Sustainable Electronics –
From dumped e-waste to circular economy: what is needed?

Mervi Paulasto-Kröckel

16.9.2021

Aalto University
School of Electrical Engineering

Merger of three leading Finnish universities

1849 Helsinki University of Technology

1871 University of Art and Design Helsinki

1911 Helsinki School of Economics

Aalto University 2010

Aalto University

A diverse community

In 2018, our students graduated with:

263 doctoral degrees,

1 628 master’s degrees,

1 218 bachelor’s degrees,

290 graduates from the MBA and EMBA programmes

12 000

full-time equivalent degree students

A staff of about 4 000, of which nearly 400 are professors. Share of international academic faculty is 40%.

A? Aalto University

Six dynamic schools

School of Arts, Design and Architecture
architecture; art; design; media; film, television and scenography

School of Business
accounting; economics; finance; management studies; marketing; information and service management

School of Chemical Engineering
bioproducts and biosystems; chemistry and materials science; chemical and metallurgical engineering

School of Electrical Engineering
communications and networking; electronics and nanoengineering; electrical engineering and automation; signal processing and acoustics

School of Engineering
built environment; civil engineering; mechanical engineering

School of Science
applied physics; computer science; industrial engineering and management; mathematics and systems analysis; neuroscience and biomedical engineering

Research infrastructure

Long-term (5–7 years) funding commitment

Regular assessment using infrastructure-specific indicators

Continue to increase the level of investments to 4–6% of budget

Electronics Integration and Reliability (EILB)

EILB develops miniaturized electronic systems in:	
POSITION II, A pilot line for the next generation of catheters and implants	ECSEL JU, 1.6.2018-31.9.2021
APPLAUSE, Advanced packaging for photonics, optics and electronics for low cost manufacturing in Europe	ECSEL JU, 1.5.2019-30.10.2022
Beyond SOI, Silicon microfabrication platform development for next generation products	BUSINESS FINLAND, 1.6.2019 – 31.12.2021
New Control, Integrated, Fail-Operational, Cognitive Perception, Planning and Control Systems for Highly Automated Vehicles	ECSEL JU, 1.5.2019-31.12.2022
Power2Power, The next-generation silicon-based power solutions in mobility, industry and grid for sustainable decarbonisation in the next decade	ECSEL JU, 1.6.2019-31.5.2022
iRel4.0, Intelligent Reliability 4.0	ECSEL JU, 1.5.2020 – 30.4.2023

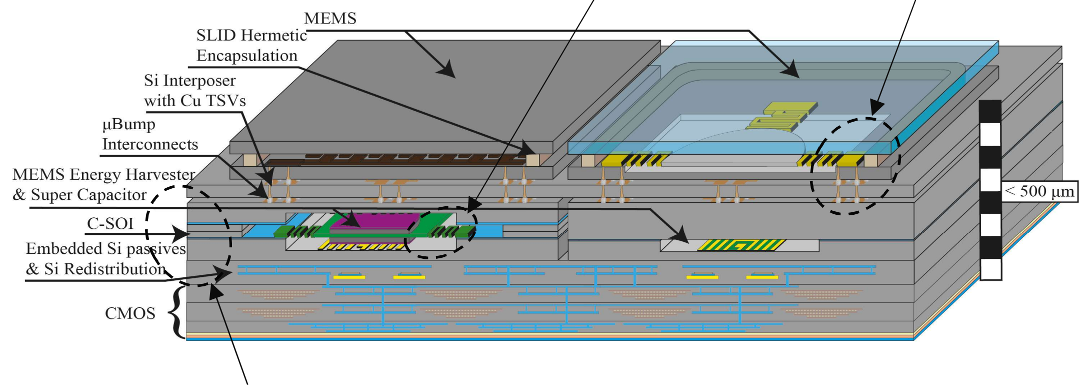
Teaching in two programs:	
Automation and Electrical Engineering / Electronic and Digital Systems	Erasmus Mundus Joint International Master in Smart Systems Integrated Solutions

EILB team:

- **1 professor**
- **1 senior lecturer**
- **3 post-docs**
- **5 (inc. 1 part-time) doctoral candidates**
- **3 research assistants/graduate students**

Aalto EILB Research Objectives

- Combine fundamental material scientific research with innovative material and design concepts for micro- and nanoelectromechanical systems (MEMS/NEMS)
- Develop a miniaturized full silicon based hermetic package platform for ubiquitous autonomous sensor systems
- Make Aalto University known as a leading institute in design for reliability methods and interconnect development for smart sensor and power electronics systems
- Support Aalto's industrial and MEMS manufacturing partners in Finland and internationally with special knowledge of Aalto EILB and train skilled workforce for them



Overarching topics:

- Integration of new materials to enable new functionalities
- Reliability of heterogeneous bonded structures and interfaces, interfacial defects, impact of impurities
- In-depth microstructural studies, chemical stabilities, micromechanical behavior and residual stress characterization

Aalto University
School of Electrical Engineering

Outline

Environmental impacts and challenges of electrical and electronic equipment

Current EU legislation

WEEE treatment, recycling chains

Assessing environmental impacts – Life Cycle Assessment (LCA)

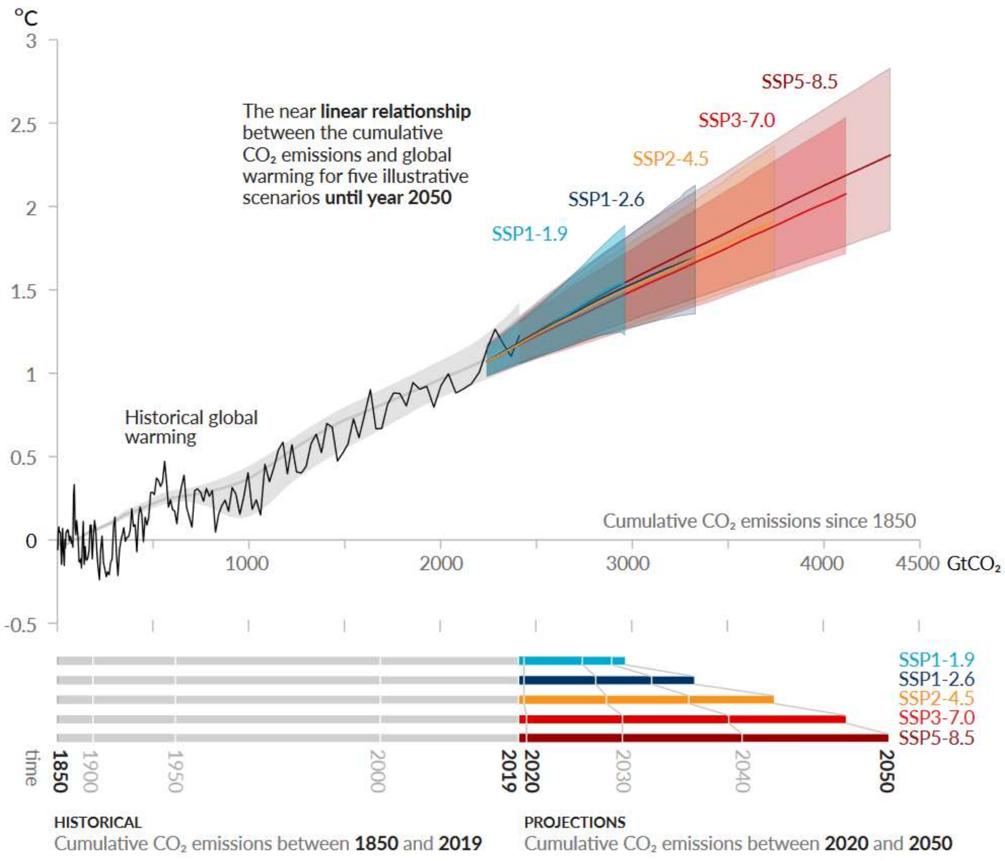
- Two case studies: smartphone and smartwatch

Ecodesign principals

Conclusions

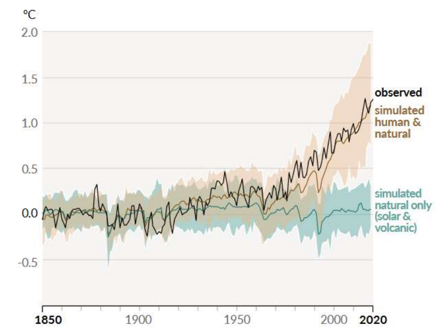
Every tonne of CO_2 emissions adds to global warming

Global surface temperature increase since 1850-1900 (°C) as a function of cumulative CO_2 emissions ($GtCO_2$)



SSPx-y
SSP = Shared Socio-economic Pathway
X = Pathway number
Y= Approximate level of radiative forcing (W/m2) resulting from the scenario in 2100

b) Change in global surface temperature (annual average) as **observed** and simulated using **human & natural** and **only natural** factors (both 1850-2020)



