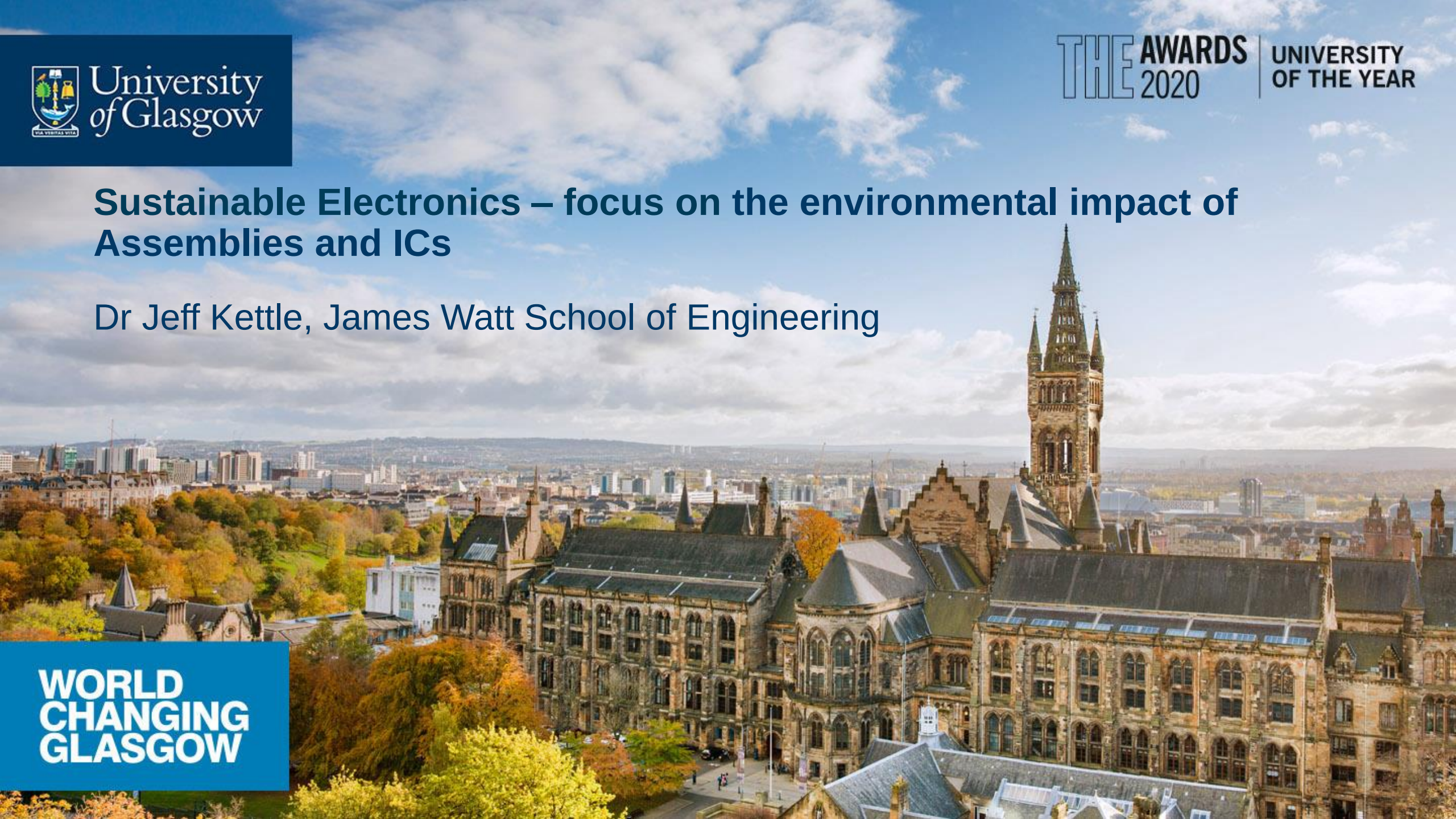
University of Glasgow

THE AWARDS 2020 | UNIVERSITY OF THE YEAR

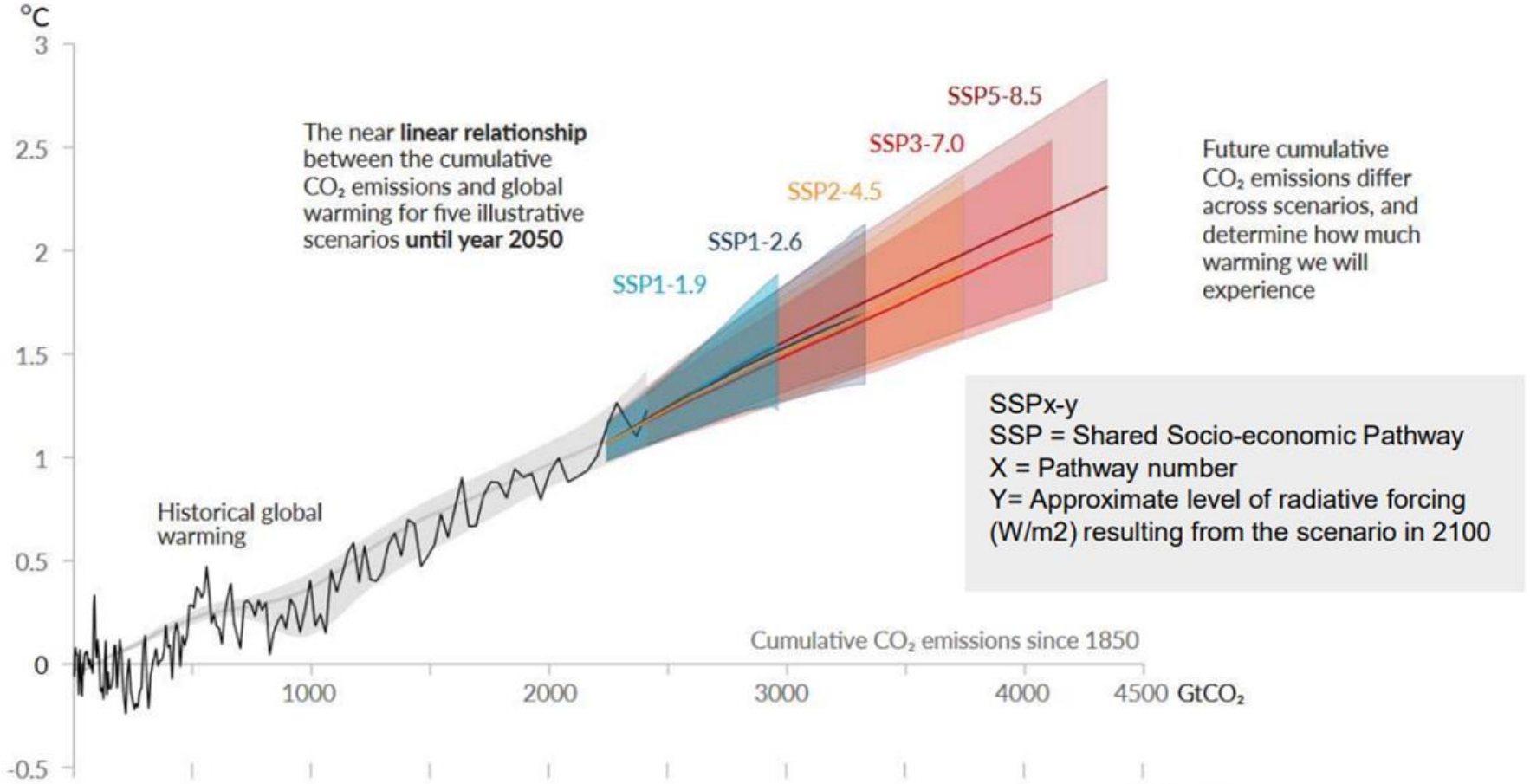
Sustainable Electronics – focus on the environmental impact of Assemblies and ICs

Dr Jeff Kettle, James Watt School of Engineering



WORLD CHANGING GLASGOW

Global surface temperature increased since 1850 as a function of cumulative CO_2 emission

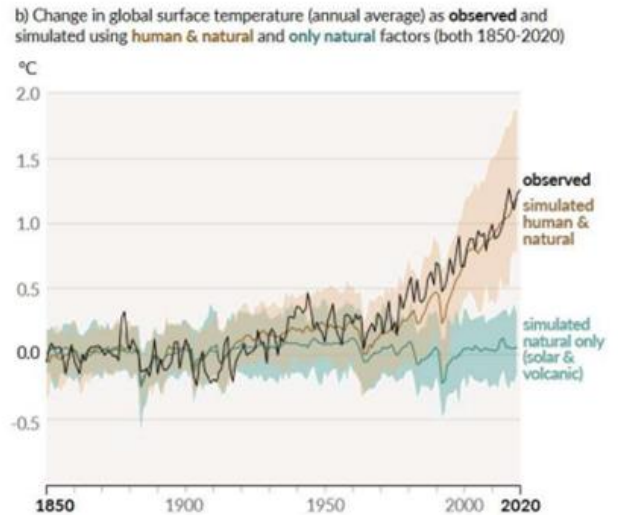


2° increase in UK?

