Circular Economy for the Data Centre Industry

Interreg North-West Europe CEDaCI

Design and Circularity of Data Centre Equipment

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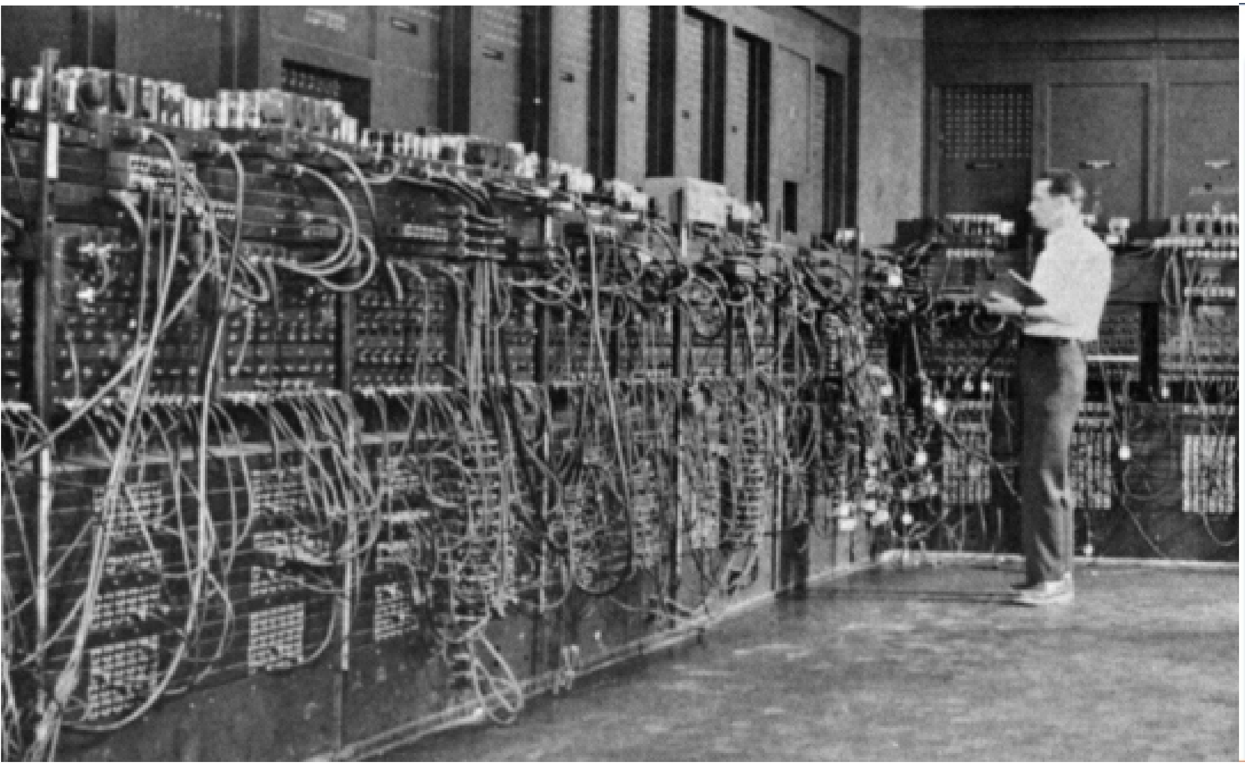
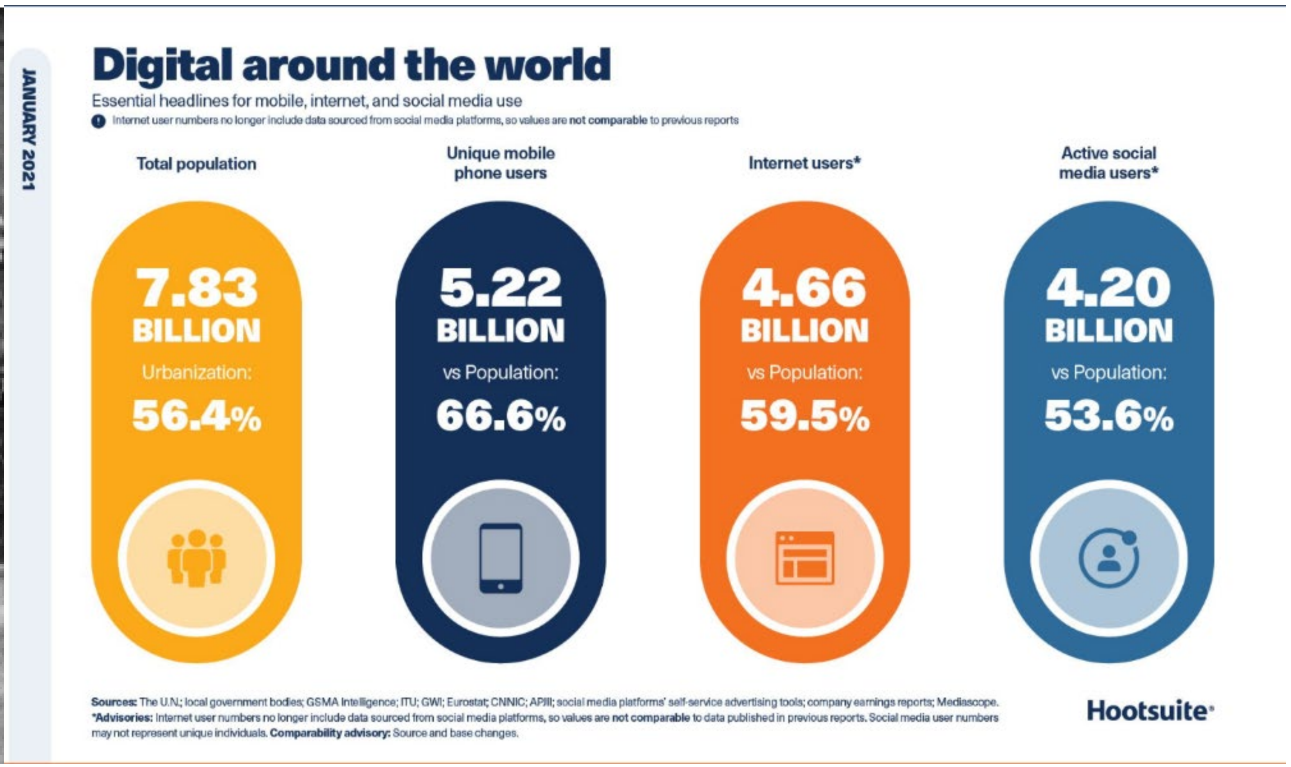
London South Bank University

Academic lead – CEDaCI

Circular Economy for the Data Centre Industry

Connectivity – 55% global population / data traffic = 4.2 trillion gigabytes / yr





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Data Centres

7.2m globally / concentration in EU - UK, Germany, France & Netherlands

2010-2020 – $100bn investment in sector

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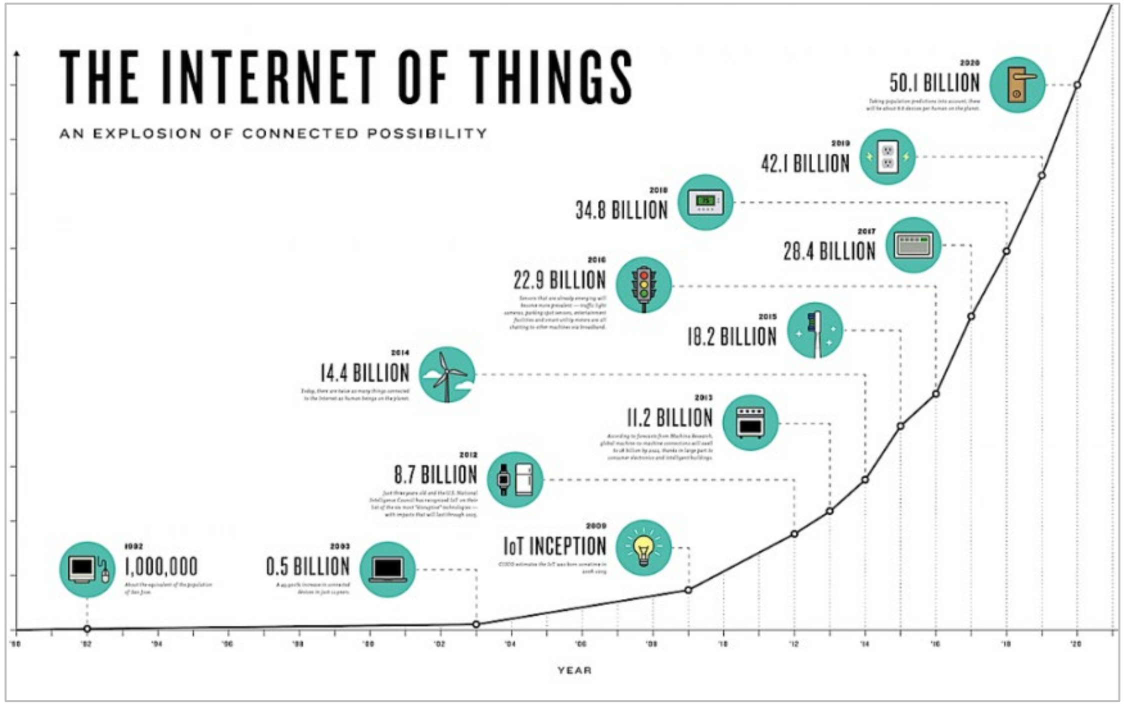
DC growth – 2018 baseline: 300% in EU by 2025 / 500% global 2030



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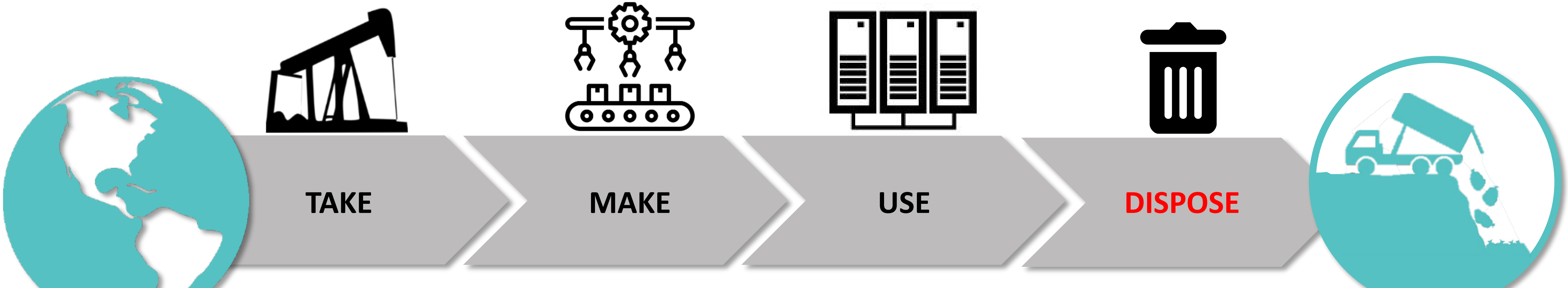
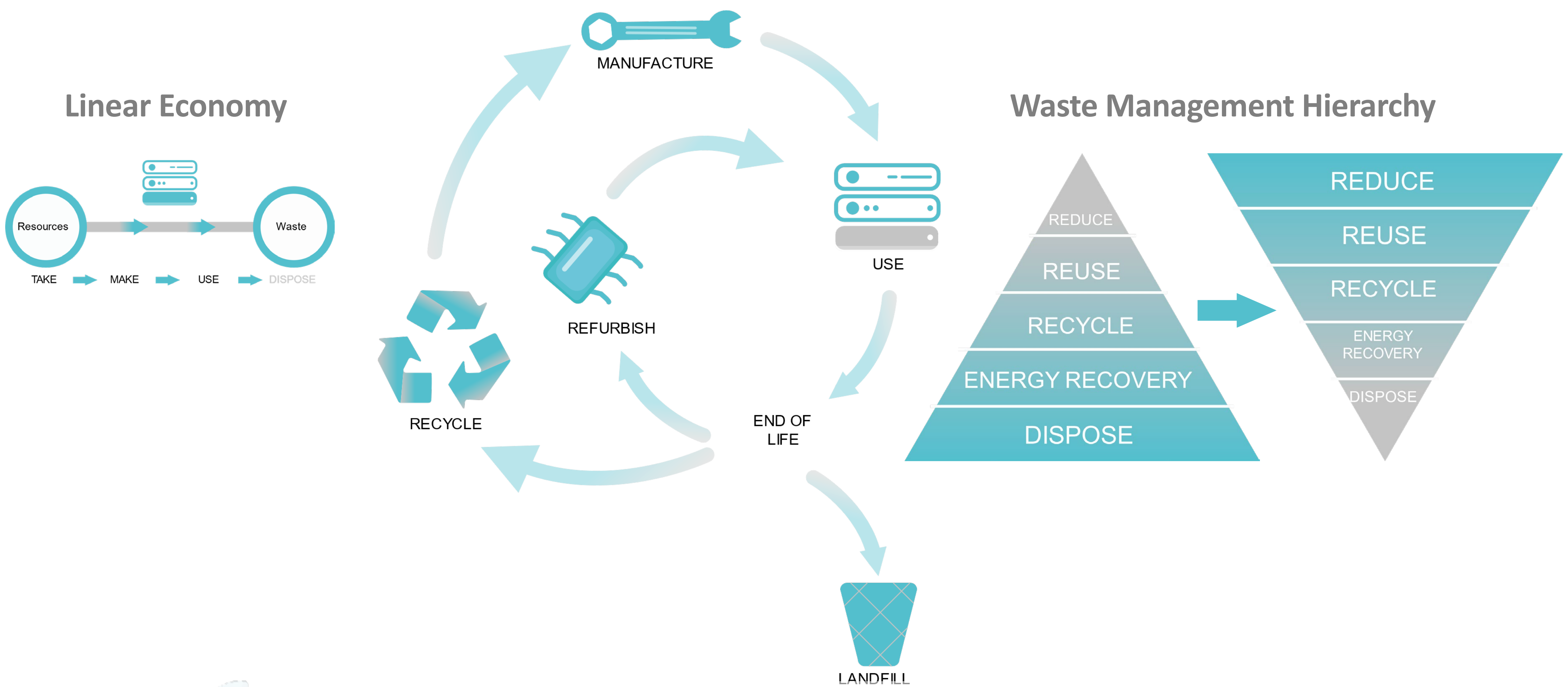
Speed of sectoral development & emphasis on service provision….

Linear model of consumption

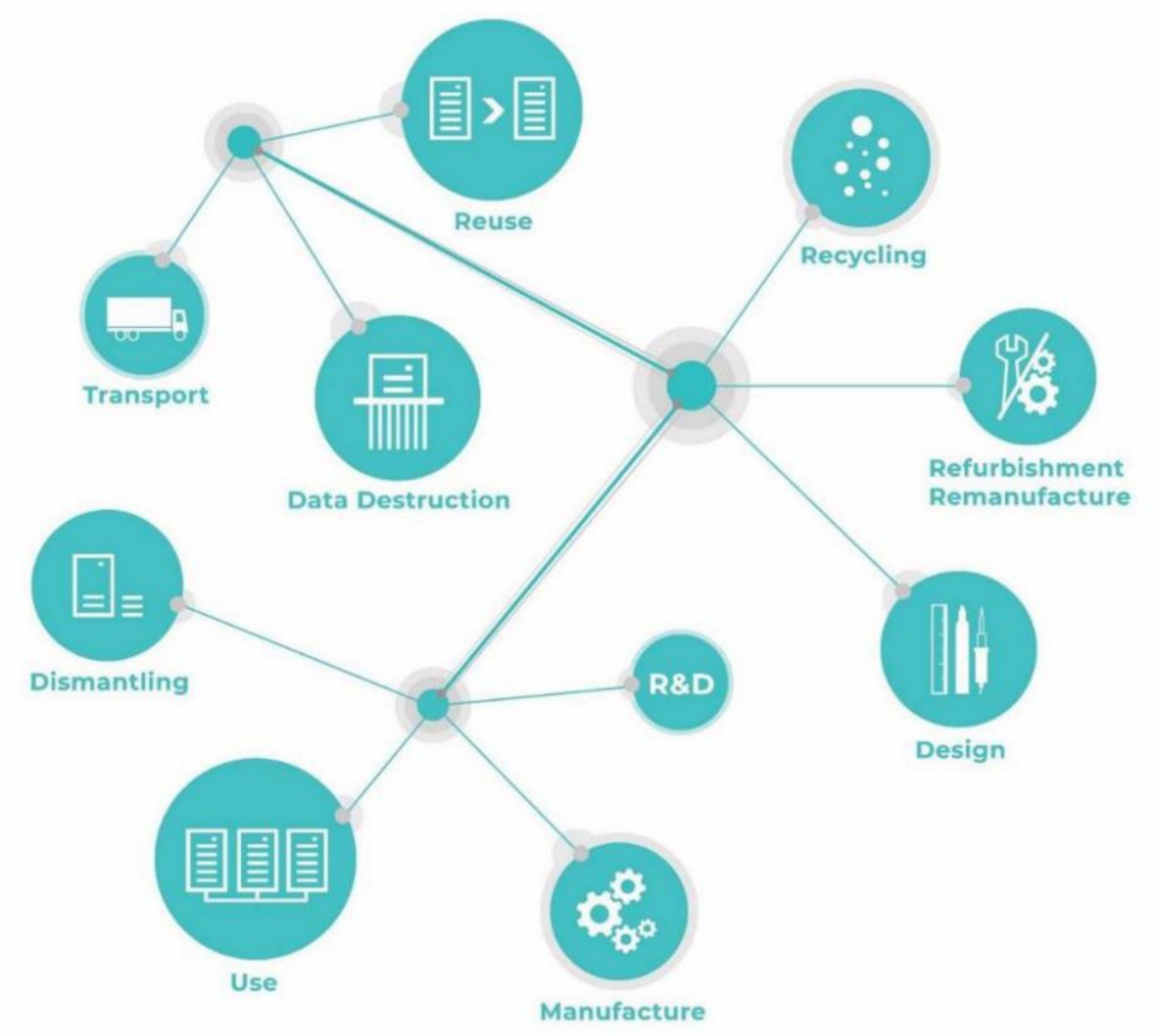


TAKE	MAKE	USE	DISPOSE
Finite resources Critical	Planned obsolescence Reuse/refurbishment - difficult by design	Short lifetimes Stockpiling Procurement barriers	Growing e-waste Low recycling rates Underdeveloped infrastructure


Linear Economy
Resources
Waste
TAKE
MAKE
USE
DISPOSE
Circular Economy
MANUFACTURE
USE
END OF LIFE
REFURBISH
RECYCLE
LANDFILL
Waste Management Hierarchy
REDUCE
REUSE
RECYCLE
ENERGY RECOVERY
DISPOSE
REDUCE
REUSE
RECYCLE
ENERGY RECOVERY
DISPOSE

CEDaCI

- unique, interdisciplinary, multi-output initiative
- uses **whole-life thinking**
- **Reactive –**
  - Pilot B – product life extension
  - Pilot C – recycling / CRM reclamation
- **Proactive –**
  - Pilot A - Design and manufacture



