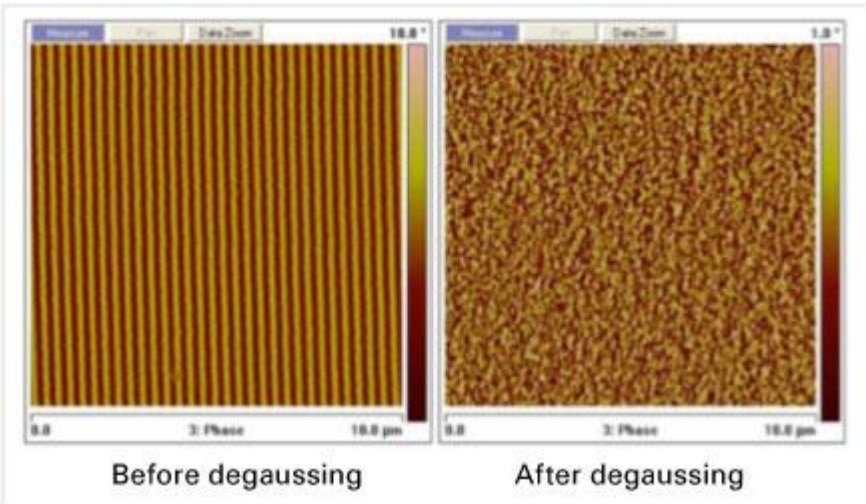

Figure 15. Magnetic domains in the hard disk drive before and after degaussing process. Image credit: Centre for Magnetic Recording Research (CMRR)

IV. Data wipe or data overwriting

Data are overwritten following different standards, depending on the country and the organisation. Data are overwritten a certain number of times with 1, 0 or random values. The cryptographic method can be used making more difficult the recovery of old data. Examples of software used, and their creators include:

- Secure Erase
- DoD 5220.22-M (US Department of Defence)
- NCSC-TG-025 (US National Security Agency)
- HMG IS5 (UK)
- VSITR (Germany)
- GOST R 50739-95 (Russia)
- Pfitzner (Roy Pfitzner)
- Random Data

V. Write Zero

This method allows the reuse of the device given that it is not physically transformed. It is a common technique and some manufacturers of drives incorporate standardised commands to enhance the data erase, such as ATA or SCSI. This approach perfectly matches a circular economy system given that reuse is supported by the design phase.

1.6.3. Dismantling

According to WEEE legislation, toxic components such as PCBs must be separated, as well as the cables and batteries. Also, some highly valuable components, e.g. CPUs, are targeted in dismantling. According to Fujitsu, they also dismantle the memories from the servers and place them in a different stream [38].

This process is fundamental in the treatment of electronic waste to get different streams to be treated by different processes. The method used to dismantle the equipment is a key step in the economic viability of the recycling process. Manual methods are usually employed although both cost and efficiency are high, Automated processes also separate various streams from a different type of sources.at the same time.

In the recycling of PCBs, dismantling the assembled components such as electrical connectors, capacitors or round batteries, presents some risks for the operators, given that, for example, capacitors may be still charged, or hazardous substances could be emitted from the solder or the mainboard. Dismantling may be carried out via physical operations such as hammering or by semi-automatic processes which include heating. Some automated dismantling lines have been proposed, based on a recognition system using Vision System and databases to identify reusable and toxic components [39] but this process is still a challenge, and research is on-going. Disassembly by hydrochloric leaching has also been investigated in Asia [40].

1.6.4. Recycling

There is no specific information about the recycling of WEEE from DCI equipment. The recycling phase of DC equipment follows the same steps than WEEE, after being reused and the data is removed.

Recycling of WEEE is based in the recovery of basic metals (steel, copper, aluminium, lead) but the highest added value is found in PM, so usually, specific recovery steps of these metals are performed. By other hand, CRMs are not usually recovered from WEEE, presenting recovery rates ~1%, where most of the recycled materials come from new scrap [33]. The main factors identified in a recent CRM Recovery project were attributed to lack of awareness among stakeholders of the importance of CRM recovery and lack of effective collection systems and technology to recover CRM. Policies and standards do not pay special attention to these type of materials and, given that the prices of CRM are volatile, the recycling processes are not ready to obtain CRM as a secondary product [6]. Besides, some CRMs present thermodynamic difficulties for extraction by traditional processes (see Figure 16), so specific research must be carried out to find economically viable routes to recover these materials.

As Reuter's metal wheel describes, some of the CRM found in data servers (PCBs) present high technical difficulties for recovery using current processes. The recycling processes are based on the manufacturing processes of society's essential metals. The associated metals could be recovered by pyrometallurgical or hydrometallurgical routes, depending on whether they are found dissolved in the molten portion or in the slag. It is evident that CRMs can be mainly found in Cu, Pb, Fe and Al routes:

- Fe: If the waste is treated by the iron-making industry, none of the materials is recovered. Only Co and Si could be part of different steel alloys. Treatment of WEEE is not efficient

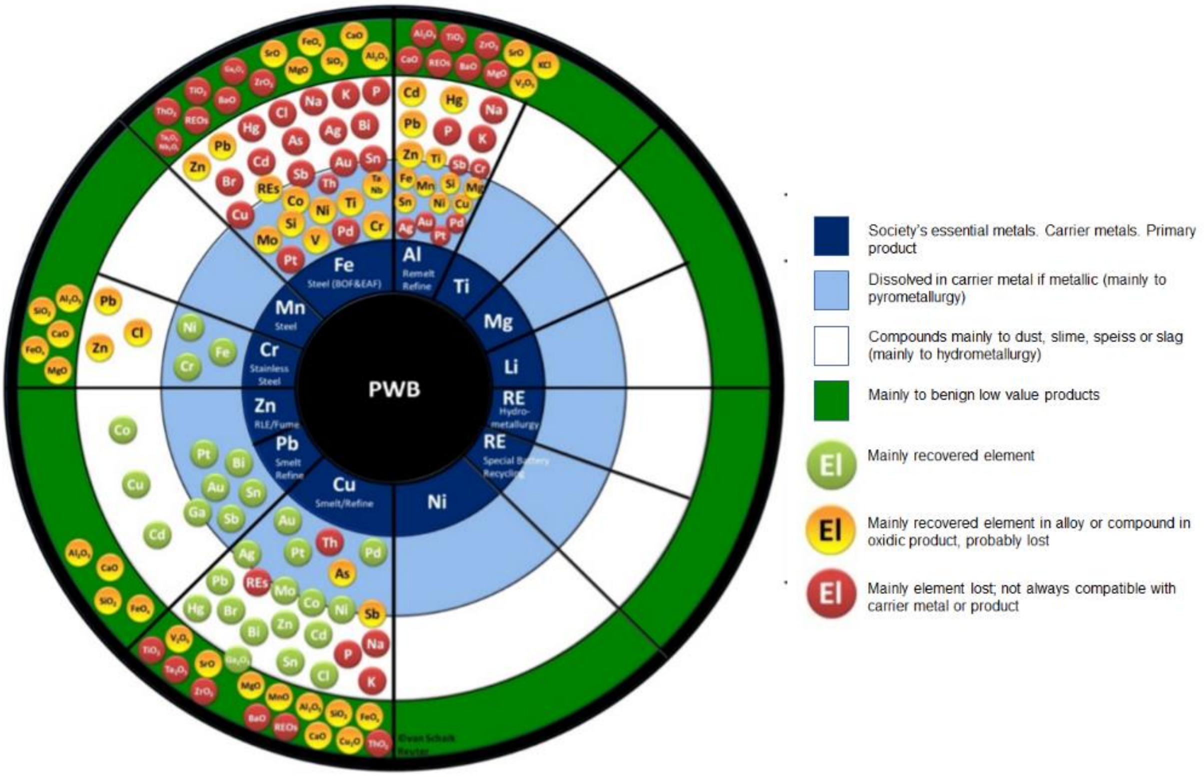

Figure 16. Wheel of metals in printed wiring boards [9]

- Al: It is a similar scenario to the iron-making industry: only some elements are reintroduced in the economic system exclusively as alloy, such as Mg. This is currently the main route of Mg from WEEE recycling.
- Cu: it is the most common route for recycling of WEEE: Co, PGM and PM can be recovered by pyro or hydrometallurgical processes. On the other hand, Sb can be recovered in alloys, but REE or Si are lost in the slag.
- Pb: Co and Sb can be recovered, as well as the PGM and PM. This route is also used in recycling of WEEE, especially as a complementary route to the copper smelting route.

I. Storage equipment (HDD, SSD, Memories) from DCs

As yet these products have no specific commercialised recycling processes. They are usually incorporated in WEEE smelting processes where REE (Nd, Dy and Pr) are lost in the slag. HDDs also include precious metals on the platters, especially in aluminium-based platters [41].

Depending on the sanitisation method, drives arrive at the recycling plant in different states of agglomeration. Even though HDD and SSD present different compositions, they are usually treated by the same method in the data destruction stage. Currently, drives arrive at the recycling plant after being shredded or crushed as a ferrous metal or PCB concentrate. They are considered as a stream rich and different materials are recovered by different recyclers. The common practice is recycling by pyrometallurgy and hydrometallurgy with the intent of recovering base metals (pyro) and precious metals (hydro) associated with PCBs. Smaller recyclers may just recover the precious metals. Devices can either be directly smelted or treated via physical separation methods (such as manual dismantling, shredding, magnetic and/or eddy current separators). When devices are directly smelted, REE goes to the slag. It is not yet economically viable to recover the REEs to produce magnets due to the presence of nickel or aluminium chromate plating on the surface of the magnets [8]. These elements need to be removed before by wet or mechanical processes making the recycling unviable at present because there is such a difference between the quality of the recycled and virgin raw materials.

Some recycling technologies are being developed for the recovery of REEs from magnets as seen in Table 18 but none of these technologies works at an industrial scale. The instability of the prices of CRMs and the recycling market (due to uncertainty in feed material availability, quality of the final product, etc.) also generate reluctance among financial bodies to support these projects.

Table 18. Magnet recycling methods (Reuter & Worrel, 2014).

Recycling method	Main characteristics	Scale
Hydrogen decrepitation	HD, jet milling, aligning and pressing, vacuum sintering, magnet remanufacturing (addition of 1% new Nd)	Pilot
Leaching	Acid leaching and generation of Fe-chloride, Nd-oxide and B-acid (no further details)	Pilot
Selective roasting-leaching	Oxidizing roasting, acid leaching of Nd with H_2SO_4 or HCl, precipitation ($Nd_2(SO_4)3$) or solvent extraction of neodymium (Tanaka Oki et al., 2013) Chlorinating with NH4Cl (T ¼ 350 C), selective dissolving of NdCl3 into water (Itoh et al., 2009)	Laboratory
Selective extraction in the molten process	Molten salt: $MgCl_2$ (T ¼ 1000 C) (Shirayama and Okabe, 2008) Molten metal: Mg (Xu et al., 2000; Okabe et al., 2003); Ag (Takeda et al., 2004) Slag (oxides): melting with LIF-(REM) F3-fluxes (Takeda et al., 2009)	Laboratory

a. *Non-fragmented devices (overwriting data sanitisation)*

Non-fragmented devices could be reused, but they need decommissioning and may need a refurbishment step before being included in another server. Thus, non-invasive data destruction methods allow expanding the product lifespan through repair. Also, it allows a higher recovery of CRMs (REE from the magnets) by hydrogen decrepitation. Recycling processes to recover the REEs are an uncommon practice (REE present <1% recycling rate and 1-10% of recycled content [34]) and some studies show that shredding further decreases the recovery rate of REE (< 10%) [42].Several research projects have been developed in Europe to recycle shredded magnets mixing the powder with primary materials to increase the recycled content of REE such as Nd and Dy [43]. At the moment, however, there is no specific industrial process devoted to recycling of magnets from old scrap.

b. *Shredded devices*

After data is erased by overwriting, the device can be reused. HDD and SSD can be shredded using the same equipment, although there are some specialized shredders for SSD to get smaller final particle sizes. Due to the small size of the memories used in SSD, the particle size after shredding must be at most <1cm to ensure that all the data is destroyed.

Silicon metal from SSDs is not being recycled and although the base metals are recovered, the silicon is lost in the process. There are no current processes to recycle silicon from WEEE although it is being recycled in the manufacturing facilities (or from new scrap). There are also projects to recycle silicon from waste solar panels. Given the expected adoption of SSDs in DCI, a recycling strategy for SSD needs to be developed as soon as possible.

Typically, drives are shredded by refurbishers and sold to PCB recyclers or ferrous and non-ferrous metals recyclers or shredded directly in the recycling facility. Shredding is a beneficial practice for SMEs given that they avoid shipping costs after reducing the volume of the waste and they can also separate the ferrous fraction easily (using magnets), increasing the concentration of valuable metals and, therefore, the value of the waste. Although the waste is smelted and the REE from HDD are lost in the slag, steel and aluminium are being recovered [44]. Silicon metal is also lost in the process given that there are no existing industrial processes to recover it from old scrap.

II. Printed Circuit Boards

First, pre-treatment processes are carried out to obtain a PCB stream. The PCB must be dismantled from WEEE according to WEEE Directive and there are different ways to separate the PCB from the device:

- Fully manual segregation: segregation of target items from other WEEE streams, followed by the manual dismantling of equipment. This is the most costly and efficient technique but given the high-value content of PCBs from IT and communications equipment, this is the most frequently used process. This phase can be followed by re-use.
- Semi-automated with commercial shredding: mechanical shredding of WEEE for size reduction and separation of saleable ferrous and non-ferrous metals, with manual downstream picking operations to recover PCBs and other components. This process is best suited to PCB recovery from items which are not cost-effective for manually sorting or items where the PCBs are physically attached, (e.g. welded), and cannot be manually removed.
- Semi-automated with commercial smashing combined with manual removal of streams. Spinning and smashing of the remaining WEEE into smaller components followed by magnetic separation and finally, manual picking lines.

Given that IT equipment (switches, routers and servers) components can be replaced easily, the time spent (1-3 mins) to obtain an independent PCB stream is cost-effective. The dismantling of equipment from the DCI is usually done by refurbishers. The waste PCBs can be sold as spare parts or shredded and ferrous metals may or may not be separated magnetically.

Once the PCB stream is obtained the recycling process takes place:

Pyrometallurgical processes are often used to treat large volumes of scrap to limit electricity consumption during the fragmentation processes and loss of precious metals [45].On the other hand, enterprises with lower capacities often use processes designed to obtain a copper concentrate which has high precious metals and PGM content. This last business model is based on the following operations:

- Shredding
- Separation of ferrous and non-ferrous metals by magnetic separation and Eddy current. Iron and aluminium streams are obtained and sent to recyclers of manufacturers using scrap as feed material.
- Pyrolysis: The organic components from the PCBs are eliminated in a 350-400°C furnace under low oxygen concentration conditions. The remaining fraction is the copper concentrate which includes PM and PGM.
- Gas treatment: gases are neutralised by several stages of remediation (post-combustion, which destroy organic halogens, DeNox (Catalytic Nitrogen Oxide reduction), sodium bicarbonate and activated carbon injection) [46].

The recovery of metals is based on pyrometallurgical practices to obtain base metals using the plastic fraction as fuel (energy valorisation) and further hydrometallurgical refining to extract precious metals and other elements such as In, Sb, Sn, etc.

9 large companies recycle PCBs at a large scale globally. They are based on copper and lead production processes, obtaining precious metals from the by-products of those processes. Other metals can also be recovered, such as Nickel which can be extracted in NiSO4 to be used in batteries electrolytes.

As an example of large-scale PCB recycler located in North West Europe, the Umicore process in Belgium and Germany is now described:

Umicore

PCB, integrated circuits (IC), processors, connectors and small electronic devices (after removal of batteries) are treated in integrated copper and precious metals smelter-refinery operations after mixing them with other precious metals-containing materials (catalysts, by-products from nonferrous metals industries). Plastic is incinerated in the process and used as a reducing agent and source of energy. The high content of plastics in PCB is also one of the limitations of the process in terms of capacity. The Top Submerged Lance (TSL) furnace used does not process PCBs with a concentration of metals <10% as feed material. Feed materials are smelted using ISASMELT technology at about 1200°C to separate Cu bullion and Pb-rich slag. Copper is leached out and follows an electrowinning (electro-extraction) process and PMs are collected in the residue. The refining of the precious metals' formula is confidential, and the optimization of this process is a key point of the economic success of the process. The slag from copper smelting is treated in a lead blast furnace, lead refinery and precious metals refinery. The resulting copper matte (a mixture of copper sulphide and a small amount of iron sulphide) is sent back to the copper smelter. Ni speiss (a mixture of impure compounds of arsenic and antimony with nickel, cobalt, iron, and other metals, produced in the smelting of cobalt and other ores) is refined to obtain Ni and PMs-rich residue. Lead is refined, and all the PMs concentrates are refined to recover Ag, Au, Pt, Pd, Rh, Ir, Ru. In another facility, special metals such as In, Se, Te are recovered by hydrometallurgical processes. This process is the one that allows the highest number of elements recovered and the smallest amount of losses reported [8].

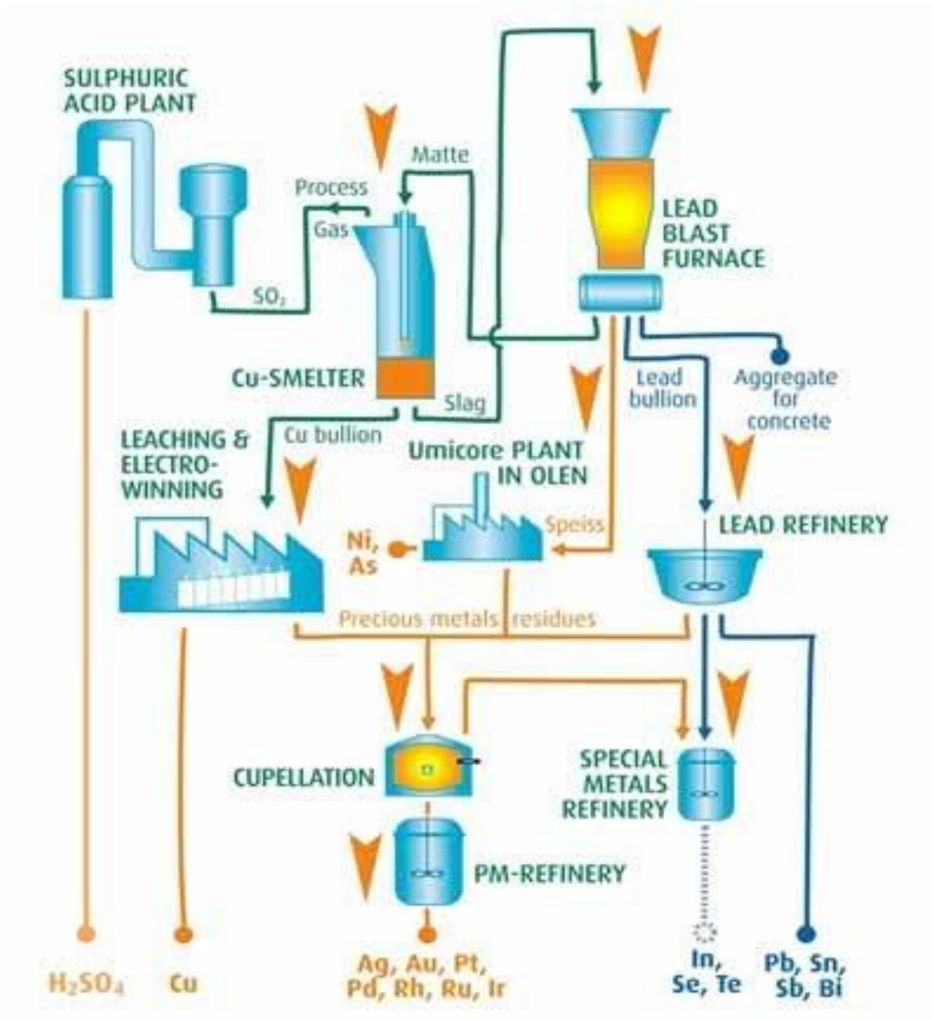

Figure 17. Umicore flowsheet [45]

III. Batteries

There is an established secondary market for batteries in Europe and 45.7% of batteries are collected in Europe. It can be assumed that the collection rates of batteries coming from industrial sectors at present are high, but specific data from DCI cannot be found.

a. Lead-acid batteries

Lead-acid batteries are one of the products with higher recycling rates and France, Netherlands, UK and Germany exceed the EU requirements for recycling efficiencies (65% EU required) and recycled lead content, as presented in the table below.