7x more extreme heat (i.e once every 3 years instead of 20 years)

80% more heavy rains

3x more drought



GWP - Global Warming Potential + the Semicon industry

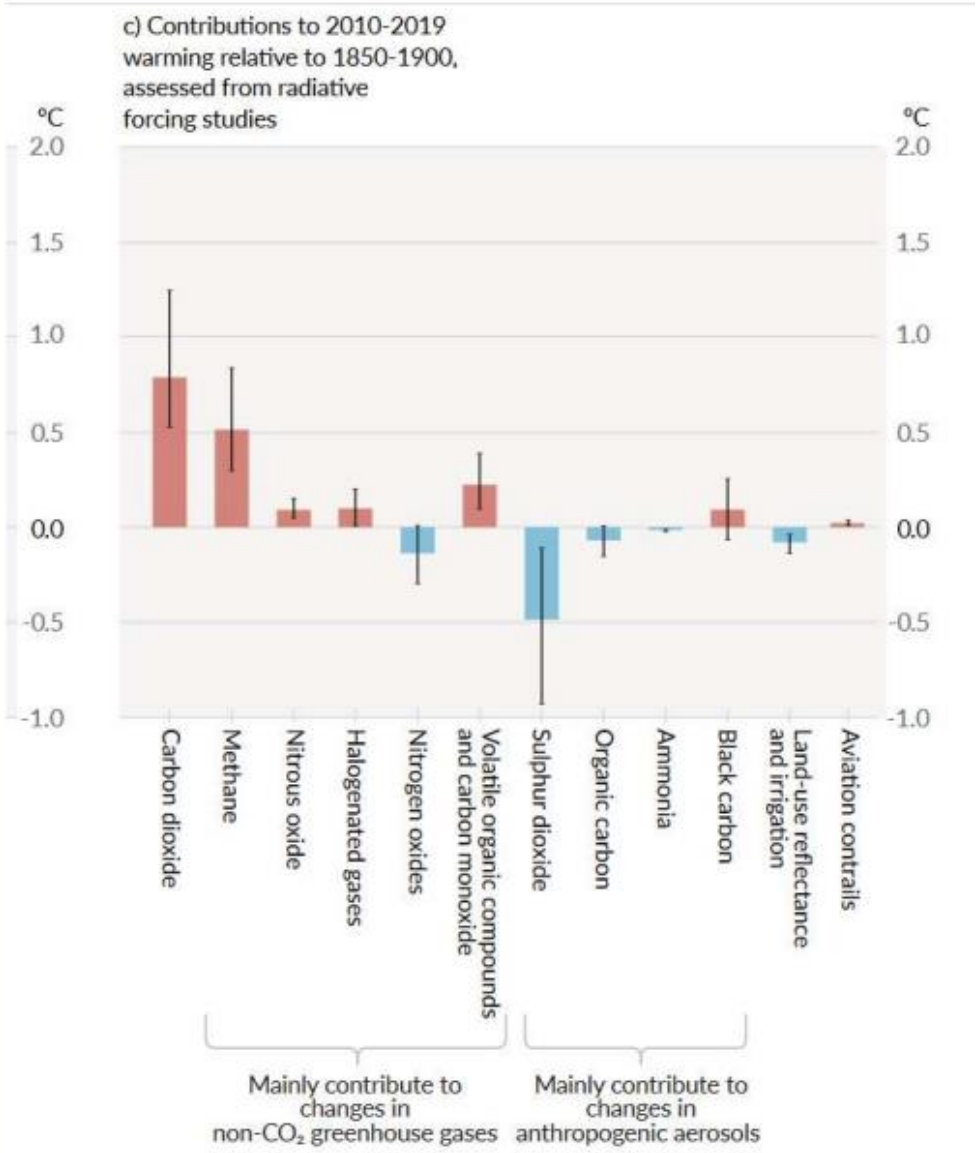
The major contributors to increases in radiative forcing in the last decade are CO_2, CH_4 , N_2O and CFCs

$$GWP_i = \frac{\int_{TR}^{TH} a_i C_i(t)\,dt}{\int_{TR}^{TH} a_{CO_2} C_{CO_2}(t)\,dt}$$

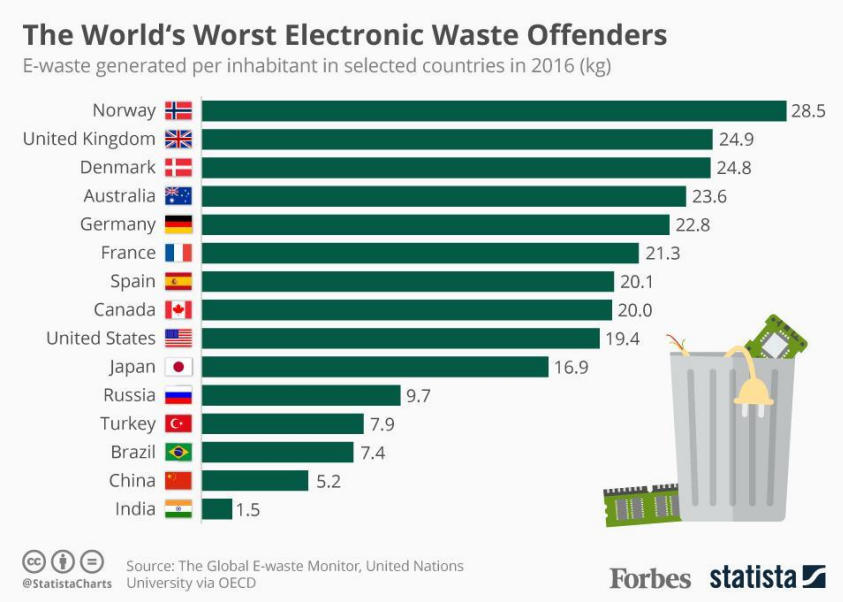
a_i = instantaneous radiative forcing due to a unit increase in the trace gas, i, concentration

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



Alternative electronics is needed because ….. E-waste



Export of e-waste

In the UK, we collect around 20% of e-waste

60-80% of e-waste is sent abroad (2019)

Why sustainable electronics?

1. E-Waste/WEEE;

- 53.6m tonnes globally in 2020, <20% collected and possibly recycled
- 66% (67 countries) of the world's population covered by e-waste legislation in 2021

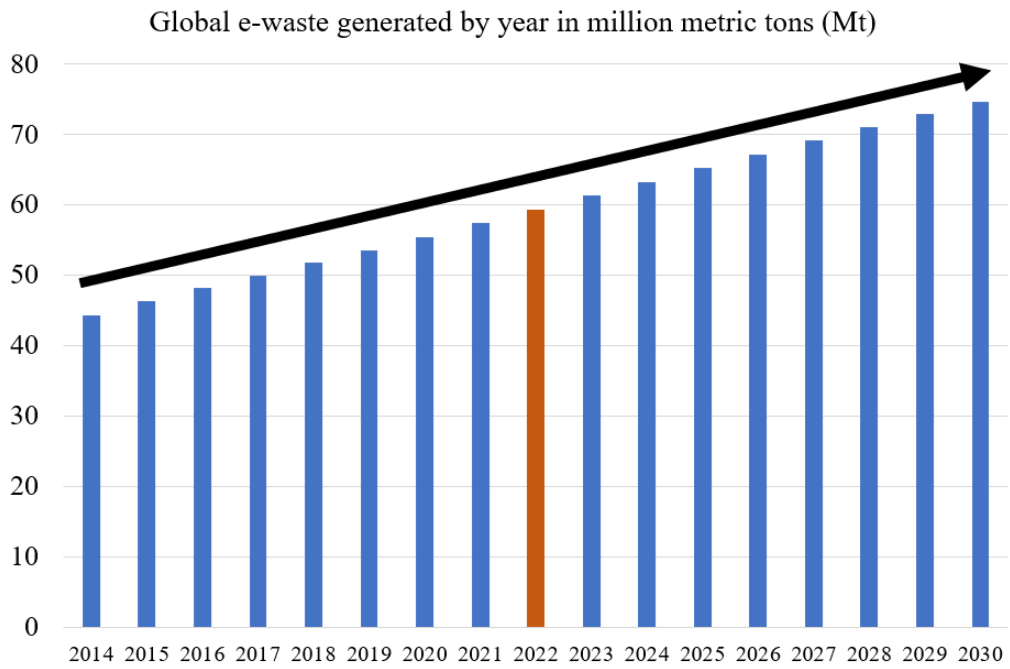
2. CRMs Critical Raw Materials

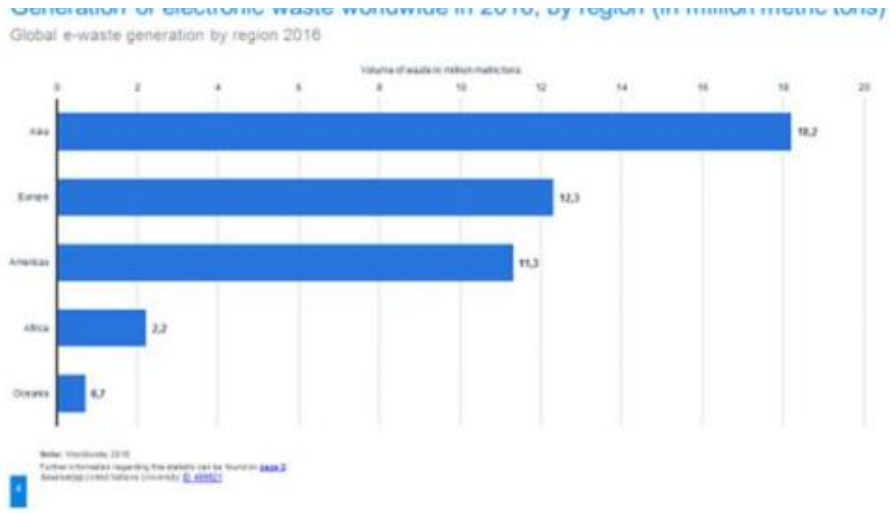
- are required in eg batteries, power electronics, photonics, and the UK is almost 100% reliable on imports (national security!)