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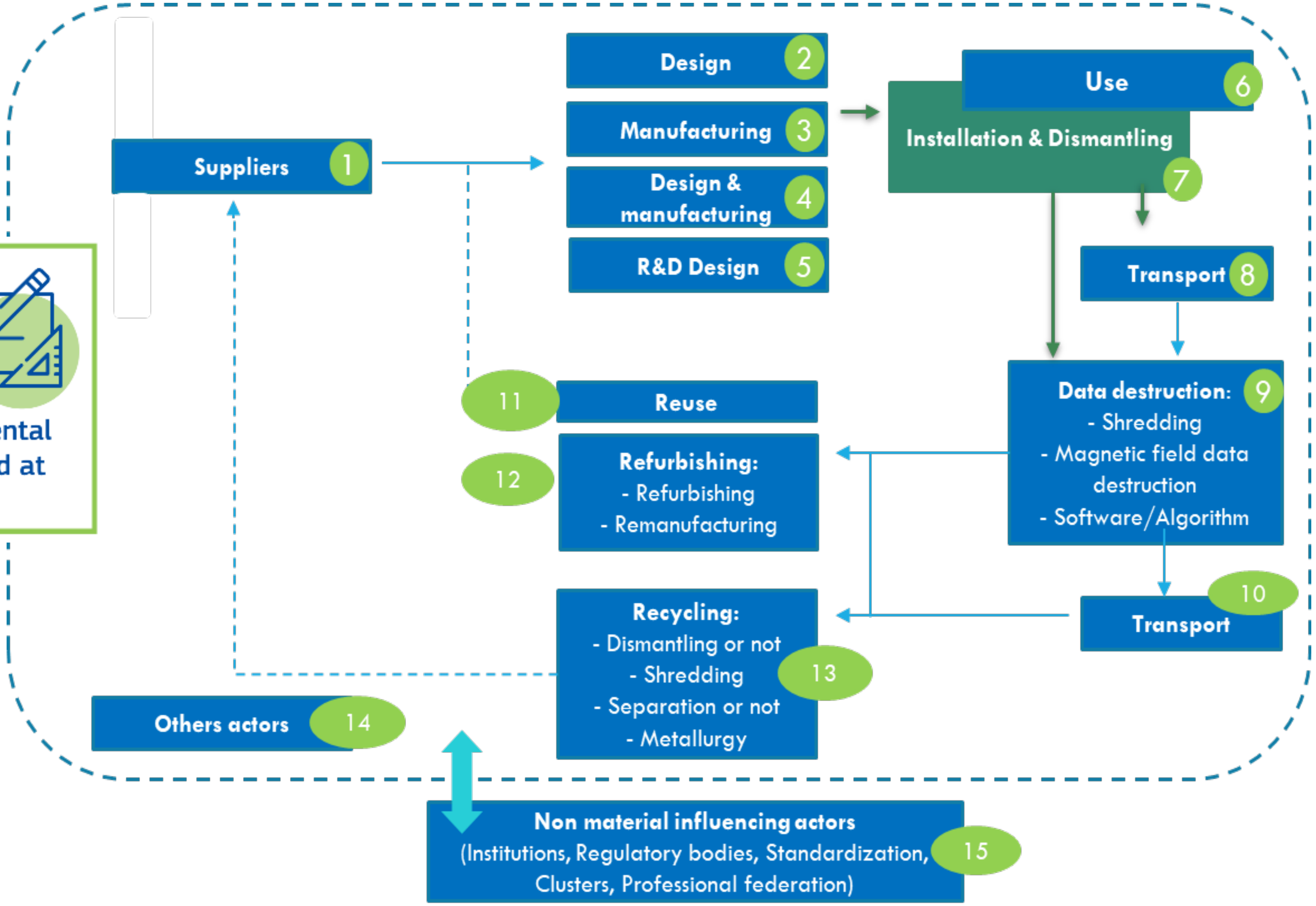
Methodology

Up to **80%** of products' environmental impacts are determined at the design phase



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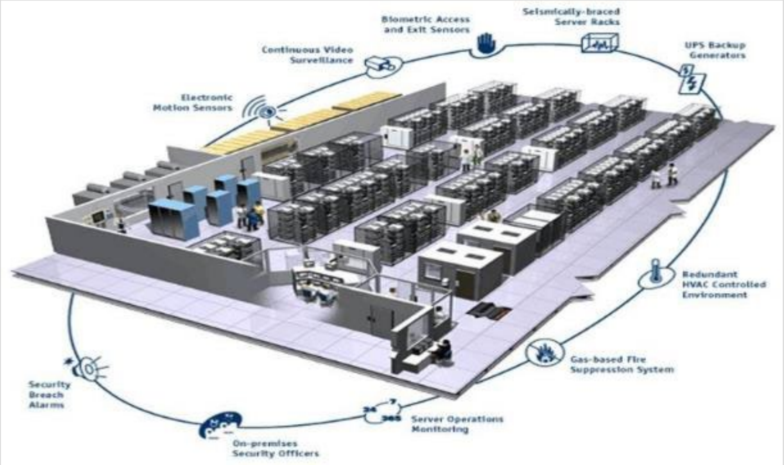

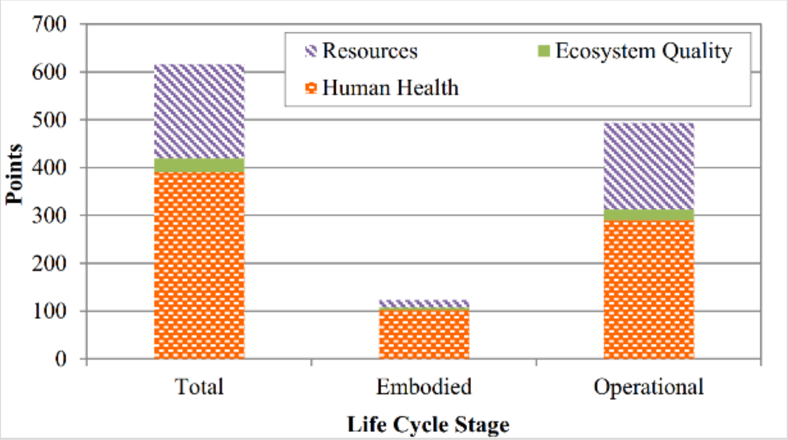

Operational impact – ~75% over life in UK / 2015

Embodied impact - building life 60 years
15% of embodied environmental impact derives from building and facilities

EE equipment is regularly refreshed –
M&E - 20 years
Switches, routers, batteries - 10 years
servers - 1-5 years

85% derives from IT equipment

20 million servers etc =
0.56 million tonnes materials

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Servers

Data Centre Equipment

Highest embodied impact

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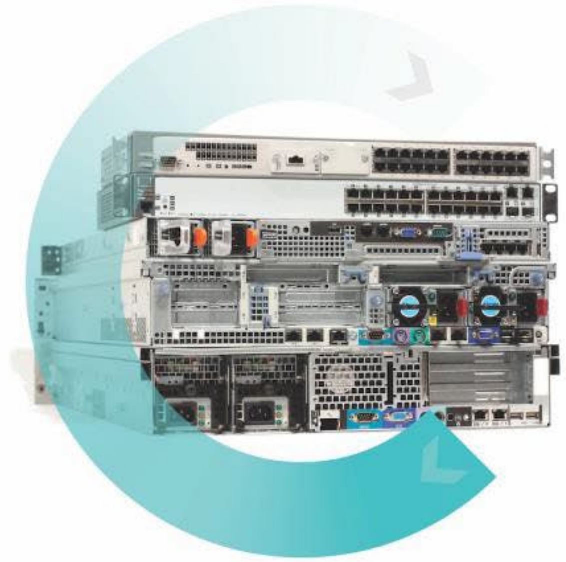

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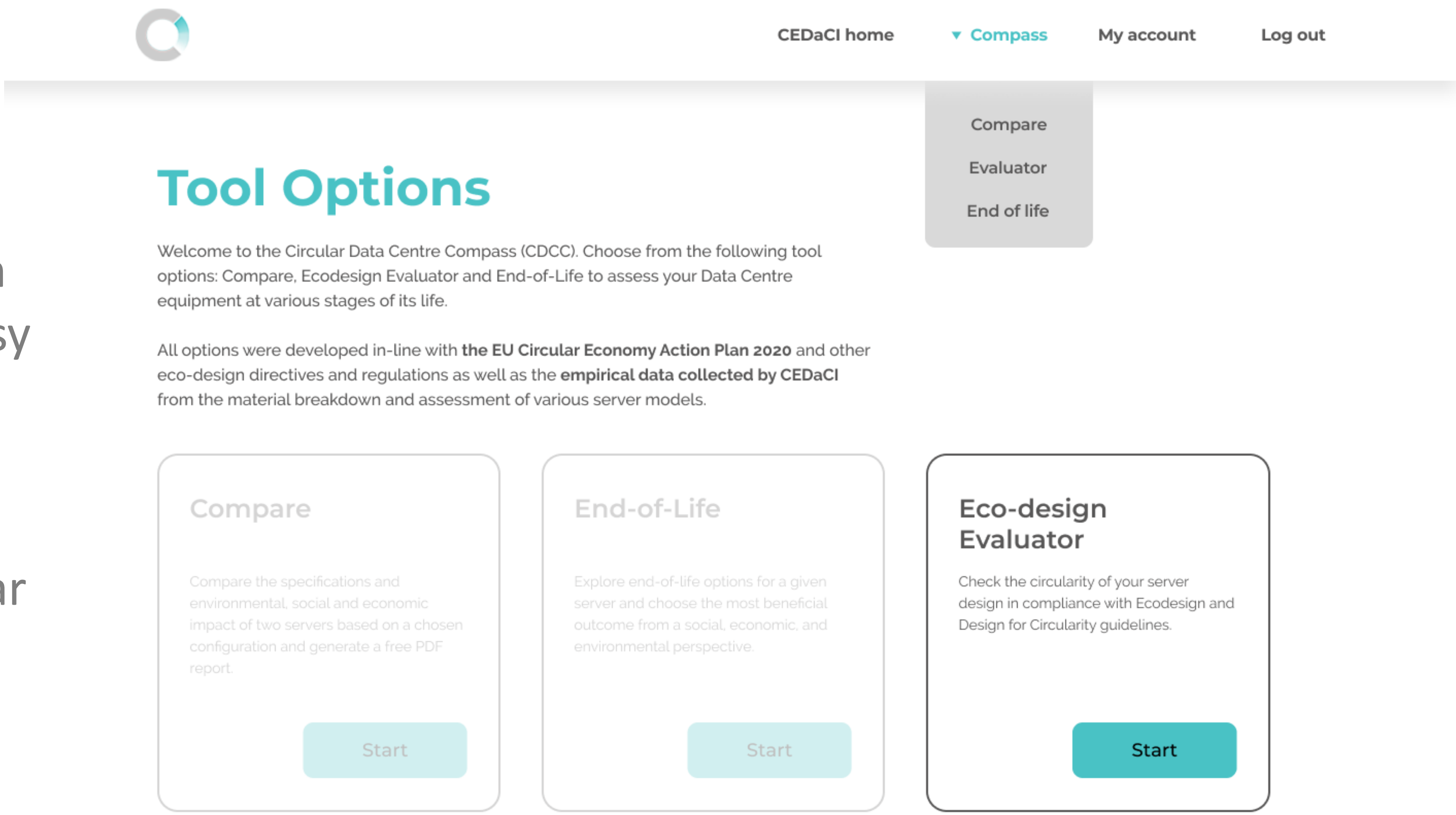
Ecodesign Evaluator consolidates EU Ecodesign Criteria in one place – easy for designers to follow

Tool includes Ecodesign guidelines from EU Circular Economic Action Plan and CEDaCI



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CEDaCI Eco-design Evaluator
created to evaluate the degree of excellence and conformity with the recommended guidelines from:

1. Lot 9 2009/125/EC DIRECTIVE
2. COMMISSION REGULATION (EU) 2019/424
3. COMMISSION REGULATION (EU) No 617/2013
4. EU Circular Economy Action Plan

Includes supplementary Eco-design Guidelines from EU Circular Economic Action Plan and CEDaCI

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European Regional Development Fund

Design must meet criteria in 10 key areas

1. Minimum PSU efficiency & Power Factor requirements
2. Security – data sanitisation / shredding
3. Software & Firmware
4. Product specific information availability from market entry point & after end-of-sale
5. Availability of instruction manuals
6. Product Disassembly
7. Design & Manufacture
8. Chemical Content & Recycling
9. Resource Tracking & Tracing
10. CE & Environmental Considerations

Eco-design Check List in line with EU Circular Economy Action Plan- THEORETICAL SERVERS

Input all the relevant information and values				Design/Model		
Year EU Reg.	Categories	Requirements		CEDaCI	G10	G13
2009/125/EC DIRECTIVE, COMMISSION REGULATION (EU) No 617/2013, COMMISSION REGULATION (EU) 2019/424; Regulation for Storage Products (Lot9)	Power Specifications		% of rated load	True Values		
		Minimum PSU Efficiency (from January 2023)	at 10% Single Output	90%	90%	90%
			at 20% Multi Output	90%	90%	90%
			at 20% Single Output	94%	94%	94%
			at 50% Multi Output	94%	94%	94%
			at 50% Single Output	96%	96%	96%
			at 100% Multi Output	91%	91%	91%
			at 100% Single Output	91%	91%	91%
		Minimum Power Factor Output	at 50% Multi Output	0.95	0.95	0.95
			at 50% Single Output	0.95	0.95	0.95
		Overall Score based on the above		18	18	18
	Security	Secure Data Sanitisation	General Availability	Y	Y	Y
		Availability of Integral Secure Data Deletion Tool at the End of Sale	Minimum 8 years	>8	8	8
		Availability of Security Updates at the End of Sale	Minimum 8 years	>8	8	8
		Overall Score based on the above		9	5	5
	Software & Firmware	Availability of the Free Latest Firmware Updates from the market entry point	Minimum for 2 years	>2	2	2
		Availability of Free Firmware Updates at the End of Sale	Minimum 8 years	>8	8	8
		Open Source Firmware/Software option for the updates/upgrades of the obsolete hardware	General Availability	Y	Unknown	Unknown
		Overall Score based on the above		12	4	4
	Availability of Product Specific Info from the market entry point and for Munimum of 8 Years from the end of sale	Availability of Product Specific Info at the End of Sale. *(Product Type, OEM Details, Model Number, PSU Efficiency, Power Factor at 50%, ASHRAE Class, Data Sanitisation Instructions/tool/standards).* (minimum 8 years)	Minimum 8 years	>8	8	8
		Availability of Recycler Specific Info at the End of Sale (minimum 8 years)	Minimum 8 years	>8	8	8
		Availability of Recycler Specific Info from the market entry point ***for indicative weight range (less than 5 g, between 5 g and 25 g, above 25 g) at component level, of the following CRM***	Cobalt Batteries	Y	Y	Y
			Neodymium in HDDs	Y	Y	Y
		Digitalisation of product information	Tagging, Digital ID etc.	Y	Y	Y
		Overall Score based on the above		11	7	7
ember 2018	Availability of Instruction Manuals	Instructions on the disassembly operations for each necessary operation and component. *(Type of Operation, type and number of fastening technique(s) to be unlocked, tool(s) required).*	General Availability	Y	Y	Y
		Repair Manuals	General Availability	Y	Y	Y
		Overall Score based on the above		2	2	2
			Data Storage	Y	Y	Y

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Design must meet criteria in 10 key areas

1. Minimum PSU efficiency & Power Factor requirements
2. **Security - data sanitisation / shredding**
3. **Software & Firmware**
4. **Product specific information availability from market entry point & after end-of-sale**
5. **Availability of instruction manuals**
6. Product Disassembly
7. Design & Manufacture
8. Chemical Content & Recycling
9. Resource Tracking & Tracing
10. CE & Environmental Considerations

Eco-design Check List in line with EU Circular Economy Action Plan- THEORETICAL SERVERS

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		Minimum PSU Efficiency (from January 2023)	at 10% Single Output	90%	90%	90%
			at 20% Multi Output	90%	90%	90%
			at 20% Single Output	94%	94%	94%
			at 50% Multi Output	94%	94%	94%
			at 50% Single Output	96%	96%	96%
			at 100% Multi Output	91%	91%	91%
			at 100% Single Output	91%	91%	91%
		Minimum Power Factor Output	at 50% Multi Output	0.95	0.95	0.95
			at 50% Single Output	0.95	0.95	0.95
		Overall Score based on the above		18	18	18
	Security	Secure Data Sanitisation	General Availability	Y	Y	Y
		Availability of Integral Secure Data Deletion Tool at the End of Sale	Minimum 8 years	>8	8	8
		Availability of Security Updates at the End of Sale	Minimum 8 years	>8	8	8
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	Software & Firmware	Availability of the Free Latest Firmware Updates from the market entry point	Minimum for 2 years	>2	2	2
		Availability of Free Firmware Updates at the End of Sale	Minimum 8 years	>8	8	8
		Open Source Firmware/Software option for the updates/upgrades of the obsolete hardware	General Availability	Y	Unknown	Unknown
		Overall Score based on the above		12	4	4
	Availability of Product Specific Info from the market entry point and for Munimum of 8 Years from the end of sale	Availability of Product Specific Info at the End of Sale. *(Product Type, OEM Details, Model Number, PSU Efficiency, Power Factor at 50%, ASHRAE Class, Data Sanitisation Instructions/tool/standards).* (minimum 8 years)	Minimum 8 years	>8	8	8
		Availability of Recycler Specific Info at the End of Sale (minimum 8 years)	Minimum 8 years	>8	8	8
		Availability of Recycler Specific Info from the market entry point ***for indicative weight range (less than 5 g, between 5 g and 25 g, above 25 g) at component level, of the following CRM***	Cobalt Batteries	Y	Y	Y
			Neodymium in HDDs	Y	Y	Y
		Digitalisation of product information	Tagging, Digital ID etc.	Y	Y	Y
		Overall Score based on the above		11	7	7
ember 2018	Availability of Instruction Manuals	Instructions on the disassembly operations for each necessary operation and component. *(Type of Operation, type and number of fastening technique(s) to be unlocked, tool(s) required).*	General Availability	Y	Y	Y
		Repair Manuals	General Availability	Y	Y	Y
		Overall Score based on the above		2	2	2
			Data Storage	Y	Y	Y

Design & Manufacture –
Degree of Excellence & Conformity with the Recommended Guidelines

Complexity of the Design
Design for Remanufacture
Design for High-Quality Recycling
Presence of Single-Use Parts
Durability
Re-Usability
Upgradability
Repairability
Degree of Premature Obsolescence
Product Specifications

Scoring

- Design must meet criteria in 10 key areas
- Each criterion awarded a score - 0-4
- Average score rating = compliance with the basic Eco-design requirements in COMMISSION REGULATION (EU) 2019/424, Lot 9 and EU CE Action Plan.
- Higher the total score = more circular design.

Input all the relevant information and values				Design/Mo		
Year EU Reg	Categories	Criteria		A	B	C
MMISSION REGULATION (EU) No 617/2013, COMMISSION REGULATION (EU) 2019/424	Power Specifications		% of rated load	True Values		
		Minimum PSU Efficiency	at 10% Single	2	2	2
			at 20% Multi	2	2	2
			at 20% Single	2	2	2
			at 50% Multi	2	2	2
			at 50% Single	2	2	2
			at 100% Multi	2	2	2
			at 100% Single	2	2	2
		Minimum Power Factor Output	at 50% Multi	2	2	2
			at 50% Single	2	2	2
		Overall Score based on the above		18	18	18
	Security	Secure Data Deletion	General Availability	1	1	1
		Availability of Secure Data Deletion Tool (End of Sale)	Minimum 8 Years	4	2	2
		Availability of Security Updates (End of Sale)	Minimum 8 Years	4	2	2
		Overall Score based on the above		9	5	5
	Software & Firmware	Availability of the Free Latest Firmware Updates from the market entry point	Minimum 2 Years	4	2	2
		Availability of Free Firmware Updates at the End of Sale	Minimum 8 Years	4	2	2
		Open Source Firmware/Software option for the updates/upgrades of the obsolete hardware	General Availability	4	0	0
		Overall Score based on the above		12	4	4
	ne	Availability of Product Specific Info at the End of				
				4	2	2
				4	2	2
				1	1	1

	Model Total Score	210	86	94	0
	Max Score	258	258	258	258
Score Reference Level	Score in %	81%	33%	36%	0%
Results	Score Level	%			
Very Good	4	90%-100%	231-258		
Good	3	75%-89%	193-230		
Average	2	60%-74%	154-192		
Low	1	40%-59%	102-153		
Very Low	0	0%-39%	0-101		

Minimum PSU efficiency and power factor requirements from 1 March 2020

	Minimum PSU efficiency				Minimum power factor
% of rated load	10 %	20 %	50 %	100 %	50 %
Multi output	—	88 %	92 %	88 %	0,90
Single output	—	90 %	94 %	91 %	0,95

From 1 January 2023, for servers and online data storage products, with the exception of direct current servers and of direct current data storage products, the PSU efficiency at 10 %, 20 %, 50 % and 100 % of the rated load level and the power factor at 50 % of the rated load level shall not be less than the values reported in Table 2.