Table 19. Batteries statistics in France, UK, Netherlands and Germany in 2016[47]

	Recycling efficiency (%)	Recycled lead content (%)	Collection rate portable batteries and accumulators (%)
France	81.4	99	44.5
UK	89.7	96.6	44
Netherlands	78	76.2	49
Germany	84.7	99.5	46.2

b. *Lithium-Ion batteries (LIB)*

Lithium-ion recyclers can be found in the US, Canada, South Korea, Japan, China and different countries in Europe. The products obtained vary from one plant to another; some processes are focused on copper and aluminium recovery while the more sophisticated plants can recover almost all the materials in the battery: lithium carbonate, cobalt sulphate and nickel sulphate by hydrometallurgical processes, following the pre-treatment processes of mechanical size reduction and pyrolysis. However, achieving high efficiency regarding materials recovery depends directly on the availability of batteries to be recycled. [30]. 85.000 tonnes of LIBs were recycled in China by over 20 companies (67kt) and in South Korea (18kt) by at least 6 companies in 2018. These two countries also have the greatest share of LIBs production. A fraction of the batteries recycled in these countries comes from Europe and some may be pre-processed before being transported.

There are different technologies of LIBs (lithium cobalt oxide (LCO), lithium iron phosphate (LFP), lithium nickel cobalt manganese oxide (NMC), lithium manganese oxide (LMO), etc.), but the most common in DCI is LCO, the typical battery used in electronics. These batteries include a high concentration of cobalt (~17%), coming from the cathode ($LiCoO_2$) which makes recycling economically profitable. Regarding the CRMs, graphite is also present in the anode, which is recoverable via hydrometallurgical processes, although it is currently lost in the recycling process. Ongoing research is investigating the substitution of graphite with other materials (silicon nanowires or lithium metal) [48].

Several facilities are recycling batteries in Europe. Most are listed in the article for the European Commission by Franco, Persio and Boon-Brett (see Table 20). This study was focused on lithium-ion batteries recycling, given the expected increase of waste flow of these batteries from the electric vehicles sector.

Table 20. Recycling of batteries facilities [49].

Battery type	Route	Company	Location	Capacity	Final product [50]
LIB, NiMH	Pyrometallurgy	Umicore	Belgium	7000	$CoCl_2$ (battery grade), Ni, Cu, Zn
NiCd, NiMH, LIB	Pyro + hydro	Accurec recycling	Denmark	6000	Black powder
LIB	Pyro + hydro	Glencore	Canada & Norway	7000	Co (not usable in batteries)
LIB	Hydrometallurgy	Recupyl S.A.	France & Singapore	110	Co (not usable in batteries)
LIB	Hydrometallurgy	AEA Technology	UK	n/a	Co (not usable in batteries)
NiCd, NiMH, LIB	Pyro + mechanical + hydro	SNAM	France	300	Co (not usable in batteries)
NiCd, NiMH, LIB, Zn alkaline	Mechanical	AkkuSer Oy	Finland	1000 (LIB)	Co (not usable in batteries)
LIB	Pyro + mechanical	Batrec Industrie AG	Czech Republic	200	Co (not usable in batteries)
LIB	Hydrometallurgy	Euro Dieuze/ SARP	France	200	Cu, Al, Ni, Co, Li
Various including LIB	Pyrometallurgy	Valdi	France	20000	
LIB (from EV)	Hydrometallurgy	LithoRec*	Germany		CoO, Li salt

*Data from Omelchuk & Eramet, 2019

Ni and Cu can be recovered after melting (following the discharge, size reduction and separation). Co can be recovered as an alloying element. The slag from the melting process can be treated by leaching and solvent extraction.

According to Eramet [50], most of the LIB recyclers located in Europe work in an open loop, i.e., the resulting product is used in a different sector because the quality or purity of the products does not allow their use in batteries. Only Umicore permits the reintroduction of Co in new batteries, as well as SNAM, who produce black powder for batteries. In Europe, mainly lithium cobalt oxide (LCO) technology is recycled (less than 5000 tons/year). The LIB recycling industry is much more developed in China where more than 20 players recycle cobalt in a closed-loop due to higher availability of spent LIBs. The LIB sector in Europe is still young with a large room for improvement and it is expected to grow simultaneously with the market for electric vehicles. The reclamation of battery-grade products can be improved, although the open-loop recycling is an alternative to decrease the use of primary CRMs in other sectors.

1.6.5. Illegal exports

The current legal framework does not prohibit illegal exports of WEEE to developing or non-developed countries. According to Zoetman, 2006, 1.9 million tonnes of WEEE are exported annually to developing countries [51]. This quantity includes legal exports of equipment to be reused and illegal exports (10-20% of total WEEE mass generated in the EU). According to the Basel Action Network report in 2018, most of the exported waste comes from municipal collection points [52]. Considering waste data centre equipment as industrial waste, it can be assumed that the export of equipment is comparatively low, and the waste is mostly treated in Europe in formal or informal/unregistered facilities.

1.7. Eco-design of DCs

Circular economy considerations must be introduced in DCI during the equipment design phase because this has a direct influence on the performance of the equipment in subsequent life cycle stages regarding sustainability. Eco-design has three main goals:

- Preservation of raw materials
- Reduction of non-valuable waste
- Make it easier to attain recycling goals

Eco-design aims to optimise dismantling, separation and/or further valorisation of materials via refurbishing, recycling or energy valorisation. It can be applied to products destined to be dismantled and shredded. The high modularity of racks of servers and the easy accessibility of the equipment (especially storage equipment) is already included in some standards (IEC Technical Report 62635:2012 or PAS 141:2011). This is already an advantage in respect to other industries, as it permits the creation of a single-product waste stream when the servers are located in high scale data centres. Although current standards do not consider the content of CRM, a life cycle approach is used to optimise the processes of dismantling, reuse, refurbishing and recycling from the design phase.

1.7.1. Environmental Footprint and Material Efficiency Support for product policy, JRC 2015.

The JRC analyses the material efficiency of enterprise servers and provides a few recommendations to improve the circular economy and material efficiency of DC equipment. An exhaustive study and an LCA showed that the reuse of components, improvements in the design for disassembly, reuse, recycling and recovery, provision of technical information and information concerning CRMs are crucial to the development of a CE. As the electronics industry is one of the largest consumers of CRMs, information about the location of CRMs within the components and products should be provided to avoid landfilling of these materials.

One of the conclusions from the LCA is that PCBs and storage devices account with the highest share of the impacts in the manufacturing phase and the overall abiotic depletion potential (by the CML 2001 impact assessment method).

The report also recommends the use of new indicators to evaluate the benefits of equipment and component reuse: i.e. the reusability index and the reusability benefit rate. The report also uses the recyclability rates based on the formula present in IEC/TR 62635 standard.

1.7.2. Eco-design Technical Assistance Study on Standards for Lot 9 Enterprise Servers and Enterprise Data Storage

The study carried out in 2016 aims to provide technical assistance to support standardisation mechanisms for enterprise servers and data storage equipment. An assessment of standards used by industry is included and shown in Table 8 above (see Table 8).

This deliverable is part of the European Ecodesign Directive, focused on sustainability in line with Europe's 2020 strategy. Enterprise servers were identified as a priority for improvement.

Different standards are assessed to study different parameters such as:

- Active state energy efficiency
- Power supply efficiency
- Power supply power factor
- Operating temperature
- Operating humidity
- Acoustic noise
- Deletion of data
- End-of-life considerations:
    - Removability of external enclosures to increase the material recovery rate
    - Removability of PCBs, processors, data storage devices (HDDs and SSDs) and batteries
    - Ease of dismantling, reuse and recycling
    - CRMs content
    - Postconsumer recycled content of CRM
    - Firmware availability and compatibility

However, regarding end-of-life, there are no test methods to identify requirements to remove external enclosures, PCBs, processors, data storage devices and dismantle servers.

1.7.3. Eco-design and energy labelling requirements for computers and servers (2014)

The scope includes small-scale servers. The initiative aims to decrease energy consumption in real-use situations, to improve reparability and reduce the burden on suppliers to facilitate compliance control by the EU Member States.

The report states that poor reparability leads to premature obsolescence and increased waste. It also highlights the need to address for still perfectly working power supplies, the most frequent reasons for irreparable damage, premature obsolescence and possibility of reuse.

1.7.4. Open Compute Project (OCP)

The Open Compute Project (OCP) is 'a collaborative community focused on redesigning hardware technology to efficiently support the growing demands on computing infrastructure.' (https://www.opencompute.org/about). It is the hardware equivalent of open-source software. The community works to create single standardised specifications that can be adopted by multiple suppliers. It aims to collaboratively 'design, use, and enable mainstream delivery of the most efficient', flexible and scalable designs.

The Open Compute Project is committed to minimising the environmental impact of infrastructure technology and energy consumption through the continual evolution in energy and material efficiency. Open Compute Project evaluates the influence of all components within the data centre ecosystem, leading to optimised energy and material use as well as reduced environmental impact. Hyperscale DC operators, who account ~30% of the server market (~$1 billion), are key and founder members of the Project, which was set up as an alternative to the large branded producers/products such as Dell. The aim is to increase modularity, strip out 'unnecessary' parts, to accelerate refresh rates, component updates and repair of servers and to minimise the number of staff required to manage and run hyper-scale DCs.

The OCP Server Project provides standardised server system specifications for scale computing. Standardisation is key to ensuring that the OCP specification pool does not become fragmented by point solutions that plague the industry today. The Server Project collaborates with the other OCP disciplines to ensure widespread adoption and achieve optimisation throughout most life cycle stages from design validation to manufacturing, deployment, data centre operations, and decommissioning.

Scope of the project includes:

1. Open Rack Compatible Chassis and Sleds
2. Open CloudServer Compatible Chassis and Blades
3. Micro-servers, Chassis and carriers included ARM, x86 (Intel)* *(*microprocessors – Intel x86 have Complex / ARM have Reduced Instruction Set Computer architecture) EIA 310-D/E 19" Rack Derivative Chassis and Sleds using Open Rack Motherboards
4. Components and Peripherals-riser cards, mezzanine I/O, accelerators, networking.
5. Specification Standards: Electrical Interfaces, Mechanical Interfaces, Manageability, debug, & Test framework.

The Server Project is composed of Platinum, Gold and Silver members, including the top 3 Chinese manufacturers (Inventec, Inspur, Huawei), Taiwanese based servers (Quanta, Mitac) and HP, IBM among others.

1.7.5. Open Data Centre Committee (ODCC)

A similar project to OCP in China, using an economical perspective.

1.8. Conclusion and perspectives in CE and CRM in DCI

Sustainable development of the DCI is a priority in Europe for the immediate and long-term future. Applying an efficient CE would lead to a decrease in their overall environmental impact, by reducing electricity consumption in the use phase, and by reducing environmental, economic and social impacts related to the material resources used in DCI. The IT equipment used in the industry is frequently replaced and storage equipment (HDDs or SSDs), data servers, batteries and network equipment are the items with the shortest lifespan (see Table 11).

All these products include CRMs in their composition. These materials are of great importance in the European economy for environmental, energy and innovative technological applications. At present, however, the risk to supply is high. Almost 100% of all the CRM used in DC equipment in the EU are imported (see Table 16). Therefore, creating a secure supply chain for these materials in Europe from waste products must be an objective to ensure the continual and economic operation of the industry; this should also improve the environmental, economic and social performance of DCs.

However, at present, the recycling industry for these materials is not currently well established in Europe. The CRMs are used in very small concentrations (e.g. at 0.05% Nd has the highest concentration in a data server, according to the 2015 estimations by JRC – see Table 15-.) and their recovery is generally not profitable yet. Cobalt is the only material being recycled from old scrap (i.e. redundant products such as spent LIBs) although there is still large room for improvements to recycle cobalt in a closed loop and increase the recycling rate. Furthermore, the LIBs technologies and composition are permanently evolving and challenging recyclers to adapt their processes. Consequently, the priorities in DCI must be aligned to CE principles of avoiding and reducing the CRMs and therefore, generation of waste, reuse, refurbishment and, ultimately recycling the DC equipment at end-of-life.

Optimising the CE of DCI requires Life Cycle Management approaches such as Life Cycle Assessment. It can be used to identify the hotspots of the DC life cycle quickly as a result of which the efforts made by the stakeholders will be focused on the critical stages/products/components that are causing highest environmental, economic and social impacts during the DC life cycle. The development of primary databases, including accurate material composition, must be created to implement efficient sustainable practices in the short term. The use of new technologies could help to boost the process; e.g. the use of Artificial Intelligence (AI) to predict variables in product design impacts, together with LCM approaches, can be used to 'ecodesign' the product and extend the lifespan of the equipment and achieve higher efficiencies in the end-of-life stages of the DC life cycle.

Avoiding the use of CRM in the design phase would decrease the economic importance of these materials in the DCI and, therefore, the criticality of these materials from this industry. Given that substituting CRMs in DCI is not always achievable, reducing the amount and number of CRMs is a more realistic goal. Innovating in the design of electrical and electronic equipment for DCI is a key step to increasing the circularity of DCI products. Therefore end-of-life considerations must be included in the design phase to optimise the circular economy through eco-design.

Reusing and refurbishing the equipment are low energy-intensive processes that reduce the demand for primary CRMs. Therefore, more collaboration among stakeholders, such as refurbishers, data destruction companies and designers is necessary to increase the efficiency of the reuse phase. Data destruction by data wiping can be enhanced from the design phase by including erasing commands for example. This is important because the use of data wiping instead of the physical destruction of devices enhances reusability and could lead to improve the PM recovery in the recycling phase, making the recycling stage more profitable.

Research into recycling processes that allow the use of recycled CRMs in new EEE is an important step in avoiding long term problems. Financing the industrialisation of these processes is another challenge because the volatile prices of CRM limit the economic viability of implementing these processes at industrial scale. Cobalt recycling from old scrap is expected to continue to increase, given the growth of demand from electric vehicles industry. Even though WEEE recycling is being developed, more focus must be given to the recovery of CRMs and innovative approaches must be developed to limit losses from conventional WEEE recycling processes (i.e. the copper and lead production routes). Some related research projects are being carried out, such as tantalum recovery via the hydrometallurgical route by TND in France; tantalum recovery by bioleaching and magnets recycling in Germany by Recycling Börse.

The implementation of economically viable processes takes years, and therefore it is necessary to tackle the problem in the short term and to focus on extending the lifetime through reuse and refurbishment. These activities are already practiced in the industry, but not as efficiently as they could be and there is not enough collaboration among stakeholders to achieve higher reuse rates. Compatibility between components in a DC equipment must be simple by enabling access to firmware updates. Despite these problems, the disassembly and dismantling of DC equipment and component is being optimised, especially since the implementation of WEEE Directive

More attention should be directed at CRMs containing components and information about the CRM content should be readily available to all the stakeholders to facilitate and increase reuse and recycling. This is, of course, dependent on the equipment design although at present these criteria are not included in the design phase.

Solutions must be initiated and led by most influential stakeholders on the circularity of DC equipment, namely designers, manufacturers and non-material influencing actors. The design should facilitate reuse, dismantling and recycling of components and materials; manufacturers must include concerns about material composition in their requirements and specifications to improve the economic and social impacts of their supply chain; non-material influencing actors, as governmental bodies or standardisation organisations in Europe should force the rest of the stakeholders to include material resource efficiency in their activities to ensure a secure supply chain for the industry. Influencing designers will not be easy given the complex supply chain for this equipment as most of the components' designers are located outside Europe. Several sub-contracted companies also participate in the design of the different components that constitute, for example, a server. Therefore, a higher circular economy efficiency for components and materials, including CRMs, can only be accomplished by collaboration among stakeholders and by informing them about the potential benefits for European industry.

2. EXPERIMENTAL STUDY

2.1. Aim of the study

This exercise aims to gain a better understanding of the DCI from the CE point of view by investigating different important aspects of data centre equipment (servers and network equipment) to analyse their performance in a circular economy and provide recommendations to improve this performance. The study includes:

- Experimental assessment of DC equipment:
    - Dismantling of equipment: servers and switches.
    - Material characterisation to ascertain the concentration of CRMs in the motherboard of one server.
- Screening LCA: to observe the environmental consequences of applying a circular economy and identify hotspots in the life cycle.
- Ecodesign recommendations: to improve the circular economy performance of DC equipment in NWE.
- Economic assessment of end-of-life servers and switches full dismantling case in Europe.

2.2. Circular economy performance assessment on data centre equipment

The equipment with higher replacements rates (shorter lifespan) was assessed. Two servers and two switches were dismantled and the environmental impacts of reusing and replacing components were assessed by screening-LCA. The motherboard from SV.1.1 was characterised to study the material composition.

The products studied are introduced in Table 21. Two servers and two switches (network equipment) were dismantled. The equipment was manufactured at different times to assess the evolution of resource efficiency. Both servers presented the capacity for two CPUs.

Table 21. Products assessed

Type of equipment	Model	ID	Year of manufacturing	Dismantling	Screening LCA	Characterisation
Data server	Dell Svr Std 2003 R2 1-4CPU 5Clt	SV.1.1	2005	Yes	Yes	Yes (PCB motherboard)
	Dell PowerEdge R320	SV.1.2	2012	Yes	Yes	Not included
Switch	HP Procurve switch 2524 J4813A	SW.1.1	2000	Yes	Yes	Not included
	HP Procurve 2610-24 J9085A	SW.1.2	2009	Yes	Yes	Not included

2.2.1. Experimental

I. Dismantling procedure

The dismantling phase was assessed before characterising the equipment. The dismantling process in the laboratory in a real refurbishing or recycling facility highlighted some differences, such as the time used to dismantle, and the number of materials streams obtained. In this case, as the goal of the process was to characterise the equipment and provide ecodesign recommendations, the components were first disassembled and separated; the materials streams and components were then weighed. A photographic record of the process is included in Annex 1. Data from the dismantling phase was then used in the economic assessment and the screening LCA.

The dismantling phase provided a better understanding of the modular design of servers. Even though HDD was not found in servers, it was noted that the installation and removal of HDDs and PSUs were straightforward, which facilitates the potential reuse and refurbishing of these components. On the other hand, the dismantling and recycling PCBs is not straightforward, even though they are the highest value components in the server, removal is difficult. One of the CPUs, placed under a plastic cover, had already been removed before arriving at the laboratory. The other CPU was located under metallic heatsink which was screwed in place. The composition of the switches was less complex, but it was evident that they were also less modular. There were no plastic levers in the switches to aid removal of any of the components, which were screwed to the chassis.

a. SV.1.1.