- Materials such as Au, Ag, Pt, Pd, Ga, Sb

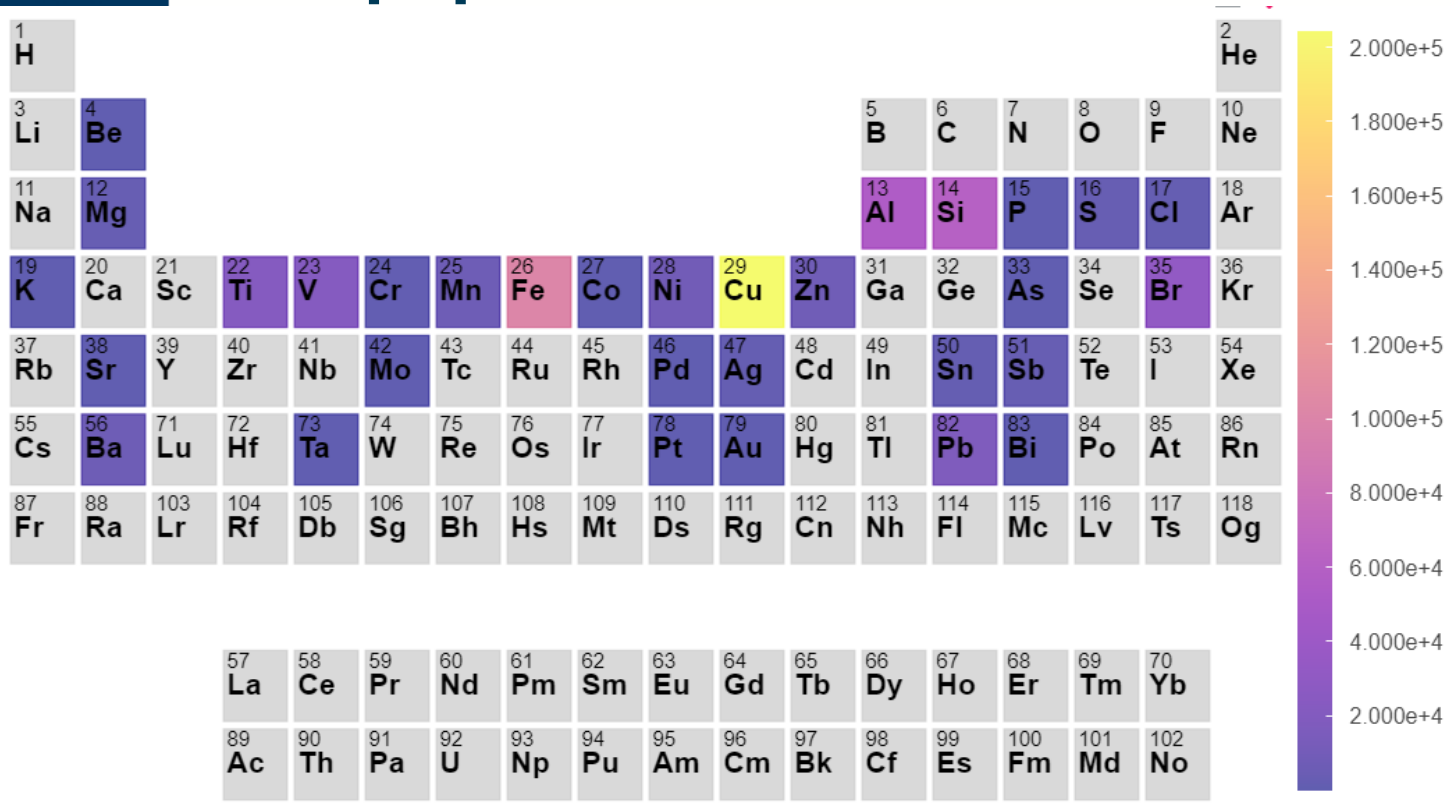
3. Emissions

- The wider electronics sector is one of the top 8 sectors that account for more than 50% of global carbon emissions, mostly attributed to the supply chain (77%) including production, manufacture, assembly, and transportation + circular economy, reuse, repair, redesign





1. E-waste = Waste Electrical and Electronic Equipment = WEEE - Global



Others by weight

Ferrous metals – 40%
Aluminium – 5%
Copper – 5%
Plastic -20%
Glass – 10%
Others – 5%

Automation?

IEEE Journal on Flexible Electronics, *1*(1), 4-23, 2022

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

- Screens, monitors televisions, laptops, notebooks, tablets

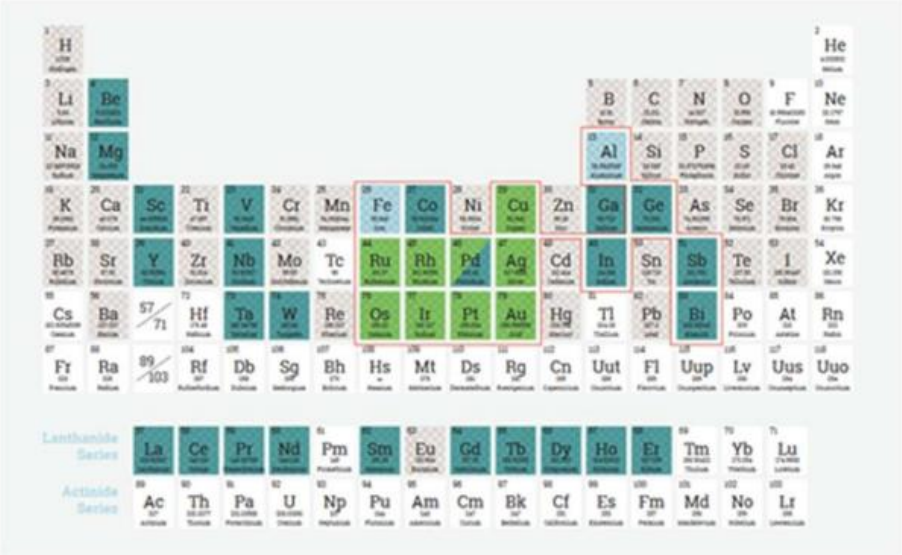
- fluorescent lamps, high intensity discharge lamps, LED lamps

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

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

- Phones, printer, laptop, tablets

2. Critical raw materials (CRMS) 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, iridium 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

Next steps - Linear vs circular economy

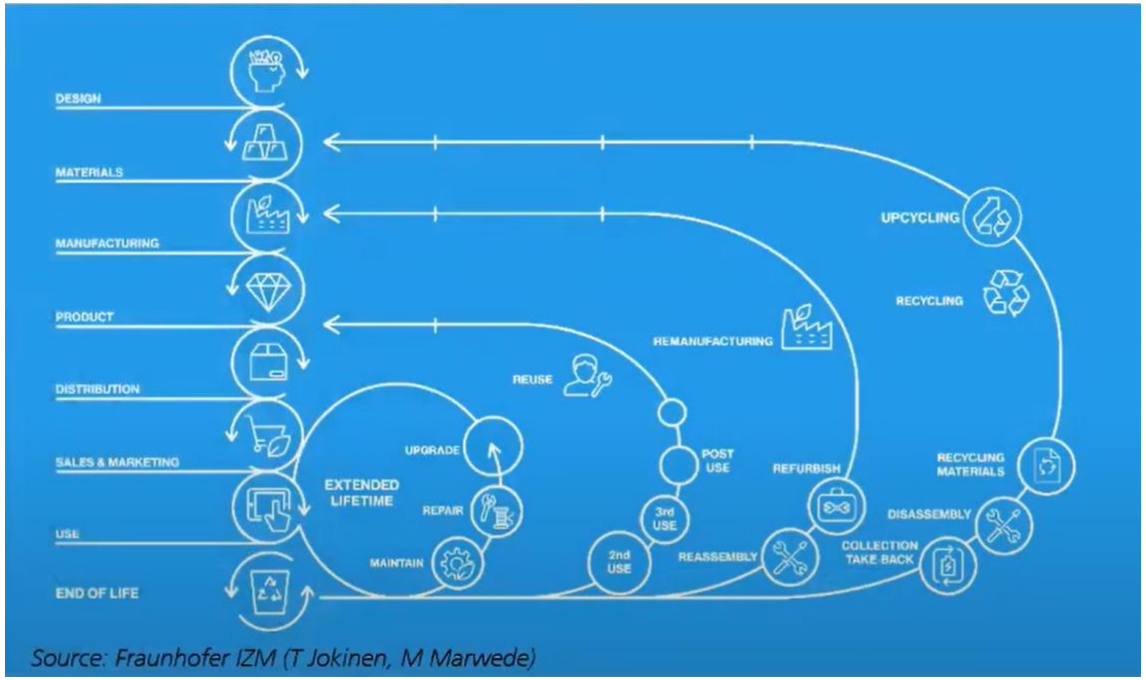
- Current systems of production organized on a linear basis

- EEE – seeing increasing consumption and new applications e.g. IoT, 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

- WEEE volumes difficult to calculate

- Adopt EU's waste hierarchy to reduce material flows – means enhancing repair, reuse, durability…. then recycling



Source: Fraunhofer IZM (T Jokinen, M Marwede)

Directives and regulations

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

Waste of electric and electronic equipment (WEEE) 2012/19/EU

Ecodesign 2009/125/EC

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

EU Conflict minerals regulation and EU CRM act

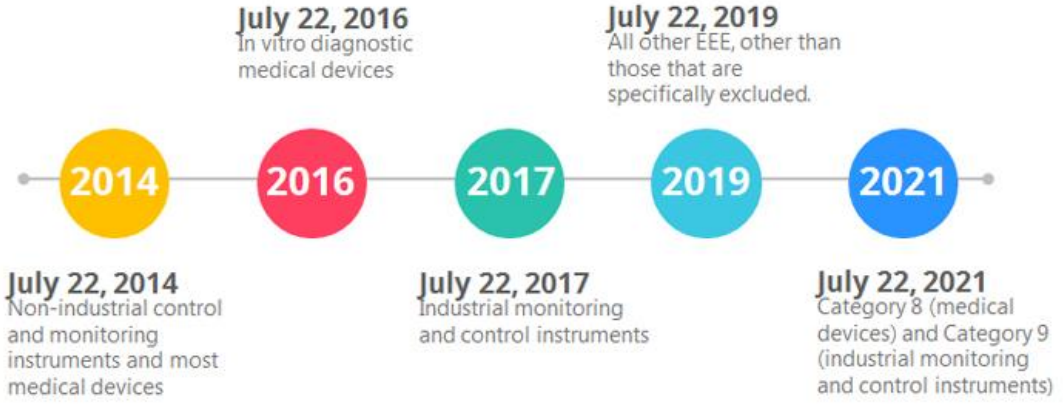
UK has implemented these (mostly) into UK law

UK and EU 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
- 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 other exemptions
- Elimination or substitution via design change or use of materials & components not requiring restricted substances is scientifically or technically impracticable
- Decision concerning duration to consider impacts on innovation
- Case by case basis