Table 2

Minimum PSU efficiency and power factor requirements from 1 January 2023

	Minimum PSU efficiency				Minimum power factor
% of rated load	10 %	20 %	50 %	100 %	50 %
Multi output	—	90 %	94 %	91 %	0,95
Single output	90 %	94 %	96 %	91 %	0,95

Power Specifications

What is the minimum PSU efficiency at 10% single output?

Select

What is the minimum PSU efficiency at 20% single output?

Select

What is the minimum PSU efficiency at 50% single output?

Select

What is the minimum PSU efficiency at 100% single output?

Select

What is the minimum power factor at 50% single output?

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Ecodesign Evaluator

0%

Overall Score

0% 50% 100%

Not circular — Circular

Power Specifications

What is the minimum PSU efficiency at 10% single output?

Select

What is the minimum PSU efficiency at 20% single output?

Select

What is the minimum PSU efficiency at 50% single output?

Select

What is the minimum PSU efficiency at 100% single output?

Select

What is the minimum power factor at 50% single output?

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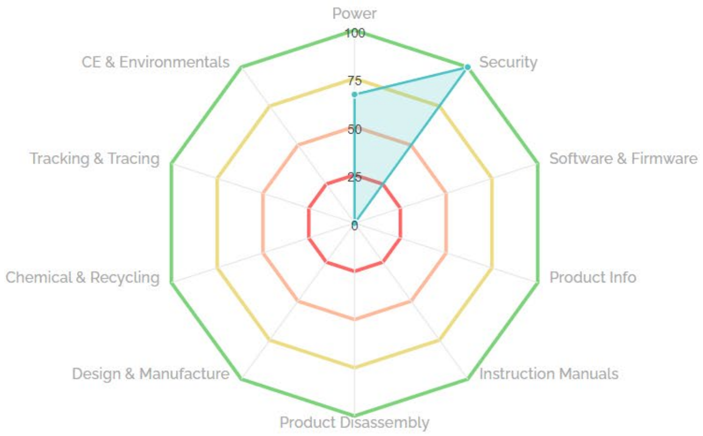
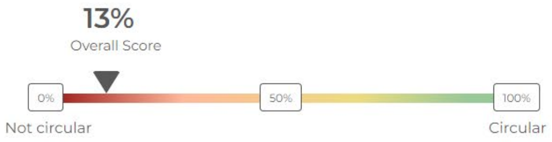
Ecodesign Evaluator





Security

Is secure data sanitisation available?

Yes

What is the availability of a secure integral data deletion tool after the end of sale?

More than 8 years

What is the availability of security updates after the end of sale?

More than 8 years

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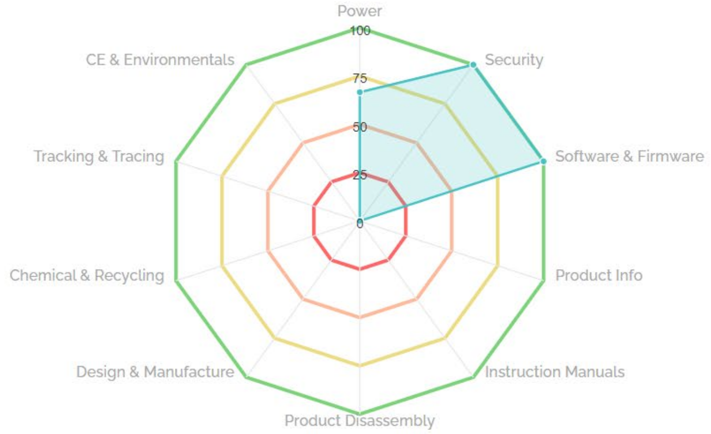
Ecodesign Evaluator



Software & Firmware

Are free firmware updates available for a minimum of 2 years from the market entry point?

More than 2 years

What is the availabilty of free firmware updates at the end of sale?

More than 8 years

Are there open source options for updates/upgrades?

Yes

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Ecodesign Evaluator

35%

Overall Score

0% 50% 100%

Not circular Circular

Design & Manufacture

Can the following parts be used/re-used across different product generations?

Data Storage	● Yes	○ No
Memory	● Yes	○ No
CPU	● Yes	○ No
Motherboard	○ Yes	● No
Expansion/Graphics Card	○ Yes	● No
PSU	○ Yes	● No
Chassis	● Yes	○ No
Batteries	● Yes	○ No
Cooling Assemblies	○ Yes	● No

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Ecodesign Evaluator

46%

Overall Score

0% — 50% — 100%

Not circular — Circular

Is the product designed for re-manufacture?

No

Can the following parts be used for more than one lifetime? Data Storage, Memory, CPU, Motherboard, Expansion/Graphics Card, PSU, Chassis, Batteries, Air Cooling Assembly.

Yes

Can the following parts be easily upgraded and re-used in newer generations, to extend their lifetime?Data Storage, Memory, CPU, Motherboard, Expansion/Graphics Card, PSU, Chassis, Batteries, Air Cooling Assembly.

Yes

Can the product be used as a service?

Yes

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Ecodesign Evaluator

58%
Overall Score

CE & Environmental Considerations

What is the recommended Product Refresh Rate?

More than 5 years

Will spare parts be available after the End of Sale?

Yes

Has the embodied CO2 assessment been carried out on the product?

Yes

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Ecodesign Evaluator

The Ecodesign Evaluator is a set of consolidated **EU Ecodesign Criteria** reorganised in one place, making it much easier for the designers to follow. The tool includes Ecodesign guidelines from both the EU Circular Economic Action Plan and CEDaCI.

Check the overall circularity of your server design by **answering questions** about various criteria considered important for circularity.

How do I use it? ↗

Video ↗

Design and Manufacture

Can the following parts be used/re-used across different product generations?

Select

Can the following parts be used/re-used across different product models?

Select

Can the following parts be used/re-used across different product brands?

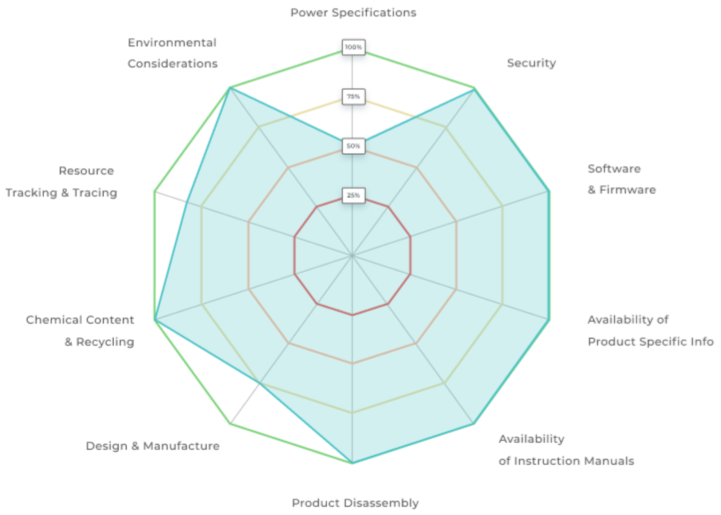
Select

Can the product be used as a service?

Select

Is the product designed to become obsolete prematurely?

Select



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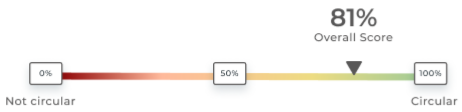

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The CEDaCI Circular Server

Simple
Standardised
Modular design
Easy to disassemble

One size fits all HDD caddy design
Up to 24 x 2.5inch or 9 x 3.5 inch HDDs

Reduced fastenings
Minimal materials variation
Reduced use of plastics

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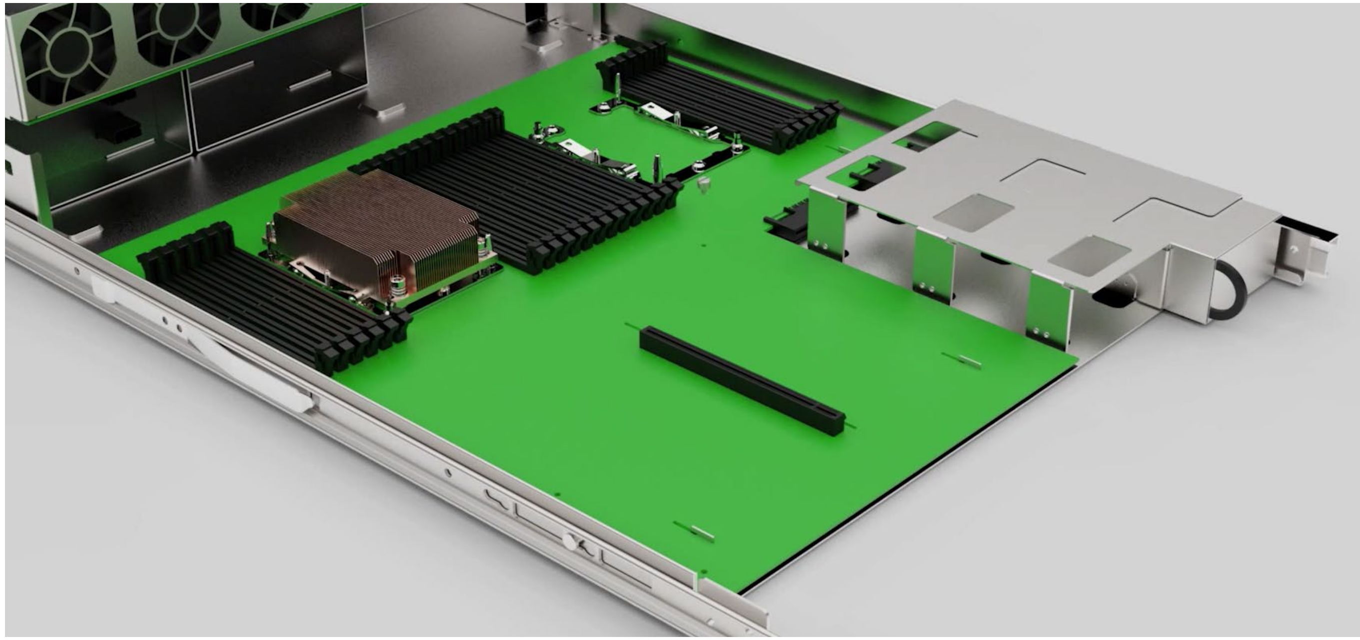
The CEDaCI Circular Server



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The CEDaCI Circular Server

Chassis mass:

CEDaCI server = 14kg

Standard server = 22kg

Total components:

CEDaCI server = 65

Standard server = 117

Mass of plastics :

CEDaCI server = 85.69g

Standard server = 889.45g

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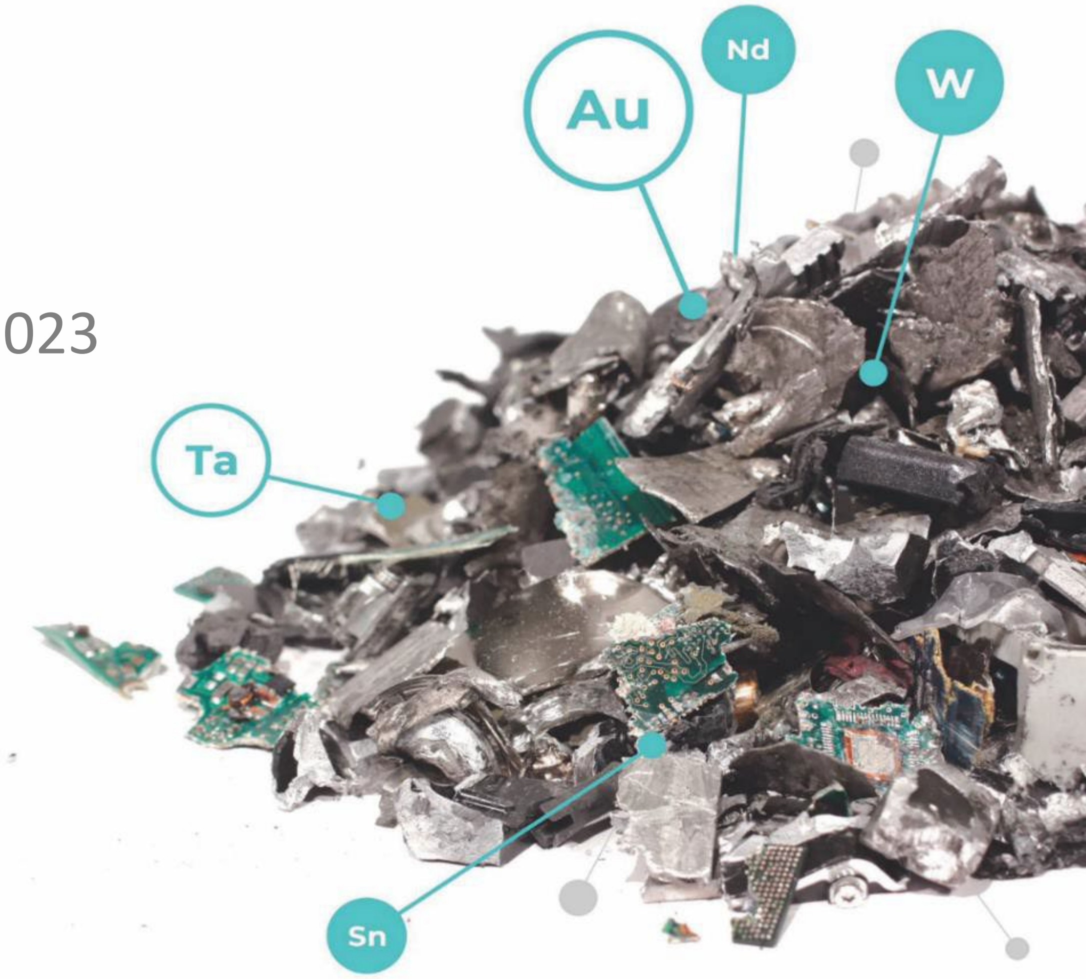
CEDaCI Circular Server

LCSA – compared with current servers - LCM Sept 2023
Can be manufactured now!
Can be developed as technology changes



CEDaCI Circular Server

Major challenges

Electronics:

PCB substrate – alternative materials – e.g. paper?

Biopolymer?

3D printed – inks loaded with conductive materials?

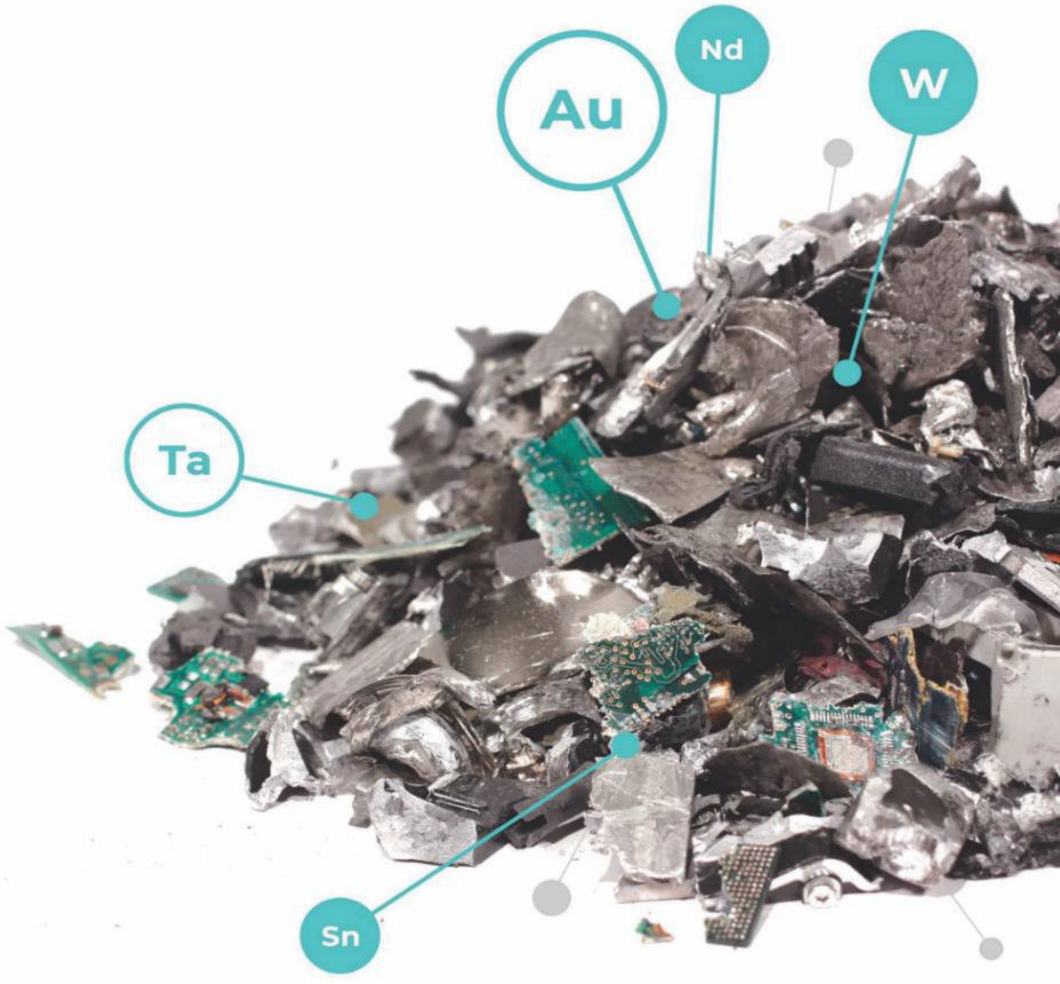
Board and components printed as one?

Individual component design –

Biodegradable capacitors etc?

Nano-sized circuits – reduce embodied materials?

Materials substitution?