The dismantling process in SV.1.1 was more straightforward due to the modularity of the component assembly.

PSUs, fans, plastic parts and some PCBs were removed manually, using plastic levers. The motherboard and other CRM-rich PCBs were attached with screws, which were removed using 3 different sizes of a screwdriver. It took quite a long time to remove the necessary screws to separate all the components (~50 units).

The chassis accounted for 62.4 % of the total server mass. PSUs and PCBs accounted for the second-highest mass (18.8% and 8.79% respectively).

Only one CPU (under the heat sinks) was found. As previously stated, the CPU located under the plastic cover had already been removed before arriving at the laboratory.

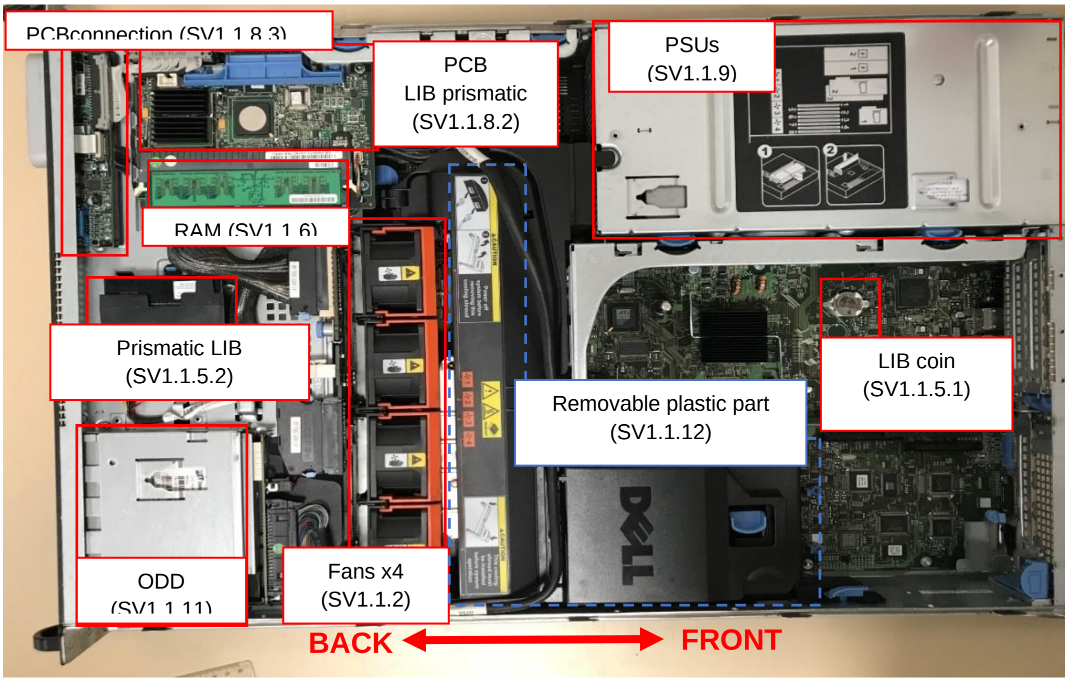

Figure 18. Inside view server SV.1.1

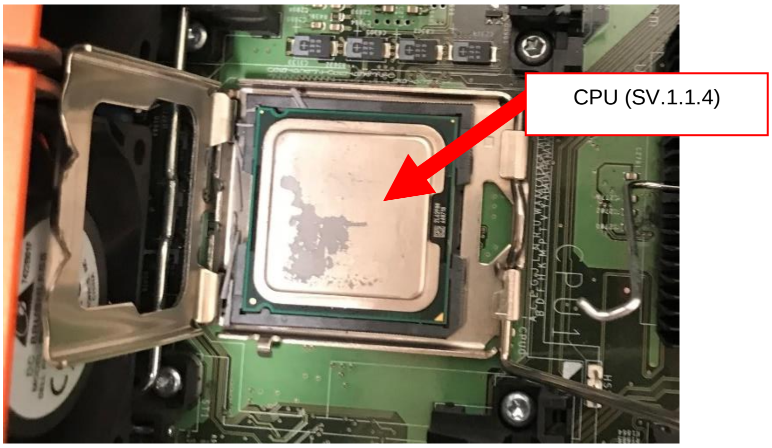

Figure 19. CPU present under heat sinks (SV.1.1.4)

Cables from all the components were dismantled (using pliers in some cases) and incorporated to the cables stream.

The PSUs were completely dismantled given that they all had a different mass but similar appearance. The metallic parts from the PSU chassis, cooler and PCBs were incorporated to the metallic stream and the difference derived from the PCBs. Different PCB technologies were also used in each PSU (see figures below).

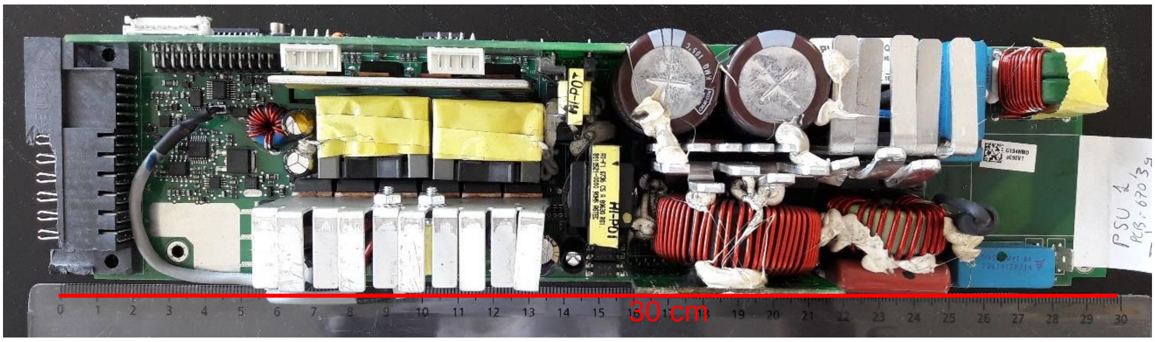

Figure 20. PCB from PSU 1 (SV.1.1.9.1.5)

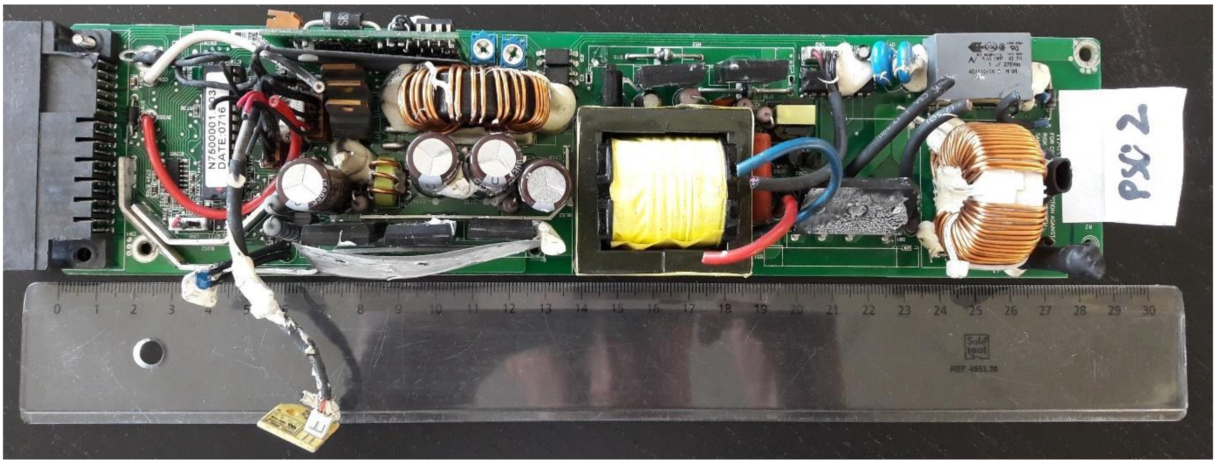

Figure 21. PCB 1 from PSU 2 (SV.1.1.9.2.5)

b. <u>SV.1.2.</u>

The dismantling process in SV.1.2 was easier and faster than SV.1.1; more levers and fewer screws facilitated the process although it had the same type of modular assembly and the same components. The total number of PCBs was higher but only the motherboard PCB from the PSU needed screwdrivers to be removed. The ODD was not present as an additional device, in consequence, there was no need to unscrew the ODD to get the PCB. There were only 34 screws in this server (18 and 8 from each PSU).

It is important to note that there was a QR code with the instructions attached to the back of the cover (Figure 23), where useful information could be found regarding the end-of-life namely:

- presence of lithium-ion batteries,
- probability of finding electrolyte capacitors in the PSU,
- absence of capacitors containing PCBs or
- presence of water in the heat sinks.

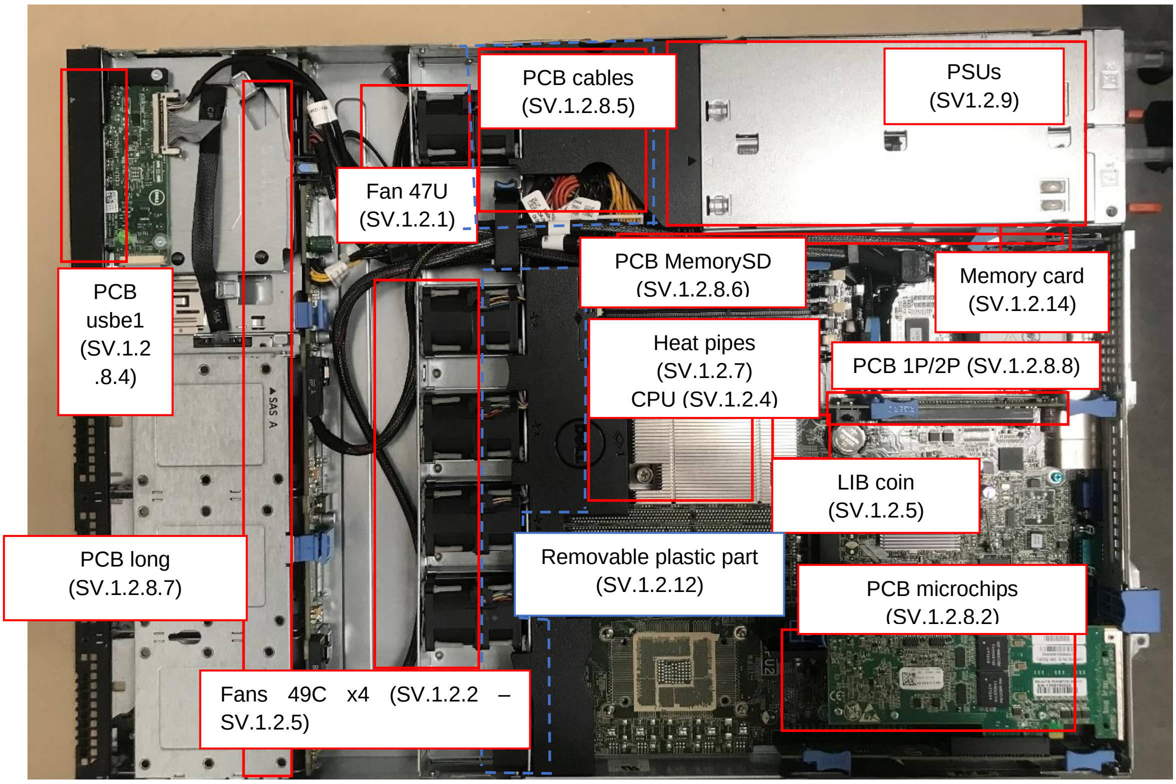

Figure 22. Inside view of server and location of components

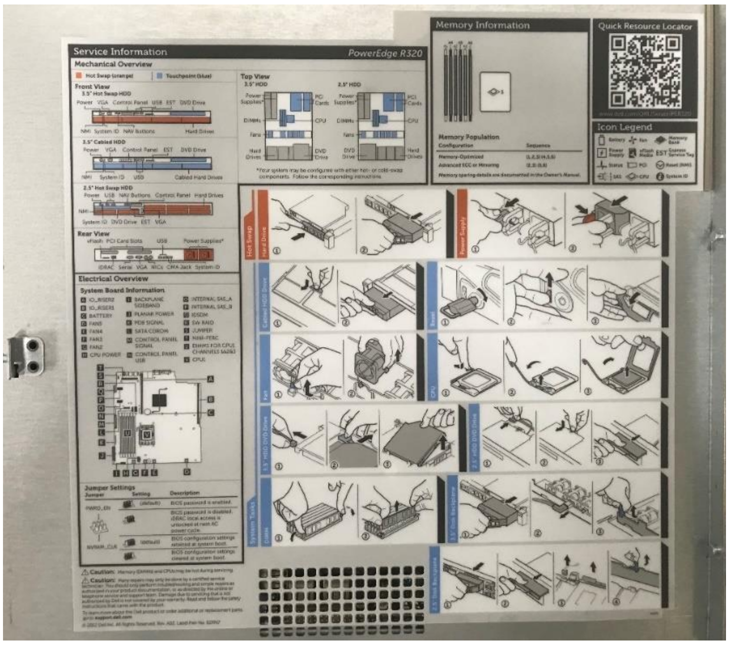

Figure 23. Instructions and QR code on the chassis cover

There were a further 6 other documents with information such as drivers and firmware download links and the associated installation procedure which facilitates reuse and refurbishment. PSUs, fans, plastic parts and some PCBs were removed manually, just using levers. In this case, there were 5 fans (although the total mass of the fans is lower than in server SV.1.1.) where one fan was dedicated to cooling the PCB connected to the PSUs.

There was no prismatic battery, only a bottom battery attached to the motherboard. The motherboard and other rich PCBs were attached with blue screws, (for easy identification) and 3 different sizes of screwdrivers and pliers were used to remove all components.

In this server, the percentage by mass of the PSUs is lower than in the first server. The PCB' fraction presents higher importance. Only one CPU (under the heat sinks/ cooling pipes) was found.

Both PSUs have a similar mass and internal configuration.

Figure 24. Open PSU1201D (SV.1.2.9.1)

The only drawback compared to the first server was the dismantling of the PSU connector. The presence of an internal screw made it difficult to access and extract.

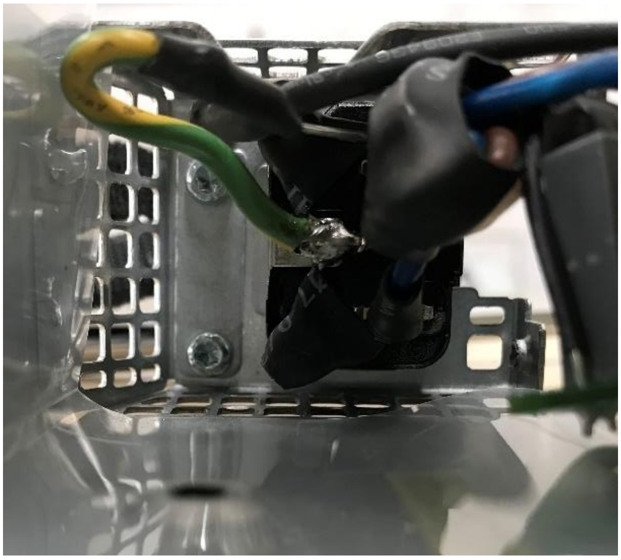

Figure 25. PSU connection (SV.1.2.9.1.2). Difficult access to screws.

c. SW.1.1.

This switch manufactured in 2000 contained 4 PCBs, one fan, a metallic and plastic chassis. Two covers (one metallic and one made of plastic) were removed by removing screws before having access to the inner components. The switch has a lot of components on the surface, as in servers.

The chassis accounts for the highest fraction of the total mass (55%) followed by the PCBs stream at 30% of the total mass. No plastic levers were found, so unscrewing was necessary to remove all the components. Large metallic parts were attached to the PCBs, especially to the old PCB which had the power supply function.

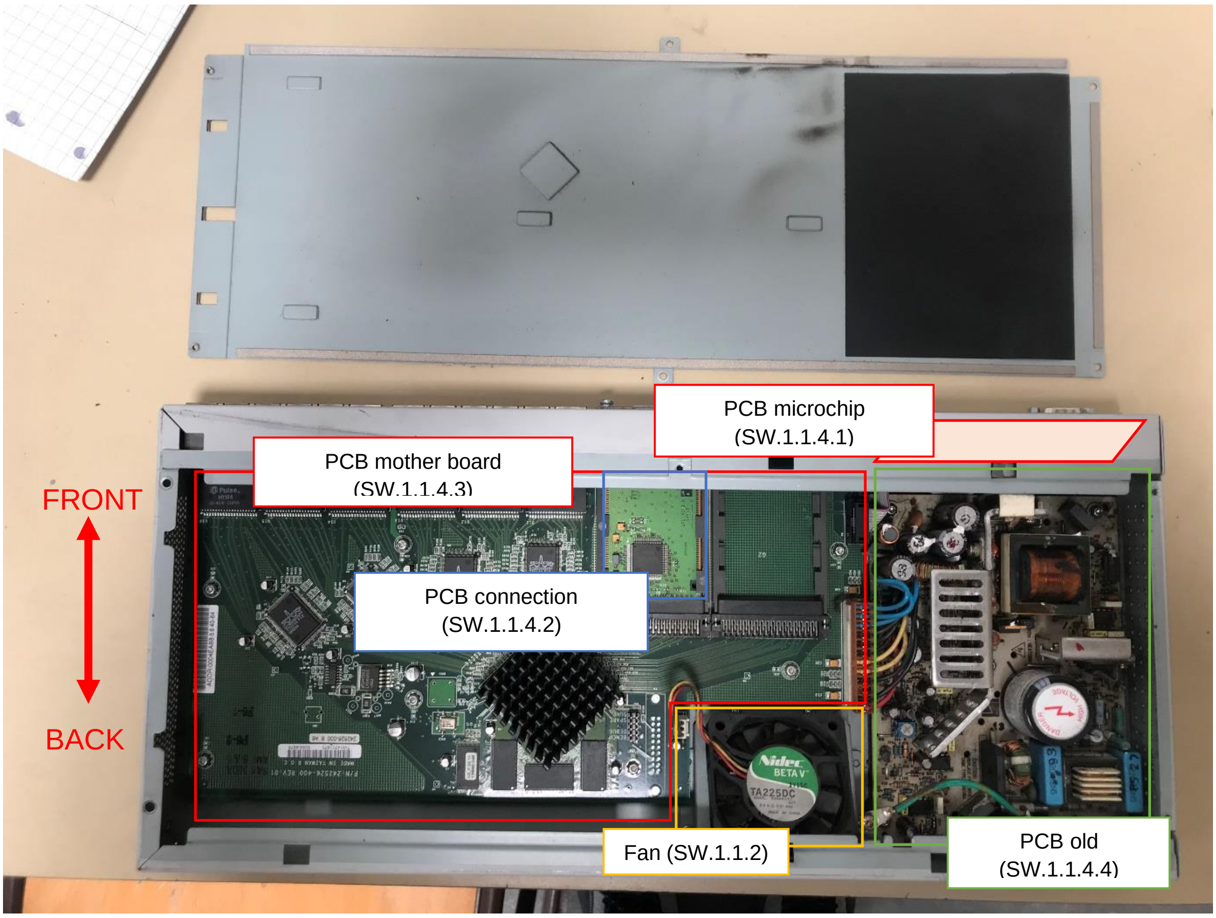

Figure 26: Inside view SW.1.1.

d. <u>SW.1.2.</u>

SW.1.2. was manufactured in 2007 and unlike to SW.1.1. and servers there was some space i.e. it was not full of components. This is evidence of developments in material efficiency in the design of switches; the PCB was also lower mass (~200 grams) which removed the need for a fan. The chassis was also 100% metal and the design was also optimised to facilitate the replacement and dismantling of components. In this case, it was only necessary to unscrew one metallic cover to access the inner components.