UK RoHS – different label – must comply, but tolerates EU until 1.1.24



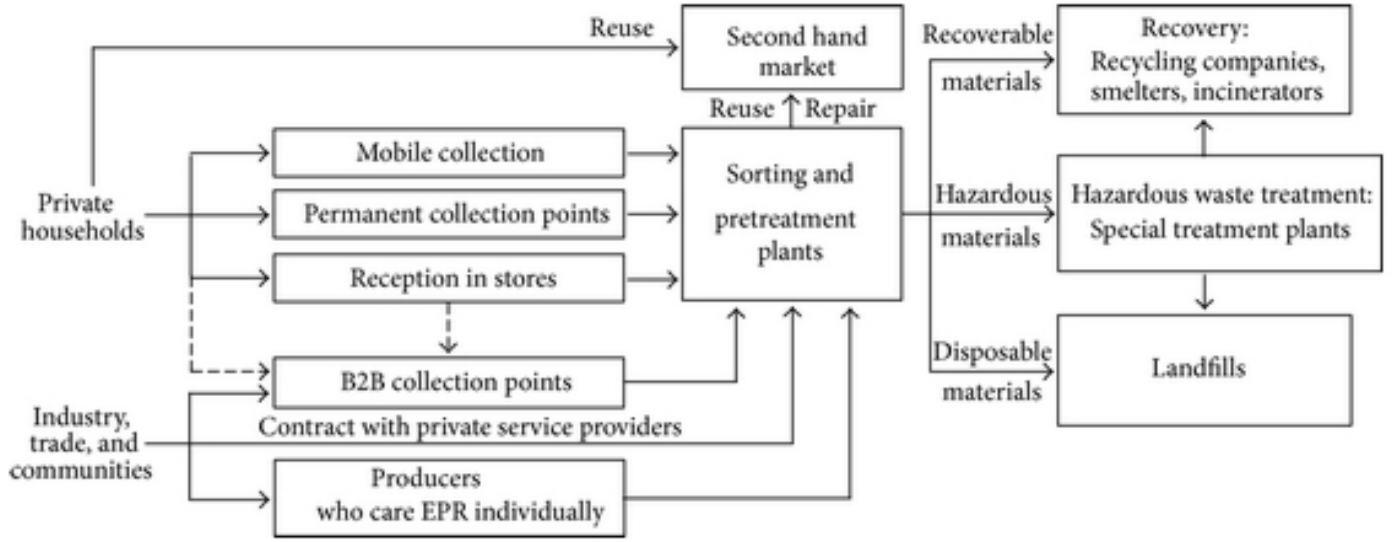
WEEE Directive 2012/19/EU

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

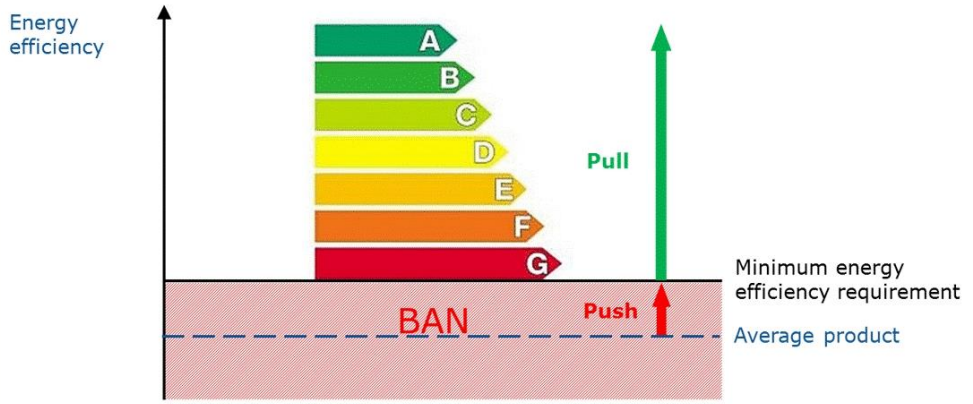
Recovery
Increase to >75% of collected WEEE

WEEE shipments
Control of transboundary movements, Basel Convention (stricter controls post Brexit!)

WEEE treatment
Min requirements for removal of substances and components e.g. CRMs



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

• Outlines recommendations to reduce waste and increase reuse and recycling
  - number of parts, time needed for disassembly, 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

Future; training for speciality repairers, promise to consumers - UK ecolabelling coming, but EU still fine ,

REACH / UK 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

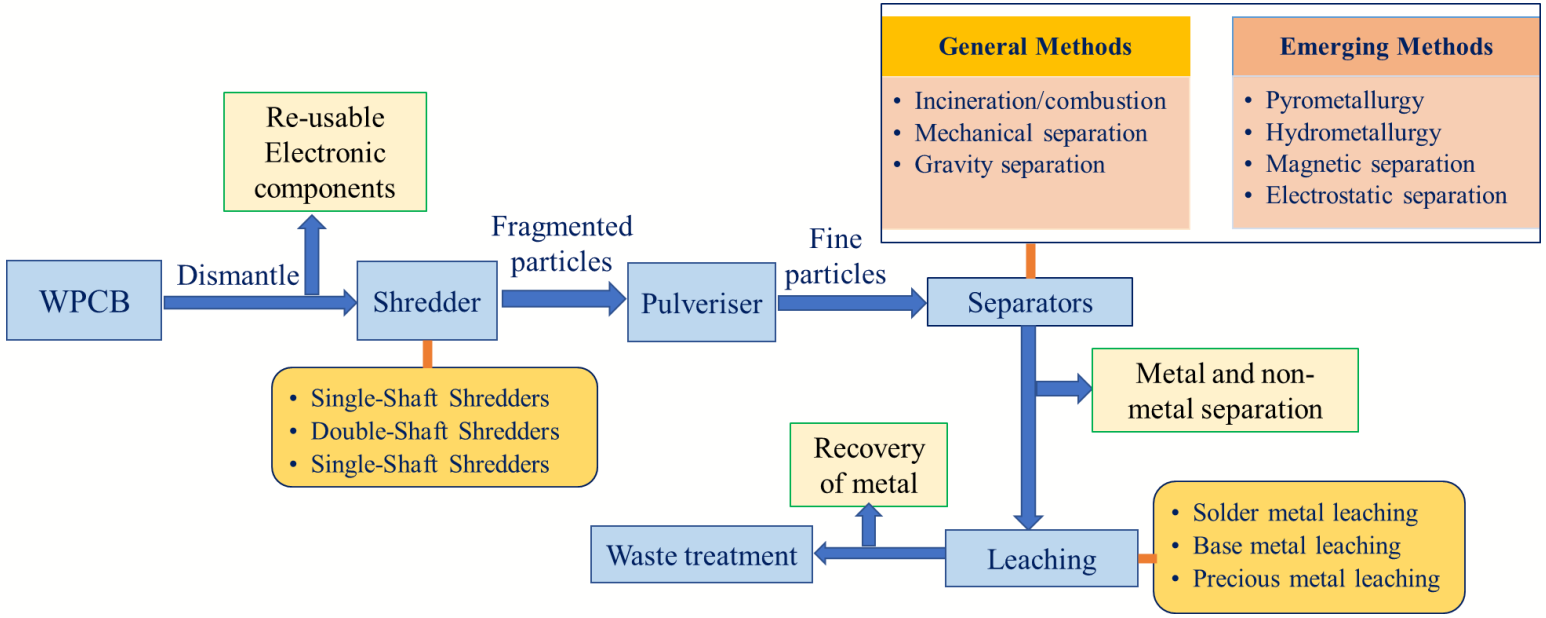
• is based on the principle that it is for manufacturers, importers and downstream users to ensure that they manufacture, place on the market or use such substances that do not adversely affect human health or the environment.

• *NI has to comply with REACH, UK doesn't*

• *UK REACH applies to GB companies for import*

• *importers will have to specifically disclose the chemicals in both the UK and the EU registration systems.*

WEEE recycling and treatment



Magnetic separation of steel

- 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!

WEEE recycling and treatment

Disassembly

- 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!

Pre-processing

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

Metallurgy

- Precious metals dominate economic & environmental value: Au, Ag, Pd, Cu and dissolved metals
- Pyrometallurgical processes most common, ”smelting”
- Hydrometallurcial processes, acid leaching (HNO_3, H_2SO_4, HCl), importance increasing

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
- As infrastructure – WEEE quality is reducing – less Au and Pd. Economics has driven material changes in electronics
- Three materials in PCBs are economically viable to recover(Au, Cu and Ni)

No copper smelters in the UK

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

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

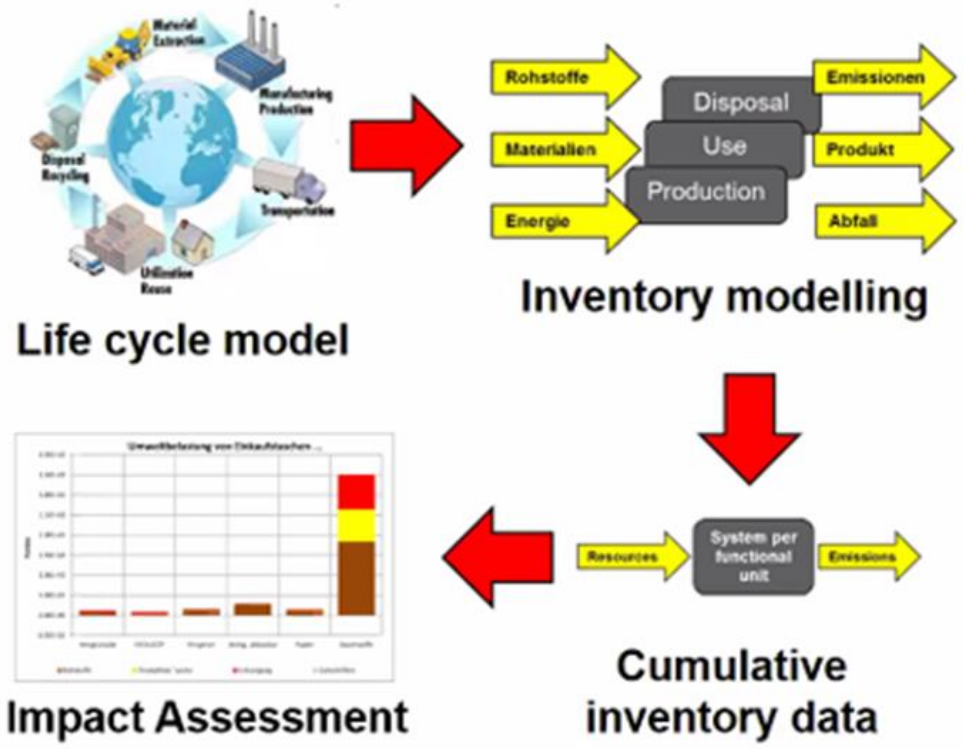
Allow for comparison of products and production processes and help to prioritize actions for improving environmental performance of products

- 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 m2) 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)