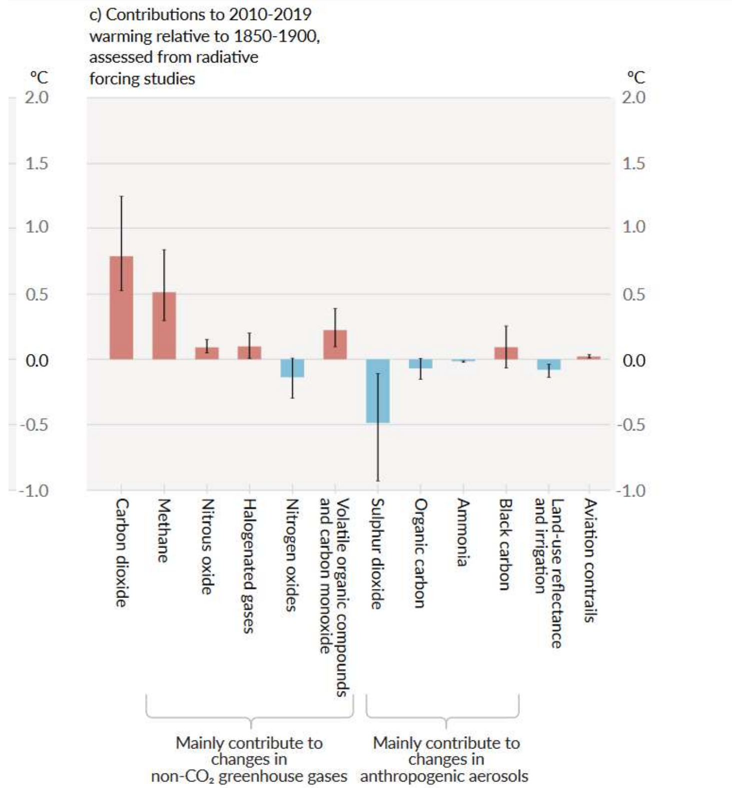
Ref. Climate Change 2021 - Summary for Policymakers, IPCC AR6 WG1, 2021
https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf

Global warming potential

$$GWP = \frac{\int_0^n a_i\, c_i\, dt}{\int_0^n a_{CO_2}\, c_{CO_2}\, dt}$$

a_i = instantaneous radiative forcing due to a unit increase in the trace gas, i, concentration
c_i = concentration of trace gas, i, remaining at time t, after its release
n = number of years over which the calculation of trace gas, i, is performed

The major contributors to increases in radiative forcing in the last decade are CO_2, CH_4, N_2O and CFCs



Ref. IPCC, 2021

Environmental impact categories

Table 5: Examples of environmental impact categories and indicators (note 7)

Mid-point Impact Categories	Mid-point Category indicator	End-point Impact Categories	End-point Category indicator	Recommended Level (Mid-point - End-point) (note 6)	Reference
Climate Change(CC) (mandatory)	Mass CO2 equivalent (Infrared forcing as GWP100-year)	Infectious diseases, Land loss	DALY, Extinction of species, Resource cost	I - Interim	IPCC [i.10]
Ozone Depletion(OD)	Mass CFC-11 equivalent (see note 1) (UV-B radiation as Ozone Depletion Potential)	Plant damage, Skin cancer	Net Primary Production, DALY	I - Interim	ILCD [i.3]
Human Toxicity (HTC), Cancer effects	Comparative Toxic Unit for humans (CTUh) (Concentration at human uptake level)	Cancer	DALY	II/III - II/interim	[i.3]
Human Toxicity (HTNC), non-cancer effects	Comparative Toxic Unit for humans (CTUh) (Concentration at human uptake level)	Memory loss	DALY	II/III - Interim	[i.3]
Respiratory inorganics/Particulate Matter (RI/PM)	Mass PM2.5 equivalent (see note 2)	Bronchitis, Asthma attacks	DALY		
Ionizing Radiation (IRH), human health	Mass U235 equivalent	Cancer	DALY		
Ionizing Radiation (IRE), ecosystems	Comparative Toxic Unit for ecosystems (CTUe)×volume×time				
Eutrophication (EA), aquatic	Freshwater: Mass P-equivalents Marine water: Mass N-equivalents	Fish population	Resource cost		
Eutrophication (ET), terrestrial	Mole N-equivalents	Herbivore population	Resource cost Extinction of species		
Photochemical Ozone Formation (POF)	Mass C2H4-equivalents (Tropospheric O3 concentration increase)	Asthma, Plant damage	DALY, Net Primary Production		
Acidification (A)	Mole H^+ -equivalent	Plant damage	Net Primary Production		
Ecotoxicity (ETFW), freshwater (note 4)	Comparative Toxic Unit for ecosystems (CTUe)×volume×time (Concentration at aquatic ecosystem species uptake level)	Aquatic ecosystem population	Extinction of species	II/III - No methods recommended	[i.3]
Land use (LU)	Mass deficit of Soil Organic Matter	Land loss	Extinction of species, Resource cost	III - Interim	[i.3]
Resource Depletion (RDW), Water	Water amount as Water use related to local scarcity of water	User cost	Resource cost	III - No methods recommended	[i.3]
Resource Depletion (RDMR), mineral, fossil, (note 5)	Minerals as Mass Sb-equivalent and fossil fuels as MJ (Resource amount as scarcity)	User cost	Resource cost	II - Interim	[i.3]

NOTE 1: CFC-11 = Trichlorofluoromethane, also called freon-11 or R-11, is a chlorofluorocarbon.
NOTE 2: PM2,5 = Particulate Matter with a diameter of 2,5 μm or less.
NOTE 3: These recommended levels are taken from ILCD guideline [i.7] clause 3.3. The same guideline has different recommended levels for Respiratory inorganics/Particulate Matter in clause 1.1, where the levels are I - I/II.
NOTE 4: There are currently no recommended methods for Ecotoxicity, marine water and terrestrial.
NOTE 5: There are currently no recommended methods for Resource depletion, renewable.
NOTE 6: At the time of publication of the present document, the recommended levels are taken from the most recent ILCD guideline [i.7]. Refer to ILCD guideline for most up to date information and the explanation of the different recommended levels.
NOTE 7: The mid-point impact assessment categories are suggested by the IL [i.3] CD [i.3] and PEF [i.6]. For other impact categories beyond Climate Change, the scientists are still debating on the suitable methodology and the Category indicators referred in this table may change in the future. Especially Land use methodology is still very open. Refer to ILCD and other documents for up to date methodology to use for each impact category.

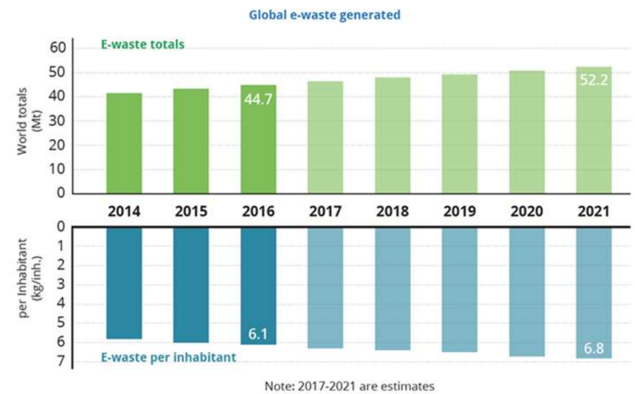
Re. ETSI ES 203 199,
https://www.etsi.org/deliver/etsi_es/203100_203199/203199/01.03.00_50/es_203199v010300m.pdf

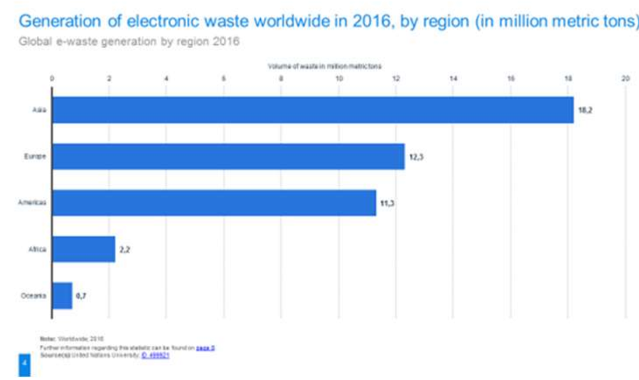
Why sustainable electronics?