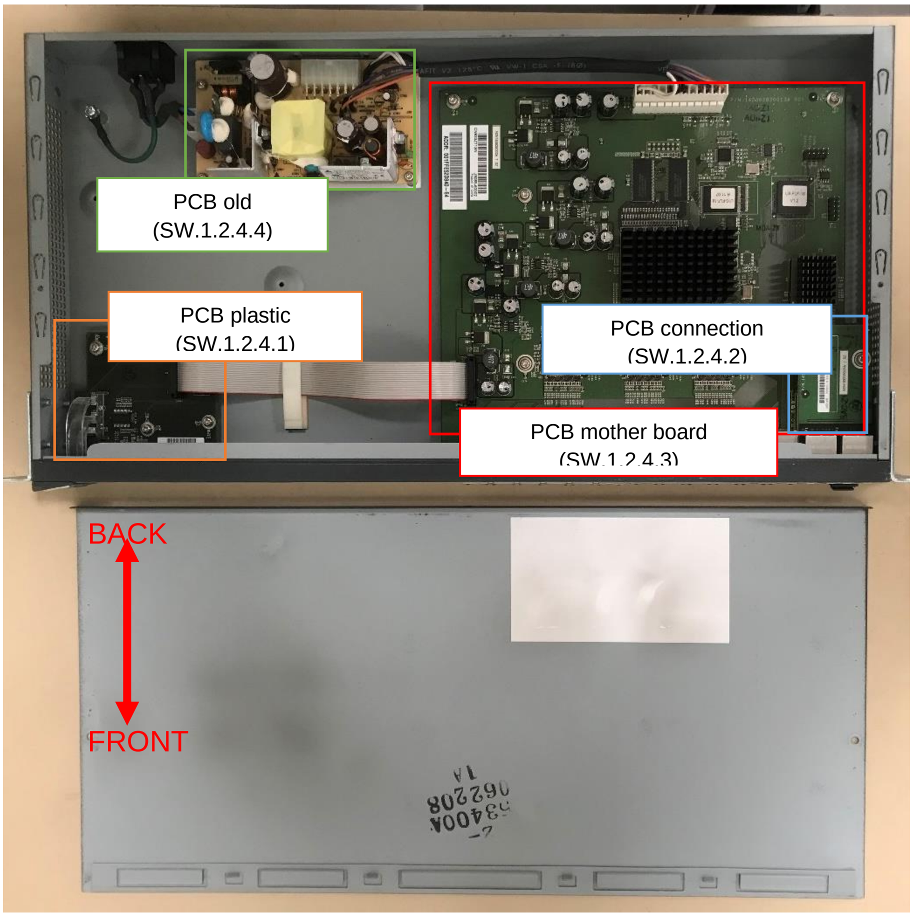

Figure 27. Inside view SW.1.2.

II. <u>Dismantling results</u>

The components found in the disassembled equipment are shown in the tables below. More comprehensive results can be found in Annex 1.

Table 22. Components found in servers.

<table>
<tr><th></th><th>Component</th><th>Quantity</th><th></th><th>Component</th><th>Quantity</th></tr>
<tr><td rowspan="6">SV.1.1</td><td>Chassis</td><td>1</td><td rowspan="6">SV.1.2</td><td>Chassis</td><td>1</td></tr>
<tr><td>Fans</td><td>4</td><td>Fans</td><td>5</td></tr>
<tr><td>Drivers</td><td>0</td><td>Drivers</td><td>0</td></tr>
<tr><td>CPU</td><td>1</td><td>CPU</td><td>1</td></tr>
<tr><td>Batteries</td><td>2</td><td>Batteries</td><td>1</td></tr>
<tr><td>RAM</td><td>1</td><td>RAM</td><td>0</td></tr>
</table>

	Heat Sinks for CPUs	1		Heat Sinks for CPUs	1
	PCBs	7		PCBs	10
	PSUs	2		PSUs	2
	Cables	7		Cables	4
	ODD	1		ODD	0
	Plastic	25		Plastic	12
	Screws	50		Screws	18
	Undefined	1		Memory SD	1

Table 23. Components found in switches.

	Component	Quantity		Component	Quantity
SW.1.1	Chassis	1	**SW.1.2**	Chassis	1
	Fan	1		Fan	0
	Plastics	1		Plastics	3
	PCBs	4		PCBs	4
	Cables	2		Cables	5
	Screws	37		Screws	25

The components were further dismantled to obtain the final streams for characterisation, based on potential recycling. 10 streams were differentiated in servers (see Table 24).

Table 24. Streams obtained from SV.1.1. and SV.1.2.

ID	Stream	Mass (g)	%	ID	Stream	Mass (g)	%
SV.1.1.S1	Metallic	14435.10	73.36%	SV.1.2.S1	Metallic	7295	69.52%
SV.1.1.S2	Plastics	1300	6.61%	SV.1.2.S2	Plastics	759.90	7.24%

SV.1.1.S3	Drives	0	0	SV.1.2.S3	Drives	0	0
SV.1.1.S4	CPU	22.17	0.11%	SV.1.2.S4	CPU	33.30	0.32%
SV.1.1.S5	LIBs	51.69	0.26%	SV.1.2.S5	LIBs	2.80	0.03%
SV.1.1.S6	RAM	14.31	0.07%	SV.1.2.S6	RAM	0	0
SV.1.1.S7	PCBs	3321.40	16.88%	SV.1.2.S7	PCBs	2161.00	20.59%
SV.1.1.S8	Cables	320	1.63%	SV.1.2.S8	Cables	240.10	2.29%
SV.1.1.S9	ODD	211.30	1.07%	SV.1.2.S9	ODD	0	0
SV.1.1.S10	Undefined	2.21	0.01%	SV.1.2.S10	Memory card	1.70	0.02%
TOTAL	SV.1.1	19678.19	99.99%	TOTAL	SV.1.2	10493.80	100.13%

Table 25. Streams obtained from SW.1.1. and SW.1.2.

ID	Stream	Mass (g)	%	ID	Stream	Mass (g)	%
SW.1.1.S1	Metallic	1591.90	58%	SW.1.2.S1	Metallic	1816	72%
SW.1.1.S2	Plastics	337.70	12%	SW.1.2.S2	Plastics	13.70	1%
SW.1.1.S3	PCBs	787.60	29%	SW.1.2.S3	PCBs	640.80	26%
SW.1.1.S4	Cables	16	1%	SW.1.2.S4	Cables	34.70	1%
TOTAL	SW.1.1	2733.20	99.75%	TOTAL	SW.1.2	2505.20	100.21%

The difference between the total mass of the individual components and that of the original equipment is the result of a human error or inaccurate weighing.

III. Equipment conclusions from dismantling

Both servers and switches were modular in that the components could be found in the same location. It is important to note that material efficiency is higher in newer equipment. However, there was no information regarding material composition and consequently, recyclers cannot select components for disassembly based on their material value for recovery at their plant.

Servers:

SV.1.1 was manufactured in 2005 (before the WEEE Directive) while SV.1.2 was manufactured in 2012 (when WEEE Directive was applied) and end-of-life information could be found by following a QR code.

First, the size was reduced in the newer so the product requires less material. The newer server is much easier to dismantle given that the number of screws to fully dismantle all the components is lower (18 vs 50). The screws are easy to identify as they are blue. Pliers are necessary to remove some of the PCBs in both servers and although the dismantling phase has been optimised, it could be adapted to facilitate PCB removal.

Switches:

As in the case of the servers, the design has been optimised and less materials are used to perform the same function, e.g. there is no fan, which eliminates a significant amount of plastic. The quantity of steel could be reduced by reducing the size of the switch, given that there is space inside the casing. Also, it presented improvements regarding the dismantling and PCBs were easily removable by unscrewing 4 screws.

2.2.2. Chemical characterisation

Obtaining a full material characterisation of PCBs requires the dissolution of more than 30 elements to study them in the Inductively Coupled Plasma Spectroscopy (ICP). First, the PCB is shredded into small pieces (5-15 cm^2) and goes through a process of pyrolysis to remove the organic matter from the sample and liberate the metals for the characterisation. Additional milling processes are used to reduce the particle size until the microns range before dissolving the sample by acid digestion. This step requires at least two cycles of introducing the sample in a mix of strong acids at high temperature and pressure. The mix of acids varies depending on the composition of the sample and the process is adjusted to suit the sample.

I. Feed material

The PCB motherboard SV.1.1.8.1 stream from the server SV 1.1 is analysed to know the material composition.

Table 26. PCB motherboard physical characteristics.

ID	Component	Mass (g)	Surface (cm^2)	Thickness (mm)
SV.1.1.8.1	PCB motherboard	1224.8	626.75	2.5

The motherboard is thicker than other PCBs and there is a high concentration of SiO_2, deriving from the glass fibre reinforcement. The acid digestion process must be adjusted to dissolve all the materials and all the fibres. Silica is dissolved using HF and HBO_3, but the concentrations, additional solvents, quantities and steps vary depending on the overall composition of the PCB.

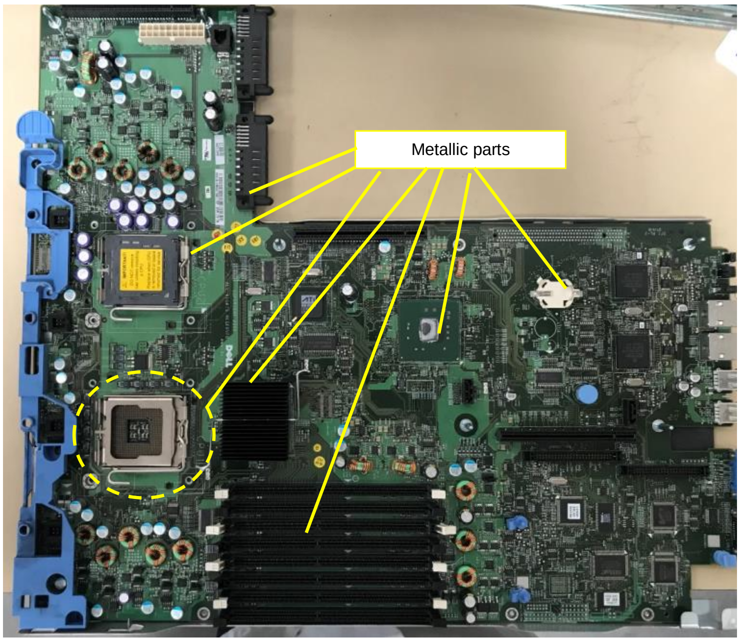

Figure 28. PCB SV.1.1.8.1 metallic parts

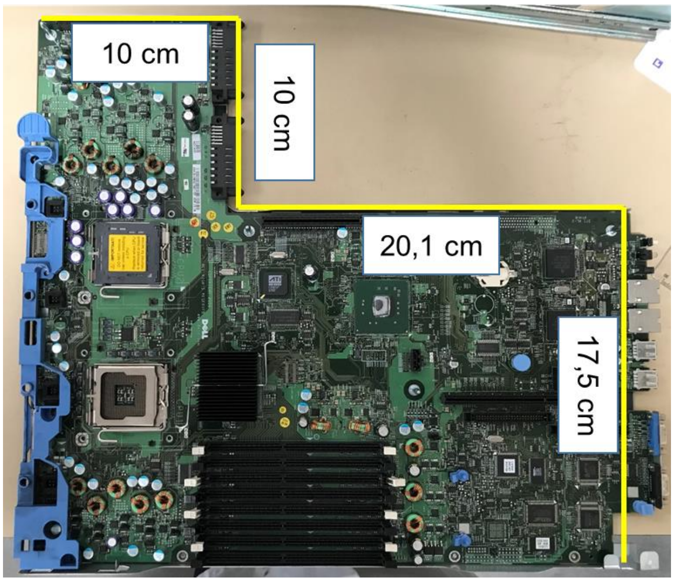

Figure 29. PCB SV.1.1.8.1 dimensions

II. Process

a. Manual cutting and removal of metallic parts

The size of the motherboard was reduced to pieces of ~ 5-15 cm². This step was required given that the motherboard did not fit into the shredder SM 100. Large size metallic parts were also removed to ease the shredding phase.

158 g of metallic components were removed.

b. Pyrolysis

The manually cut pieces without the metallic parts were put into the high-temperature furnace. The temperature is set at 500ºC; it takes 2 hours to reach this temperature and then one hour to heat the materials. The process is carried out at normal atmospheric pressure without varying the conditions (i.e. no introduction of reducing or oxidizing agents). Samples are cooled in the furnace for 18 hours.

The remaining PCB components weighed 859.2 g, so 197 g (16.1% of the total mass) evaporated during pyrolysis.

Figure 30. PCB after pyrolysis

c. Cutting mill: SM 100

After pyrolysis, the remaining PCB parts are manually introduced to a cutting mill where they are milled. It was noted that some particles were lost in the air and that these were probably disassociated carbon particles after the pyrolysis. Some organic (green) components were observed, so second pyrolysis was implemented to remove all the organic matter before the second size reduction phase.

The final mass obtained was 846.4 g meaning that 12.8 g were lost in the process.

After the second pyrolysis, only 14.4 grams has evaporated (1.2% of the total mass of the PCB). This means that most of the organic matter was successfully removed in the first pyrolysis.

Figure 31. PCB after cutting mill

d. *Vibrating disc mill RS 200*

A second milling step is carried out, this time, using a vibrating disc mill that allows the micro-particles (~4 µm) to be collected. The weight of the resultant black powder after this process (some hours after finishing it, given that it was weighted before starting the acid digestion) increased by 0.4%. Consequently, it is assumed that 4.8 g of water was absorbed, which could be more if we consider some losses during the milling process.

Table 27. Mass balance and losses in the preparation for the characterisation process.

Process	Stream	Mass (g)	%
Manual separation and cutting	Metallic fraction	158.0	12.9%
	PCB fraction	1056.2	86.2%
	Loss fraction	-10.6	-0.9%
1st Pyrolysis (1h at 500°C)	Start weight	1056.2	86.2%
	End weight	859.2	70.2%
	Loss fraction	-197.0	-16.1%
Shredding SM 100 4 mm	Start weight	859.2	70.2%
	End weight	846.4	69.1%
	Loss fraction	-12.36	-1.05%
2nd Pyrolysis (1h at 500°C)	Start weight	846.4	69.1%
	End weight	832.0	67.9%
	Loss fraction	-14.4	-1.2%
Shredding RS 200	Start weight	832.0	67.9%
	End weight	836.8	68.3%
	Water absorption	4.8	0.4%
	Loss fraction	-12.8	-1.05%

Table 28. Mass balance summary of preparation for characterisation process

Stream	Mass (g)	% of the initial mass
Initial weight	1224.8	100.0%
Metallic parts	158.0	12.9%
Lost by pyrolysis (organic matter)	211.4	17.3%
Lost by manipulation (non-willing loss)	23.4	1.9%
Water absorption (non-willing addition)	4.8	0.4%
End weight (ready for analysis)	**836.8**	**68.3%**

e. Sampling

The powder was mixed manually, and a sample of 300 mg was taken for the acid digestion.

Figure 32. Sampling process of the black powder after vibrating disc mill.

f. Acid digestion

This step aimed to dissolve the sample compounds into an acidic mixture as molecules or ions or the formation of complexes in liquid phase to enable identification in the ICP. The manipulation is done in a security chamber with fume extraction.

A mix of acids is used to dissolve the samples at high temperature and pressure. Hydrofluoric acid (HF) and aqua regia can be used to dissolve silicates from glass fibres and noble metals (e.g. gold, platinum). Considering the high thickness of the PCB, the percentage of glass fibres is high, so relatively large amounts of HF (hydrofluoric acid) are needed to dissolve all the silicon fibres (see Figure 33). Boric acid can be used to complete the excess of free fluoride after the digestion, forming fluoroboric acid.

The process had to be adjusted after the first cycle given that some particles remained solid. The semi-quantitative analysis revealed that silver was present in the non-dissolved particles, so it could be assumed that AgCl derived compounds were formed. They can be re-dissolved as AgCl-2.

Figure 33. PCB glass fibre layers

g. The chemical characterisation in ICP

The tables of results are presented in Annex 3. The results are expressed in a colour code, regarding the percentage of each PM or CRM found in its ores.

2.2.3. Economic assessment: Full dismantling business case

To achieve higher recovery rates for all materials, a full dismantling must be carried out to deliver different streams depending on the materials to be recovered and a hypothetical business case to this effect is now presented.

A new stakeholder in the DCI would fully dismantle the equipment and deliver the different streams to the appropriate recycler. The equipment would be obtained from refurbishers once it is considered as waste. The operations would be carried out in North of France, where it would be easy to access waste equipment from data centres and refurbishers in France, Germany, the Netherlands and Belgium. It will also be located near the Flanders region where the recycling ecosystem is well developed for all kind of materials, especially electronic waste.

Some assumptions are made regarding the components found in the server delivered by refurbishers. Missing components in the assessment of the hypothetical business case were not considered in the business model, assuming that in a real case refurbishers would recover some of them for reuse or sale. The main problems are the lack of one CPU, some memory and hard disk drives. Another assumption is made concerning the transport of materials, where 130 km were assumed (from Liège to Antwerp).

The value of the scrap equipment is shown in Table 29 and Table 30. Hard disk drives are included to highlight their high value as scrap. The feasibility study only takes into account the newest servers and switches dismantled, given that, in a real business case implemented in the next 3-5 years, the highest share of equipment found would be manufactured after 2009.

Table 29. Scrap value per stream and server unit.

ID	Stream	Mass (g)	Price scrap (€/g)[9]	Price scrap (€/server)
SV.1.1.S1	Metals	14435.10	9.01E-05	1.30E+00
SV.1.1.S2	Plastics	1300.00	3.96E-05	5.15E-02
SV.1.1.S3	Drives[10]	0.00	1.99E-03	5.21E+00
SV.1.1.S4	CPU	22.17	3.96E-02	8.79E-01
SV.1.1.S5	LIBs	51.69	2.58E-03	1.33E-01
SV.1.1.S6	RAM	14.31	2.22E-01	3.18E+00
SV.1.1.S7	PCBs	3321.40	Motherboard: 4.95E-3 Medium grade: 2.86E-3 Low grade: 4.95E-4	7.39E+00
SV.1.1.S8	Cables	320.00	3.0E-03	1.06E+00

[9] Values found in USD in the references were converted into Euro by applying a conversion factor of 1.11 USD = 1 EUR

[10] Not included in the feasibility assessment

SV.1.1.S9	ODD	211.30	3.06E+00 (€/unit)	3.06E+00
SV.1.1.S10	Undefined	2.21		
TOTAL	SV.1.1	19678.19		22.26
SV.1.2.S1	Metals	7295.00	9.01E-05	6.57E-01
SV.1.2.S2	Plastics	759.90	3.96E-05	3.01E-02
SV.1.2.S3	Drives[11]	0	1.99E-03	6.94E+00
SV.1.2.S4	CPU	33.30	3.96E-02	1.32E+00
SV.1.2.S5	LIBs	2.80	2.58E-03	7.21E-03
SV.1.2.S6	RAM	0	2.22E-01	0.00E+00
SV.1.2.S7	PCBs	2161.00	Motherboard: 4.95E-3 Medium grade: 2.86E-3 Low grade: 4.95E-4	4.96E+00
SV.1.2.S8	Cables	240.10	3.30E-03	7.92E-01
SV.1.2.S9	ODD	0		
SV.1.2.S10	Memory card	1.70	2.22E-01	3.78E-01
TOTAL	SV.1.2	10493.80		15.09

Table 30. Scrap value per stream and switch unit.