How can we measure a PCBA's environmental impact

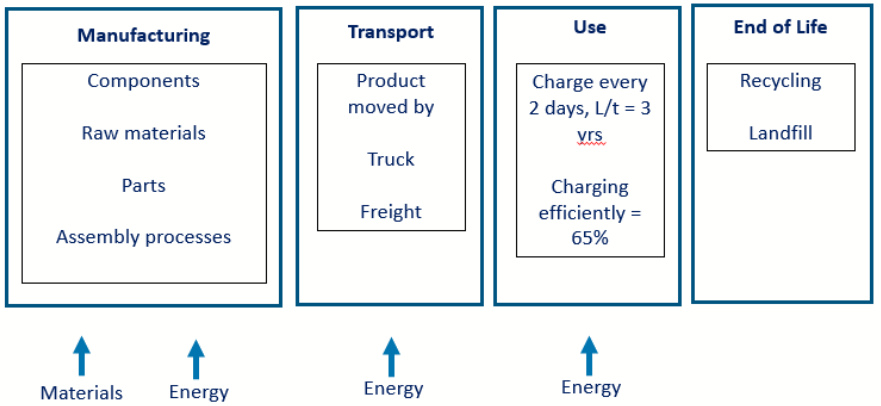
…with Life Cycle Assessment method



Source: Roland Hischier, EMPA

- **LCA is a Comprehensive approach** that quantifies ecological and human health impacts of a product or service over its complete life cycle
- **LCA uses credible scientific methods** using specialist software which contains databases with environmental impact information for standard procedures
- **LCA helps decision makers** to understand the scale of the many environmental and human health impacts of competing products, services, policies etc
- **Basic principle** is a 2-step procedure
  - **Collection** of all interactions of a systems with the environment (Input-Output-Analysis)
  - **Assessment** of exchanges with nature
- Gabi – rare metals and electronic components

LCA – example - smartphone



Dataset based on GaBi

Division of LCI results show the manufacturing phase in baseline scenario in GWP ~80-90% in most impact categories

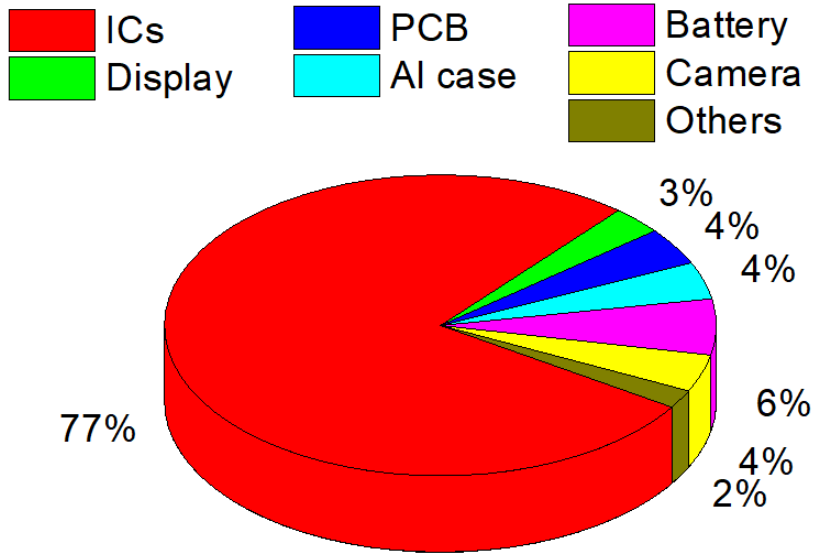
Highest proportion of consumption in the ICs

Nanofabrication processing has the most significant impact

Uncertainty on displays/cameras, ICs, materials, processes etc

'Usage' % increases for 24/7 equipment

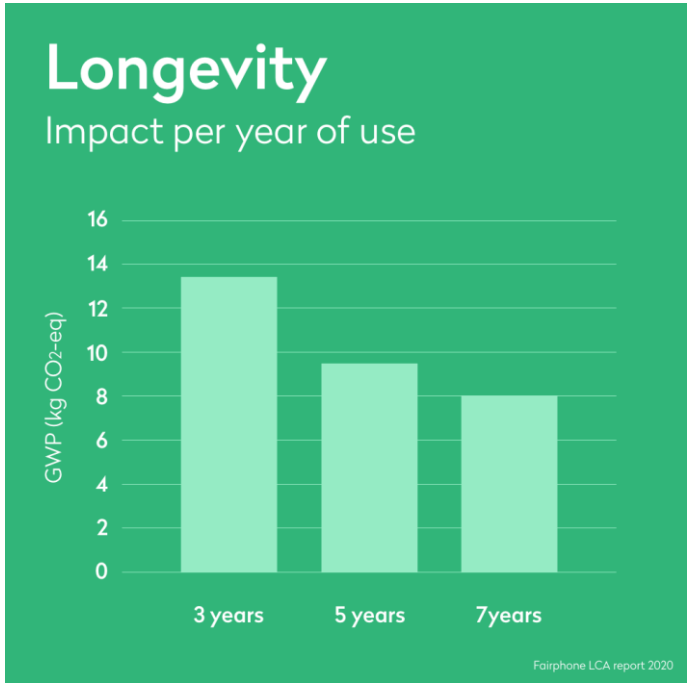
Global warming potential (GWP)



LCA – example - smartphone

Fairphone

- Modularity comes with a price; connectors, PCB substrate, module housing
- *Worse environmental profile at point of purchase*
- Some of these approaches now adopted by Samsung



Alternatives for metals, semiconductors and substrates?

Commercial alternate substrates for flex-PCB

- Polyethylene terephthalate (PET) <70°C, PEN has a higher T_G but is 10x expensive than PET. Some reports PET can enzymatically degraded
- Fluorinated ethylene propylene (FEP) >200°C, Poly ether ether ketone (PEEK) >200°C
- Thin glass-epoxy sheets (<200µm) ~105°C
- CMG (flexible glass) – expensive

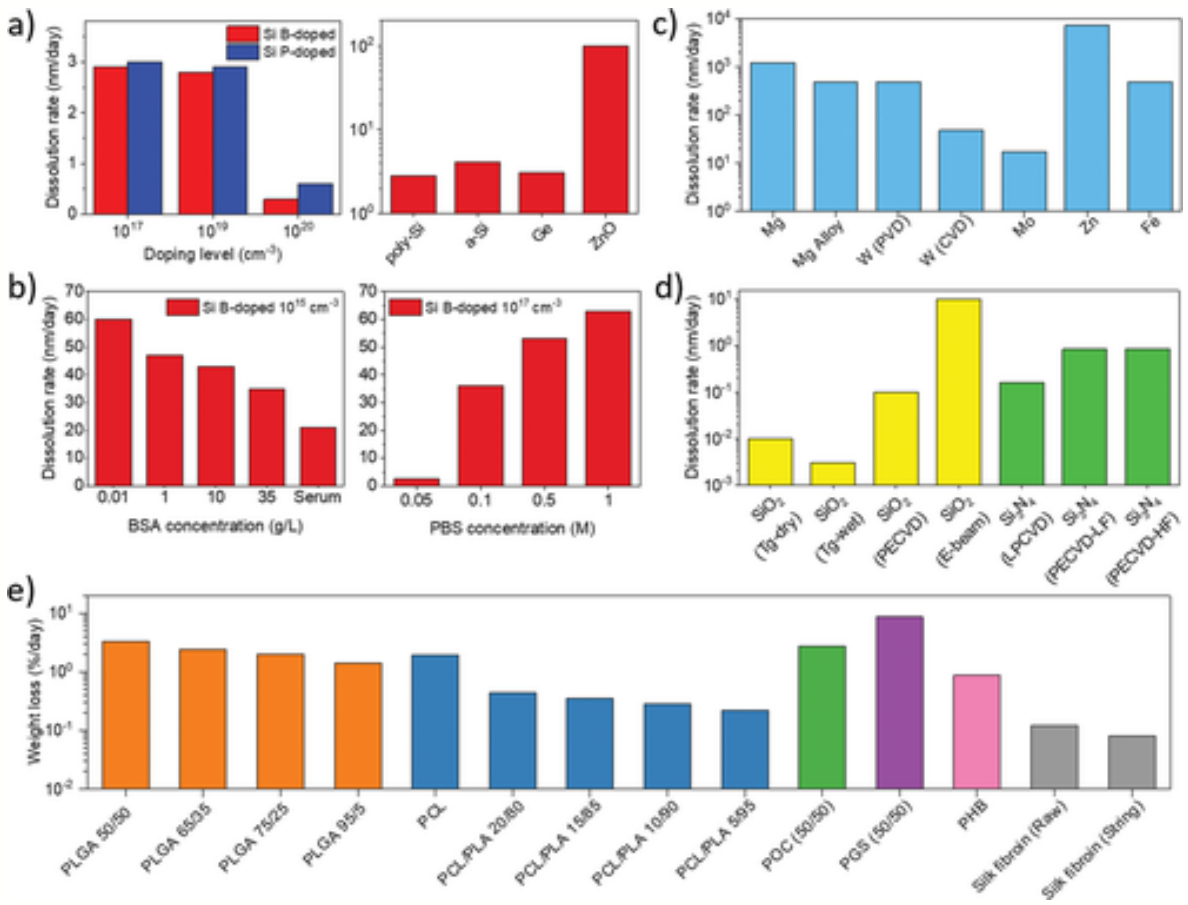
Challenges

- Temperature, temperature, temperature
- Electrodeposited (ED) copper (chemical compatibility etching process likely to an issue for many of the above substrates except for polyimide)
- Rolled annealed (RA) copper foil (chemical compatibility still an issue) – l
- How to apply QC through processing (alignment and AOI is a process key
- Can it be laminated to form multi layers structures - how to add single ar
- Compatibility with solder mask materials
- Cost….