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Thank you for listening

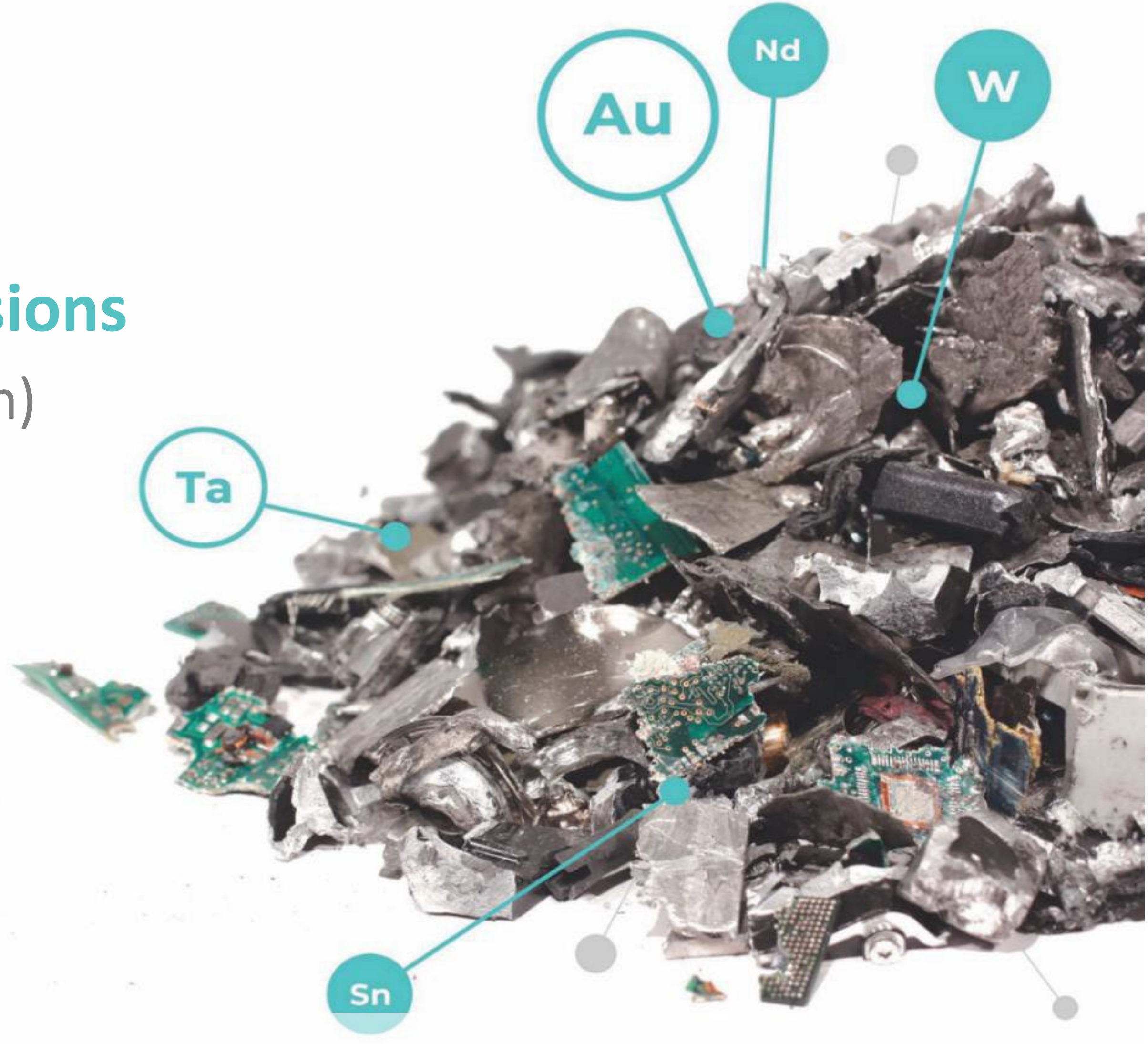
CEDaCI – runs until Sept 2023

Join us - fully funded SME training sessions

February 21, 2023: 08:30-11:30 GMT (French)

March 28, 2023: 14:00-17:00 GMT (English)

April 25, 2023: 09:00-12:00 GMT (English)



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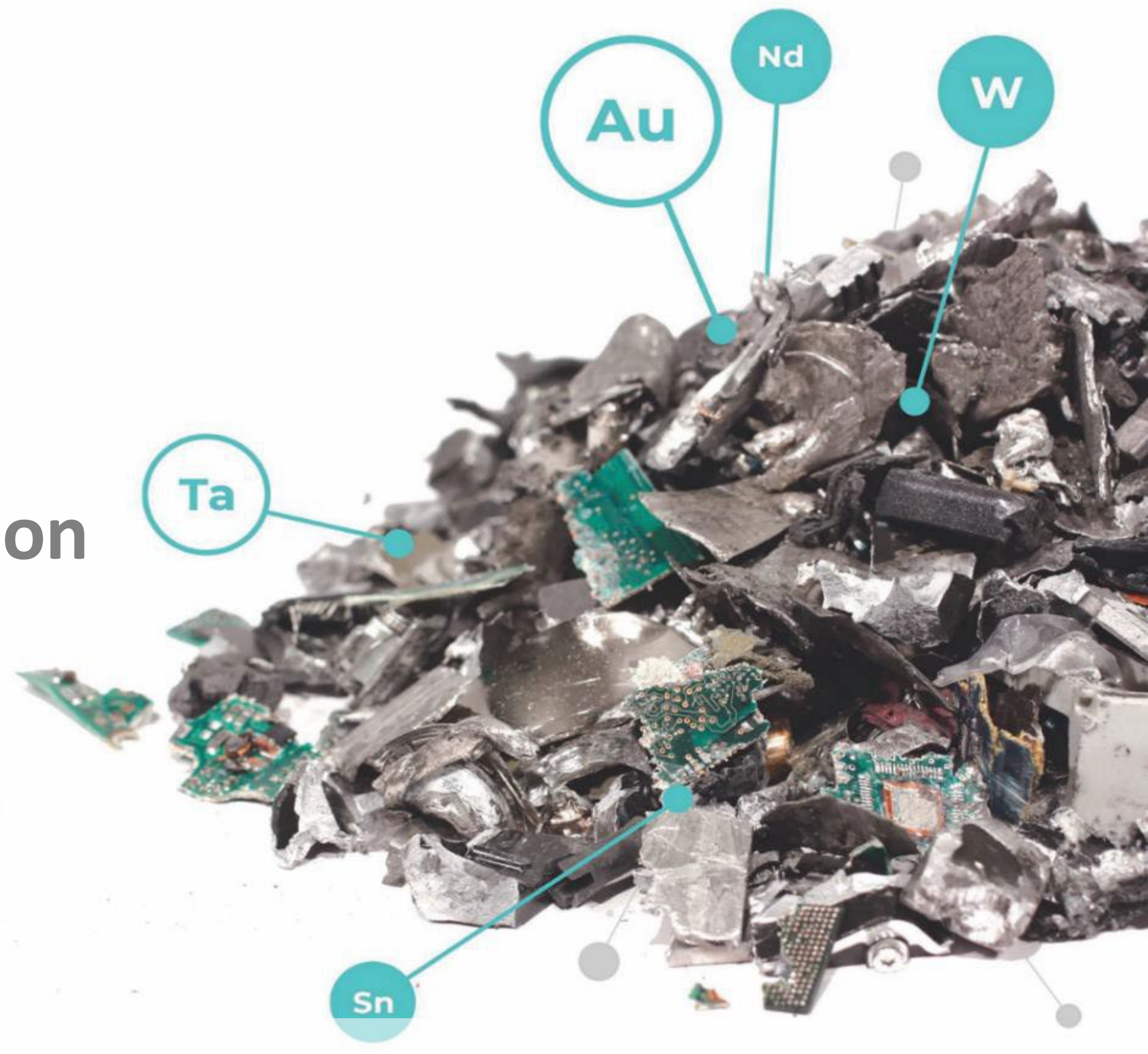
Circular Economy for the Data Centre Industry

itc

Horizon –

building team / developing application

Circular Electronics – using AI to increase CRM recycling & reclamation



We have some partners –

are you interested in participating?

Deborah.Andrews@lsbu.ac.uk

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CIRCULAR ECONOMY SYSTEMS FOR LITHIUM-ION BATTERIES - THE REUSE OPTIONS AFTER THE FIRST-LIFE IN THE ELECTRIC VEHICLE

Thesis at the University of St.Gallen
Nina Meyer

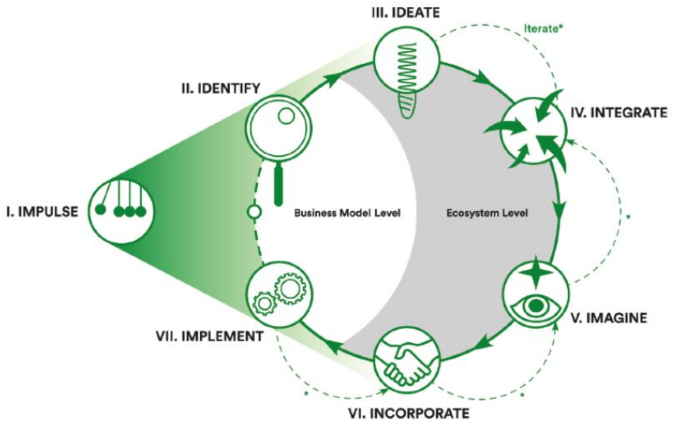
CONTENT

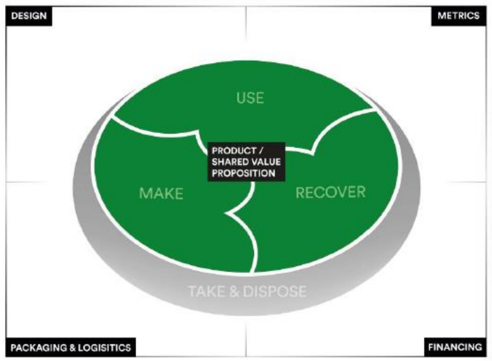
RESEARCH QUESTION

Which **concepts** exist **for lithium-ion batteries** at the end of their first life in the EV and what are the **advantages or disadvantages** of the individual concepts?

METHODOLOGICAL APPROACH

ANALYTICAL FRAMEWORK





DOCUMENT ANALYSIS

15 concepts

- **Lead-acid battery recycling system**
  Clarios
- **9 OEMs**
  Volkswagen, Tesla, Mercedes-Benz, Renault, BMW, Volvo, Nissan, Toyota, BYD
- **Car recycling company**
  ARN
- **Energy management project**
  Mitsubishi, Peugeot, EDF, Forsee Power
- **2 battery full-service companies**
  Spiers New Technologies, upVolt
- **Circular economy project**
  die Post

EXPERT INTERVIEWS

6 experts

- **Michael Sattler**
  Expert in second-life, Ökozentrum
- **Pascal Städeli**
  Board member of the VESE*
- **Urban Windelen**
  CEO of the BVES**
- **Janet Kes**
  Corporate and public affairs, ARN
- **Christian Ochsenbein**
  Head of Swiss Battery Technology Center, Switzerland Innovation Park
- **Dr. Andreas Pfrang**
  Researcher on batteries for mobility applications at the Joint Research Centre, European Commission

*Verband unabhängiger Energieerzeuger
**Bundesverband Energiespeichersysteme

RESULTS

FIELDS OF ACTIVITY OF THE INDIVIDUAL CONCEPTS

	Material-gewinn-ung	Batterie-herstell-ung	Zero-Life	Fahrzeug-herstell-ung	First-Life	Repara-tur	Samml-ung	Umbau	Second-Life	Recycl-ing	Entsorg-ung
Volkswagen		X		X		X	X	X	X	X	
Mercedes-Benz		X	X	X		X			X	X	
Renault		X		X		X	X	X	X	X	
BMW		X		X			P		X	P	
Volvo		X		X		X		P	P	P	
Nissan		X		X			X	X	X	P	
Toyota				X		P	P		P	P	
BYD		X		X			P		P	X	
Tesla		X		X		X	X			X	
ARN							P	P	P	P	
Energy-Management-Projekt								X	X		
Spiers New Technologies						X	X	X	X	P	
UpVolt						X		X	X		
Die Post								X	X		

RESULTS

Additional value creation opportunities
(grid services, energy storage, balancing energy, service models)

Nationally organized ecosystem

Economic difficulties in long-term establishment of remanufacturing step in second-life

Experts favor different concepts

Details to implementation of concepts not available (design, financing, action plan)

ARN system is realistic on a national level
(advanced recycling fee,
specialized treatment by different companies,
collect and process large quantities efficiently,
capacities enable investments to be made)

ARN system in EU is dependent on involvement of OEMs
(data accessibility, regulations)

CONCLUSIONS

01 Concepts on the market show inconsistencies and lack forward planning, especially regarding the implementation.

02 A circular economy for LIB in Europe is in its initial phase and should be established as far as possible before large quantities of batteries reach their EoL in EV.

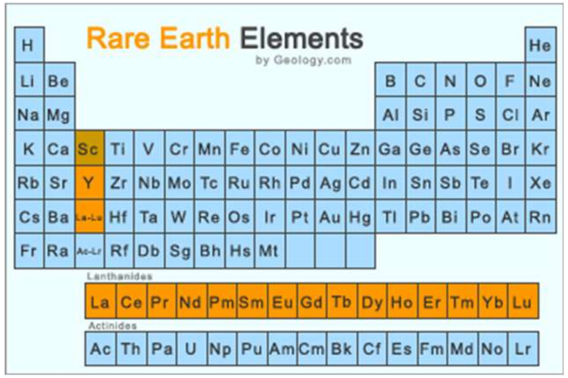
03 The current state of planning and implementation cannot yet provide clarity on the future course of action regarding the establishment of a circular economy for LIB from EV.

Recycling of rare earth elements from electric motors of the e-mobility

Torta Gianluca, Fabrizio Passarini

Department of industrial chemistry “Toso Montanari”, University of Bologna

Rare Earth Elements (REEs)

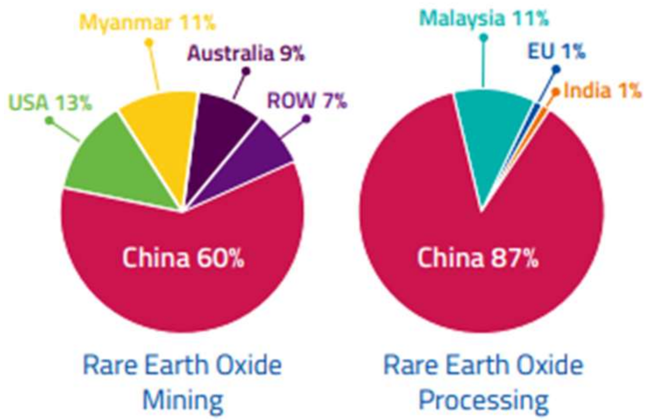


2020 Critical Raw Materials (new as compared to 2017 in bold)		
Antimony	Hafnium	Phosphorus
Baryte	Heavy Rare Earth Elements	Scandium
Beryllium	Light Rare Earth Elements	Silicon metal
Bismuth	Indium	Tantalum
Borate	Magnesium	Tungsten
Cobalt	Natural Graphite	Vanadium
Coking Coal	Natural Rubber	**Bauxite**
Fluorspar	Niobium	**Lithium**
Gallium	Platinum Group Metals	**Titanium**
Germanium	Phosphate rock	**Strontium**

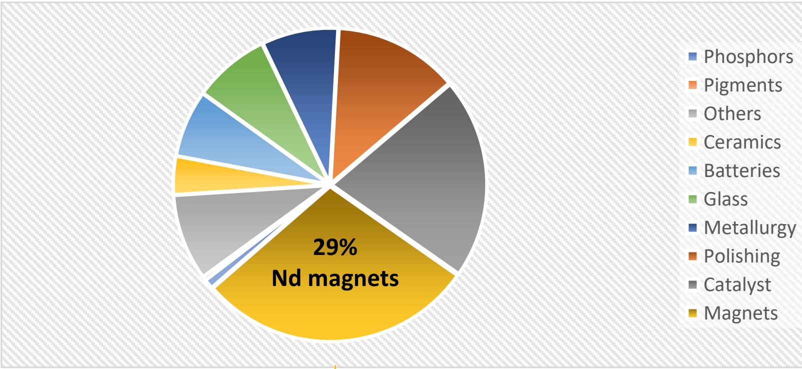
Why REEs are so critical?

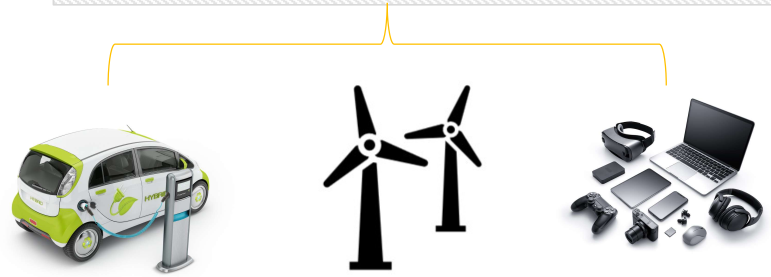
1) Geographical distribution of the global production

- 60% located in China
- 0% in Europe (100% dipendent from import)

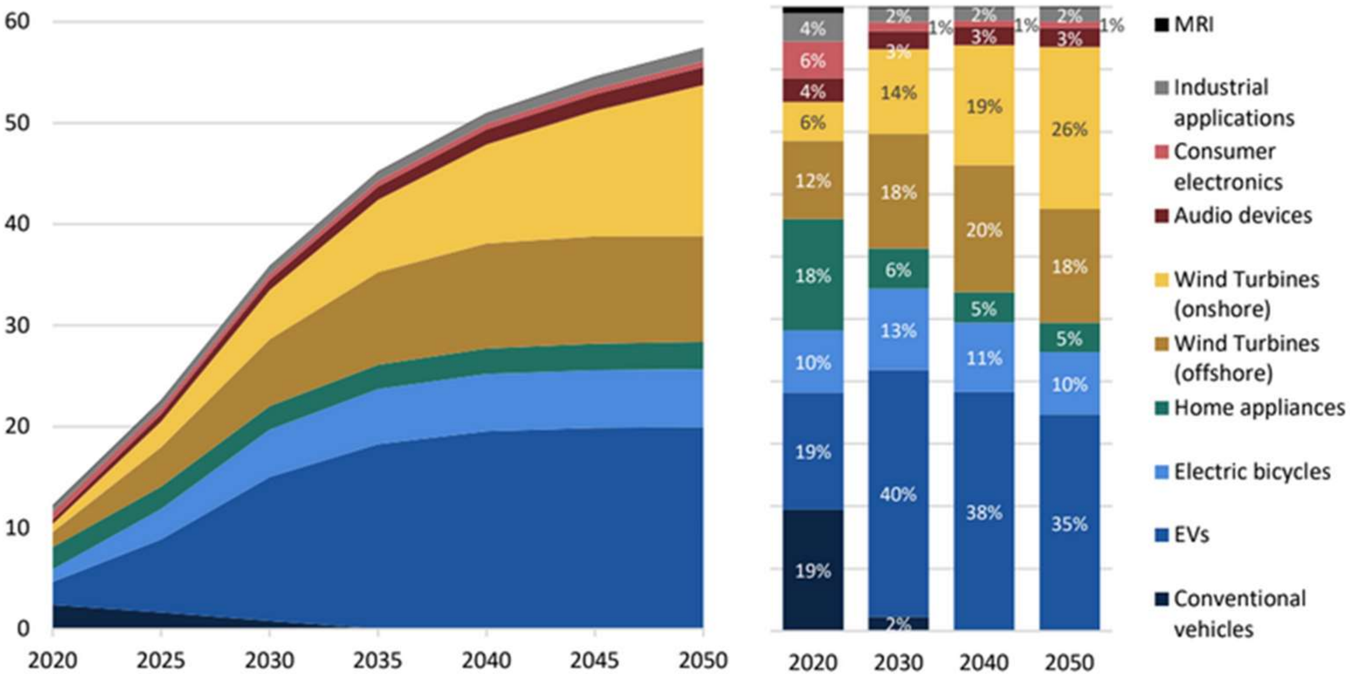


2) Main application in NdFeB permanent magnets





European NdFeB magnets demand



6x

≈10kt → ≈60kt

(2020) (2050)

Source: DEVELOPING A SUPPLY CHAIN FOR RECYCLED RARE EARTH PERMANENT MAGNETS IN THE EU, Vasileios Rizos, Edoardo Righetti, Amin Kassab, December, 2022 - 07

How to mitigate the problem: recycling

- UE one of the main consumer of products containing REES
- Volume of waste containing NdFeB magnets is increasing

Feedstock of EoL NdFeB Permanent Magnets in Europe					
tons/year	2020	2025	2030	2035	2040
HDD	580	350	370	440	480
Wind Turbines	-	1	10	1350	1700
Air Conditioners	450	500	565	750	nd
E-vehicles	-	5	330	4460	8000
E-bikes	405	1000	2970	4590	nd

European Nd magnets production capacity : 1 000 t

European Nd magnets demand : 21 000 t

Source: Valomag project

Source: Metals for clean energy: Pathways to solving Europe’s raw materials challenge

How to mitigate the problem: recycling

- UE one of the main consumer of products containing REES
- Volume of waste containing NdFeB magnets is increasing
- By 2050 recycling could cover more than 75% of european REEs demand

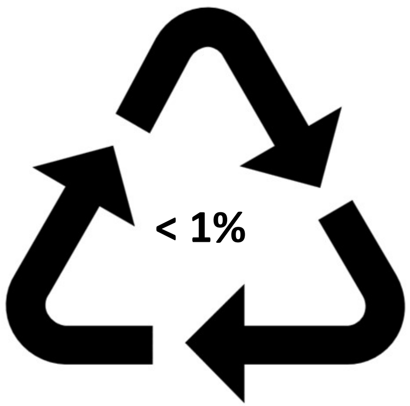
How to mitigate the problem: recycling

	Kg CO2 eq / Kg magnete
Magnet from raw materials	25
Recycled magnet	5

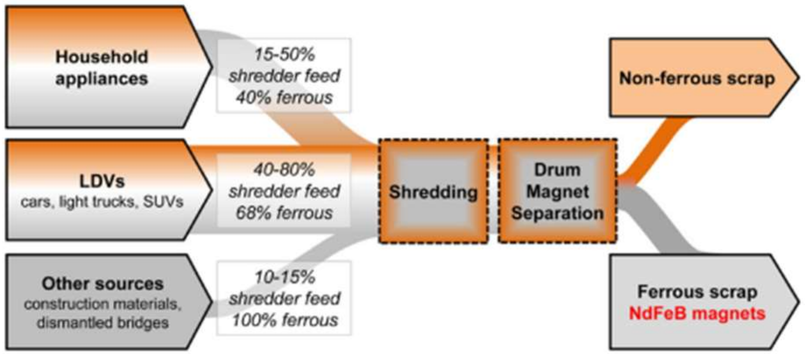
- UE one of the main consumer of products containing REES
- Volume of waste containing NdFeB magnets is increasing
- By 2050 recycling could cover more than 75% of european REEs demand
- Recycled magnets have 5 times lower CO_2 emission