- **44,7 million tonnes (here also metric ton) of E-waste globally in 2016**
  - 20% collected and recycled

- **66% (67 countries) of the world's population covered by e-waste legislation in 2016**
  - 41 countries have official e-waste statistics

→ **Electrical and electronic equipment one of the fastest growing waste sources in the world**
  - Environmental concern: pollution, toxicity
  - Economical concern: waste valuable resources, metals like Au, Cu, Ag, Pt, Pd, Al
    - *Total value of all raw materials in e-waste estimated at 55 billion € in 2016*
    - *Could reduce primary resource extraction*

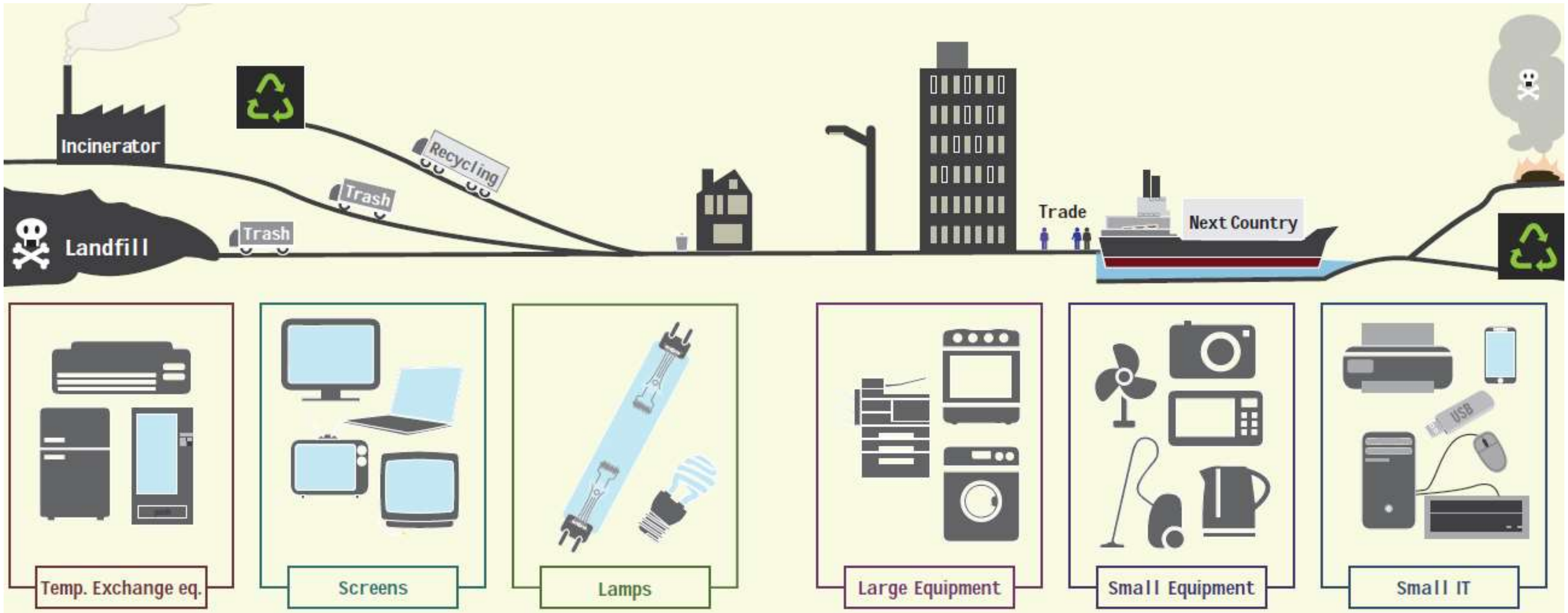




Aalto University
School of Electrical Engineering

Ref. UNU report 2017

E-waste = Waste Electrical and Electronic Equipment = WEEE



- cooling and freezing equipment
- refrigerators, air conditioners, heat pumps

- Screens, monitors televisions, laptops, notebooks, tablets

- fluorescent lamps, high intensity discharge lamps, LED lamps

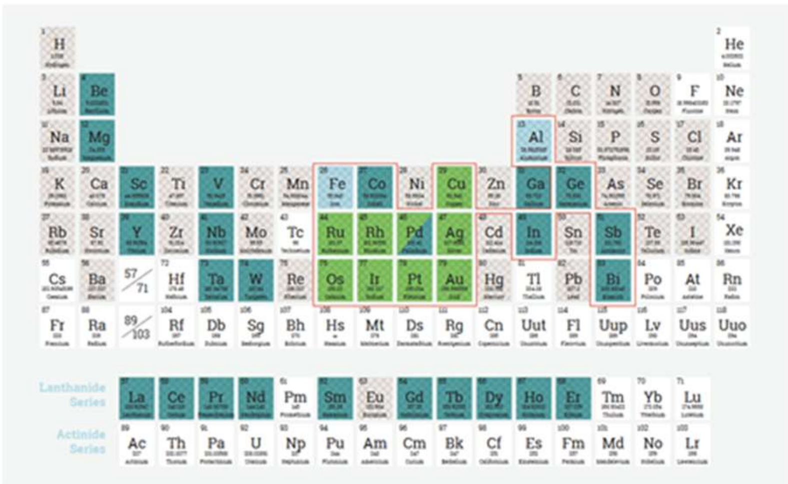
- washing machines, dryers, large copy machines, photovoltaic panels

- vacuum cleaners, microwaves, toasters, electrical and electronic tools, medical devices

- Small IT and telecommunication equipment mobile phones, calculators, PCs

Aalto University
School of Electrical
Engineering

Critical raw materials identified by the EC and their application in EEE



Critical raw material	Application in electrical and electronic equipment	End of life recycling input rate
Antimony (Stibium)	Flame retardants.	11 %
Beryllium	Electric/ electronic connectors.	19 %
Borates	Glass of LDCs and to a small extent in flame retardants.	0 %
Chromium	Stainless steel.	13 %
Cobalt (Cobaltum)	Li-ion and NiMH batteries.	16 %
Coking coal	No application in electrical and electronic equipment	0 %
Fluorspar (Fluorite)	Not considered in Chancerel et al. (2015).	0 %
Gallium	LEDs and integrated circuits.	0 %
Germanium	LEDs and electronic components	0 %
Indium	LCD panels, to a minor extent in LEDs, solders and semi-conductors	0 %
Magnesite	Not considered in Chancerel et al. (2015).	0 %
Magnesium	Casings	14 %
Natural graphite	Li-Ion batteries.	0 %
Niobium	Some magnets.	11 %
Phosphate rock	Not considered in Chancerel et al. (2015).	0 %
Platinum group metals	Palladium in electronic components and PCB, platinum and ruthenium in hard disk drives, iririum in LEDs	35 %
Heavy rare earth elements	Magnets in motors, drivers and loudspeakers, NiMH batteries, phosphors of CCFL and LED backlighting systems.	0 %
Light rare earth elements		0 %
Silicon metal (Silicium)	Silicon semiconductors in chips.	0 %
Tungsten (Wolframium)	Not considered in Chancerel et al. (2015).	37 %

Chancerel, P. et al. 'Estimating the quantities of critical metals embedded in ICT and consumer equipment', Resources, Conservation and Recycling. Elsevier B.V., 98, pp. 9–18. doi: 10.1016/j.resconrec.2015.03.003 and European Commission, 2014

Environmental impacts of Electrical and Electronic Equipment (EEE)

Resource intensive manufacturing

- Electrical energy in mfg and upstream processes
- Valuable and scarce materials, conflict minerals Au, Sn, Ta, W

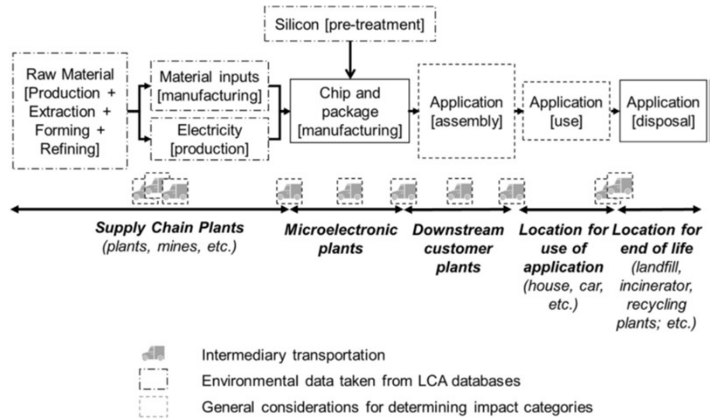
Process emissions in semiconductor components manufacturing

Electricity consumption in the use phase

Transportation

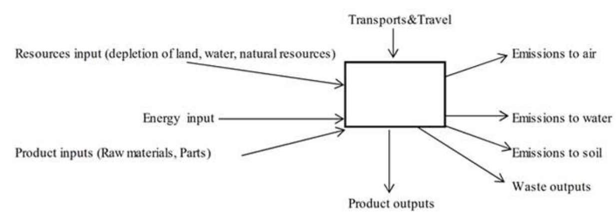
Waste Electrical and Electronic Equipment (WEEE) treatment

- Electrical and electronic equipment one of the fastest growing waste sources in the world
- Waste streams still ineffective and recycling processes under developed



A. Villard et al. / Journal of Cleaner Production 86 (2015) 98-109

Generic unit process with inputs and outputs considered



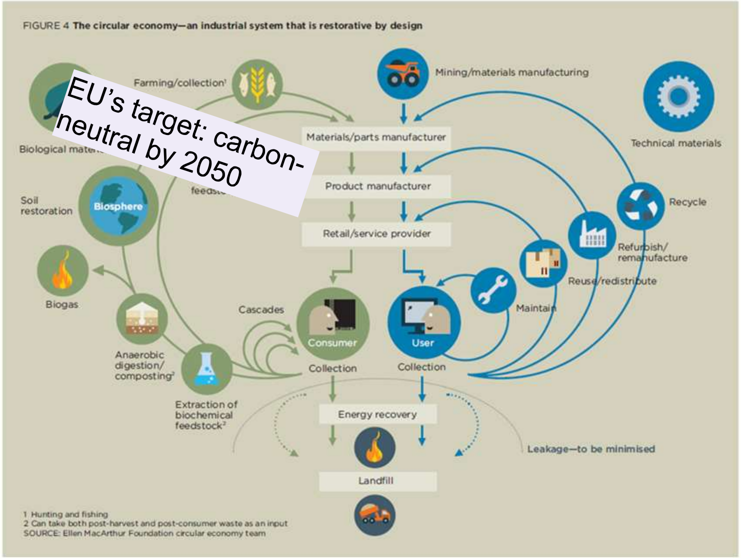
Aalto University
School of Electrical
Engineering

Linear vs circular economy

- Current systems of production organized on a linear basis

- Specifically characteristic for EEE with increasing consumption, short life spans and inappropriate waste treatment
- Most WEEE today were designed without considering recycling issues and even less to be eco-efficient, repaired, reused, remanufactured or refurbished
- Incentives needed to avoid focus on high turnover and rapid discarding!