Alternatives - biodegradable/bioresorbable electronics

Bioresorbable materials that fully dissolve in the body with biologically benign byproducts

Biodegradable materials that fully dissolve in the environment (typically soil) with biologically benign byproducts



(rates @ pH 7.4 and 37 °C – note: some group to group variation in rates)

https://doi.org/10.1002/advs.201902872

Large number of possible substrates (e.g PLGA)

- also Silk, cellulose, PLA, PLGA, PCL, PVA, PHB, PHV, Ecoflex
- None of these are high temperature compatible

-Semiconductors

– Silicon nanomembranes, ZnO

- Indigo, beta-carotene, perylene bisimides, PDPP-PD (Z Bao, PNAS, 2016)

-Organic conductors

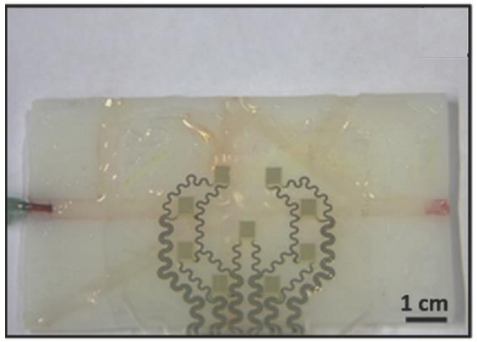
-PEDOT:PSS, polyaniline and polypyrrole, CNTs, Graphene, Graphite,

Encapsulants/dielectrics - oxides and nitrides - MgO, SiO_2, Si_3N_4, AlO_x

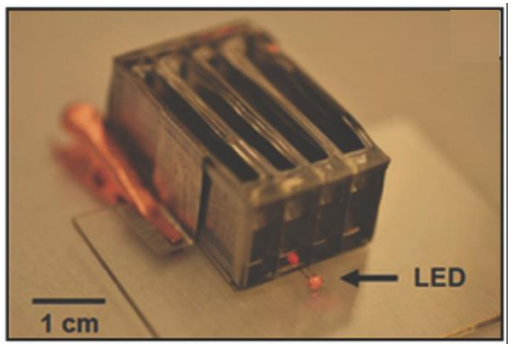
Metals – Mg, W, Mo, Zn and Fe,

Alternatives - Example biodegradable applications

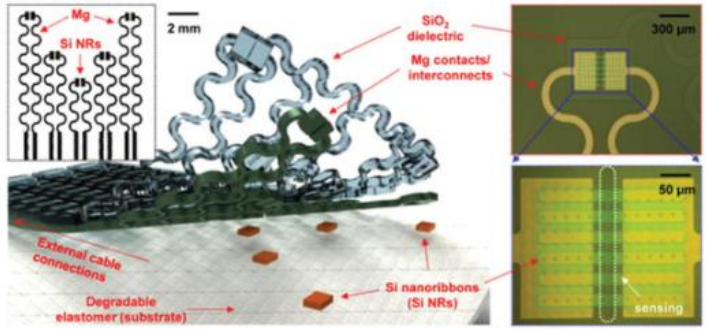
Temperature sensor



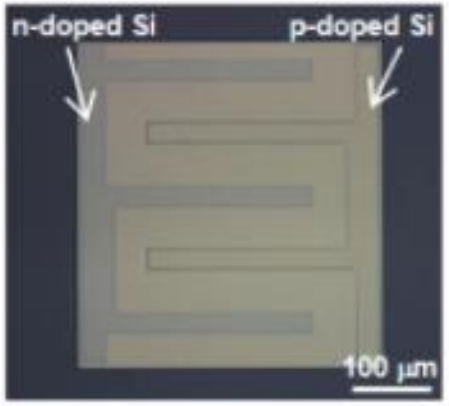
Battery



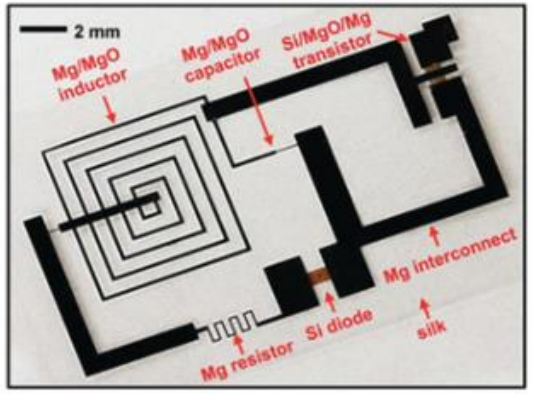
pH sensor



Solar cells

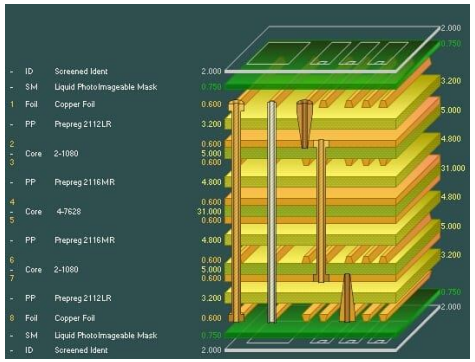


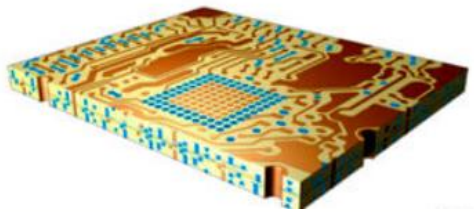
RF antenna

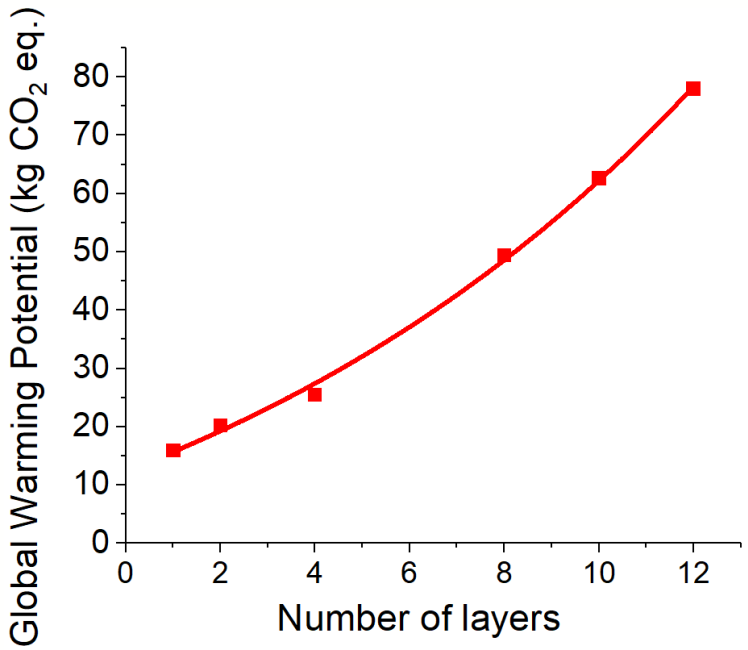


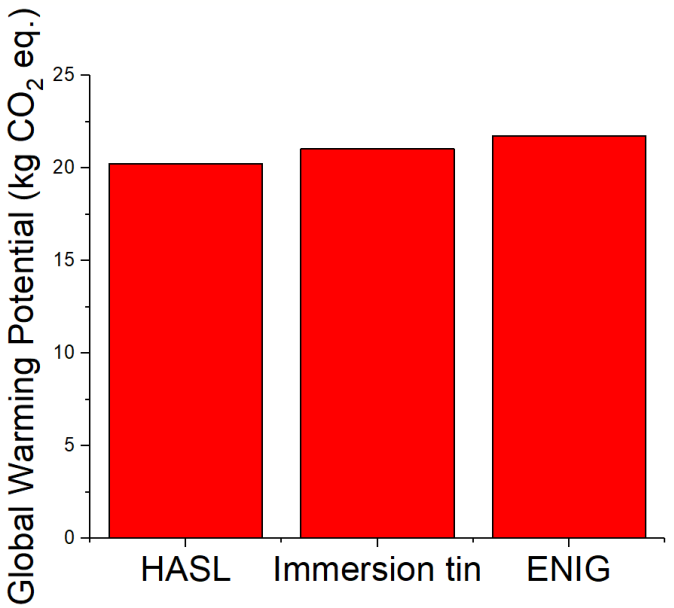
Agriculture applications

PCBA's environmental impact – key take aways

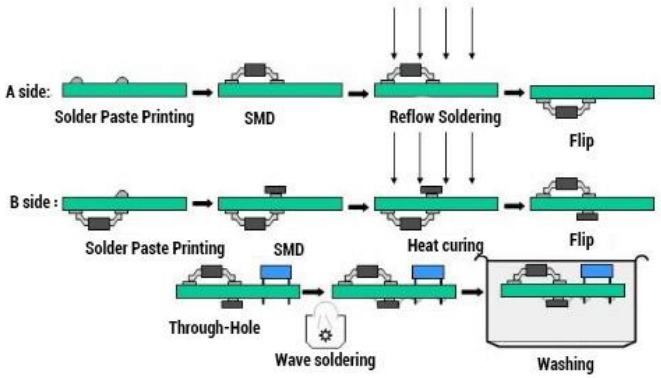








- Stacked SLP uses up to 20. This permits for a higher density of components in a given surface area.
-The iPhone X had has a 10-layer AP board, eight-layer RF board and two layers of interposers.