Source: Stefano Cuccurachi, University of Leiden, SusCritMOOC seminar

Actual situation



- REEs are not recovered through traditional recycling process in-use
- REEs diluted in ferrous fraction



Source: Value Analysis of Neodymium Content in Shredder Feed: Toward Enabling the Feasibility of Rare Earth Magnet Recycling, 2014

Aim of the project

Fiat Ducato electric

FIAT 500 electric

Jeep Compass plug-in hybrid

- Quantification of Nd magnets content inside end-of-life electric vheicles
- Characterization of magnets composition to calculate the economic potential
- Development of a recycling process of REEs from eletric vheicles of e-mobility

Quantification of Nd magnets content

Nd magnets content in different components of electric vehicles

Vehicle	Component	Magnets mass g	Total mass g
Ducato 100% electric	electric drive motor electric power steering Air conditioning	1550 131 81	1762
FIAT 500 electric	Electric drive motor electric power steering Air conditioning	1080 42 81	1202
Jeep Compass hybrid	Electric power steering Air conditioning Electric gear Electric gear Alternator	84 81 410 68 363	1007

Quantification of Nd magnets content

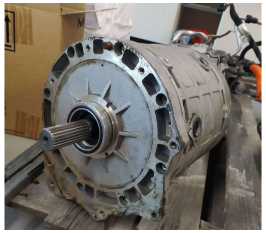
Nd magnets content in different components of electric vehicles

Vehicle	Component	Magnets mass g	Total mass g
Ducato 100% electric	electric drive motor	1550	1762
	electric power steering	131	
	Air conditioning	81	
FIAT 500 electric	Electric drive motor	1080	1202
	electric power steering	42	
	Air conditioning	81	
Jeep Compass hybrid	Electric power steering	84	1007
	Air conditioning	81	
	Electric gear	410	
	Electric gear	68	
	Alternator	363	

Electric drive motor

Fiat 500

Fiat Ducato



Quantification of Nd magnets content

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Jeep Compass hybrid	Electric power steering	84	1007
	Air conditioning	81	
	Electric gear	410	
	Electric gear	68	
	Alternator	363	

Electric power steering

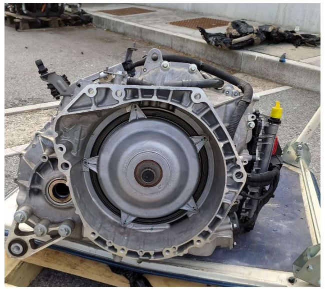
Air conditioning

Quantification of Nd magnets content

Nd magnets content in different components of electric vehicles

Vehicle	Component	Magnets mass g	Total mass g
Ducato 100% electric	electric drive motor	1550	1762
	electric power steering	131	
	Air conditioning	81	
FIAT 500 electric	Electric drive motor	1080	1202
	electric power steering	42	
	Air conditioning	81	
Jeep Compass hybrid	Electric power steering	84	1007
	Air conditioning	81	
	Electric gearbox	410	
	Electric gearbox	68	
	Alternator	363	

Electric gearbox



Alternator

Characterization of magnets composition

REEs content in magnets

Vehicle	Component	% REEs			REEs mass in magnets		
		Nd (%)	Pr(%)	Dy(%)	Nd (g)	Pr(g)	Dy(g)
Ducato 100% elettric	Electric drive motor	20,4	6,8	4,5	316	105	70
	electric power steering	30,1	6,2	0,0	39	8	0
	Air conditioning	22,4	5,4	1,2	18	4	1
FIAT 500 Elettrica	Electric drive motor	28,4	4,4	0,0	307	47	0
	electric power steering	19,9	5,0	1,7	8	2	1
	Air conditioning	22,4	5,4	1,2	18	4	1
Jeep Compass	electric power steering	20,2	5,2	0,0	17	4	0
	Air conditioning	22,4	5,4	1,2	18	4	1
	big electric gear	20,8	4,5	2,2	85	18	9
	small electric gear	19,5	4,2	0,0	13	3	0
	Alternator	18,4	5,1	0,0	67	18	0

Economic potential

- The recovery of REEs is economically interesting

Economic value of REEs in every component

Vehicle	Component	Economic value Nd (€)	Pr (€)	Dy (€)	Total €
Ducato 100% electric	Electric drive motor	42,3	20,9	24,9	88,0
	electric prower steering	5,3	1,6	0,0	6,9
	Air conditioning	2,4	0,9	0,3	3,6
FIAT 500 electric	Electric drive motor	41,0	9,3	0,0	50,3
	Electric power steering	1,1	0,4	0,3	1,8
	Air conditioning	2,4	0,9	0,3	3,6
Jeep Compass hybrid	Electric drive motor	21,7	5,0	8,5	35,1
	Electric power steering	2,3	0,9	0,0	3,1
	Air conditioning	2,4	0,9	0,3	3,6
	Alternator	8,9	3,6	0,0	12,6
	Big electric gearbox	11,4	3,7	3,1	18,2
	Small eletric gearbox	1,8	0,6	0,0	2,4

Economic potential

- The recovery of REEs is economically interesting
- The dismantling of these components from the vehicle has not a significant impact on the economicity of the recovery (except for the electric power steering)

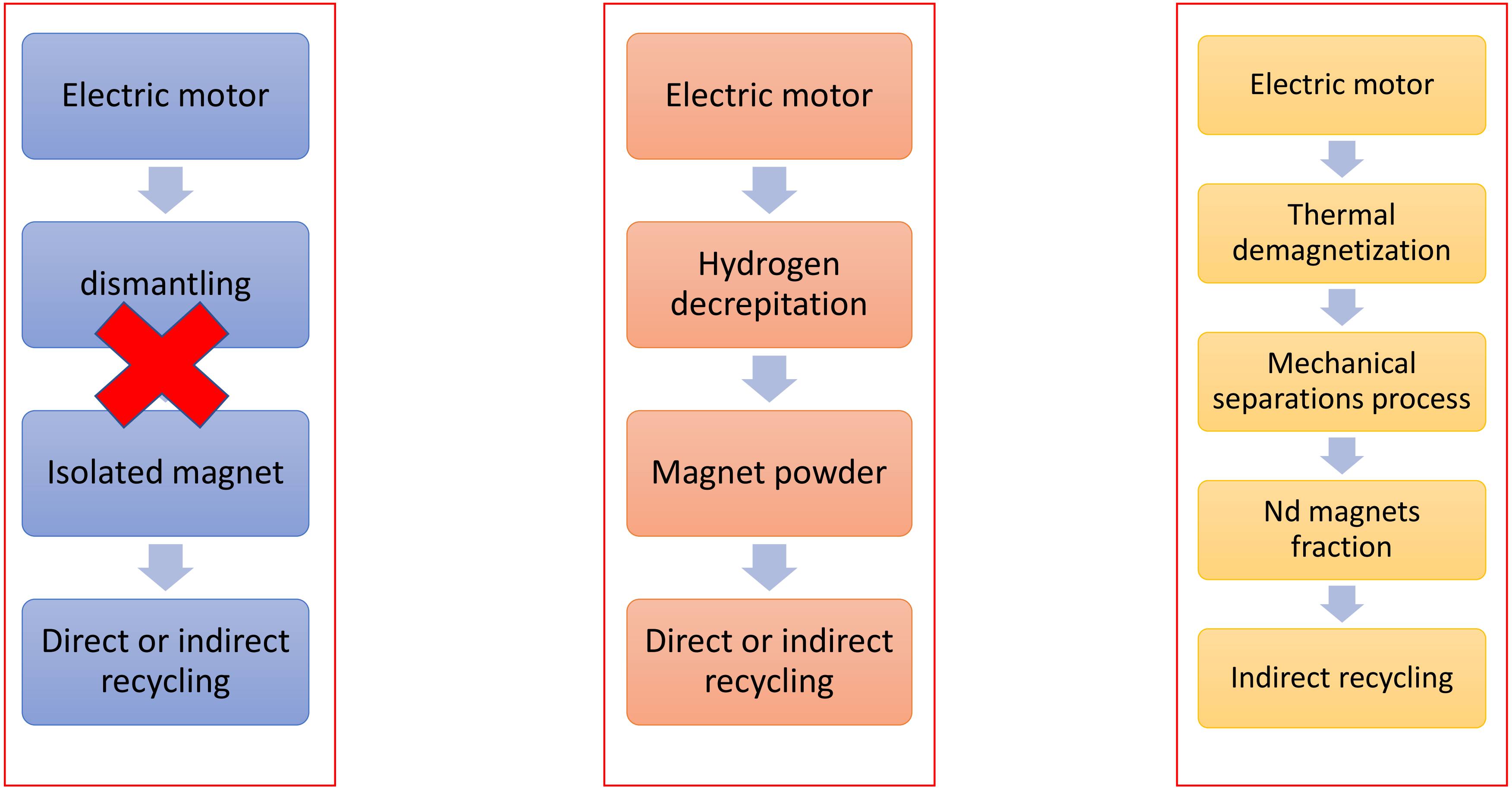
Economic value of REEs in every component

Vehicle	Component	Economic value Nd (€)	Pr (€)	Dy (€)	Total €
Ducato 100% electric	Electric drive motor	42,3	20,9	24,9	88,0
	electric prower steering	5,3	1,6	0,0	6,9
	Air conditioning	2,4	0,9	0,3	3,6
FIAT 500 electric	Electric drive motor	41,0	9,3	0,0	50,3
	Electric power steering	1,1	0,4	0,3	1,8
	Air conditioning	2,4	0,9	0,3	3,6
Jeep Compass hybrid	Electric drive motor	21,7	5,0	8,5	35,1
	Electric power steering	2,3	0,9	0,0	3,1
	Air conditioning	2,4	0,9	0,3	3,6
	Alternator	8,9	3,6	0,0	12,6
	Big electric gearbox	11,4	3,7	3,1	18,2
	Small eletric gearbox	1,8	0,6	0,0	2,4

Economic value of Cu, Fe, Al inside an alternator (endothermic car)

Material	% w/w	Price (€/Kg)	Value per alternator (€/motor)	Total (€/motor)
Fe	59	0,27	0,64	6,24
Al	30	2,1	2,52	
Cu	11	7	3,08	

How to recycle these components?



The recycling process we are developing

160 Kg electric motors

12,4 kg of Nd magnets inside

→

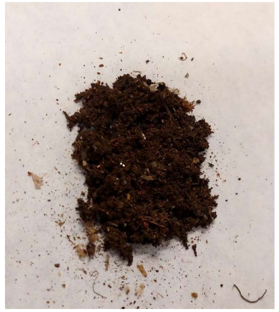
Complete thermal demagnetization

→

Mechanical processing

Yield ≈ 50-60%

→



≈90% Nd magnet

Conclusions

- Interesting economic potential of REEs inside electric vehicles for recovery
- The dismantling of components containing Nd magnets from the vehicle is not economically impactful
- Recycling is technologically feasible
- Recycling is not the solution but can mitigate the problem

Thank you

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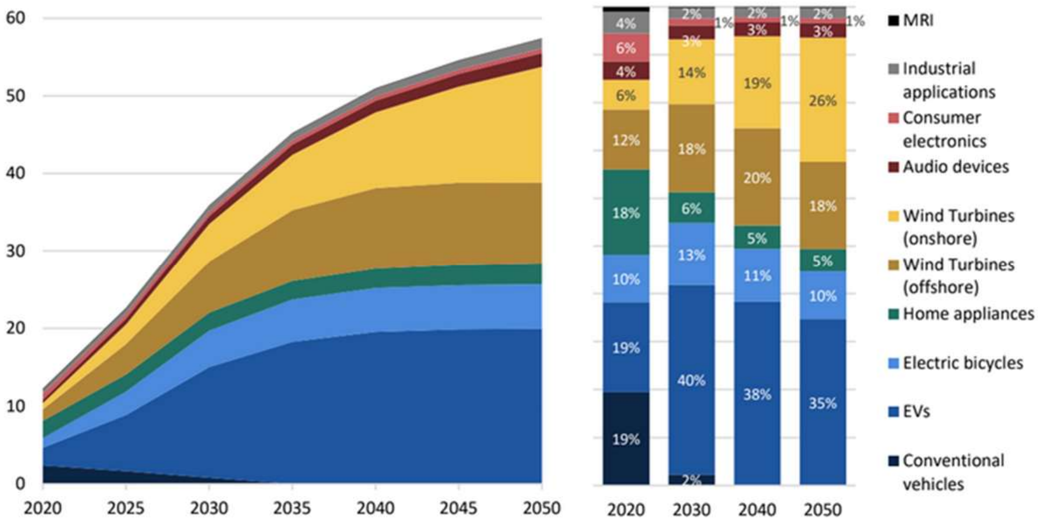
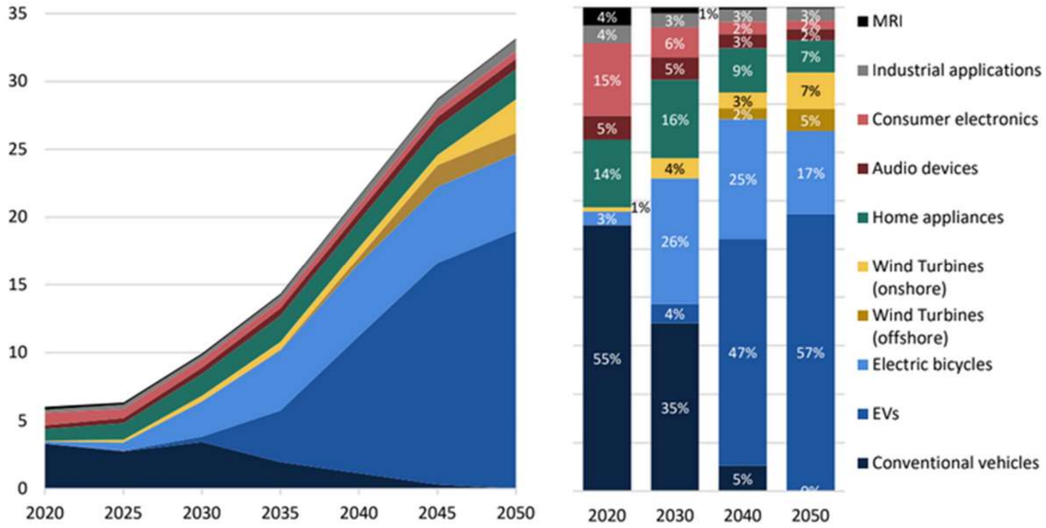
NdFeB magnet demand in the EU from selected applications, thousand tonnes (left) and shares (right)



NdFeB magnet theoretical recycling potential in the EU from selected applications, thousand tonnes (left) and shares (right)



Source: DEVELOPING A SUPPLY CHAIN FOR RECYCLED RARE EARTH PERMANENT MAGNETS IN THE EU, Vasileios Rizos, Edoardo Righetti, Amin Kassab, December, 2022 - 07

AMES NATIONAL LABORATORY

Creating Materials & Energy Solutions

U.S. DEPARTMENT OF ENERGY

IOWA STATE UNIVERSITY

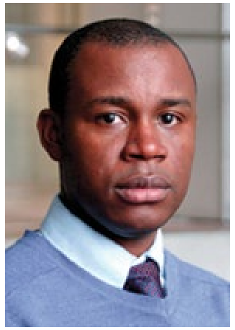
IRTC Conference 2023 (11:30 AM, February 17, Lille/France): Session 6 – Design for circularity

Addressing criticality in rare earths through the decarbonization in permanent magnets recycling

Denis Prodius, Ikenna C. Nlebedim

Critical Materials Institute/

Ames National Laboratory US DOE



Critical Materials Institute

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Regents Innovation Fund

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- Caleb Stetson, Aaron Wilson (INL, S/WWT)
- Dan Bina, Scott Roberts, Kevin Stoll, Travis Patterson (TdVib LLC)
- Denis Prodius (project lead, 2021 -)

Adapted from https://www.ameslab.gov/cmi/cmi-project-3313-recovery-critical-materials-dilute-electronic-waste-streams

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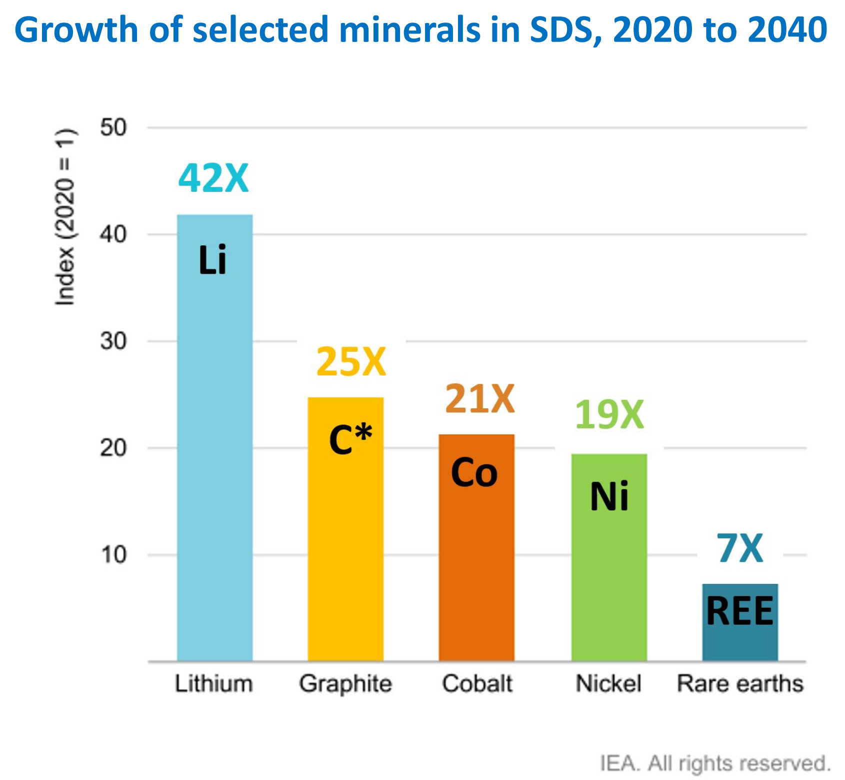
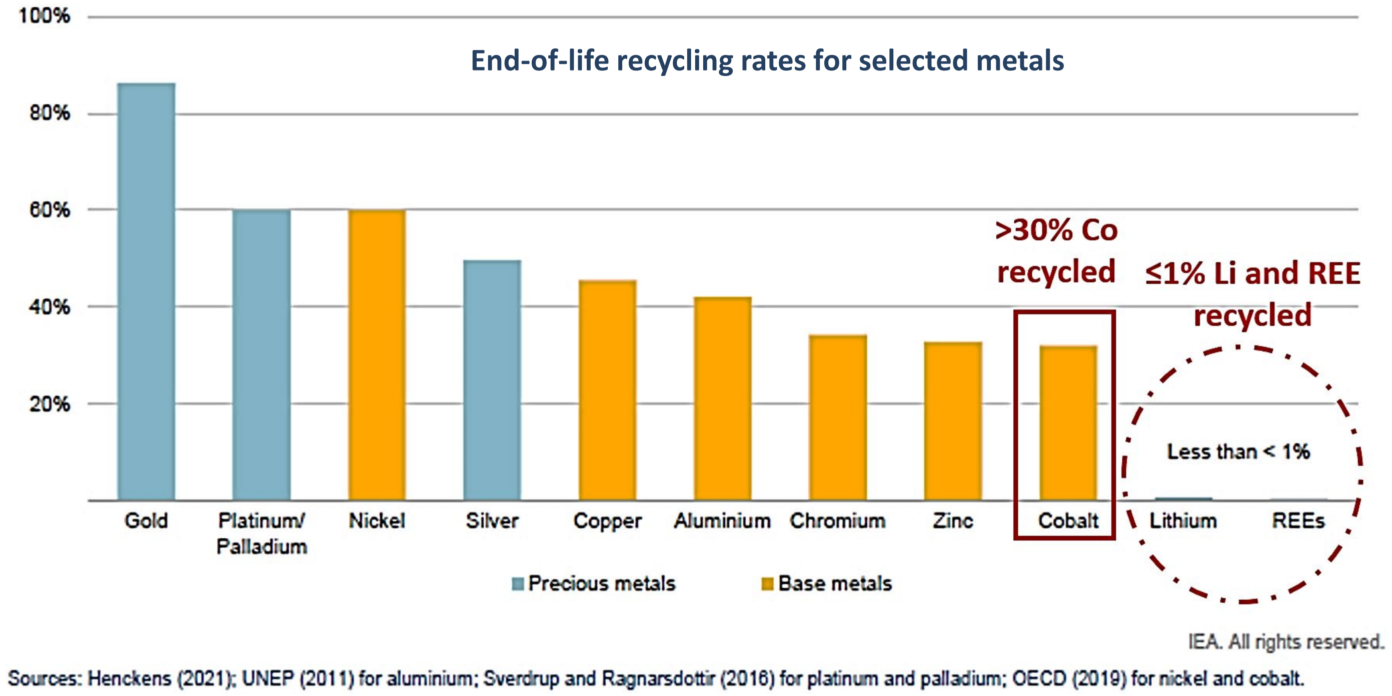
- Dan Ginosar
- Scott McCall
- Ruby Nguyen
- Yoshiko Fujita

Adapted from https://mse.utk.edu/critical-materials-institutes-winter-meeting-2022/

Why Recycle Rare Earths from E-wastes





Figures (modified) from IEA report 2021, The Role of Critical Minerals in Clean Energy Transitions.