ID	Stream	Mass (g)	Price scrap (€/g)	Price scrap (€/switch)
SW.1.1.S1	Metals	1.59E+03	9.01E-05	1.43E-01
SW.1.1.S2	Plastics	3.38E+02	3.96E-05	1.34E-02
SW.1.1.S3	PCBs	7.88E+02	Motherboard: 4.95E-3 Medium grade: 2.86E-3 Low grade: 4.95E-4	2.48E+00
SW.1.1.S4	Cables	1.60E+01	3.30E-03	5.28E-02
TOTAL	SW.1.1	2.73E+03		2.69
SW.1.2.S1	Metals	1.82E+03	9.01E-05	1.64E-01
SW.1.2.S2	Plastics	1.37E+01	3.96E-05	5.43E-04
SW.1.2.S3	PCBs	6.41E+02	Motherboard: 4.95E-3 Medium grade: 2.86E-3 Low grade: 4.95E-4	2.29E+00
SW.1.2.S4	Cables	3.47E+01	3.30E-03	1.14E-01
TOTAL	SW.1.2	2.51E+03		2.57

[11] Not included in the feasibility assessment

It is assumed that the company is an SME and, the feasibility of the business is calculated using NPV (Net Present Value) and Rate of Return (RoR). CAPEX and OPEX calculations can be found in Annex 2. The efficiency of the process factor represents an unexpected time lost during the dismantling phase. Significant changes in the RoR and NPV are obtained given the relatively low investment needed to launch the activity by decreasing the efficiency of the process around 10%. The year of reference for the NPV calculations is the year the project will start.

Net Present Value (NPV) (€)	Rate of Return (RoR)	Efficiency of process
6.615.39	**29%**	**0.90**
-6.933.51	**-3%**	**0.80**

Table 31. NPV and RoR for 5 years.

I. Conclusions from economic assessment

The introduction of a new stakeholder carrying out the full dismantling of servers is not feasible considering the assumptions that were made and the high dependence on the efficiency of the process factors. Neither the volatility of scrap prices nor administrative fees were included in the case study. Consequently, the introduction of a new stakeholder could not be the best option to carry this activity, but given those high efficiencies of the dismantling process led to positive NPV and RoR, full dismantling could be an interesting option to carry out in-house. The implementation of circular economy life cycles (reuse, refurbish and preparation for recycling) by operators or data centre managers could lead to economic and material resource benefits. This assessment is short-term and is based on 5 years, while other benefits would be present in long term (linked to PCBs and equipment prices assuming that higher recycling rates of materials enable the manufacturing stage to take place in Europe). Also, the main costs of this business case derive from salaries. Salaries could be reduced when ecodesign simplifies the dismantling process and reduces the time required for the process. More equipment could be dismantled at the same time by a person, which will generate higher income. According to the calculations of operational costs (see Table 46), every minute used to dismantle costs 0.52 €, so achieving time savings in the dismantling process by changing the design would influence the whole economic feasibility of the recycling phase.

2.2.4. Screening LCA

I. Goal and Scope

The goal of this assessment is to estimate the environmental performance of switches and servers and the consequences of implementing reuse and recycling strategies and developing a circular economy for data servers, storage equipment and switches from DCI in NWE. The model is focused on the end-of-life scenarios and the different possibilities for DC equipment. A comparison between different ages of equipment is carried out to investigate resource efficiency and related improvements associated with the application of the WEEE Directive. The study is a screening LCA within the framework of the CEDaCI project, and consequently, the results of this assessment can be used internally to highlight the most efficient strategies for the end-of-life stage of data centre equipment. Moreover, LCA can be used to guide further eco-design of the equipment and to facilitate communication with stakeholders to optimise the material resources used in the DCI.

a. *Geographic validity*

The assessment is addressed for European DCs. Transport, end-of-life and energy mixes apply to European scenarios.

b. *Conformity to other documents and photographic report*

The report follows the structure extracted from ISO 14040 2006. The raw materials with higher concentration and the most valuable metals from PCBs are modelled following the PEFCR guidance v6.3.

c. *Function and functional unit*

The products' function and functional unit are described in the following table:

Table 32. Function and functional unit of equipment assessed.

Equipment	Function	Functional Unit
Rack enterprise server	Store data and give access to other systems.	1 data server ready to be used in an enterprise DC for 3-8 years
Switch	Connect hosts to the network and forward messages.	1 switch ready to be used in a DC for 3-5 years, composed at least by chassis and PCBs
Storage equipment	Store data	1 Tb drive suitable in an enterprise server ready to be used for 3-5 years

d. *Scope*

The assessment is focused on data servers, storage equipment and switches. Given that studying the energy efficiency of DCs is not among the objectives of the study, the use phase, known as the most impactful stage of data centres' life cycle, is neglected.

e. *Life cycle stages*

Those life cycle stages included in the study are shown in the figure below, the excluded stages are presented in the grey boxes.

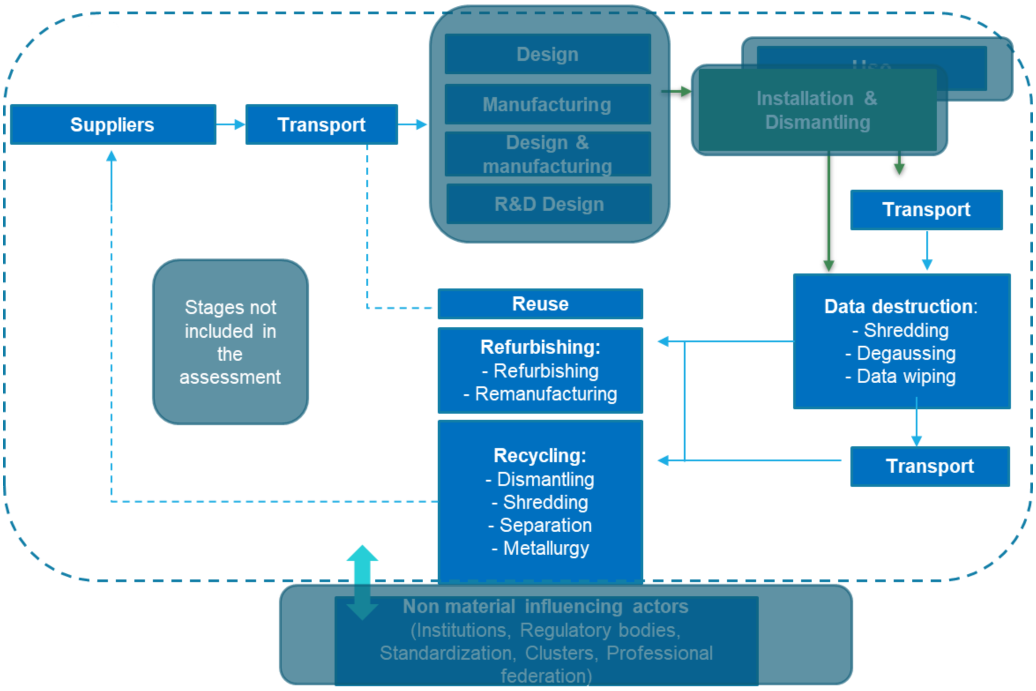

Figure 34. Life Cycle stages included in the assessment - 'greyed out' stages excluded

The resource extraction and the energy consumed in the transformation of the raw materials are considered in the chosen datasets for the model. The design, R&D activities, assembly of components, the use phase, the installation and dismantling of the equipment are not considered in the screening LCA. The next phase is the data destruction phase, which is carried out when the equipment is dismantled, before reuse (by data wiping) it or before sending it to the waste management facility (by shredding). The data destruction is carried out as many times as the equipment is reused before the end of life scenario (recycling, incineration and landfilling).

f. *Products description*

Data servers and switches are composed of the components detailed in the table below.

Table 33. Products studied and components.

Equipment	Components
Servers	Chassis
	Fans
	Storage equipment
	CPU
	Batteries
	RAM
	Heat Pipes for CPUs
	PCBs
	PSUs
	Cables

	ODD
	Plastic parts
	Screws
Switches	Chassis
	Fans
	Plastics
	PCBs
	Cables
	Screws

Two servers and two switches were dismantled and weighted component by component. The servers were assessed including the components

II. Life Cycle Inventory (LCI)

a. Data collection, data quality and relating data to unit processes

Data were obtained by dismantling servers and switches in the framework of CEDaCI project in 2019. Ecoinvent v3.5 with Simapro software was used to model the materials and the electricity mix. Steel was modelled using WorldSteel 2018 datasets and ELCD 3.2 datasets were used for modelling transport and end of life scenarios.

b. Equipment description

Table 34. Components in SV.1.1 and SV.1.2 used in the modelling.

	Component	Quantity (units)		Component	Quantity (units)
SV.1.1 (2005)	Chassis	1	**SV.1.2 (2012)**	Chassis	1
	Fans	4		Fans	5
	Drivers[12]	6		Drivers[1]	8
	Batteries	2		Batteries	1
	Memory	1		Memory	1[13]
	Heat Pipes for CPU	1		Heat Pipes for CPU	1
	PCBs	7		PCBs	10
	PSUs	2		PSUs	2
	Cables	7		Cables	4
	ODD	1		ODD	0
	Screws	50		Screws	18

[12] No drivers were found in the server before dismantling. The number of drivers used in the modelling is equal to the maximum capacity of the server.
[13] No RAM was found in the dismantling. The RAM from SV.1.1 was used as a proxy.

Table 35. Components in SW.1.1 and SW.1.2 used in the modelling.

	Component	Quantity (units)		Component	Quantity (units)
SW.1.1 (2001)	Chassis	1	**SW.1.2 (2007)**	Chassis	1
	Fans	1		Fans	0
	PCBs	4		PCBs	4
	Cables	2		Cables	5
	Screws	37		Screws	25
	Plastics	1		Plastics	1

The mass of each component obtained in the dismantling phase is described in Annex 1. The considered life cycle stages are shown in Table 36 and Table 37. These stages are selected to assess their performance in a circular economy.

Table 36. Stages included in different product systems for servers.

Servers	Equipment not reused	Equipment reused without additional components	Equipment reused with additional components
Raw materials & Production			
Transport manufacturer-user			
Use			
Transport user-refurbisher/DS			
Data sanitisation (data wiping)			
Transport refurbisher-user			
Reuse		Downcycling factor + Preparation for reuse	HDDs + Memory + Operational energy benefit + Preparation for reuse
Data sanitisation (shredding)			
Transport user-EoL			
End-of-Life			

The reuse phase may include the use of new raw materials if some components (drivers and memories) are replaced. An operational energy benefit rate deriving from the use of new components is included and it is assumed that energy consumption is optimised. When energy-related products are reused to extend the lifespan of the server, operational energy increment is also considered, as well as a downcycling factor (k), which accounts for the more frequent maintenance of reused components.

Table 37. Stages included in different product systems for switches.

Switches	Equipment no reused	Equipment reused without additional components
Raw materials & Production		
Transport manufacturer-user		
Use		
Transport user-refurbisher		
Refurbishing		Preparation for reuse impacts + downcycling factor
Transport refurbisher-user		
Reuse		
Data sanitisation		
Transport user-EoL		
End-of-Life		

Table 38. Parameters used to model the reuse phase.

Parameter	Description
Preparation for reuse	Impacts related to dismantling, decommissioning and refurbishing (in case of need) if little adjustments need to be done. It corresponds to 0,5% the impacts of the production. This value is applied to components reused and replaced.
Downcycling factor, k	It represents the higher need for maintenance of reused components. It corresponds to 1% the impacts of preparation for reuse. It is only applied to components reused.
Operational energy benefits	It represents the energy savings obtained by using a new and more efficient component. The factor is applied to the total energy consumed by the equipment.

Table 39. Assumptions, limitations, cut-offs, proxies and comments on data quality.

	Data quality and proxies	Assumptions	Cut-offs	Limitations
Components	The mass obtained by dismantling equipment in the framework CEDaCI project. Plastic, HDDs and ODD from SV1.1 composition are based on JRC, 2015. PCBs are modelled using PCB PM-rich and PM-poor processes from ESR* database. ABS used as a proxy when no information was available	All the servers use the same HDDs (with the different amount depending on the capacity of the server) and same packaging and memory. PCBs assumed to be hole mounted and Pb free.	CPUs are not included in the assessment due to lack of data.	Plastic composition for most parts of the servers dismantled is unknown. There is no available information about SSDs and CPUs composition. The criticality of Raw Materials is not properly considered in the measurement of resource depletion impacts. For example, Rare Earths characterisation factors do not consider geopolitical factors affecting the supply.
Transport	Distances are extracted from the JRC, 2015 and PEFCR report assumptions for the end-of-life scenario. Transport distance to refurbishing is assumed as same distance than recycling.	50 km landfilling 100 km incineration 150 km recycling	Transport to warehouse is cut-off (as well as the storage phase). Transport of each component is cut-off.	
Manufacturing		It's considered as having no impacts and being done in the same place than the production of components.	Manufacturing (assembly) phase and transport to assembling place are cut-off.	
Installation & Dismantling		Assumed as presenting no impacts	Impacts are considered as the cut-off	

Data destruction	Data extracted from different secondary sources. Dup Eraser is the source for data wiping. Different catalogues were used to obtain power consumption of degausser and shredders.	Only electricity consumption is included. Data wiping is used before reusing HDDs and shredding before recycling	The equipment (e.g. the shredder) is not considered. Material recovery efficiency in the recycling process is not linked to the data destruction method.	The electricity consumption of data wiping processes should be assessed in depth. Limitations are found to know the right power consumption.
Reuse	Reuse modelling is based on JRC, 2015. Same parameters are used. Electricity, low voltage {Europe without Switzerland}| market group for | Cut-off, U was used to calculate the electricity saved by using newer components.	Preparation for reuse, downcycling factor and operational energy benefits factor are applied (see Table 38).		Data about the power consumption of servers and switches are obtained from the literature (Koomey, 2002). These values change depending on the age and technology used and present a high influence on the results.
Refurbishment		The refurbishment activity impacts are assumed as replacement of components and impacts from decommissioning and little adjustments (preparation for reuse)	Energy consumed in the refurbishing process is considered as the cut-off	No available for remanufacturing processes.
EoL	Data from Eco-système and Recyclum WEEE database were used for PCBs and magnets. The CFF was used to model steel, copper, aluminium and ABS. Gold EoL process is used as a proxy for tantalum. All incineration processes are assumed to be done with energy recovery.	WEEE from DCI is considered as industrial waste with high collection rates (~100%). Equipment is fully dismantled, and each material is recycled in their correspondent recycling plant. ESR datasets including benefits where sued, assuming the use of recycled materials in primary products. European average values for incineration and landfilling of municipal solid waste are used to calculate the impacts of the end of life stage.	Recycling efficiencies do not change with the data sanitisation method.	No transparency in ESR database. REEs from magnets are not recovered, only the steel. PMs, Cu, Pb are recycled following Cu and Pb pyrometallurgical routes and further refining.

* ESR database uses data from the take-back scheme

III. Life Cycle Impact Assessment (LCIA)

Please note that the impact assessment results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks.

SimaPro v9.0 was used and the EF method v1.0 2010 without toxicity categories (for normalisation and weighting) was the method selected to carry out the LCIA. Characterized results for the three toxicity-related impact categories (Human toxicity, cancer; Human toxicity, non-cancer and Ecotoxicity, freshwater) are included in the report. However, the normalized and weighted results do not include the three toxicity-related impact categories following the PEF Guidance document of the European Commission (also these indicators are not part of the benchmark values). The long-term emissions are excluded when extracting the results following the PEF Guidance.

a. *Servers*

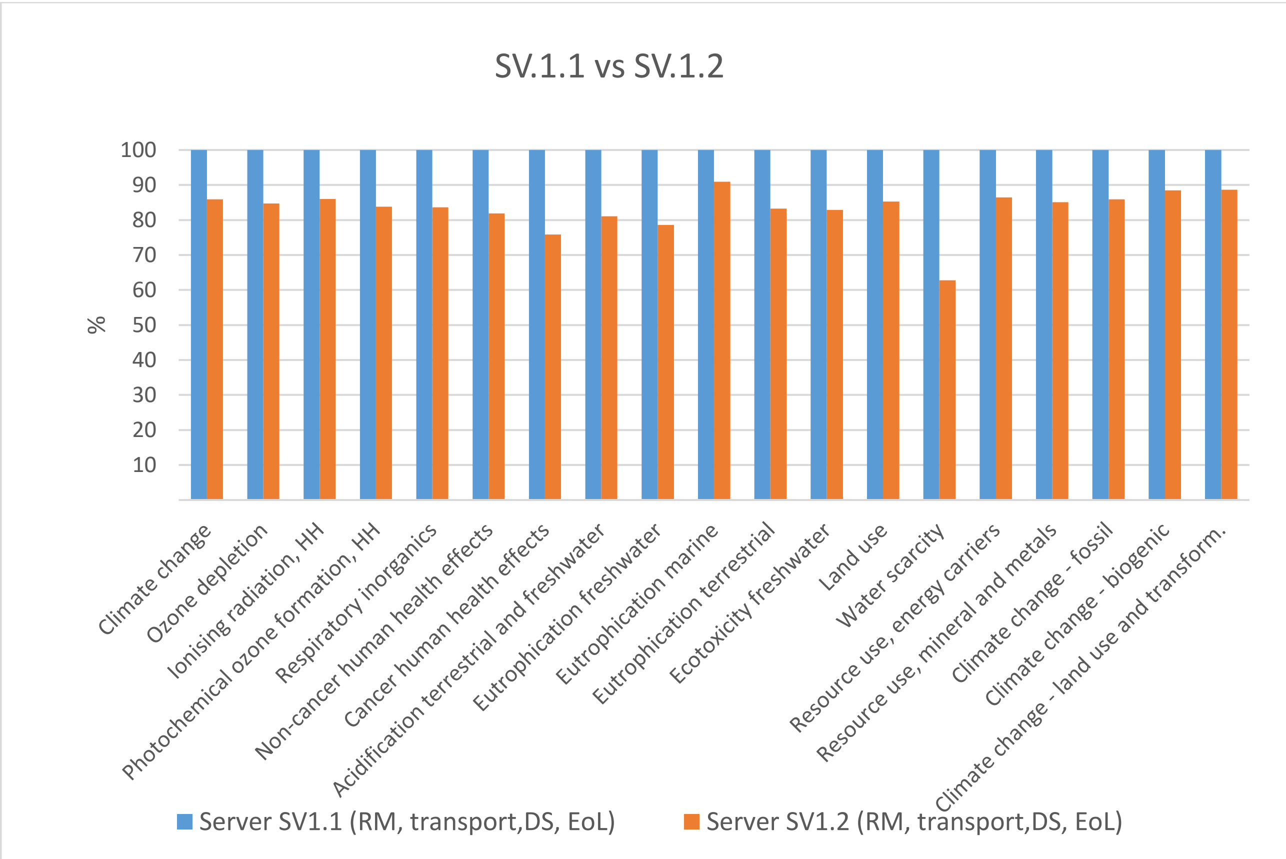

Figure 35. SV.1.1. vs SV.1.2. characterization results.