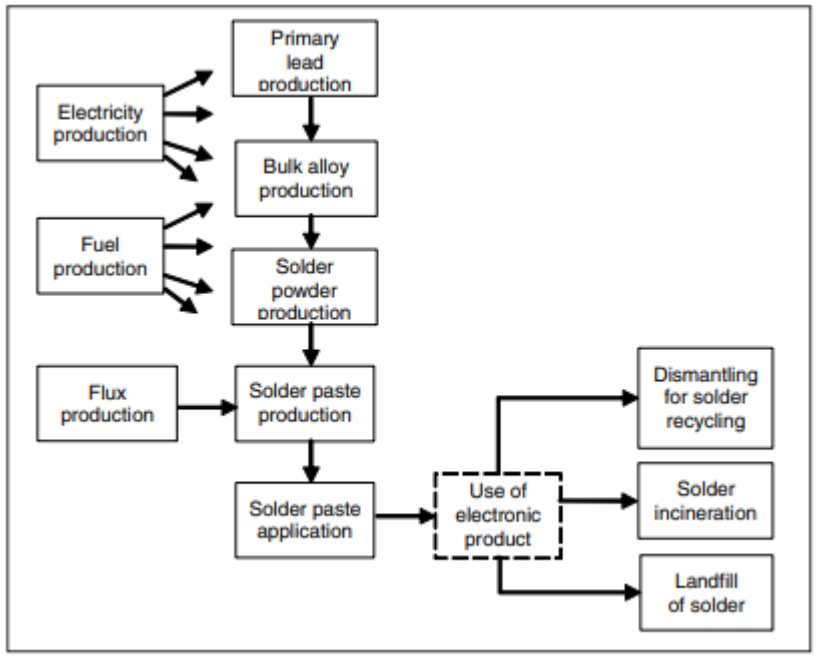


2 layers board Mixed Assembly

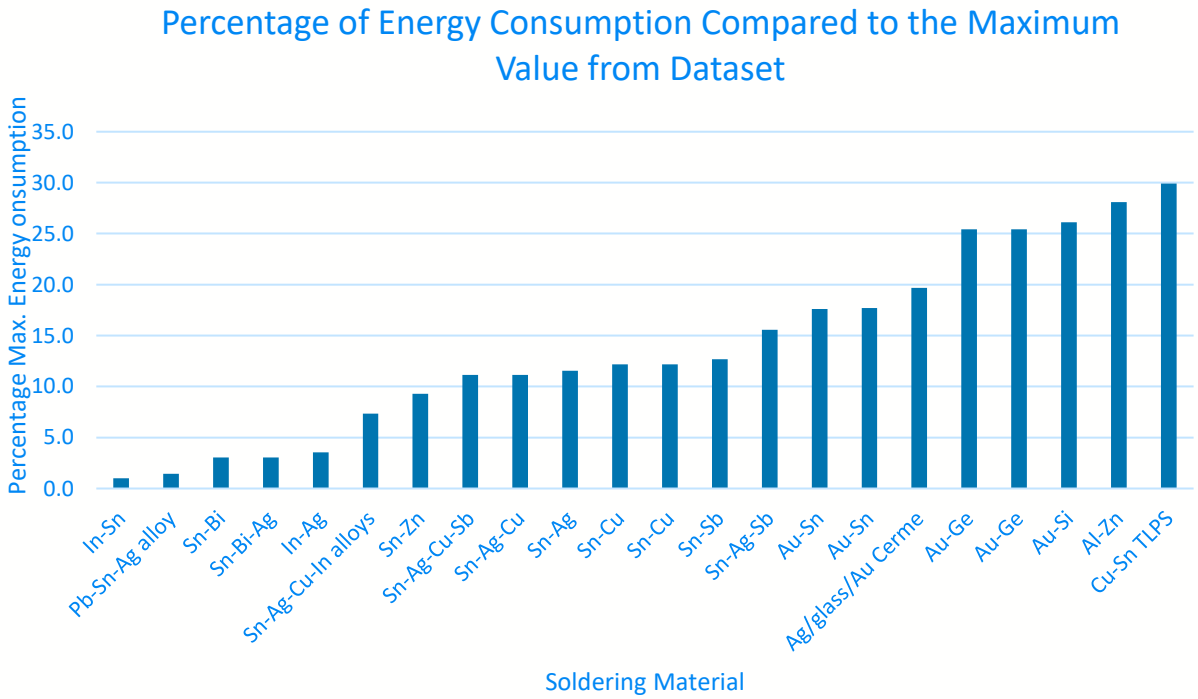
Source: PCB-way.com

Solders and Die attach materials for ICs

Higher reflow energy needed for Pb-free materials
Reference – 300mm^3 of SnPb – adjusted for different material designed , flux constituent and share of the weight is assumed to be the same for both solder paste
Volume 600 PCBs/hr on

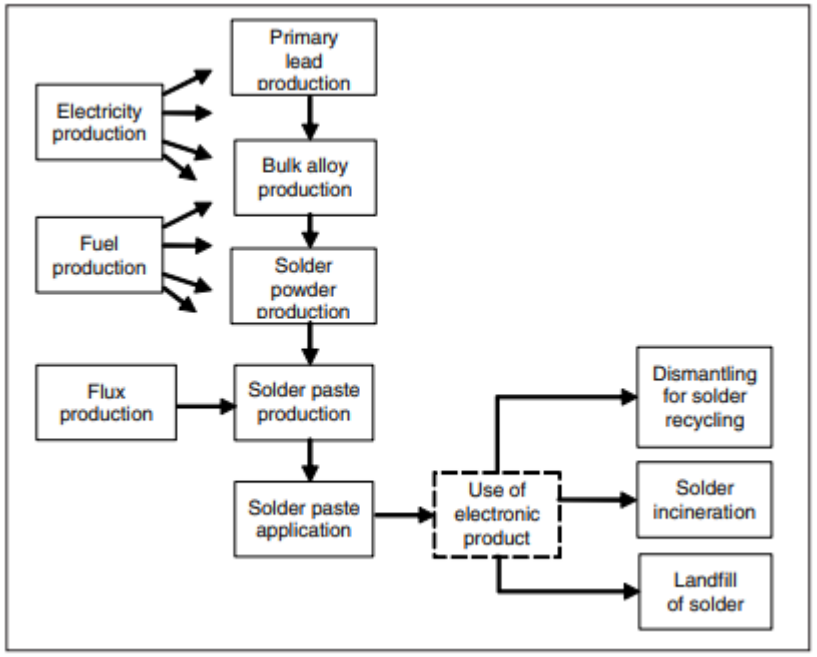


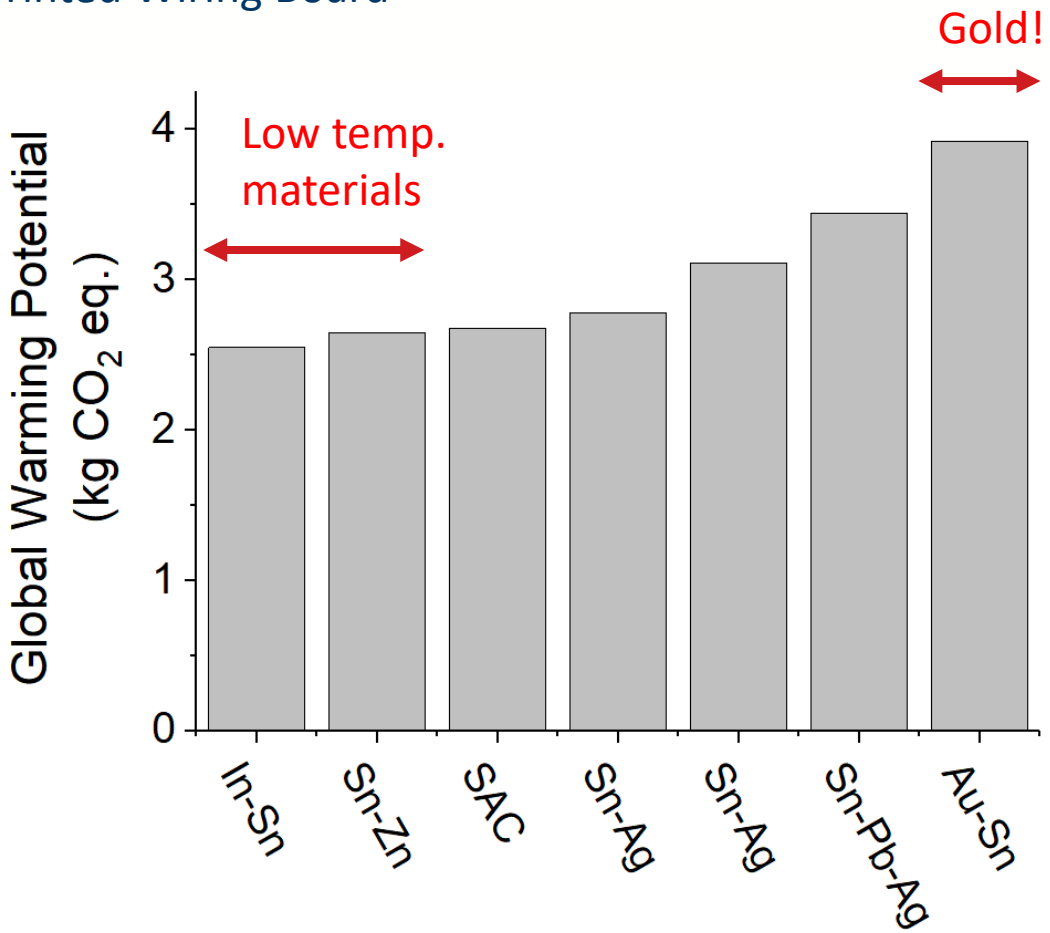
Source: Andrae, A. S., Itsubo, N., Yamaguchi, H., & Inaba, A. Materials transactions, 48(8), 2212-2218.