- EU's systemic approach to waste reduction managing material flows, enhancing repair, reuse, durability and recycling



Aalto University
School of Electrical Engineering

Directives and regulations

Restriction of hazardous substances (RoHS) 2011/65/EU

Waste of electric and electronic equipment 2012/19/EU

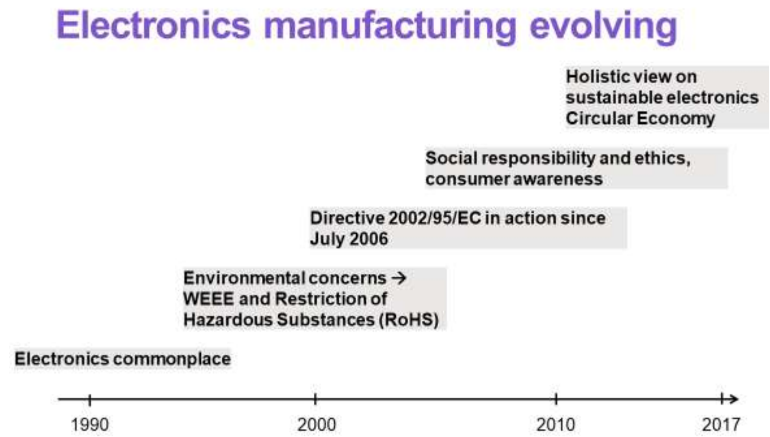
Ecodesign 2009/125/EC

Registration, Evaluation, Authorisation and restriction of CHemicals (REACH) Regulation (EC) No 1907/2006

EU Conflict minerals regulation

RoHS - History

- The first RoHS directive was given in 2002 (2002/95/EC)
  - Applied to new electrical and electronic equipment (EEE) from 1 July 2006
  - Scope: certain categories of EEE (ref. WEEE directive 2002/96/EC) as well as electric light bulbs and luminaires in households



- RoHS Recast in 2011 (2011/65/EU)
  - Open scope and a new definition of a product's dependency on electricity
  - New categories of EEE included: medical devices, monitoring and control instruments, other EEE
  - Cables and spare parts included
  - Gradual extension to new categories, from 22 July 2019 all EEE covered unless exempted from the scope
  - Exemptions: either certain EEE (e.g. military purposes, photovoltaic panels) or exemptions listed in Annex III or IV → no need to fulfill RoHS requirements

RoHS – Restricted substances & exemptions

- Lead (0,1 %)
- Mercury (0,1 %)
- Cadmium (0,01 %)
- Hexavalent chromium (0,1 %)
- Polybrominated biphenyls (PBB) (0,1 %)
- Polybrominated diphenyl ethers (PBDE) (0,1 %)
  - From 1 July 2006
- Bis(2-ethylhexyl) phthalate (DEHP) (0,1 %)
- Butyl benzyl phthalate (BBP) (0,1 %)
- Dibutyl phthalate (DBP) (0,1 %)
- Diisobutyl phthalate (DIBP) (0,1 %)
  - From 22 July 2019 other EEE / 22 July 2021 medical and monitoring/control EEE

- Exemption doesn’t weaken environmental & health protection afforded by REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals)
- Elimination or substitution via design change or use of materials & components not requiring restricted substances is scientifically or technically impracticable
- Reliability and/or Availability of substitutes is not ensured
- Total negative environmental, health & consumer safety impacts related to substitution > total benefits thereof
- Socioeconomic impact of substitution to be considered
- Life Cycle thinking shall apply where relevant
- Decision concerning duration to consider impacts on innovation

WEEE Directive 2012/19/EU

Collection

From 2019 minimum collection rate to be achieved annually 65 % of the average weight

Recovery

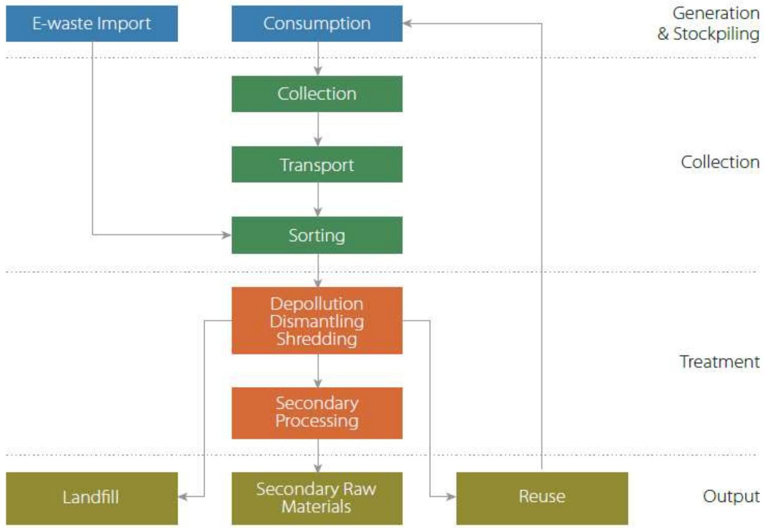
Increase to 75-85% of collected WEEE (Annex V, depending on EEE category, Annex I & III)

WEEE shipments

Control of transboundary movements, Basel Convention

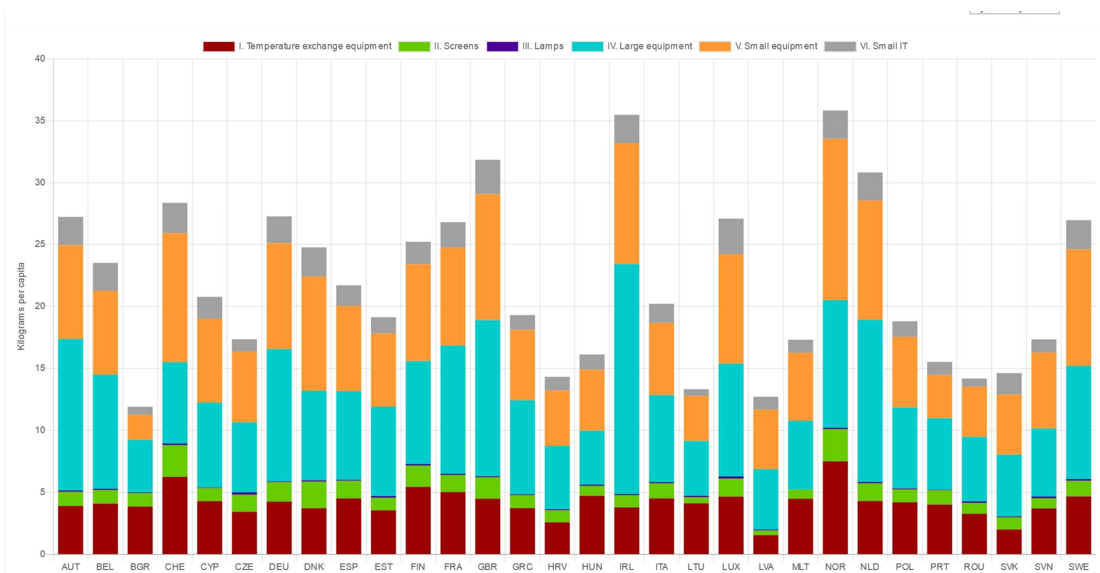
WEEE treatment

Min requirements for removal of substances and components (Annex VII)

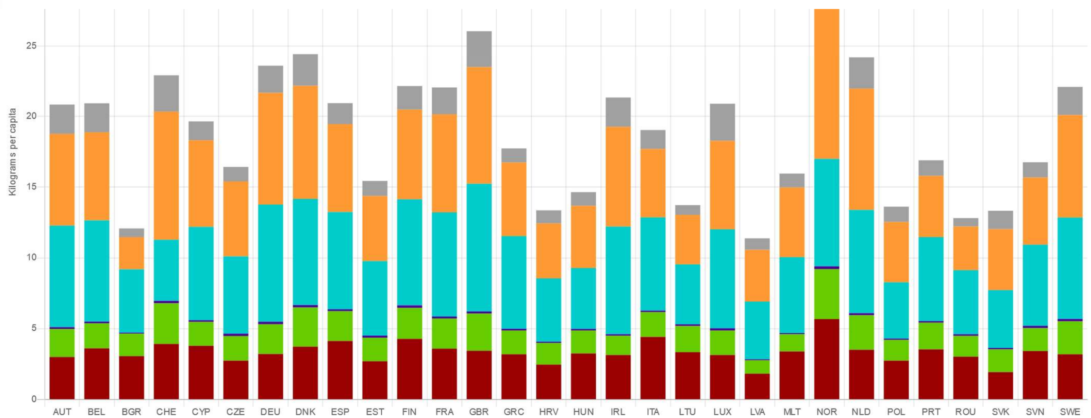


POM and WEEE collected by country per capita – 2020

Products put on the market:



Waste collected:



Aalto University
School of Electrical Engineering

http://www.urbanmineplatform.eu/urbanmine/eee/weightpercapita

Ecodesign Directive 2009/125/EC

- Establishes a framework for the setting of Community ecodesign requirements for energy-related products with the aim of ensuring the free movement of such products within the internal market
- In the past main objective to improve energy efficiency of a product
- Annex I Part 1.2 and 1.3 outlines recommendations to reduce waste and increase reuse and recycling
  - number of parts, time needed for dissassembly, use of recyclable materials etc – no numerical targets
- New resource efficiency criteria to improve reparability, extend product life and use of secondary raw materials
  - Displays among first to be regulated, will need to include marking on special materials, e.g. Cd, Hg, plastic parts weighing more than 50 grams
  - Ecodesign preparatory studies on ICT products e.g. mobile phones, smartphones and tablets underway

REACH

Regulation (EC) No 1907/2006 on the Registration, Evaluation, Authorisation and Restriction of Chemicals

- aims to ensure a high level of protection of human health and the environment, including the promotion of alternative methods for assessment of hazards of substances, as well as the free circulation of substances on the internal market while enhancing competitiveness and innovation
- lays down provisions that apply to the manufacture, placing on the market or use of substances
- is based on the principle that it is for manufacturers, importers and downstream users to ensure that they manufacture, place on the market or use such substances that do not adversely affect human health or the environment.

List of restricted substances is available on the ECHA website.

EU Conflict minerals regulation

The member states and companies obligated to ensure Au, Sn, W and Ta are sourced responsibly throughout the supply chain

- Impacts e.g. 500 smelters and refiners globally

EC list of countries considered for conflict-affected and high-risk areas

Regulations outside of EU:

US legislation Dodd Frank Act Section 1502

- Companies listed on US stock markets to carry out due diligence on minerals sourced from the Democratic Republic of Congo and neighboring countries

Several African countries have passed laws requiring companies to check their supply chains

China has due diligence guidelines for responsible mineral supply chains

WEEE recycling and treatment

Dismantling
- Removal hazardous components, such as batteries, cathode ray tubes and mercury bulbs
- Separation efficiency influenced by used technology and type of material connections
- Full liberation of all parts currently not possible – function of product design!

Other pre-processing
- Shredding – sampling – shredding
- Rotation, electromagnetic separation of ferrous materials, eddy current separation of plastics, aluminum and copper plus other metals, density separators

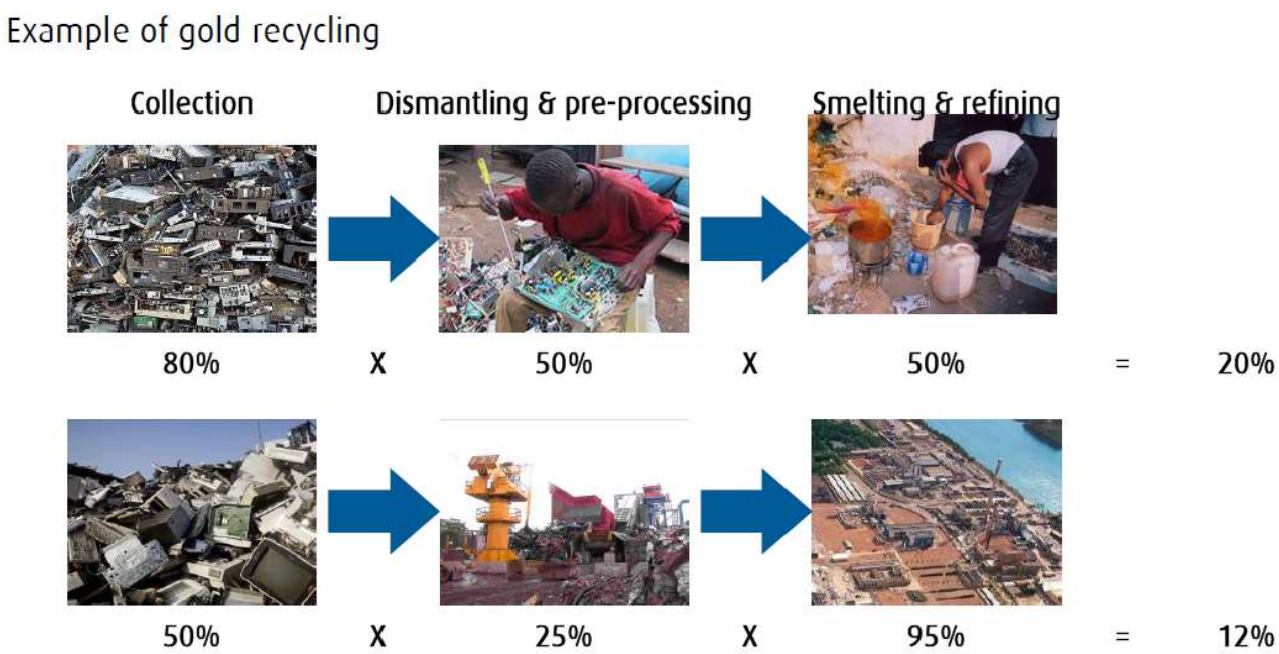
Extractive metallurgy
- Precious metals dominate economic & environmental value: Au, Ag, Pd, Cu and dissolved metals
- Pyrometallurgical processes most common, ”smelting”
- Hydrometallurcial processes, acid leaching (HNO3, H2SO4, HCl), importance increasing

Ref. www.dingsmagnets.com


Magnetic separation of steel

Recycling efficiency

Entire recycling chain and its interdependences need to be considered!



Ref. Umicore

Materials recycling status notebook PCB

Average composition of printed circuit boards in notebooks and average recycling rates of different materials from PCBs separated for recycling

Material in PCB	Average composition	Recycling rate	Material in PCB	Average composition	Recycling rate
Ag	0.11%	95%	Pd	0.02%	95%
Al	5.00%	0%	Sn	1.60%	75%
As	0.003%	0%	Sr	0.04%	0%
Au	0.02%	95%	Ta	0.58%	0%
Ba	0.56%	0%	Zn	1.60%	50%
Be	0.01%	0%	***Glass:***		
Bi	0.01%	80%	• SiO2	18%	0%
Cd	0.0001%	0%	• B2O3	3%	0%
Cl	0.10%	0%	• K2O	0.20%	0%
Co	0.01%	0%	• CaO	6%	0%
Cr	0.35%	0%	• MgO	0.35%	0%
Cu	19%	95%	• NaO	0.20%	0%
Fe	4%	0%	***Plastics:***		
Ga	0.001%	0%	• C	30%	0%
Mn	0.75%	0%	• Br	3.50%	50%
Ni	0.60%	90%	• Sb	0.30%	80%
Pb	0.98%	80%	***Others***	3.11%	

Ref. JRC, European Commission, 2020 and Chancerel P. et al, Feasibility study for setting-up reference values to support the calculation of recyclability / recoverability rates of electronic products, Publications Office of the European Union; 2016.

Challenges in WEEE recycling

Still developing infrastructure and technologies for WEEE recycling

- Better segregation of WEEE into specific, clearly-defined streams at the collection stage, e.g. LCD panel treatment

Poor recycling of many critical elements e.g. Co, Ge, Nb, In, Sb, rare earth elements

- low concentrates of some critical raw materials in WEEE and undeveloped recycling processes

Material changes in electronics, also driven by RoHS

- Development of new recycling technologies critical

Miniaturization and hybrid materials in electronics

Recovery of pure polymers

- Treatment of non metallic fraction of PCB instead of incineration
- Separation and treatment of variety of plastics commonly encountered in EEE
- Reduction of types and marking of polymer used in electrical and electronic products in order to facilitate more effective recycling

Sustainability assessment – LCA

Life cycle assessment (LCA) currently most widely accepted measure to quantitively assess environmental impacts of products or services

Process to evaluate the environmental burdens associated with a product throughout its entire life cycle – “cradle-to-grave”

- Provides quantitative measures of the environmental impact of specific products from the extraction of raw materials, through to manufacturing, transport, packaging, use and disposal

Overall assessment avoids reducing one life cycle stage impacts at a cost of another