The figure above presents the characterized results of SV.1.1. (2005) and SV.1.2. (2012) and includes all the life cycle stages except the operational energy at the use phase (according to Table 36).

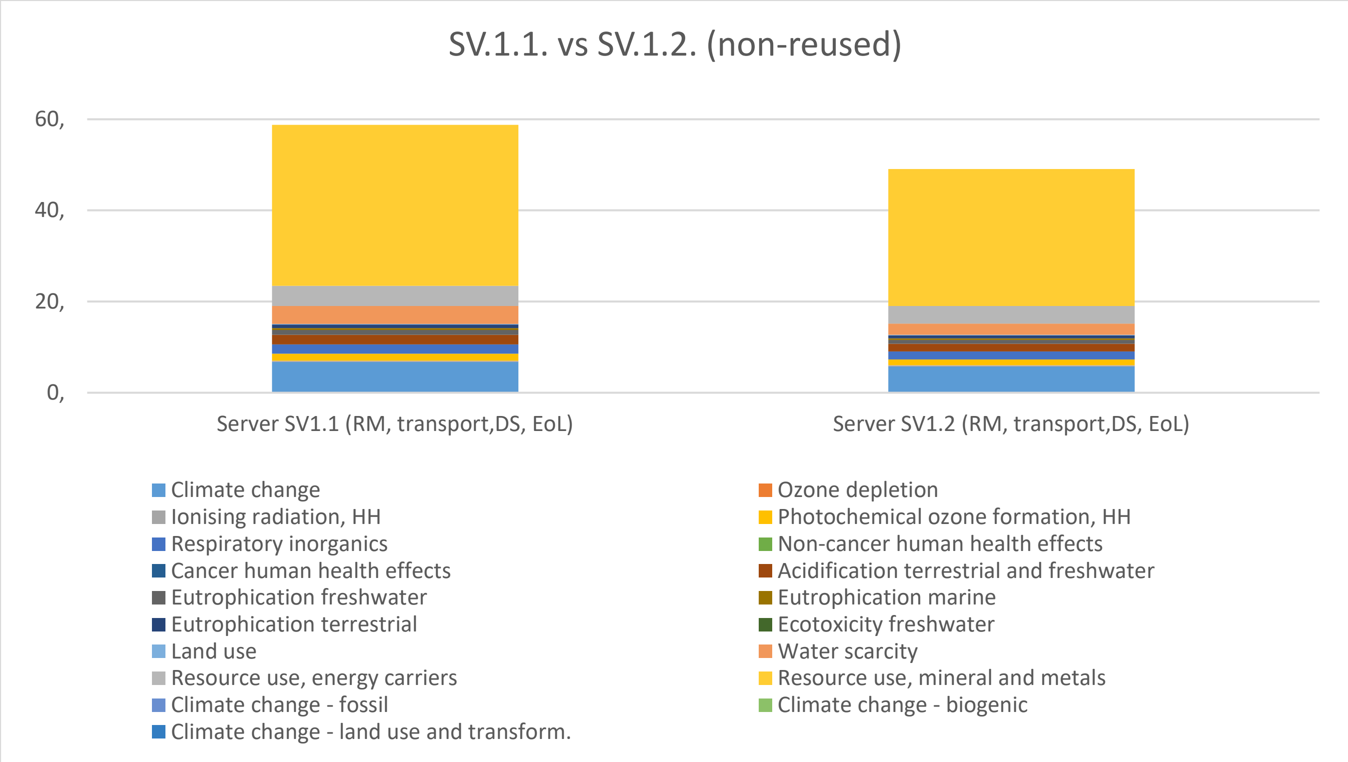

Figure 36. SV.1.1. vs SV.1.2. normalized and weighted results.

The normalised and weighed results are calculated using the Product Environmental Footprint (PEF) method. The most relevant impact category is the minerals and metals resource use.

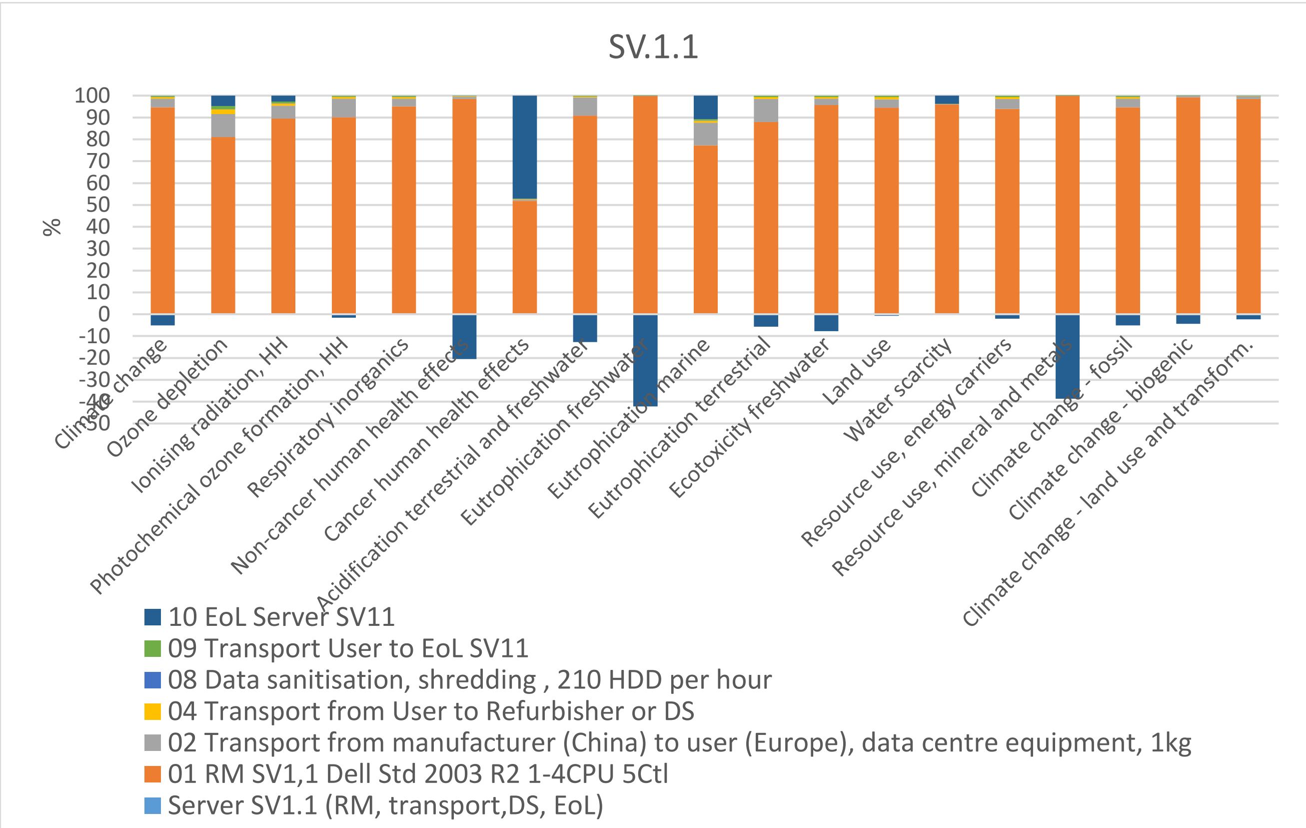

Figure 37. SV.1.1. characterized results.

The impacts of a non-reused server are shown in the previous figure. The raw materials (> 50% of total impacts in all the categories) have a significant influence on the environmental performance of the server.

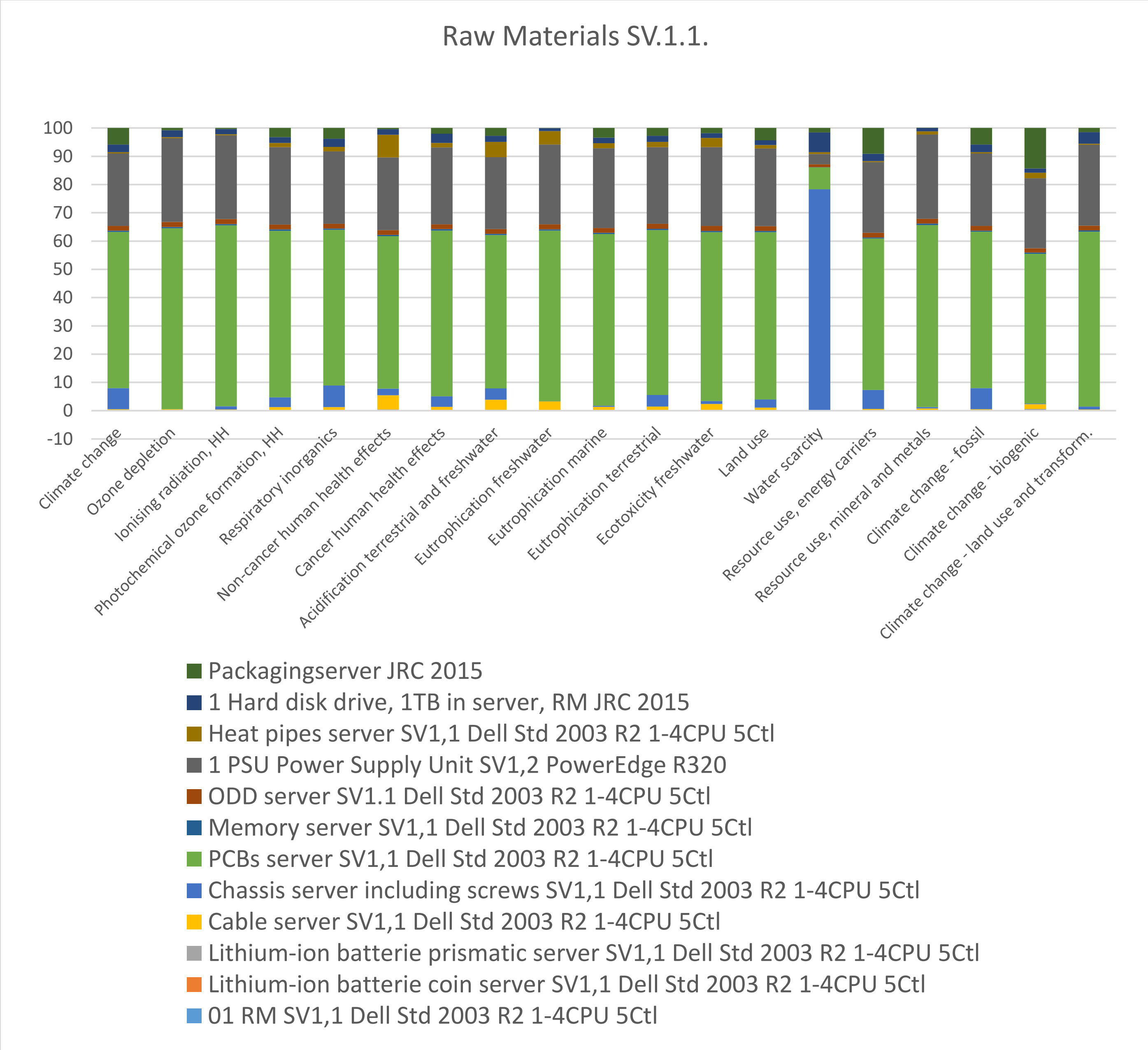

Figure 38. Raw materials from SV.1.1. characterized results.

The raw materials phase was subsequently assessed. This revealed that PCBs and PSUs, (which are composed of 40% and 48% PCB in SV.1.1.) (see Annex 1), account for the highest fraction of the impacts. A hotspot analysis to identify the most relevant processes in the PCB data set used from Ecoinvent v3.5 is shown in the table below.

Table 40.Most relevant processes in the PCB dataset from the Ecoinvent database.

Number	Process	Unit	Value	%
Total	Printed wiring board, through-hole mounted, unspecified, Pb free {GLO}| market for | Cut-off, U	mPt	27,97	100%
1	Gold {RoW}| production | Cut-off, U	mPt	6,93	24,79%
2	Silver {RoW}| silver-gold mine operation with refinery | Cut-off, U	mPt	3,05	10,91%
3	Gold {ZA}| production | Cut-off, U	mPt	1,63	5,82%
4	Gold {US}| production | Cut-off, U	mPt	1,56	5,58%
5	Gold {AU}| production | Cut-off, U	mPt	1,53	5,46%
6	Tin {RoW}| production | Cut-off, U	mPt	1,01	3,61%
7	Gold {RoW}| silver-gold mine operation with refinery | Cut-off, U	mPt	0,77	2,74%
8	Gold {CA}| production | Cut-off, U	mPt	0,75	2,70%
9	Gold {PE}| gold-silver mine operation with refinery | Cut-off, U	mPt	0,65	2,33%
10	Gold {RoW}| gold-silver mine operation with refinery | Cut-off, U	mPt	0,61	2,18%
11	Sulfidic tailing, off-site {GLO}| treatment of | Cut-off, U	mPt	0,59	2,11%
12	Silver {RoW}| gold-silver-zinc-lead-copper mine operation and refining | Cut-off, U	mPt	0,50	1,79%
13	Tin {RER}| production | Cut-off, U	mPt	0,50	1,78%
14	Hard coal {CN}| hard coal mine operation and hard coal preparation | Cut-off, U	mPt	0,35	1,24%
15	Gold {TZ}| production | Cut-off, U	mPt	0,30	1,09%
16	Copper {RoW}| gold-silver-zinc-lead-copper mine operation and refining | Cut-off, U	mPt	0,30	1,08%
17	Electricity, high voltage, for internal use in coal mining {CN}| electricity production, hard coal, at coal mine power plant | Cut-off, U	mPt	0,24	0,84%
18	Diesel, burned in building machine {GLO}| processing | Cut-off, U	mPt	0,22	0,78%
19	Zinc concentrate {GLO}| zinc-lead mine operation | Cut-off, U	mPt	0,20	0,72%
20	Lead concentrate {GLO}| zinc-lead mine operation | Cut-off, U	mPt	0,16	0,58%
21	Blasting {RoW}| processing | Cut-off, U	mPt	0,16	0,56%
22	Gold {PG}| gold-silver mine operation with refinery | Cut-off, U	mPt	0,14	0,51%
23	Gold {CA-QC}| gold-silver mine operation with refinery | Cut-off, U	mPt	0,14	0,49%
30	Copper concentrate, sulfide ore {RAS}| copper mine operation, sulfide ore | Cut-off, U	mPt	0,09	0,31%
31	Silver {CL}| silver-gold mine operation with refinery | Cut-off, U	mPt	0,09	0,30%
Total	Hotspot analysis: process contribution	mPt	22,46	80,29%

As seen in the hotspot analysis, gold (53%) and silver (13%) account for the highest share of the impacts from the PCBs, and consequently, from the servers.

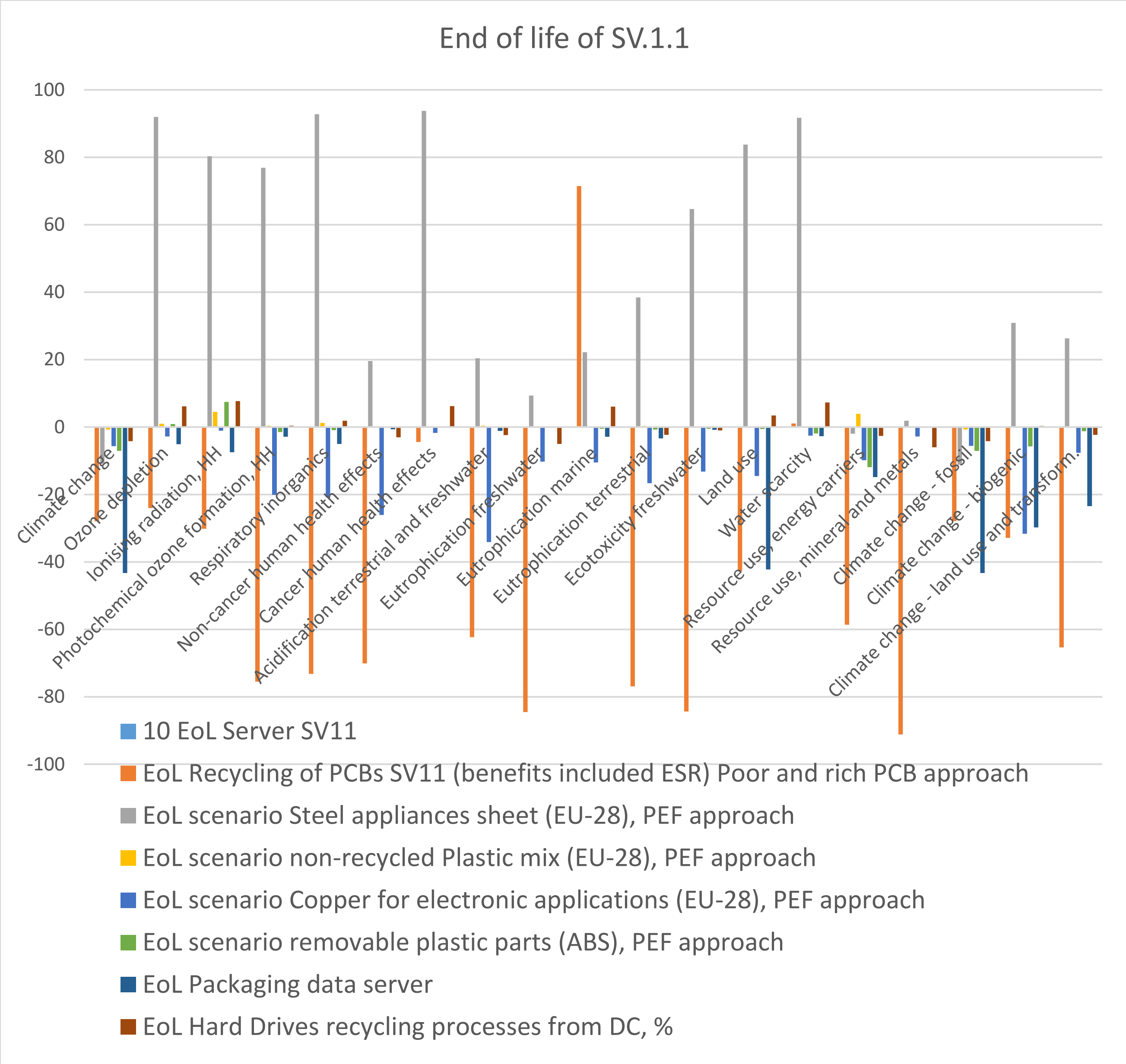

Figure 39. End of life phase of SV.1.1. characterized results

As seen in the previous figure, recycling PCBs brings important benefits (according to the methodology used by ESR database). Impacts from steel recycling are linked to the fact that the recycling of steel is done by introducing steel in the converter in the same route of manufacturing as the primary steel. Also, PCBs are directly modelled in the ESR database, using the Product Environmental Footprint (PEF) approach, and steel was modelled manually with World Steel datasets.

Figure 40 highlights the benefits of recovering Tantalum from a PCB by comparing the impact of recovery with and without Tantalum. The end of life scenario (recycling TA) was modelled using the end of life of gold from PCBs as proxy and ESR database.