For lithium, cobalt, and rare earth elements (REEs), the top three producing nations control well over three-quarters of global output. In some cases, a single country is responsible for around half of worldwide production.

Adapted from https://foreignpolicy.com/2019/05/01/mining-the-future-china-critical-minerals-metals/

Sources and Types of Magnets for Recycling

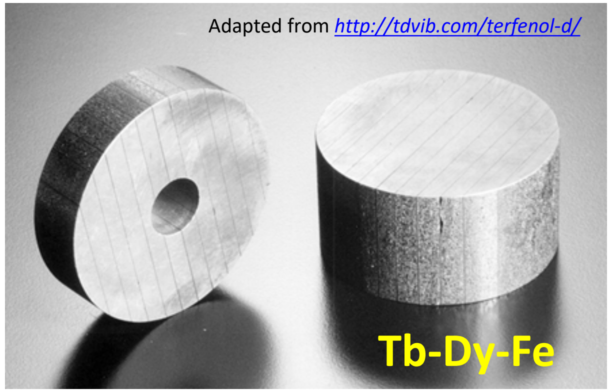
Sources:

- Electronic waste (e.g., hard disk drives, etc.)
- Scrap magnets from industrial manufacturing wastes.
- Swarfs from post-manufacturing operations (grinding, slicing, etc.).
- Any other magnet source.

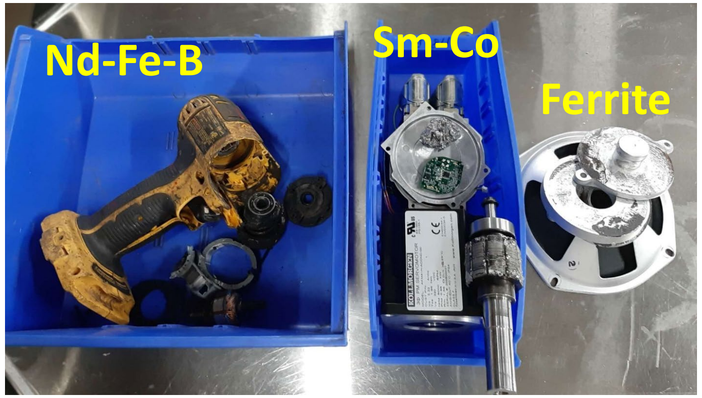
Adapted from https://pixabay.com/vectors/hard-disk-storage-computer-159264/

Types:

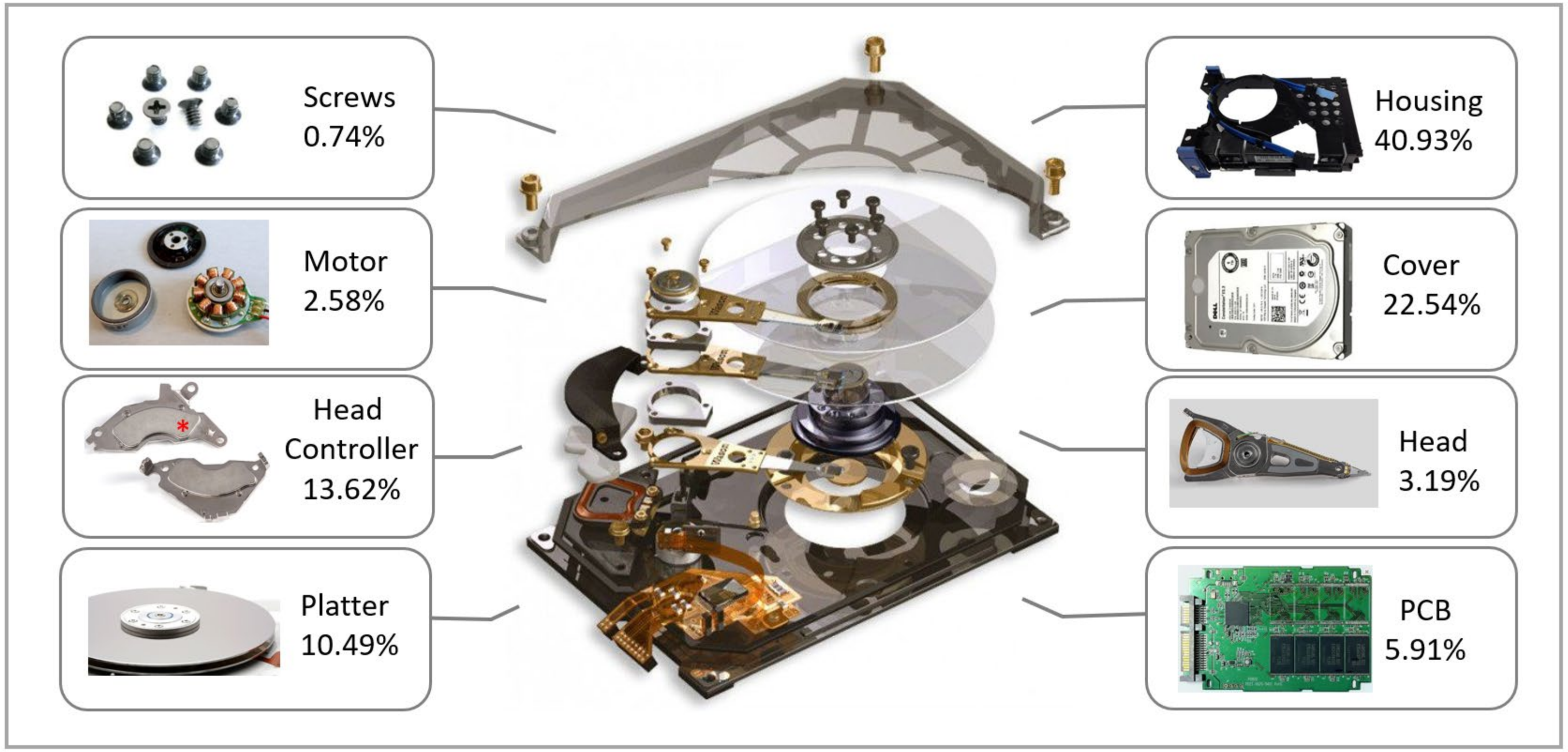
- Nd-Fe-B
- Sm-Co
- Terfenol-D (not a magnet).



Adapted from http://tdvib.com/terfenol-d/



Permanent magnets as viable sources for REEs



* Permanent magnet: 2.03%

Adapted from https://www.backblaze.com/blog/ssd-vs-hdd-future-of-storage/ and https://www.destroydrive.com/services/

*Every year in the United States, roughly 20 million hard drives are retired from data centers: ~35% **MUST** be shredded*

Pyrometallurgical vs. Hydrometallurgical Approaches

Pyrometallurgical Approaches		Hydrometallurgical Approaches	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
Generally applicable to all types of magnet Compositions	Larger energy input required	Applicable to all types of magnet compositions.	Many process steps required before obtaining product.
No generation of waste water except if hydrometallurgical step is needed in addition.	Unsuitable for oxidized magnet materials	Applicable to non-oxidized and oxidized alloys	Consumes large amounts of chemicals
Can result is REE products as metals and alloys	Generates large amounts of solid wastes.	Same processing steps as those for extraction of rare earths from primary ores	Generates large amounts of waste water and can produce solid wastes.
	Typically requires magnet pre-concentration for e-wastes.		Typically requires magnet pre-concentration for e-wastes.
	May require subsequent hydrometallurgical operations.		

Adapted from Binnemans et al. *http://dx.doi.org/10.1016/j.jclepro.2012.12.037*

Ideal REEs Recovery Technology…

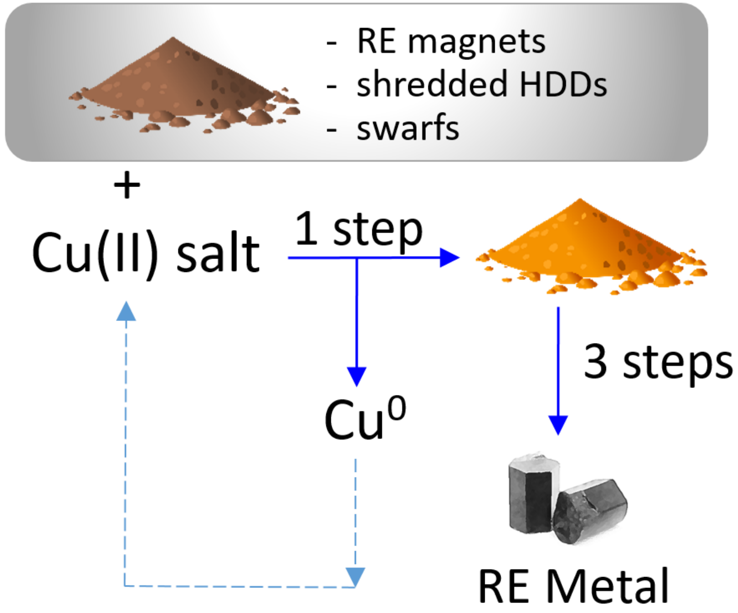
- Allows for recycling of other components in a device housing the rare earth elements containing materials
- Results in valuable recycling by-products
- Minimizes or eliminates pre-processing steps prior to recovering REEs
- Safe to deploy, energy efficient and minimal negative environmental impact
- Results in products suitable to be reinserted into the rare earth elements supply chain
- Enable each REE constituents to be recovered separately rather than in mixed forms

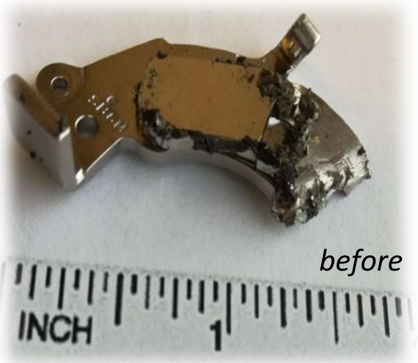
Source: Nlebedim and King, JOM, **70** (2018) pp 115–123

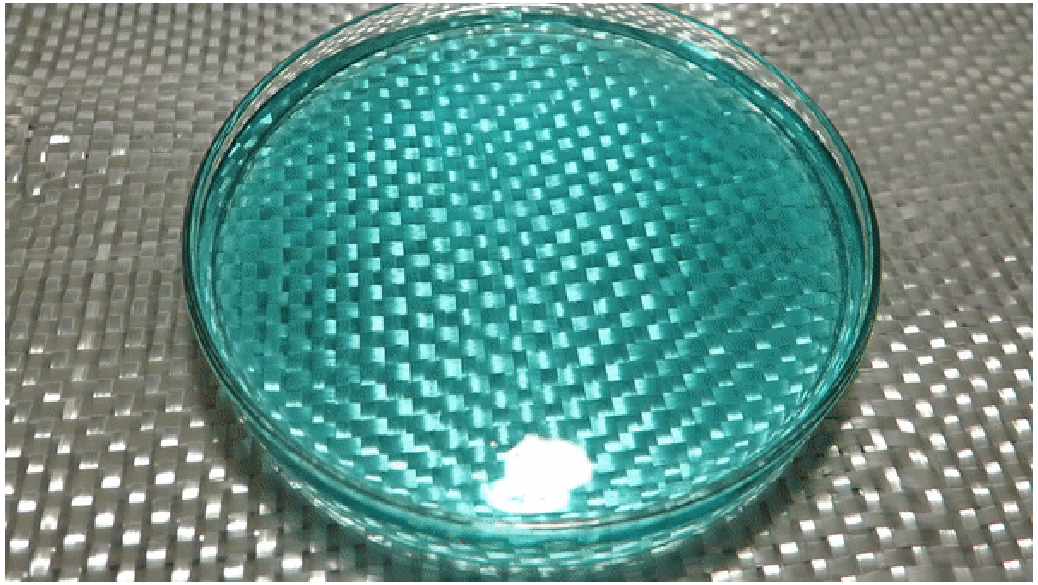
Acid-free Dissolution Recycling Technology

- A hydrometallurgical approach accomplished *via* selective REDOX process.

$$2RE_2Fe_{14}B + 34Cu^{2+} + \frac{21}{2}O_2 \xrightarrow{RT} 4RE^{3+} + 28Fe^{2+} + Cu_3(BO_3)_2\downarrow + 15Cu_2O\downarrow + Cu^0\downarrow$$

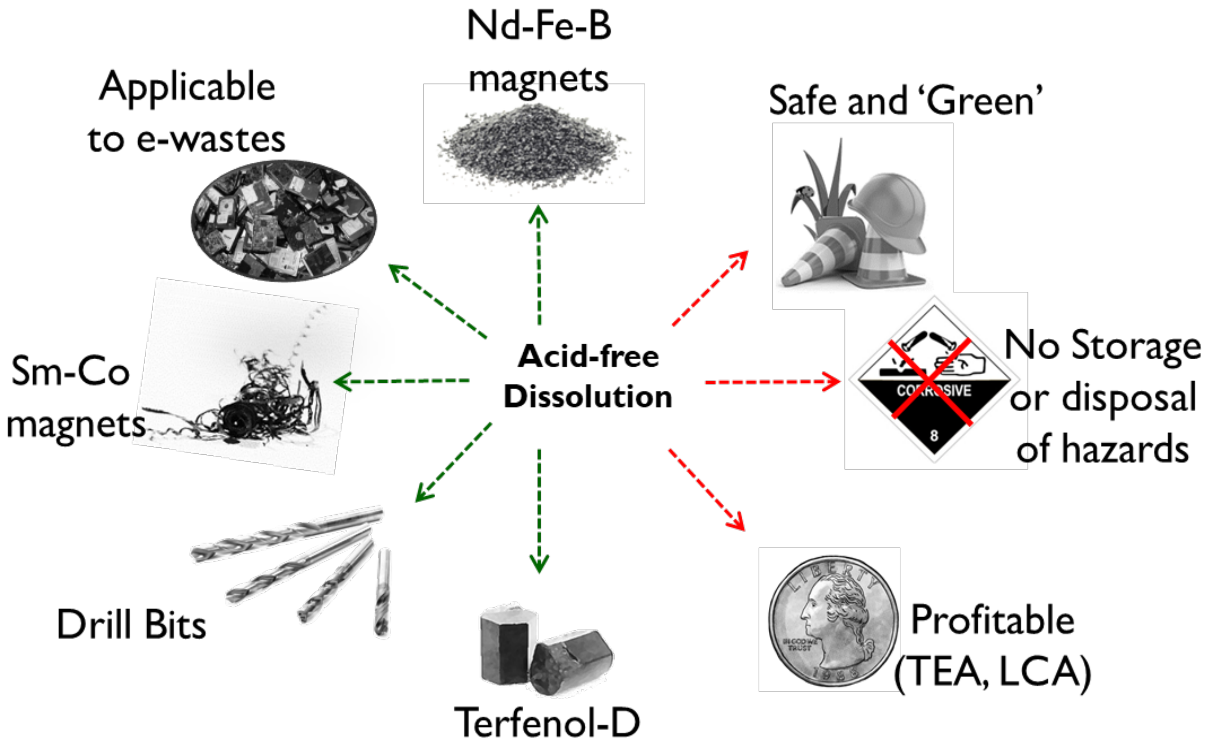






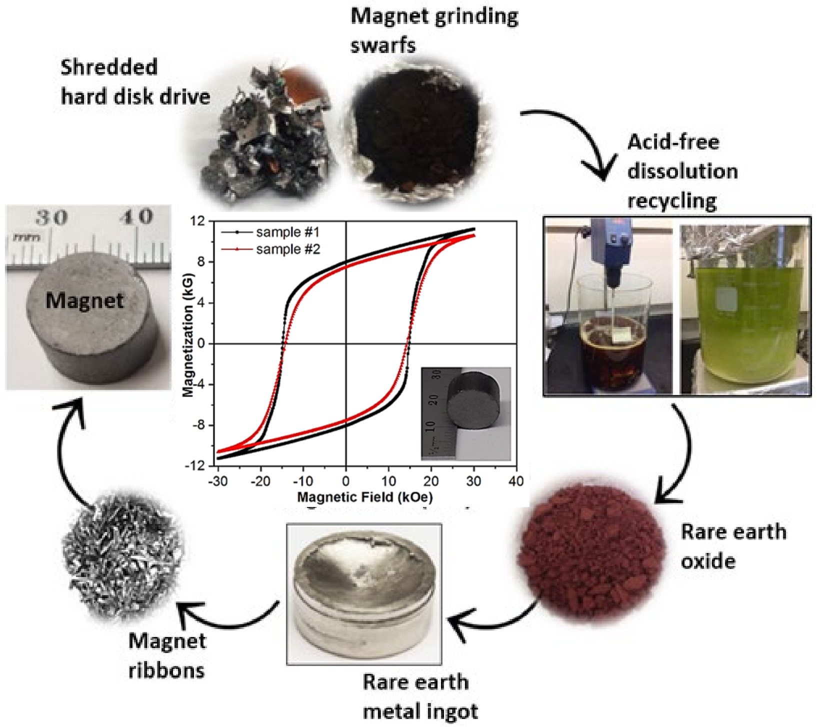
adapted from https://www.youtube.com/watch?v=lBavcpUgiGE (Author: Ilusys Systems)