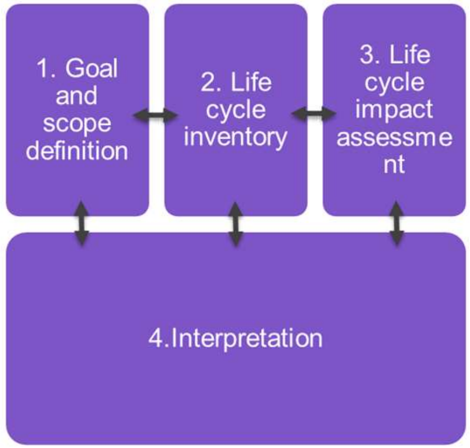
Allow for comparison of products and production processes and help to prioritize actions for improving environmental performance of products

- Note functional unit (= a reference unit in which the LCA is calculated, e.g., one piece of product, a service of 10 years, or a service per m^2) critical in device or service comparisons, development trends etc

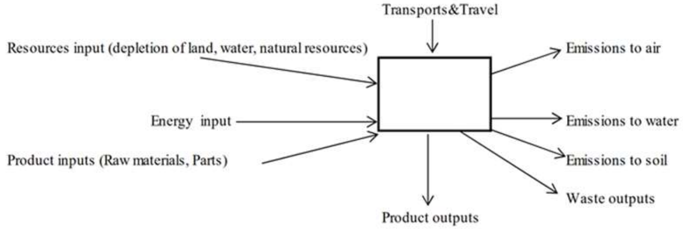
Other design and decision support tools include risk assessment, Material Flow Analysis (MFA), Multi Criteria Analysis (MCA)

LCA Framework per ISO 14040 Standard

1. Goal and scope definition
   - Define functionality of a product
   - Define boundaries, what is included, what is excluded
2. Inventory analysis
   - List of all the materials, substances and chemicals taken from the environment (input) and released into the environment (output)
3. Impact analysis
   - Relating inventory to impact on environment
   - Climate change, toxic impacts…
4. Interpretation of results
   - Analyse where impacts are occurring, major areas of environmental concerns



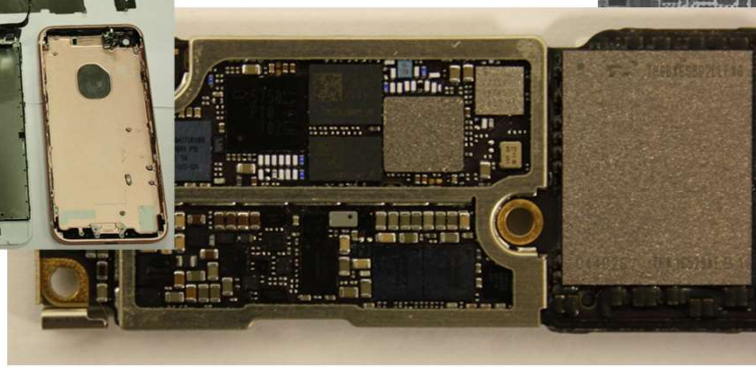
Unit process with inputs and outputs considered

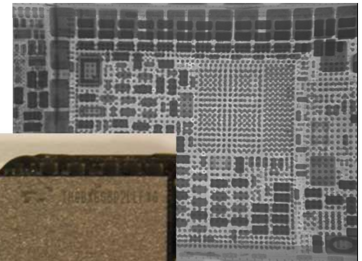


Aalto University
School of Electrical
Engineering

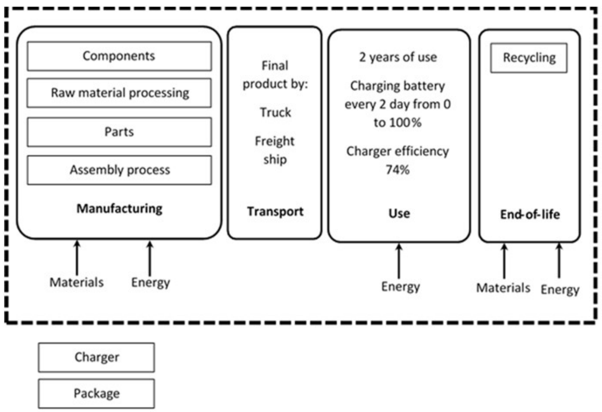
LCA – Case Smartphone

iPhone 7

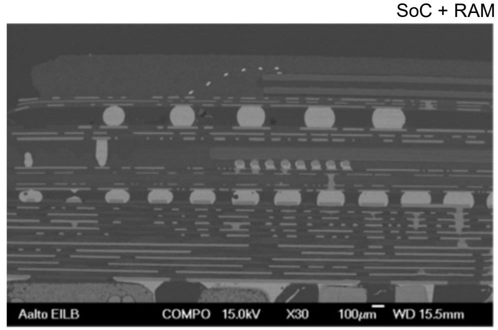




System boundaries



SoC + RAM



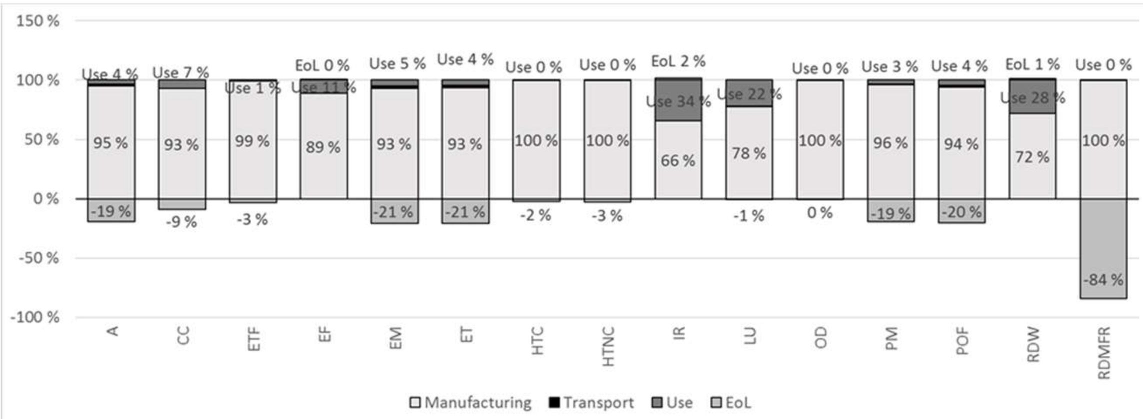
Inventory data of smartphone manufacturing

Aggregated data input	Amount	Unit	Corresponding dataset in model
Battery	27,5	g	CN: single cell, lithium-ion battery, lithium manganese oxide/graphite, at plant
Phone cover, buttons	26,8	g	Aluminium sheet
Steel plates, taptic engine, SIM card slot	16,6	g	Steel plate
Loudspeakers	4,47	g	Loudspeaker (dynamic, Nd magnet)
Plastics	1,78	g	Plastic part (unspecified)
Cameras	1,24	g	Transistor DPAK TO252 (290mg) 6.6x6.2x2.2
Screws	0,84	g	Stainless steel screw
Plastic foil	0,44	g	Plastic film (unspecified)
Copper parts	0,2	g	Copper sheet
Microphones (normal and MEMS)	0,116	g	Microphone (electret condenser SMD)
LEDs	0,09	g	LED SMD high-efficiency max 0.5A (235mg) Flip Chip 9.0x7.0x4.4
Capacitors	0,00488	g	Capacitor ceramic MLCC 01005 (0.06mg) 0.4x0.2x0.22
	0,04896	g	Capacitor ceramic MLCC 0201 (0.17mg) 0.6x0.3x0.3
	0,296	g	Capacitor ceramic MLCC 0603 (6mg) 1.6x0.8x0.8
Resistors	0,0176	g	Resistor flat chip 0402 (0.6mg)
	0,004	g	Resistor flat chip 0603 (1.9mg)
Display	0,0066	m2	Liquid Crystal Display (LCD), Panel Assembly LED TFT, mixed TN-IPS
Printed wiring boards, connectors, flex circuits	0,00141	m2	Printed wiring board chem-elec AuNi 8-layer (subtractive method)
ICs	0,701	pcs	IC BGA 144 (181mg) 10x10mm
	1,43	pcs	IC BGA 144 (466mg) 13x13x1.75
	1	pcs	IC BGA 256 (4g) 27x27
	4,07	pcs	IC BGA 48 (70mg) 6x6x1.1mm
	5,48	pcs	IC BGA 48 (72mg) 8x6 mm
	0,744	pcs	IC QFP 32 (180mg) 7x7x1.5
	2,27	pcs	IC SO 8 (80mg) 4.9x3.9x1.7
	0,342	pcs	IC SSOP 14 (120mg) 6.0x5.3x1.75
	2,3	pcs	IC TQFP 44 (260mg) 10x10x1.0
	1	pcs	IC TSSOP 8 (23mg) 3x3 mm (flash)
	1,74	pcs	IC WLP CSP 196 (400mg) (12x12x1.41mm) CMOS logic (22 nm node)
	0,776	pcs	IC WLP CSP 49 (10.2mg) (3.17x3.17x0.55mm) MPU generic (130 nm node)
Transistors	1,79	pcs	Transistor signal SOT23 3 leads (10mg) 1.4x3x1
Oscillators	0,3	pcs	Oscillator SMD Epson MC406 (0,23 g)