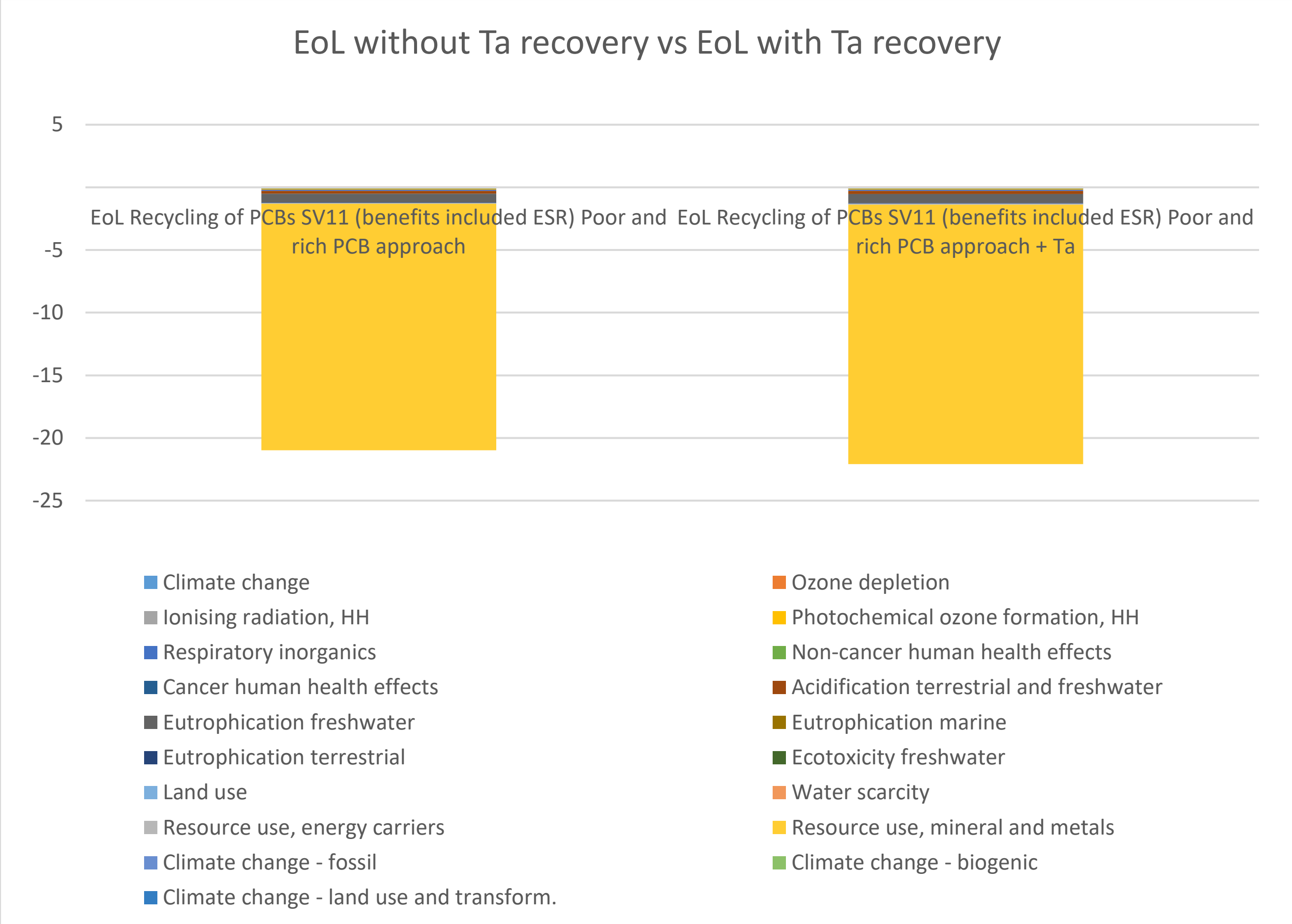

Figure 40. EoL without Ta recovery vs EoL with Ta recovery of SV.1.1.

A comparison of the environmental impacts for five different HDD data destruction methods is shown in Figure 41.

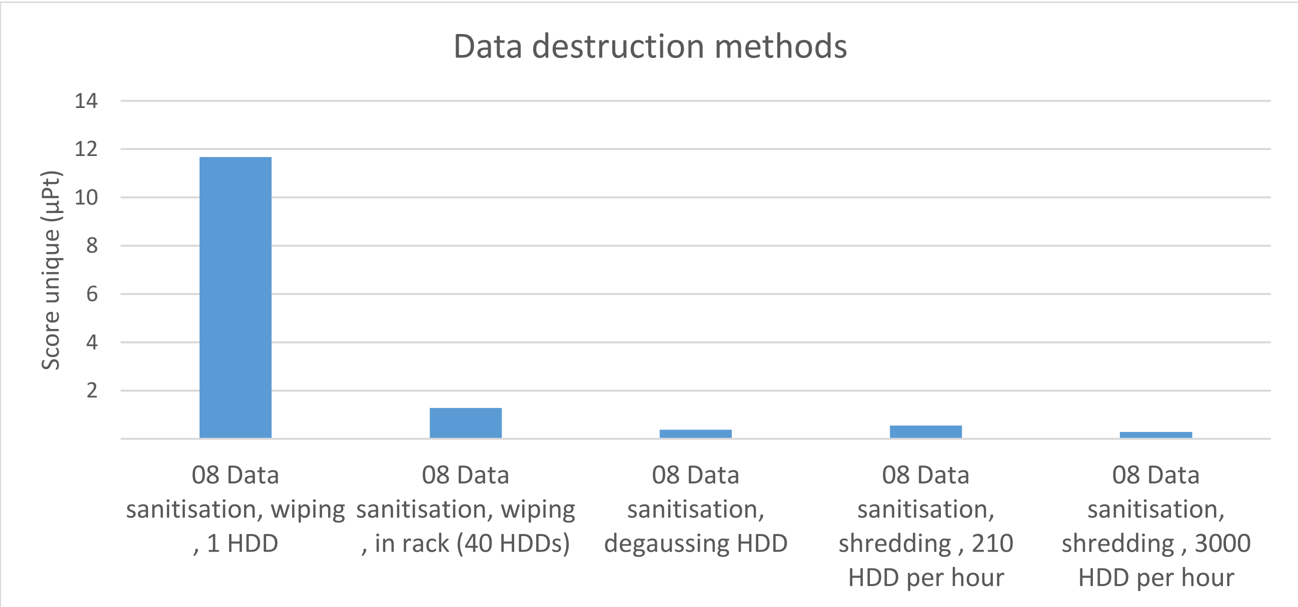

Figure 41. Normalized and weighted results for data destruction methods.

The results of an analysis of replacement components excluding the energy benefits from the use phase is shown in Figure 42.

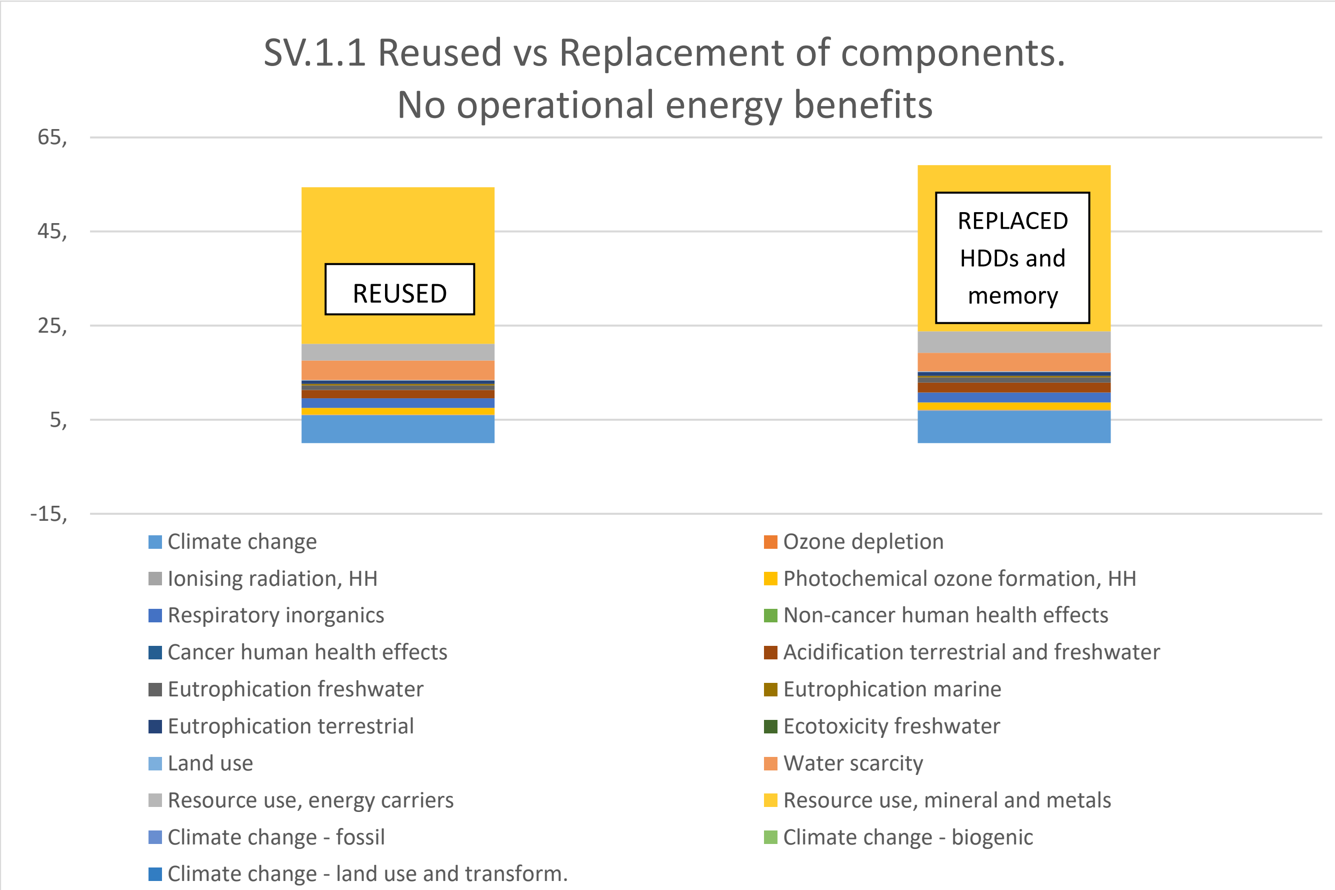

Figure 42. Reuse vs replacement of HDDs and memory in SV.1.1.

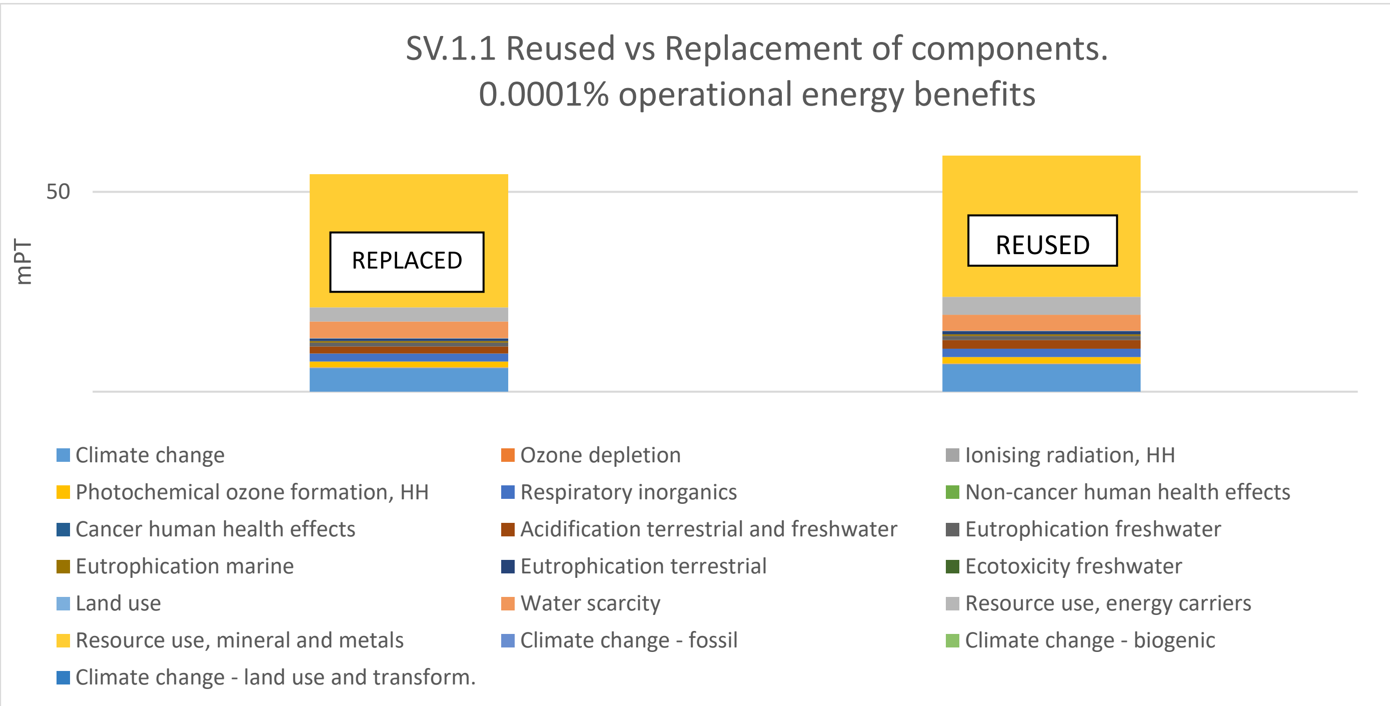

Figure 43. Reuse vs replacement of components 0.0001% operational energy benefits in SV.1.1.

When an operational energy benefit factor is applied (i.e. where a server consumes 0.0001% less electricity than before the replacement of components), the overall impacts of a reused server with replaced components are lower than the completely reused server.

Figure 44 shows that similar relevant categories and processes hotspots are present in switches and servers.

b. Switches

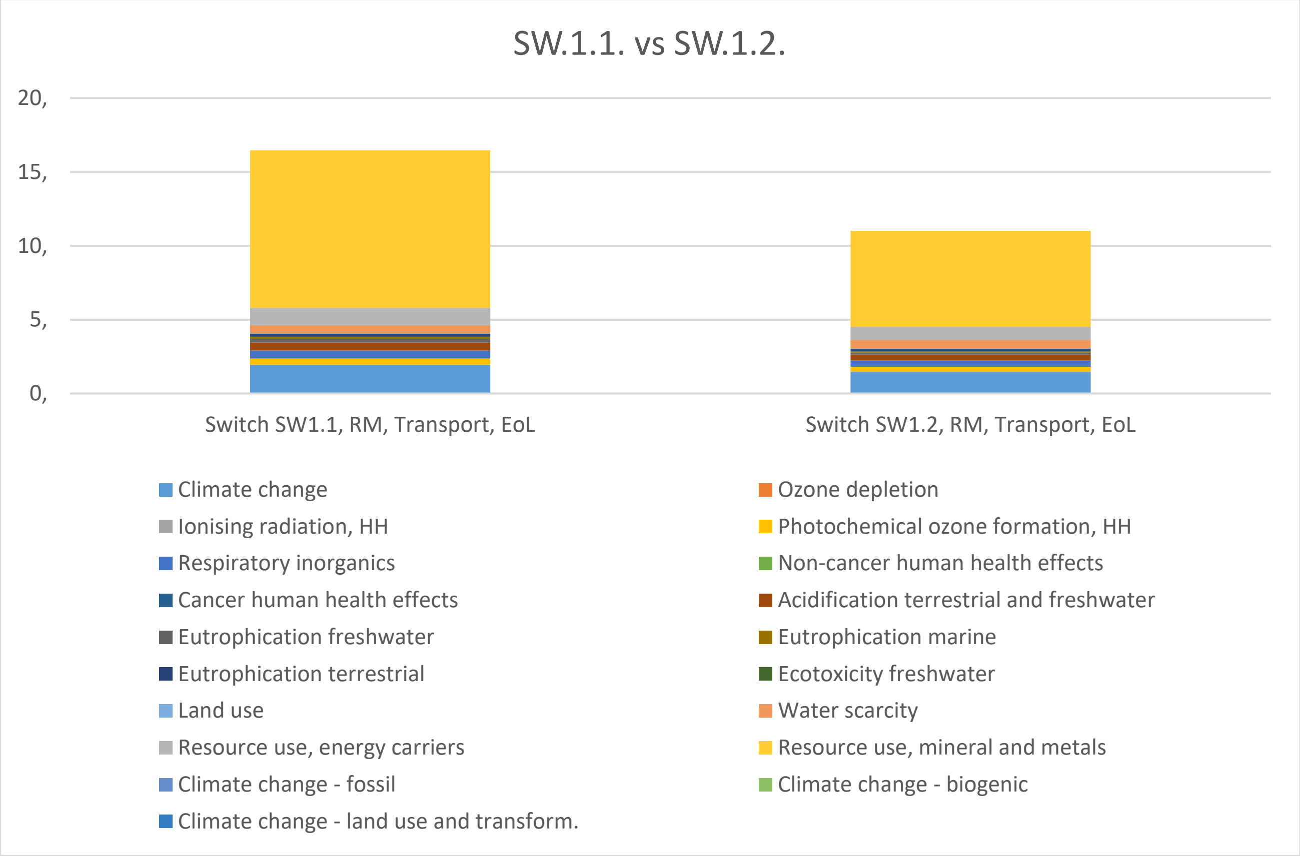

Figure 44. Non-reused SW.1.1. and SW.1.2.

IV. Interpretation

The results obtained in the LCIA show the need to minimise the use of primary raw materials for servers and switches, especially for PCBs (see Figure 37 and Figure 38) to minimise the overall environmental impacts of data centre equipment. These components include metals in their composition (such as gold (Au) or silver (Ag)) that require large amounts of energy and chemicals for extraction and processing into a usable state; in consequence, the environmental footprints of these materials are very high (see Table 40). Recycling PCBs is very beneficial to the environmental performance of data centre equipment if the recovery of materials (a minimum of gold, silver, copper, lead and platinoids) is of a high enough quality to be reused in new PCBs, and that the methods used by recyclers registered in the proposed take-back scheme are followed. The recovery of gold (Au) is the most important driver of the recycling process because this generates the largest economic and environmental benefits. Given that the end-of-life of PCBs is modelled using ESR database, which uses data from the take-back scheme, results must be analysed carefully, keeping in mind the need for higher collection rates and use of official take-back systems. Transport, processing and usual recovery efficiencies are included. Most of the PCB recycling in the take-back scheme is carried out in NWE, however, the majority of reclaimed materials is not reused in the fabrication of new electronic products. As shown in Figure 40, the environmental benefits of recycling increase when more materials are recovered from the PCB, as illustrated by the additional reclamation of Ta. As explained in different sections (Critical Raw Materials in data servers Page 37 and 1.6.4 page 47), recycling and recovery of Ta are not yet practised, although processes are being developed. Gold recovery was selected as a proxy for tantalum recovery because the hydrometallurgical processes are similar. However, in the real Pelts studies to recover these materials, the copper and lead smelter routes are not used, because they are separated from the PCBs in another dismantling exercise to obtain a concentrate of tantalum (Ta). The influence of tantalum recovery on the recovery rates and efficiency of other metals should be further studied, given that during the dismantling phase of components from PCBs, most of the components attached to the PCBs (capacitors, coils, etc.) are separated. This means that other highly concentrated metals in these components, such as copper (Cu) or aluminium (Al), could be lost in the tantalum (Ta) recovery process which will reduce the efficiency in the overall recycling process.