Solders and Die attach materials for ICs

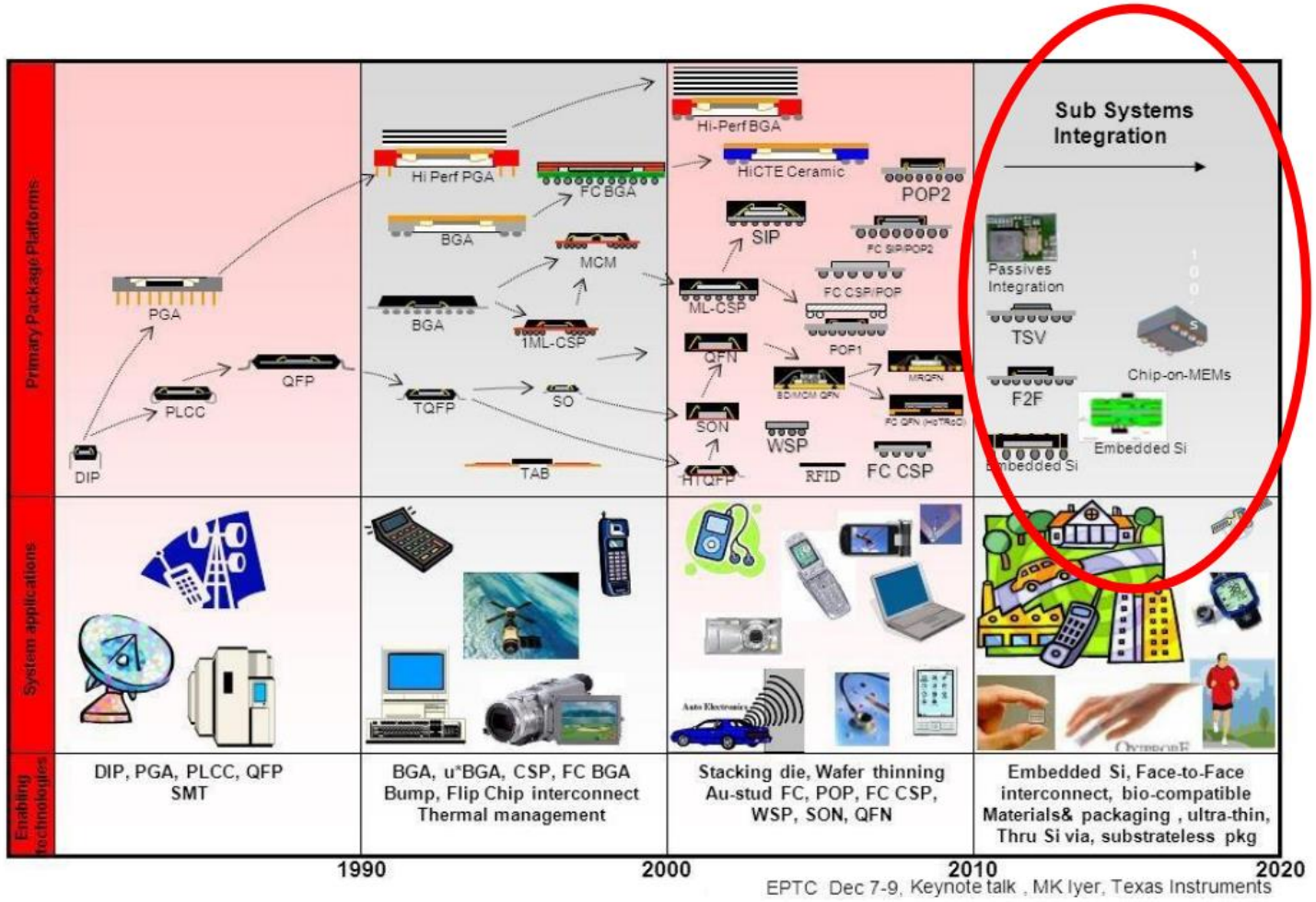
-Higher reflow energy needed for Pb-free materials
-Reference – 100mm^3 of SnPbAg – adjusted for different material designed , flux constituent and share of the weight is assumed to be the same for both solder paste
-Volume 600 PCBs/hr on interconnection material needed to mount two microcircuits of type Quad Flat Pack-200 onto one test Printed Wiring Board





Not considering metallisation or use stage where reliability has a

IC layout/Packaging



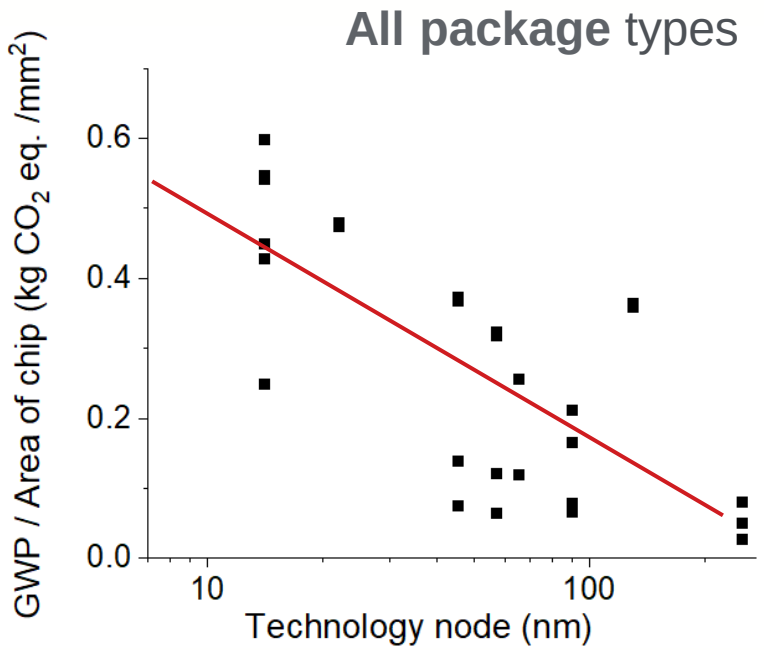
Components has always been pushed off the PCB and onto silicon as it simplified assembly and lowered costs

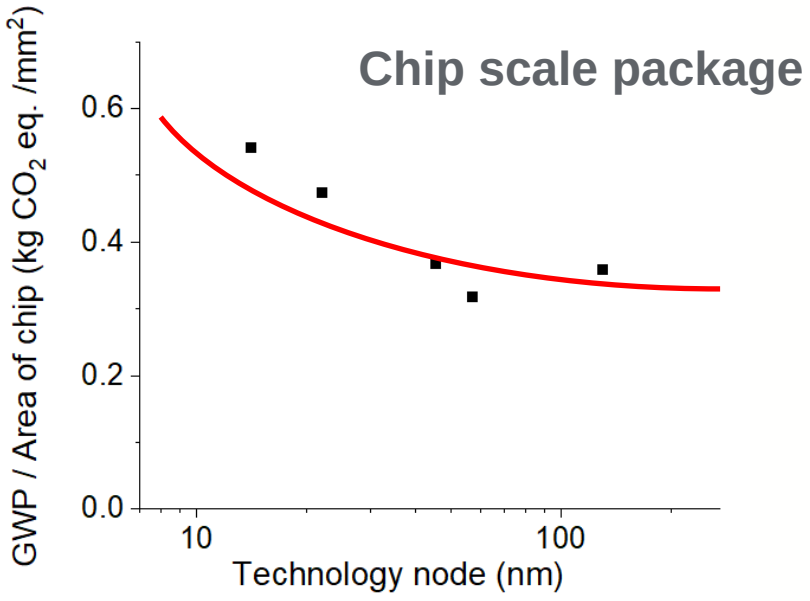
Now going the other way so substrates/packaging must help i.e. “end of Moore’s law” push back

IC layout/Packaging

Knowns – most literature LCAs are on >14nm node technology
Lack of information from industry's proprietary information
Lots of different new approaches used – COO
How you measure e.g GWP affects your results – per die, per cm^2, per MB

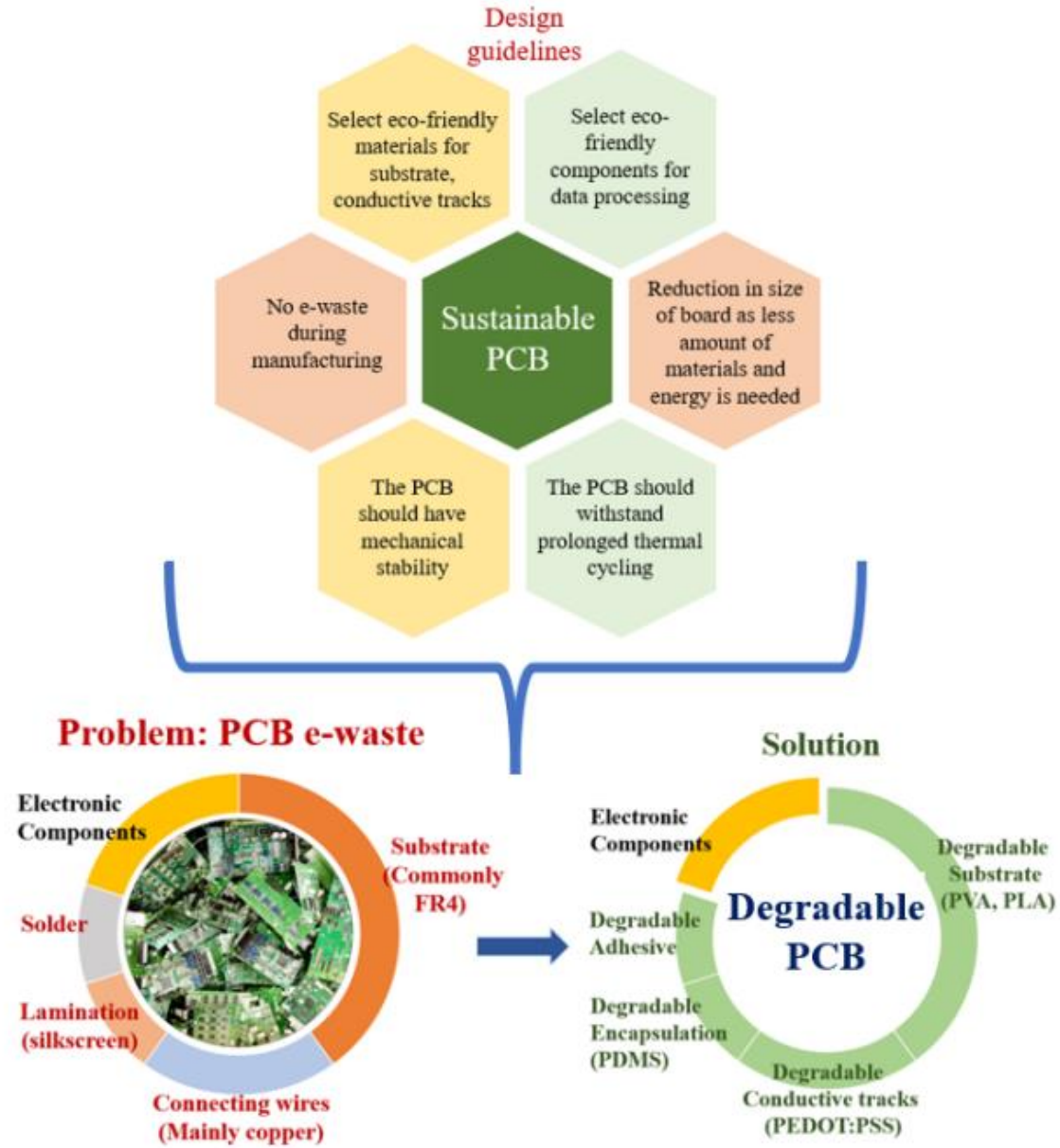
What general trends from GaBi database?





Energy costs have increased with IC technology node, hence GWP, but die sizes have also increased

Improving the environmental impact



Conclusions

WW legislation needed and beign developed

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

Efficient and cost effective recycling processes for e-waste and extraction of materials still needed

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

Improving product durability, reusability and upgradability important

Ecodesign tools and standards needed for EEE, e.g. ICT products. Understanding of the product full life cycle impact on the environment

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