Progress in the Development of the Acid-free Dissolution Process



Inman et al. *Clean Technol. Recycl.* (2021), doi:10.3934/ctr.2021006

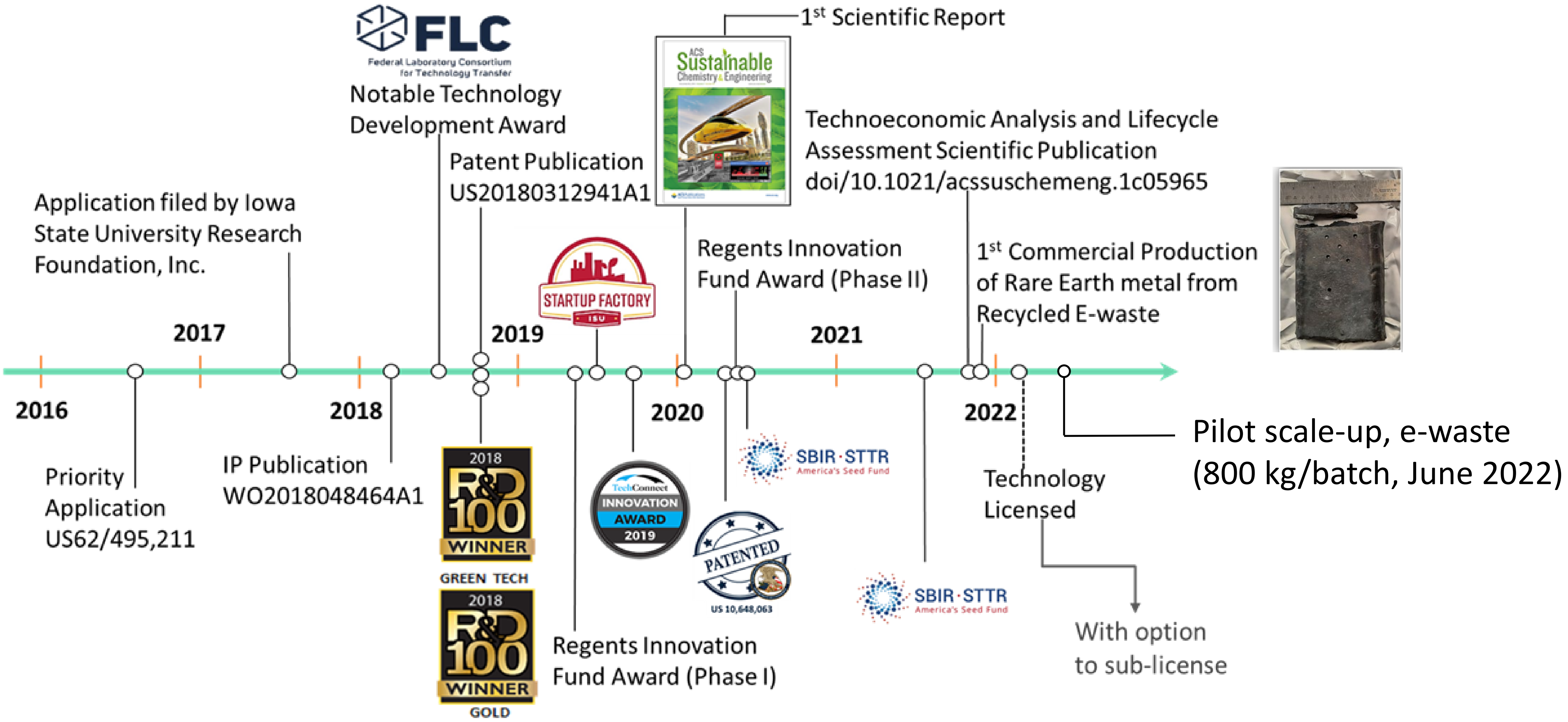
Lab-scale: magnets made with recovered REEs



Lab-scale: leaching efficiency for REE magnets in e-waste = 75%

Prodius et al. *ACS Sust. Chem. Eng. (2020),* https://doi.org/10.1021/acssuschemeng.9b05741

Timeline of Technology Maturation (2016-2022)

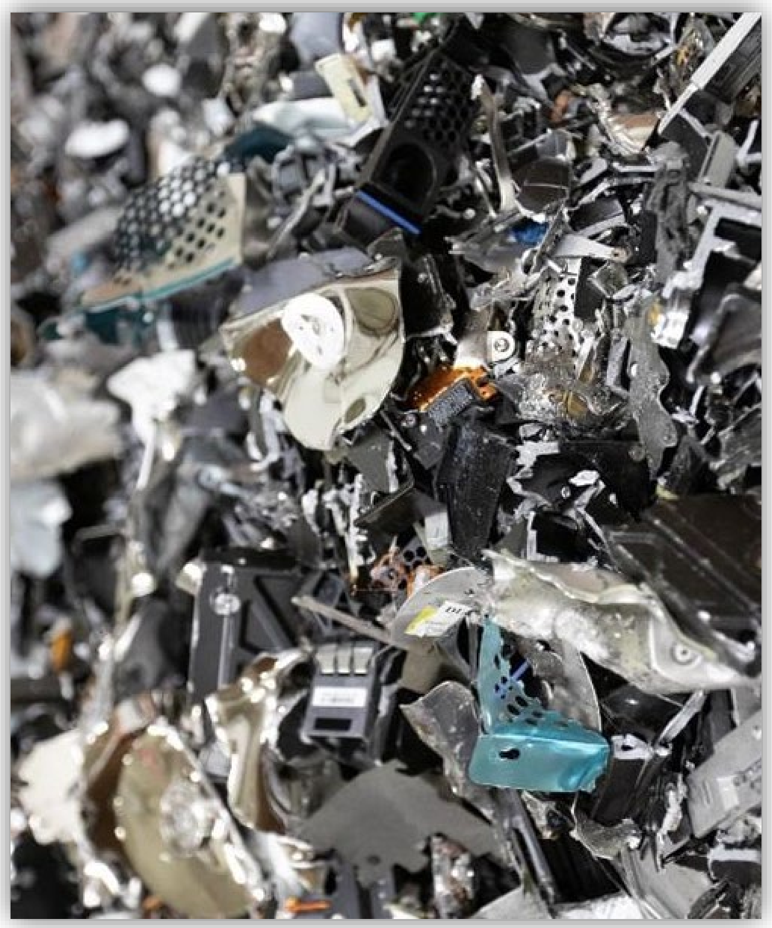


Initial Commercialization Phase: 2019-2020

Adapted from https://www.news.iastate.edu/news/2022/08/01/state-fair

Regents Innovation Fund
IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Current Commercialization Phase: 2021-2023



Adapted from https://src.iastate.edu/innovation-work-numbers

Adapted from https://www.linkedin.com/company/tdvib-llc/

1st Commercial Rare Earth Metal

Technoeconomic Analysis based on 2020 Pricing

Summary of Economic Outcomes under the Worst-Case (0% Dy in Magnet and 96% REE Recovery Efficiency)and Best-Case (6% Dy in Magnet and 99% REE Recovery Efficiency) Scenarios of the Nd-Fe-B Swarf Recycling Process[a]

category	value ($/year)	cost contribution
direct cost	$611,754	54%
material cost	$364,792	32%
utility cost	$49,664	4%
other cost	$197,298	18%
capital cost (amortized)	$76,478	7%
indirect cost	$120,330	11%
general cost	$284,0244–$717,034	~28%
total cost	$1,092,585–$1,525,596	100%
total revenue (A)	$1,242,542–$2,685,911	
net profit (B)	$149,956–$1,160,315	
net profit margin ratio (B/A)	12–43%	

- 100 metric tons of Nd-Fe-B magnet swarf per year to produce 32 metric tons of REOs
- Due to the revenue differences between the worst-case and the best-case scenarios, income taxes also changed, resulting in a range of total costs.

For February 2022 prices, net profit margin ≈55 – 59%.

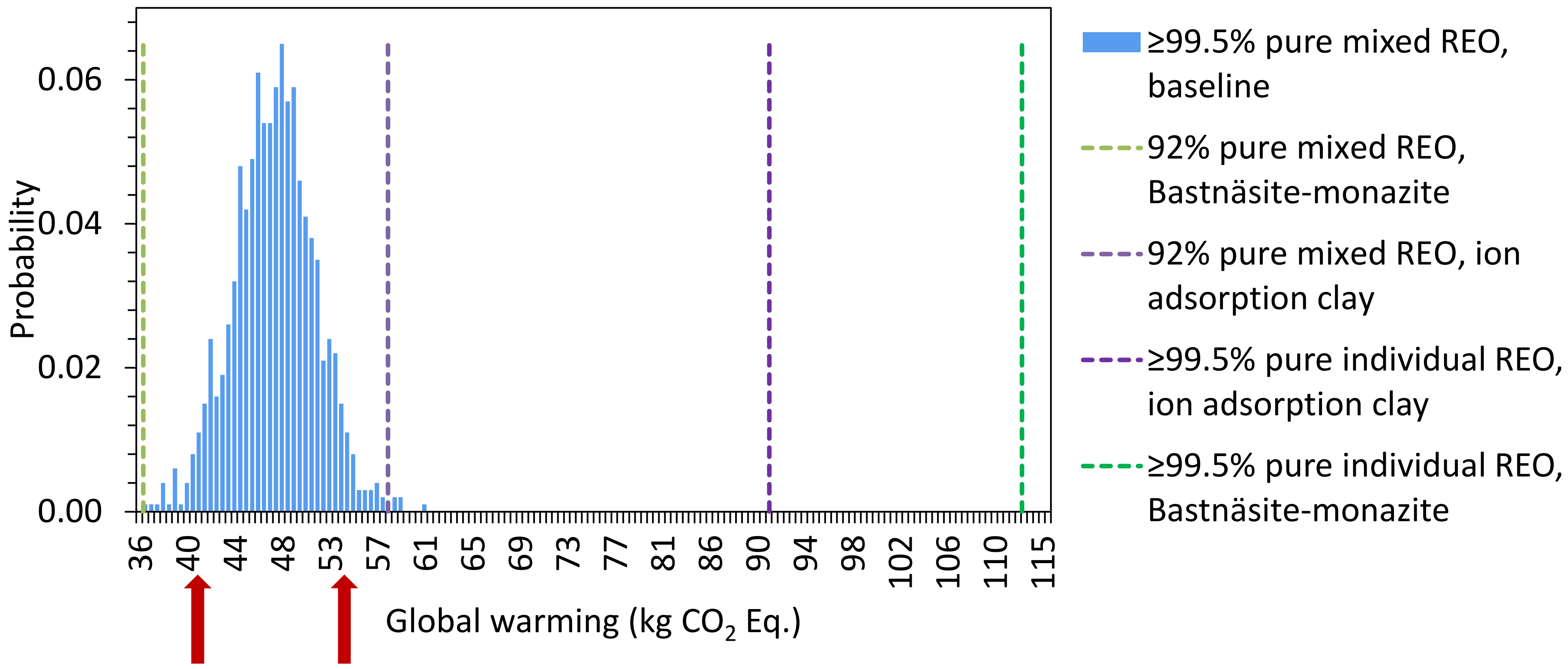
Environmental Impact

Impact category	Unit	Acid-free dissolution	Bastnasite-monazite from Bayan obo		Ion adsorption clay	
		Baseline (A)	Upper bound (A/B)	Lower bound (A/C)	Upper bound (A/D)	Lower bound (A/E)
Ozone depletion	kg CFC-11 eq	5.7E-06	25%	68%	33%	74%
Global warming	kg CO_2 eq	3.8E+01	33%	102%	33%	51%
Smog	kg O_3 eq	1.7E+00	10%	21%	24%	38%
Acidification	kg SO_2 eq	1.8E-01	19%	44%	2%	2%
Eutrophication	kg N eq	8.4E-02	45%	130%	2%	2%
Carcinogenics	CTUh	7.1E-07	12%	26%	15%	22%
Non carcinogenics	CTUh	6.4E-06	32%	100%	17%	26%
Respiratory effects	kg PM2.5 eq	3.0E-02	5%	9%	23%	37%
Ecotoxicity	CTUe	1.0E+02	35%	102%	18%	27%
Fossil fuel depletion	MJ surplus	7.0E+01	37%	113%	55%	77%

- 1 kg of REO from Nd-Fe-B magnet swarf vs virgin production from Bayan Obo ores and ion adsorption clay in southern China after applying economic allocation.
- (B) and (D) represent the environmental impacts of producing 99.5% individual REO; (C) and (E) represent the environmental impacts of producing 92% mixed REO

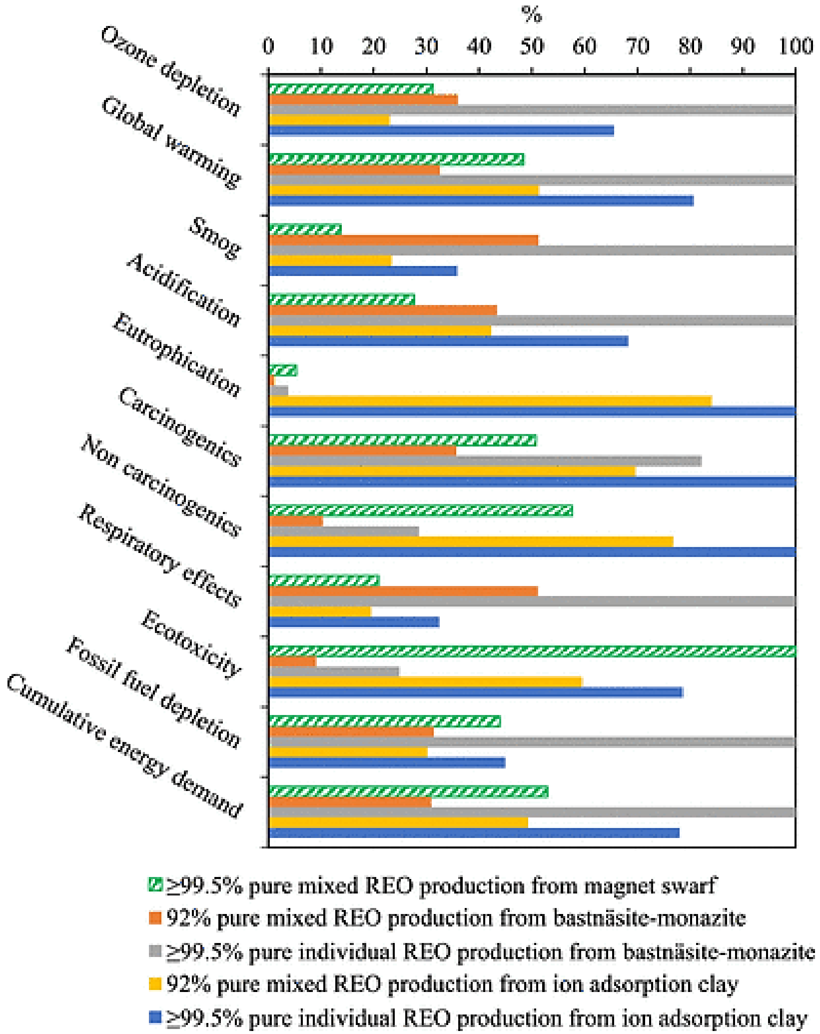
Chowdhury et al. *ACS Sust. Chem. Eng. (2021)* https://doi.org/10.1021/acssuschemeng.1c05965

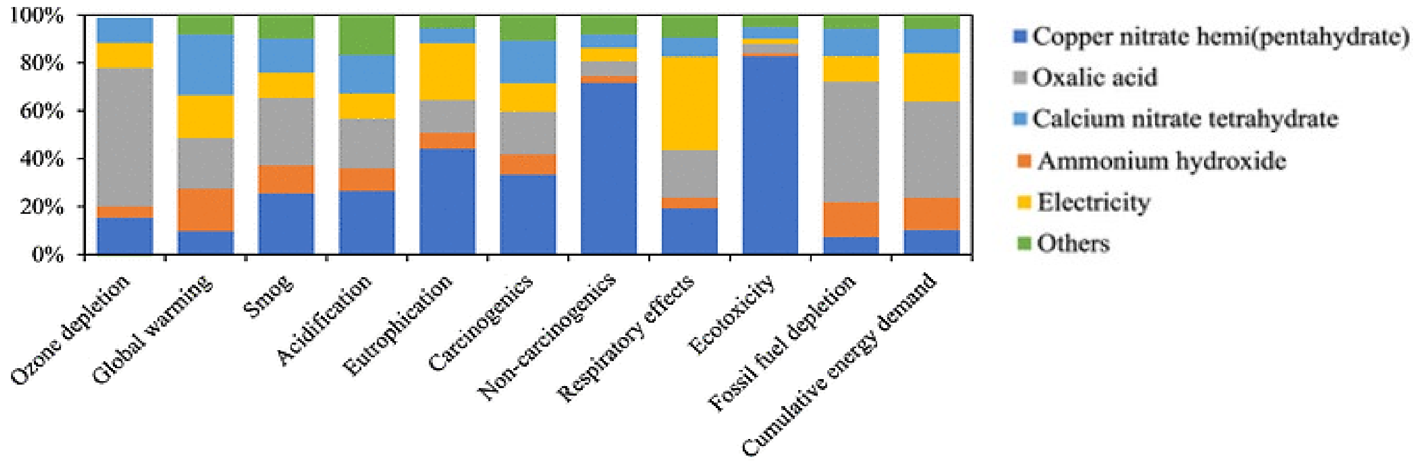
Results: Uncertainty analysis

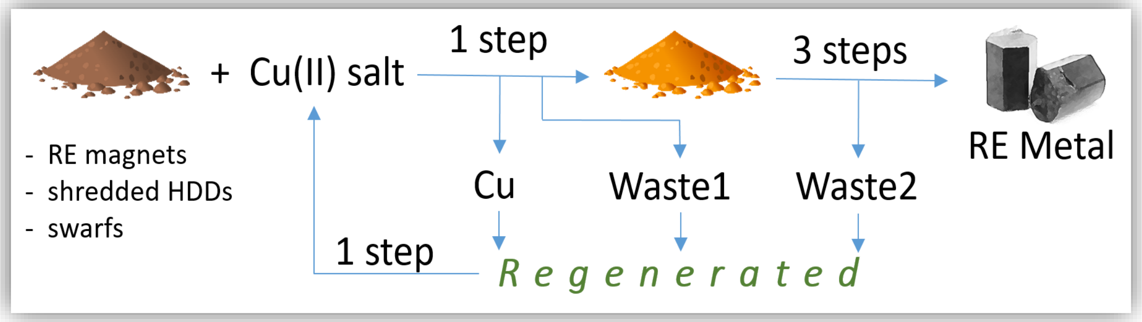


Chowdhury et al. *ACS Sust. Chem. Eng. (2021)* https://doi.org/10.1021/acssuschemeng.1c05965

Environmental Impact







- **A new version of the technology valorizes >99% of copper(II) salt, eliminating its contribution to all the impact categories.**

Chowdhury et al. *ACS Sust. Chem. Eng. (2021)* https://doi.org/10.1021/acssuschemeng.1c05965

Environmental Impacts: Different Copper(II) Salts

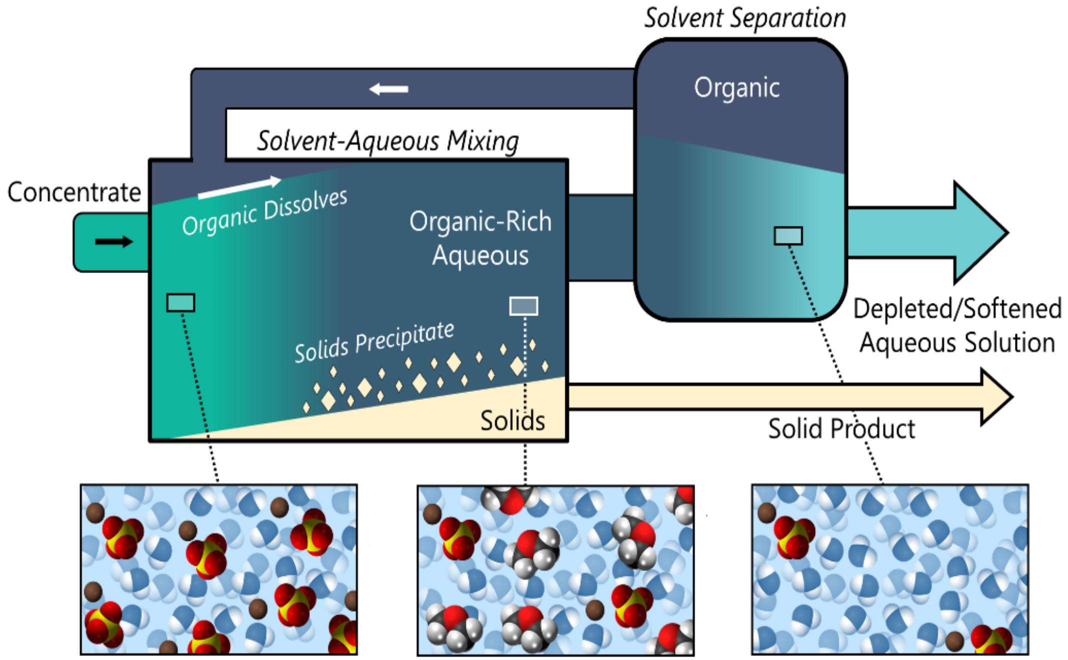
Category	Unit	Copper nitrate hemi(pentahydrate) (A)	Copper chloride dihydrate (B)	Copper sulfate pentahydrate (C)	Copper acetate monohydrate (D)
			(A/B)	(A/C)	(A/D)
Equivalent amount	kg	1.00	136%	93%	117%
Market price	$/kg	1.50	60%	83%	122%
Ozone depletion	kg CFC-11 eq	1.10E-06	83%	97%	86%
Global warming	kg CO_2 eq	3.98	123%	142%	130%
Smog	kg O_3 eq	0.42	102%	107%	108%
Acidification	kg SO_2 eq	0.10	96%	98%	103%
Eutrophication	kg N eq	0.17	57%	95%	100%
Carcinogenics	CTUh	1.53E-06	94%	95%	99%
Non carcinogenics	CTUh	4.33E-05	95%	95%	100%
Respiratory effects	kg PM2.5 eq	0.01	92%	94%	97%
Ecotoxicity	CTUe	921.29	88%	88%	100%
Fossil fuel depletion	MJ surplus	4.79	81%	98%	69%

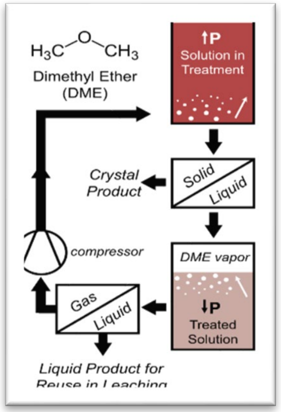
Effects of different copper(II) salts on the economic and environmental performance of Nd-Fe-B swarf recycling process.