One notable limitation in the interpretation of the results is the absence of criticality factors in the characterisation factors of CRMs and consequently, the impacts of mineral resource depletion might also be underestimated.

a. Reuse phase

The reuse of components is an interesting mean of maintaining materials (including CRMs) in the European economy. However, in the case of HDDs and memory components, the overall environmental footprint can be higher compared to use a new component, (see Figure 42) These components currently have the highest reuse rates, but given their high power consumption in a data centre, replacing them with new more energy-efficient components could decrease the overall environmental footprint. This result supports the adoption of SSDs by DCI if the energy consumption is lower because SSDs would also minimise the energy consumption of cooling systems and the use of REEs.

3. CONCLUSION AND ECODESIGN RECOMMENDATIONS

Given the increasing number and volume of DCs in Europe and the high economic and social importance they represent, a secure supply chain for materials must be ensured. Servers, storage equipment, network equipment and batteries are the components that are replaced most frequently. Information about the materials composition of these components is not easily available to end-of-life managers. It is known that these components include CRMs which are essential to their operation, but not their concentration and the location in it. DCI is experiencing a shift to hyper-scale data centres and different technologies of storage equipment (from HDDs to SSDs), so the material composition is also changing. The design of some equipment is also changing and more 'stripped down' equipment with fewer components and embodied materials is being introduced to hyper-scale DCs via the Open Compute Project although the benefits of this practice are significantly outweighed by the on-going rapid growth of DC provision. In consequence, a circular economy strategy should be followed to minimise the use of primary raw materials and imports from non-European countries. Influencing the first stages of the data centre equipment life cycle is crucial to increase the efficiency of the circular economy. However, the EEE has a complex supply chain which means that manufacturers, assemblers or vendors have specific requirements. These concerns should also be supported in regulations.

Several improvements should be made during the life cycle to develop and implement a profitable circular economy in DCI and ensure a secure raw materials supply chain:

3.1. DESIGN OF THE EQUIPMENT

The equipment is currently modular which aids the disassembly of many of the components. However

- The design should be changed to simplify the removal of PCBs, which are the components with the highest economic value and environmental impacts (from manufacturing phase) and therefore the recycling is most beneficial. The use of screws to fix the PCBs leads to longer recovery time, which also affects the economics of the dismantling process. The metallic cooling components attached to the PCBs are particularly difficult to remove. The use of mechanical joining and separation methods, such as clips and pliers, is highly recommended where possible.
- Simpler component disassembly methods are required to make full disassembly economically feasible.
- Although plastic components were not characterised, several different types of plastic were used in the server. Minimising the number of types of plastic will also increase circularity as the server design changes to facilitate complete disassembly. This requires communication and agreements between different component manufacturers and designers (e.g. fans, chassis, ODD, etc.) to encourage the use of the same type of plastic for particulars types of product/component. Regulation support agreement given it is a multi-stakeholder task.
- PSUs require additional time to remove the PCBs and to be completely dismantled. Only one PSU included between 10 and 15 screws which took 6 mins to be fully dismantled. Mechanical attachments (with less interaction for removal), such as clips or rivets, are recommended to facilitate recycling, even if the attachments have to be broken to remove the PCBs from PSUs. This conclusion was highlighted in the results of the screening-LCA which showed that reusing

the components does not necessarily result in lower environmental impact if the new product is more energy efficient.

Given that the designers and producers are mainly located in Asia, European stakeholders should update their design brief and specifications and include a mandate to minimise the use of CRMs in servers. This is one of the most important issues to be resolved by European stakeholders.

Information about the location of CRMs inside the equipment should be clear and easily identified by refurbishers and recyclers. Adherence to standards such as BS EN 45559:2019 Methods (which states that the information related to material efficiency aspects of energy-related products must be provided) would facilitate the recycling stage and increase materials recovery rates.

3.2. DATA DESTRUCTION

Data wiping at a high scale is recommended as this data destruction method will improve the circular economy of data storage equipment. Even though data wiping has a higher environmental impact compared with other methods, the contribution to the whole life cycle impacts of this phase is very low and data wiping is the only method that allows the reuse of HDDs and SSDs for example. Data wiping will also reduce the loss of PMs that occurs because fine particles are lost during the shredding process.

3.3. END-OF-LIFE SCENARIO

Interviews with CEDaCI project partners indicate that the reuse, refurbishment and collection rates are higher in big DCs (which have internal reuse mechanisms), than in small and private data centres. Reuse and refurbishment are recommended when the component is still energetically efficient in comparison with new products. Firmware updates must be available and although some brands or component manufacturers may not provide them, according to FICT, a QR code in the 2012 server (SV.1.2)., linked to readily available firmware updates.

Recycling PCBs is the most complex process, but it creates the highest environmental benefits, especially in the material resource depletion impact category. The benefits increase when more materials are recovered and reintroduced into the product life cycle. Plastics and CRMs are the most problematic materials to be recovered and although plastics can be used in the recycling process as fuel, the amount of plastic use limits pyrometallurgical copper recycling. There are very low concentrations of CRMs in PCBs, so R&D and up-scaling pilot and lab-scale processes must be supported to increase CRM recovery rates, and especially the most highly concentrated CRMs

- Antimony (Sb): mainly used as a flame retardant. Some R&D processes are being carried out in TND to recover this from PCBs.
- Silicon metal: there are currently no recovery processes from WEEE. The recovery of silicon metal by the current pyrometallurgical Cu and Pb routes is not possible given that Si will be oxidized and the recovery from the slag is not economically profitable. Hydrometallurgical routes for PCBs could be considered to recover Si and other valuable metals (PMs, Cu). In this case, the preparation processes (dismantling and separation) must be optimised within the design to enhance the economics of the process. Once the use of SSDs is widespread in the industry, the amount of Si available for recovery will increase and there could be an economical opportunity to recycle silicon metal from PCBs, although PM will still be the priority because of their high value.

- REE: rare earth element from magnets are not recycled. To recover the REE, an independent stream for HDDs should be created and sent to potential magnet recyclers. The most sustainable option for DCI is to progressively decrease the use of HDDs and adopt SSDs, which include less CRMs. The high price of SSDs is the only barrier to overcome.
- Special metals: specific hydrometallurgical processes for special metals (such as Ta) would increase the overall recovery rates of CRMs from WEEE. Specific processes, like the pilot project developed by TND, are possible once the CRMs are located in the components (e.g. Ta is found in some types of capacitors). In consequence, independent streams can be obtained by physical (and cheap) separation processes to increase the concentration of these metals and recover them. Other special metals (such as In) are currently being recovered by large scale processes – for example, the Umicore process although the economic feasibility not only depends on the recovery of these metals but also on the high volume of waste to be recycled.

Dismantling for recycling: Some conclusions are extracted from the full dismantling business case in North of France. This phase should be optimised to achieve high recovery rates of CRMs. Characterisation results are needed to know whether a full dismantling is economically and environmentally beneficial for PSUs. If the concentration of valuable metals in the PCBs is high, full dismantling should be simplified by reducing the number of screws; this will be executed as part of the redesign.

3.4. NON-MATERIAL INFLUENCING ACTORS

Regulation should include limiting the use of CRMs, but this must be evaluated against function and performance requirements.

Standards that communicate material composition should be used by industry to increase the circular economy efficiency. In Europe, new standards are intended to simplify the communication about CRMs in energy-related products.

R&D activities should be supported to limit the use of these materials in EEE and IT equipment and to minimise quantities when the substitution is not possible.

3.5. COLLABORATION AMONG STAKEHOLDERS

Every stakeholder should be aware of the benefits of implementing an effective circular economy for the industry. Minimising the environmental impacts and maximising the recycling rates of all the materials in data centre equipment would ensure the continuous and economically stable operation of the industry in Europe in the long-term. The high dependency on CRMs and high risk to supply these materials should be tackled by reducing the number of CRMs in the equipment, by reusing and refurbishing components. To do so, stakeholders must know where these materials are located and be made aware of their significance, so they are treated properly at the end-of-life.

3.6. LCA

Introduction of LCIA methods that consider criticality in the characterisation factors. Using the GRI (Governance Resources Indicator) method [53], which includes the scarcity, recyclability and geopolitical considerations in the calculation of the characterisation factors could be an option to include criticality in LCA.

A deeper analysis of the metal's recovery efficiencies and the related aggregation state of the waste equipment must be carried out. In this assessment, the influence of the data destruction method in the metal recovery rate is not included but is assumed to be lower when the equipment is shredded.

Specific databases for data centre equipment should be developed to better assess the impacts of the raw materials and the benefits obtained from recycling.

3.7. CONCLUSION

Digital communication is facilitated by human-centred technology (e.g. laptop and desktop computers and mobile phones) and data centres (DCs) which house digital data processing, networking and storage (ICT) equipment. The sector has already expanded rapidly to manage the increasing volume of data and it is predicted to grow 500% globally by 2030. DC operation is energy-intensive and the sector currently consumes 1% of the global electricity. It is also resource-intensive and although the mass of materials utilised across the sector is unknown, it is estimated to be millions of tonnes.

The sectoral focus has always been the provision of 100% uninterrupted service and performance and although economic and environmental considerations have encouraged operational energy efficiency, the impact of design and manufacture have been largely overlooked and consequently, most DC equipment is designed for a linear economy. This is becoming an increasing problem because the first life of much DC equipment is only 1 to 5 years; to date, circular practices such as refurbishment, reuse and recycling at end-of-life are limited by human and technical factors and consequently the sector contributes to the growing global electrical and electronic equipment waste stream.

The CEDaCI project was initiated to kick-start a sectoral Circular Economy ahead of the predicted growth, to simultaneously increase resource efficiency and reclamation of Critical Raw Materials and reduce waste. The DC sector is comprised of highly specialised sub-sectors; however, it is silo-based and knowledge exchange between sub-sectors is rare. Conversely, a Circular Economy is holistic by default and therefore expertise from all constituent sub-sectors is essential to enable development.

The assessment in this report illustrates the urgent need to achieve higher material resource efficiency in DCI to ensure a secure supply chain of materials, especially CRMs. PCBs have been identified as the most environmentally impactful components of DC equipment and the ones with the highest economic and environmental benefits if recycled by take-back schemes. There is still large room for improvements in the design of equipment to allow higher material recoveries. To overcome design challenges, the CEDaCI project employs design-based methodologies.

The importance of stakeholder engagement to the development of the Circular Economy cannot be under-estimated and this report shared examples of tools and practice from the CEDaCI to support the development of the CE. Much more collaboration among stakeholders in DCI is needed to ease reuse, refurbishing and recycling of equipment. Given the high complexity of the electronics equipment supply chain, regulatory bodies should oversee encouraging best practices and banning actions that limit higher circularity.

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ANNEXE 1: DISMANTLING RESULTS

Table 41. Mass of components SV.1.1 (highlighted components not included in the LCA)

Component	Sub-component 1	Sub-component 2	Mass Sub-component 1 (g)	Mass Sub-component 2 (g)	Mass Component (g)	% Wt
Chassis					**12280.00**	62.40%
Fans					**480.00**	2.44%
Drivers					**0.00**	0.00%
CPU					22.17	0.11%
LIBs					**51.69**	0.26%
	LIB coin		2.7937			
	LIB prismatic		48.9			
RAM					**14.31**	0.07%
Heat Pipes					**365.00**	1.85%
PCBs					**1729.90**	8.79%
	PCBmotherboard		1232.0000			
	PCBprismatic		106.6			
	PCBconnection		37.7			
	PCBpoor1		23.6			
	PCBpoor2		92.3			
	PCBpoor3		162.1			
	PCBpoor4		75.6000			
PSUs					**3700.00**	18.80%
	PSU1		1640			
		Chassis		791.50		
		Connector		47.70		
		Cables		9.90		
		Fan		106.90		
		PCB PSU1		670.60		
		Plastics		13.80		
		Screws		0.00		
	PSU2		2060			
		Chassis		848.40		
		Connector		19.50		
		Cables		9.90		
		Fan		115.50		
		PCB PSU2		997.40		
		Plastics		35.00		
		Screws		0.00		
Cables					**220.00**	1.12%
ODD					**226.80**	1.15%
	ODD		211.00			
	PCBODD		15.8			
Plastic					**540.00**	2.74%
Screws					**40.00**	0.20%
Undefined					2.21	0.01%

Table 42. Mass of components SV.1.2 (highlighted components not included in the LCA)

Component	Sub-component 1	Sub-component 2	Mass Sub-component 1 (g)	Mass Sub-component 2 (g)	Mass Component (g)	% Wt
Chassis					**6480.00**	61.83%
Fans					**468.50**	4.47%
	Fan47U		93.3			
	Fan49Ca		93.8			
	Fan49Cb		93.7			
	Fan49Cc		93.9			
	Fan49Cd		93.8			
Drivers						
CPU					33.30	0.32%
LIB coin					**2.80**	0.03%
RAM						
Heat Pipes					**213.00**	2.03%
PCBs					**1475.40**	14.08%
	PCBmotherboard		852.20			
	PCBmicrochips		105.8			
	PCBgreycooler		79			
	PCBusbe1		22.6			
	PCBcables		213			
	PCBmemorySD		13.9			
	PCBlong		106.7			
	PCB1P/2P		37.90			
	PCB1P		36.20			
	PCBsmallconnector		8.10			
PSUs					**1490.20**	14.22%
	PSU1 201D		745.5			
		Chassis		275.40		
		Connector		10.30		
		Cables		9.50		
		Fan		41.90		
		PCB		392.80		
		Plastics		9.20		
		Screws		6.30		
	PSU2 21LJ		744.7			
		Chassis		274.40		
		Connector		10.20		
		Cables		9.50		
		Fan		42.00		
		PCB		393.10		
		Plastics		9.10		
		Screws		6.30		
Cables					**150.40**	1.44%
ODD					**0.00**	
Plastic					**168.70**	1.61%
Screws					**10.00**	0.10%
Memory card					1.70	0.02%

Table 43. Mass of components SW.1.1.

Component	Sub-component 1	Mass Sub-component 1 (g)	Mass Component (g)	% Wt
Chassis			**1520.00**	55.47%
Fan			**41.90**	1.53%
Plastics			**295.80**	10.80%
PCB			**836.40**	30.53%
	PCBmicrochip	19.90		
	PCBconnection	21.60		
	PCBmother	451.30		
	PCBold	343.60		
Cable			**16.00**	
Screws			**22.10**	0.81%

Table 44. Mass of components SW.1.2.

Component	Sub-component 1	Mass Sub-component 1 (g)	Mass Component (g)	% Wt
Chassis			**1800.00**	72.00%
Plastics			**19.10**	0.76%
PCBs			**640.80**	25.63%
	PCBplastic	29.70		
	PCBconnection	26.60		
	PCBmother	441.80		
	PCBold	142.70		
Cables			**29.30**	1.17%
Screws			**16.00**	0.64%

ANNEXE 2: ECONOMIC ASSESSMENT

Table 45. CAPEX calculation

Year	0	1	2	3	4
Tools	4 000.00	300.00	300.00	300.00	1 000.00
Containers	4 000.00	300.00	-	-	300.00
Computer	2 000.00	-	-	-	500.00
Printer	1 000.00				500.00
Shelving	2 000.00	-	-	-	-
Other equipment	5 000.00		2 000.00		1 000.00
TOTAL	18 000.00	600.00	2 300.00	300.00	3 300.00

Table 46. OPEX calculation

Year	0	1	2	3	4
Operators[14]	50 000.00	50 000.00	50 000.00	50 000.00	50 000.00
Manager	34 500.00	34 500.00	34 500.00	34 500.00	34 500.00
Transport	15 000.00	15 000.00	15 000.00	15 000.00	15 000.00
Plant (325 m2)	19 200.00	19 200.00	19 200.00	19 200.00	19 200.00
TOTAL	118 700.00	118 700.00	118 700.00	118 700.00	118 700.00

Table 47. Parameters used in the calculation of the number of servers and switches.

Number of operators	h/operator	Total working time (h/year)	h/server	h/switch	Servers ratio	Switches ratio
2	8	3800	0.45	0.1	0.95	0.05

Table 48. Incomes (efficiency of 80 %)

	Units in 1 year	Value per unit (€)	Income (€)
Servers	7 768.00	15.09	117 226.05
Switches	1 840.00	2.57	4 730.75
Total	9 608.00		121 956.80

Table 49. Incomes (efficiency of 90 %)

	Units in 1 year	Value per unit (€)	Income (€)
Servers	8 022.00	15.09	121 059.13
Switches	1 900.00	2.57	4 885.01
Total	9 922.00		125 944.15

[14] Salaries of operators and managers include taxes to pay by the contractor (23.5 % in Belgium)

Table 50. Streams prices references.

Stream	Reference for the price (22/07/2019)	Comments
Metallic	https://www.capitalscrapmetal.com/prices/	Unprepared steel
Plastics	https://www.plasticsmarkets.org/view/sortforvalue	Non-sorted rigid plastic
Drives	https://cashforcomputerscrap.com/current-pricing	Complete and sanitised
CPU	https://www.scrapmonster.com/scrap/cpu-processors/76	0,04 €/g was chosen, assuming that the value of the previously removed CPU is higher.
LIBs	https://www.scrapmonster.com/scrap-metal-prices/electronics-scrap/lithium-ion-battery/344	Only 3 months old prices were available
RAM	https://cashforcomputerscrap.com/current-pricing	
PCBs	https://cashforcomputerscrap.com/current-pricing	SV.1.1.8.2, SV.1.1.8.3, SV.1.2.8.2, SV.1.2.8.3 and SW.1.1.4.1 are considered as Medium grade PCBs, the rest are considered as Low grade (except motherboards)
Cables	https://www.scrapmonster.com/scrap-metal-prices/copper-scrap/1-copper-wire-and-tubing/18	Copper wire and tubing
ODD	https://cashforcomputerscrap.com/current-pricing	
Memory SD	https://cashforcomputerscrap.com/current-pricing	Assumed the same price than for memory RAM

ANNEXE 3: CHARACTERISATION RESULTS

The result of the characterisation process is presented according to colour intensity. Greener the cell, higher the metal content in comparison to their respective ores (average from literature revue different sources).

Table 51 Equipment Composition in Server SV 1.1.

	SV.1.1.4	SV.1.1.6	SV.1.1.8.1	SV.1.1.8.2	SV.1.1.8.3	SV.1.1.8.4	SV.1.1.8.5	SV.1.1.8.6	SV.1.1.8.7	SV.1.1.9.1.5	SV.1.1.9.2.5	SV.1.1.11
Ag												
Au												
Co												
In												
Sb												
Sn												
Sr												
Ta												
Ti												
W												
Zr												

Table 52 Equipment Composition in Server SV 1.2.

	SV 1.2.4	SV.1.2.8. 1	SV.1.2.8. 2	SV.1.2.8. 3	SV.1.2.8. 4	SV.1.2.8. 5	SV.1.2.8. 6	SV.1.2.8. 7	SV.1.2.8. 8	SV.1.2.8. 9	SV.1.2.8. 10	SV.1.2.9.1 .5	SV.1.2.9.2 .5
Ag													
Au													
Co													
In													
Sb													
Sn													
Sr													
Ta													
Ti													
W													
Zr													

Table 53 Equipment Composition in Switch SW 1.1.

	SW.1.1.4.1	SW.1.1.4.2	SW.1.1.4.3	SW.1.1.4.4
Ag				
Au				
Co				
In				
Sb				
Sn				
Sr				
Ta				
Ti				
W				
Zr				

Table 54 Equipment Composition in Switch SW 1.2.

	SW.1.2.4.1	SW.1.2.4.2	SW.1.2.4.3	SW.1.2.4.4
Ag				
Al				
Au				
Co				
In				
Sb				
Sn				
Sr				
Ta				
Ti				
W				
Zr				