Aalto University
School of Electrical
Engineering

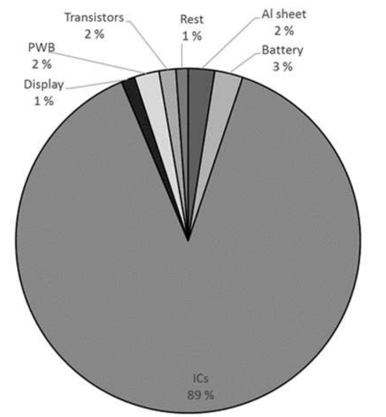
LCA – Case Smartphone

Calculated* life cycle impacts of smartphone baseline scenario in different impact categories



*GaBi professional

Division of LCIA results of manufacturing phase in baseline scenario in GWP



Impact category	Abbreviation	Unit
Acidification midpoint	A	Mole of H+ eq.
Climate change midpoint, incl biogenic carbon	CC	kg CO2 eq.
Ecotoxicity freshwater midpoint	ETF	CTUe
Eutrophication freshwater midpoint	EF	kg P eq.
Eutrophication marine midpoint	EM	kg N eq.
Eutrophication terrestrial midpoint	ET	Mole of N eq.
Human toxicity midpoint, cancer effects	HTC	CTUh
Human toxicity midpoint, non-cancer effects	HTNC	CTUh
Ionizing radiation midpoint, human health	IR	kBq U235 eq.
Land use midpoint	LU	kg C deficit eq.
Ozone depletion midpoint	OD	kg CFC-11 eq.
Particulate matter/Respiratory inorganics midpoint	PM	kg PM2.5 eq.
Photochemical ozone formation midpoint, human health	POF	kg NMVOC eq.
Resource depletion water, midpoint	RDW	m^3 eq.
Resource depletion, mineral, fossils and renewables, midpoint	RDMFR	kg Sb eq.

Aalto University
School of Electrical
Engineering

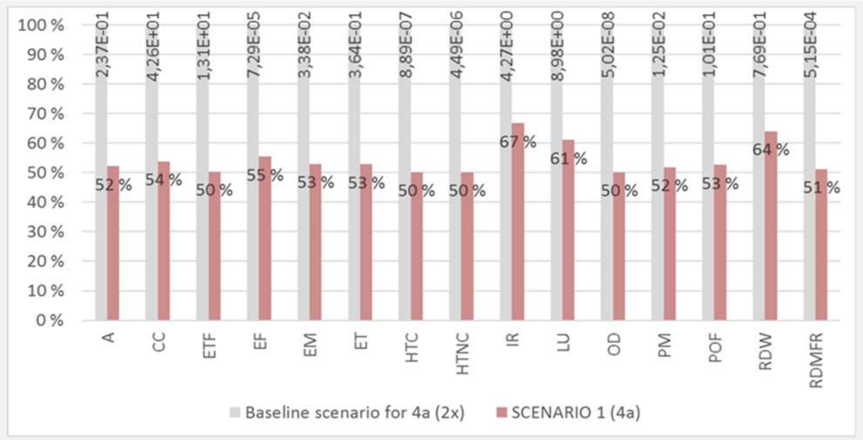
Impact of lifetime and miniaturization

Parameters of baseline and additional scenarios

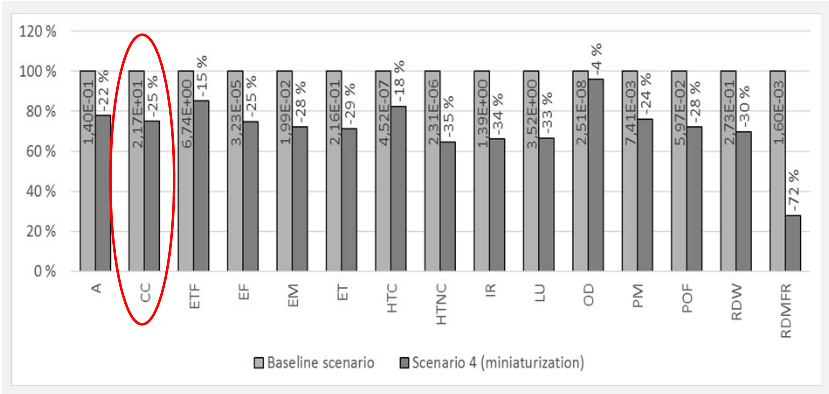
Scenario	Lifetime	Energy source in use	IC model	EoL
Baseline	2 a	EU-28 average	ICs based on product inventory	recycling of electronics and mechanics
1	4 a			
2		Hydropower		
3		Electricity from hard coal		
4			Miniaturization of IC components*	
5				No recycling

*) All ICs modelled as IC WLP CSP components based on pin count

Prolonging lifetime from 2 to 4 years reduce the environmental impacts in average by 46%



Miniaturization and wafer level processes has significant potential to reduce mfg related emissions



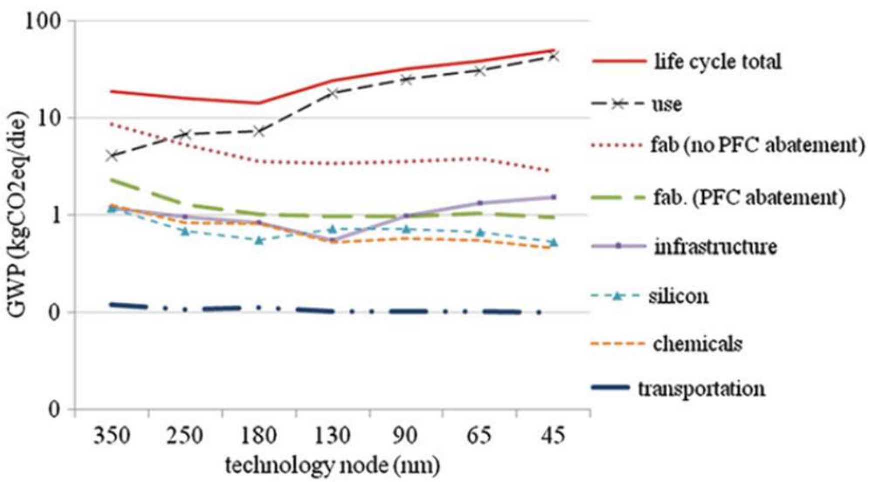
Note estimation based on scaling and available WLCSP datasets in GaBi electronics database!

Aalto University
School of Electrical Engineering

Uncertainties in LCA of semiconductors and components

- Models at component level not modifiable, linear scaling is a compromise!
- Impact of IC technology node, package type may not be available
- Chemicals and other manufacturing details proprietary information
- Process data from publications and specifications, EIO LCA and modeling
- Yield
- Energy consumption of a die

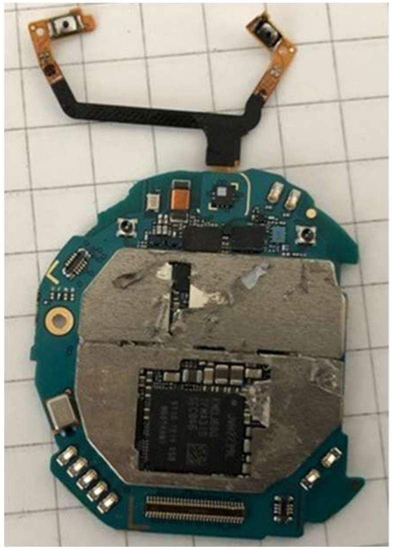
Global Warming Potential development with the technology node for a large (about 140 mm2) logic die over a lifetime of 6,000 h



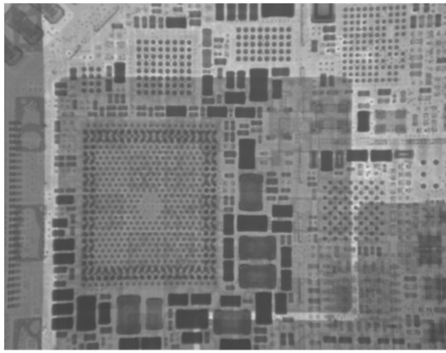
Ref. S. Boyd, Life-cycle Assessment of Semiconductors, 2012

LCA – Case Smartwatch

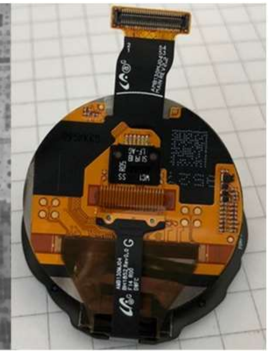
Galaxy watch



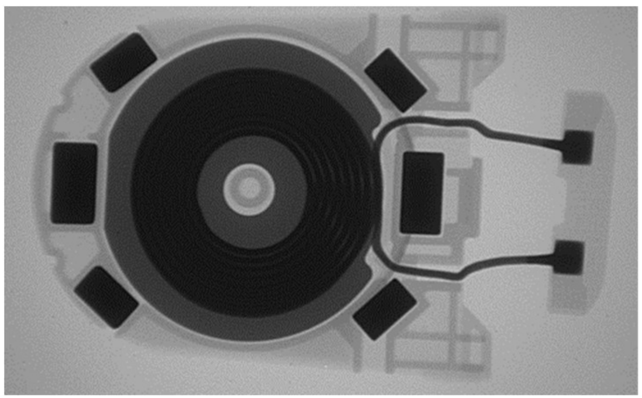
Samsung Exynos 9110 SoC



Display flex



Wireless charging unit



Main inventory data of smartwatch manufacturing

		Type/Material	Pcs.	Size [mm]	Weight [g]
Charger	"Traditional" phone type with micro USB connector.Input 100-240V;Output 5V/0.7A				33,47
Wireless Charging Unit					
	Plastic parts	PC	2		14,11
	Rubber+tape		2		0,71
	Metal frame	Galvanized steel			12,02
	Screws	Stainless steel	4		0,18
	EMI shields	Stainless steel	1		0,35
Motherboard					
	FR-4	6-layer, NiAu		~7*12mm+40*15mm=~700 mm^2	
	IDT P923 5A-16NDGI wireless power transmitter with a 32 bit ARM® Cortex®-M0 processor				
Charging coil module					13,89
	Plastic cover	PC			8,089
	Cu coil				2,56
	PCB	1 side FR-4; NiAu			0,24
	Magnets	Neodyne?	6		3,03
Watch					
	Wristband	Rubber	3		21,92
	Wristband	Stainless steel parts	4		5,23
	Screws	Stainless steel	5		0,25
	Other metal parts (incl. EMI shields)	Stainless steel	3		0,99
	Foil	Cu	1		0,039
	Metal frame (incl. 2 buttons)	Stainless steel			22,66
	Metal frame black (outer ring) incl. magnets	Stainless steel			5,9
	Plastic back frame (incl. microphone, ambient light sensor?, service port, and pressure sensor)	PC			4,00
	Plastic inner frame	PC			4,52
	Other plastic parts	?	2		0,76
	Display	OLED		Diameter 35mm, thickness 3,1mm	7,21
	Display flex with connector (excl. driver and ambient light sensor)	PI; NiAu			
	Display driver	Flip Chip IC, few hundred Ios		2*8mm	
	Ambient light sensor	Flip Chip 6 IOs		1,2*2mm	
	Other flex circuitry/ribbon cable (incl buttons)	PI HASL	1		0,10
	NFC antenna	PI NiAu+ Cu coil			0,98
	Battery	Li-ion		24*24*5mm	7,53
Heart rate sensor (incl. ribbon cable)					0,41
	LED	Wire bond, 6 IOs		1,6*1,8mm	
	Texas Instruments TI 8AWKJYP SN1712025 ultra-small, integrated AFE (analog front end) heart rate sensor chip	30 Ios			
	Loudspeaker				1,00
	Vibration motor				1,02
	Hall sensor array [incl. 3 components (wire bond, 4 Ios), FR4, PI flex and NiAu male connector]				0,089
Motherboard					3,79
	Samsung Exynos 9110 SoC (dual-core, 1.15 GHz)				
	NXP 80T17 NFC controller	HVQFN40		6 x 6 x 0.85 mm	
	Broadcom BCM430131 WiFi/BT chip				
	Broadcom BCM47758-GPS/GLONASS chip	77-ball WLBGA			
	Skyworks 77651-21	32 (?) I/O QFN			
	Skyworks 77652-11 multimode/multiband power amplifier modules for 3G/LTE	MCM, 28-pad		4.0 x 3.65 x 0.75 mm	
	S910 NFY55 WR1				
	STMicroelectronics barometric pressure sensor				
	ST Micro ST33G1M2 32-bit ARM® SecurCore® SC300 (secure element)				

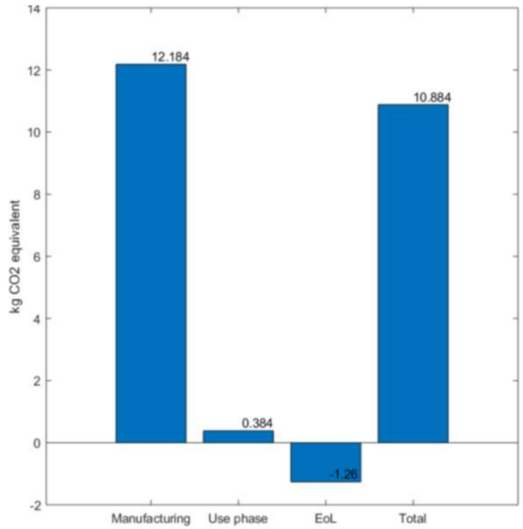
LCA – Case Smartwatch

Use phase consumption	538 Wh
Electricity	Finnish average
EoL scenario	100% Recycling

Calculated life cycle impacts of smartwatch in different impact categories

Environmental quantities	Total	Manufact.	Usage	Recycling
Abiotic Depletion (ADP elements) [kg Sb eq.]	−2,70E−05	0,000848	2,00E−08	−0,00088
Abiotic Depletion (ADP fossil) [MJ]	138	150	0,996	−12,6
Acidification Potential (AP) [kg SO2 eq.]	0,0592	0,0785	0,000248	−0,0195
Eutrophication Potential (EP) [kg Phosphate eq.]	0,003542	0,00432	3,27E−05	−0,00081
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.) [kg DCB eq.]	0,0967	0,107	0,000466	−0,0108
Global Warming Potential (GWP 100 years) [kg CO2 eq.]	10,6	11,8	0,1	−1,26
Global Warming Potential (GWP 100 years), excl biogenic carbon [kg CO2 eq.]	11	12,2	0,1	−1,26
Human Toxicity Potential (HTP inf.) [kg DCB eq.]	8,56425	9,13	0,00925	−0,575
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) [kg DCB eq.]	6211	6,46E+03	10,2	−259
Ozone Layer Depletion Potential (ODP, steady state) [kg R11 eq.]	9,44E−09	9,44E−09	2,24E−16	1,14E−15
Photochem. Ozone Creation Potential (POCP) [kg Ethene eq.]	0,00385	0,00474	2,40E−05	−0,00091
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB eq.]	0,0777	0,0817	0,000136	−0,00411

Calculated GWP of smartwatch in different life cycle stages



Use phase consumption	459 Wh
Electricity	Chinese average
EoL scenario	100% Recycling

Impact category	GaBi model, 40 g	New model, 10 g
ADP elements (kg SB eq)	$3.02\cdot10^{-6}$	$4.74\cdot10^{-6}$
ADP fossil (MJ)	1.60	3.59
AP (kg SO_2 eq)	$9.5\cdot10^{-4}$	$24.50\cdot10^{-4}$
EP (kg P eq)	$7.6\cdot10^{-5}$	$14.30\cdot10^{-5}$
FAETP inf. (kg DCB eq)	0.02	0.02
GWP, incl biogenic (kg CO_2 eq)	0.13	0.30
HTP inf. (kg DCB eq)	0.06	0.16
MAETP inf. (kg DCB eq)	55.20	111.00
POCP (kg ethene eq)	$5.10\cdot10^{-5}$	$16.20\cdot10^{-5}$
ODP (kg R11 eq)	$5.90\cdot10^{-9}$	$3.30\cdot10^{-9}$
TETP inf. (kg DCB eq)	$2.30\cdot10^{-3}$	$3.90\cdot10^{-3}$

Impact of electricity central also in mfg phase. Database (German electricity) vs calculated model (Chinese supply mix energy) for NMC battery cell

Aalto University
School of Electrical Engineering

Towards circular economy for EEE

WW legislation – inc. WW agreement of what is e-waste and delivery of e-waste statistics (to measure success of legislation)

- Enforcement of legislation with covering collection and recycling targets
- Full material declarations through the supply chain to ensure conformance to legislation

Efficient recycling processes for e-waste and extraction of materials

Focus on Ecodesign - product design avoiding hazardous materials, improving resource efficiency and considering product lifetime inc. end of life

Ecodesign tools and standards needed for EEE, e.g. ICT products

Understanding of the product full life cycle impact on the environment

Economic benefits for sustainable design and production for companies

Customer demand

- Eco-labeling programs
- ISO 14000 environmental management system standards

Ecodesign strategies

- Design for repair: spare parts availability and time frames
- Design for upgradability: being able to upgrade a product as customer's needs or technology changes
- Design for reliability: create products that last longer, clear product level reliability targets, e.g. resistance to accidental drops for mobile devices
- Design for dematerialization: reducing the overall size, weight and number of materials involved in a design
- Design for disassembly: a product is designed so that it can be easily and cost effectively taken apart at the end of life, including marking on materials
- Design for recyclability: using materials in the design which can be recycled and recycling processes exist, marking of materials to facilitate manageable waste streams

Conclusions

- Improved WEEE collection and more sophisticated waste streams needed to improve material recovery
- Co-operation needed between teams responsible for EEE design development and recycling process development
- Comprehensive LCA powerful for analyzing environmental impacts and potential for ecolabeling – however in EEE standards needed how to apply to ensure comparability
- At SC level largest emission reduction potential is most likely in using renewable energy sources for manufacturing electricity
- Miniaturization and wafer level processing in modern facility provides additional opportunities for mfg impact reduction
- Ecodesign requirements critical to be implemented to increase reuse and
- Product level reliability will become more important

Thank you for joining! ☺

Aalto University
School of Electrical
Engineering