Chowdhury et al. *ACS Sust. Chem. Eng. (2021)* https://doi.org/10.1021/acssuschemeng.1c05965

REE separation: pure materials for metal making

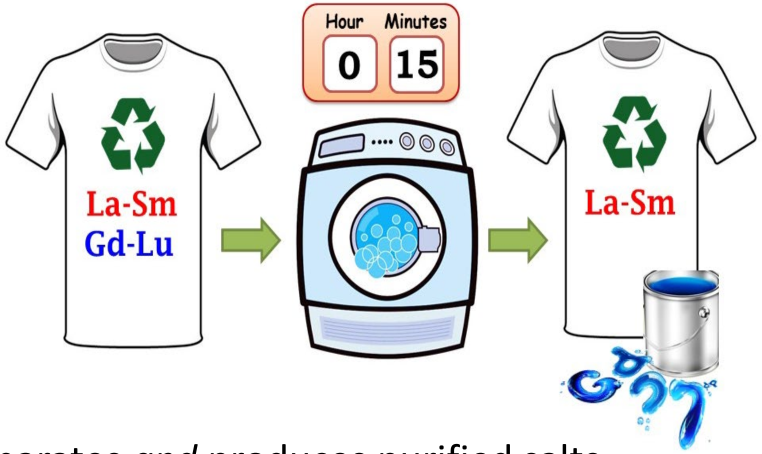
Solvent-Driven Fractional Precipitation



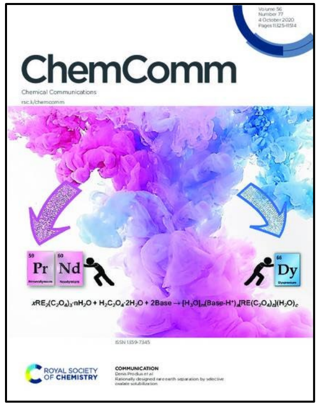


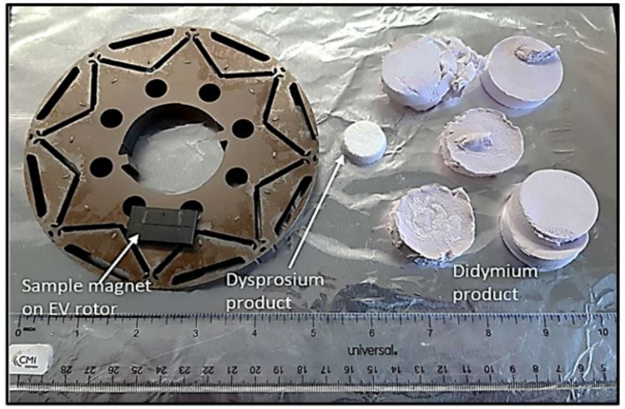
Samarium sulfate produced in DME-aqueous system

C. Stetson, A. et al. *Nature Commun.* 13 (**2022**), 3789



Separates *and* produces purified salts





Prodius D. et al. *Chem. Commun.* 56(77) (**2020**), 11386-11389

AMES NATIONAL LABORATORY

Creating Materials & Energy Solutions

Critical Materials Institute
AN ENERGY INNOVATION HUB

1 **Ames National Laboratory** (Ames, Iowa)
2 **Idaho National Laboratory** (Idaho Falls, Idaho)
3 **Oak Ridge National Laboratory** (Oak Ridge, Tennessee)
4 **Lawrence Livermore National Laboratory** (Livermore, California)

T **Team Members** A **Affiliates**

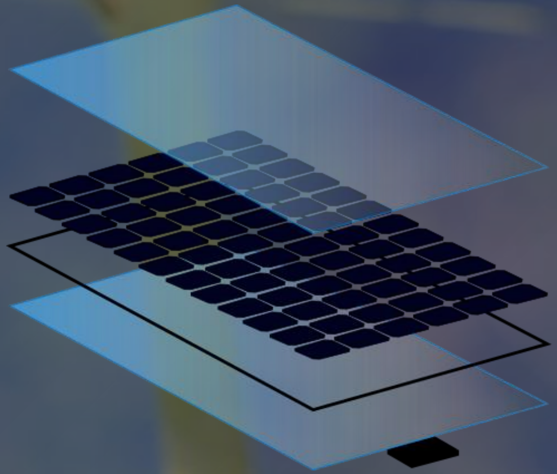
Questions?

The Critical Materials Institute, an Energy Innovation Hub, is supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office.

Thank you!


BIOSPHERE
IRTC
2023

01-SUMMARY

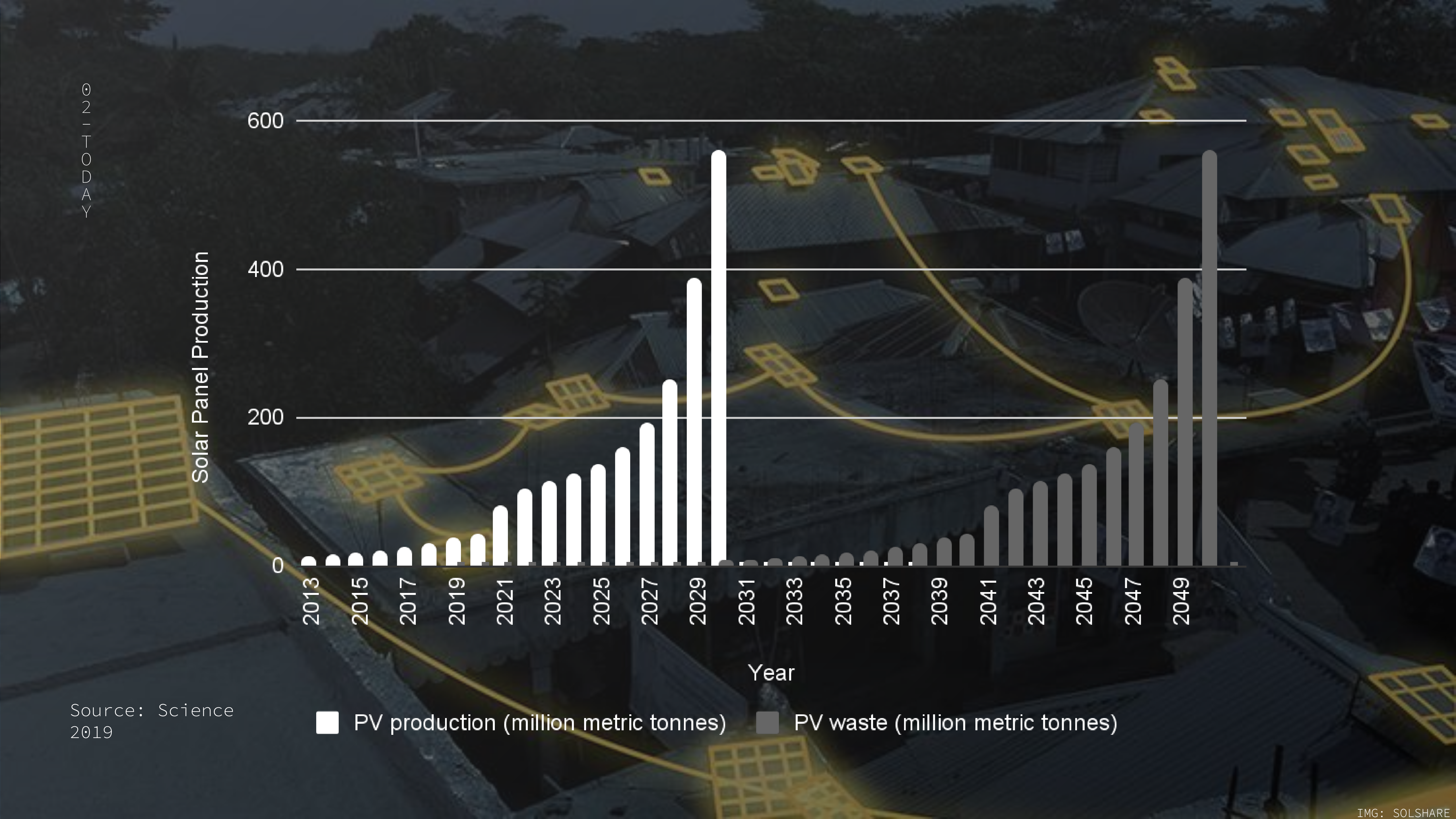


BIOSPHERE SOLAR: A REVOLUTION IN SOLAR

Biosphere Solar is redesigning solar panels to enable circular raw material flows at End-of-Life.

CURRENT STATUS

Fund raised: €30,000
Development: 5 iterations
Accelerator: Circular Valley Wuppertal


02-TODAY
Solar Panel Production
600
400
200
0
2013
2015
2017
2019
2021
2023
2025
2027
2029
2031
2033
2035
2037
2039
2041
2043
2045
2047
2049
Year
PV production (million metric tonnes)
PV waste (million metric tonnes)
Source: Science 2019
IMG: SOLSHARE

02 - TODAY

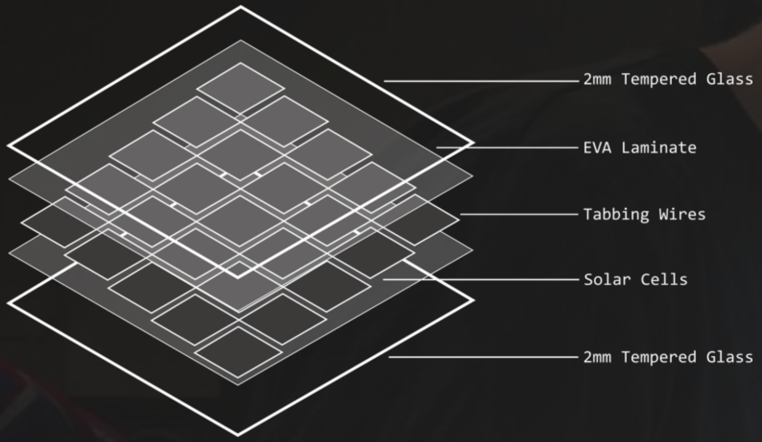
LANDFILLING & ECOTOXICITY

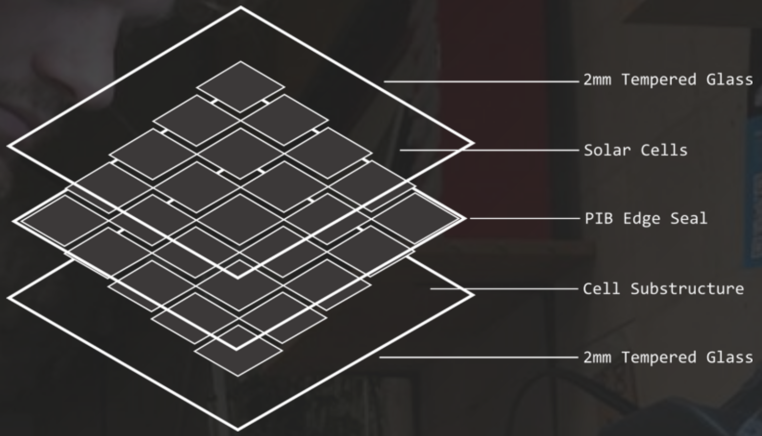
But will solar energy be sourced from panels made to be thrown away and landfilled after a lifetime of 20 years? Will the toxic elements be left to leach into our lands, poisoning future generations?

IMG: HILARY SWIFT

THE TECHNOLOGY

INNOVATING PV FOR A GOOD ANTHROPOCENE





STANDARD SOLAR PANEL

- Hard to recycle
- Intransparent supply chains

BIOSPHERE SOLAR

- Repairable
- European supply chain

03 - DISRUPT

COMPONENT MANUFACTURING

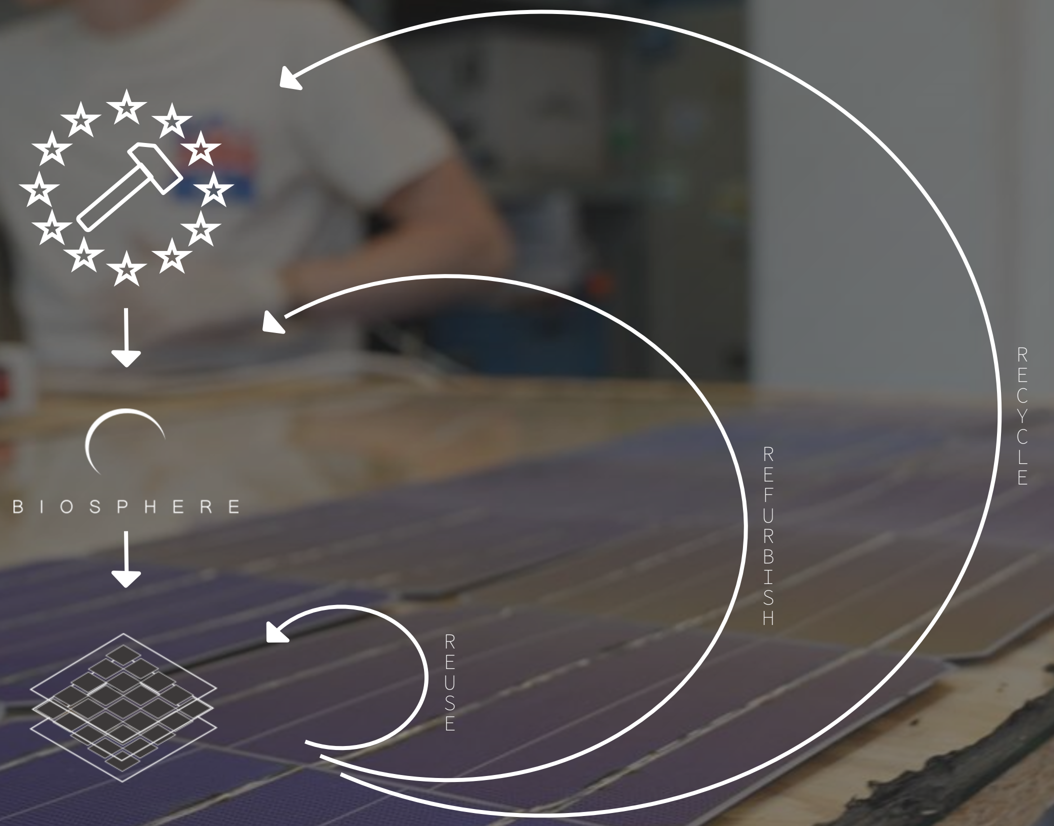
recyclable materials will be turned into new components by our partners

MODULE MANUFACTURING

reusable components are plugged into refurbished modules by biosphere solar and partners

USE PHASE

the product is designed to be highly durable, and can be re-used multiple times



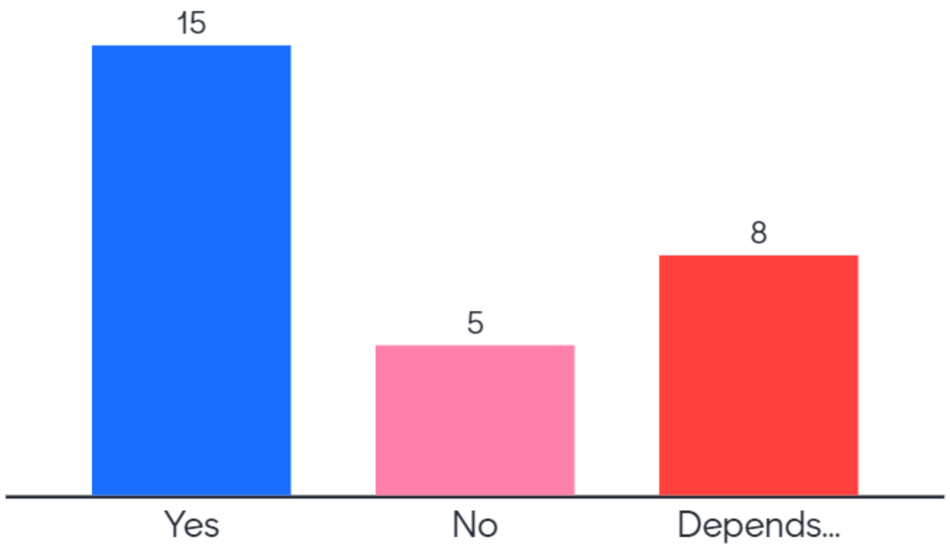
MORE R's

Mentimeter - Interactive Presentations

Go to **www.menti.com** and use the code **2893 3956**

Does it make sense to make a circular product in a linear economy?

Mentimeter



28

OUR ROADMAP

MILESTONES, DEVELOPMENT & INVESTMENT

minimum viable product

certification

TRL 6

launching customer pool

first production series

TRL 7

market expansion

TRL 8

large-scale production

TRL 9

product for global markets

open-source production line

distributed power plant model

V0
PROTOTYPE

2023

V1 (MVP)
COMPETITIVE DESIGN

2024

V2
LOCALLY DISRUPTIVE DESIGN

2025

V3
GLOBALLY DISRUPTIVE DESIGN

investment timeline

PRE-SEED | SEED (SAFE) | SERIES A | SERIES B | SERIES C | IPO

DISRUPTING THE SOLAR INDUSTRY

To bring about a circular revolution in the solar industry, Biosphere Solar requires a clear timeline. The past year has been about developing V0 of the Biosphere Solar solar panel: a prototype which builds towards an MVP. With each iteration of Biosphere Solar's new design, an additional layer is placed: in 2023, Biosphere Solar's solar panel V1 will be launched - a fully certified product which can compete on the solar market; in 2024, a locally disruptive design will be released (V2), allowing large scaling production and a market expansion; and the year 2025 will see Biosphere Solar releasing V3, a globally disruptive design for the solar panel.

Ch5

04 - TEAM

BSc International Business
MSc Industrial Ecology

Kushal Gorti - Circular Business Developer

Domonkos Planer - Industrialisation Developer

Victor Beccaria - Industrialisation Developer

BSc Maastricht Science Programme
MSc Industrial Ecology

Judit Klooster - Community Builder

BSc Applied Physics
MSc Sustainable Energy Technology

Falko Baatsen - Mechanical Engineer

Rutger Ritsma - Design Engineer

Yoop Kroon - Interconnection Designer

BSc NanoBiology
MSc Industrial Ecology

Liam McClain - Content Creator

Go to www.menti.com and use the code 4920 0538

How can product developing startups contribute to transparent, circular supply chains?

Mentimeter

know their supplier
sharing data
design
showing advanced cases
as a service business
cooperate with ri institu
link with a funder
work with a uni
challenging industrials
outreach
innovation
collaboration
data sharing
deliver what you promise
inovation
innovative project ideas
out of the box thinking
disrupting status quo
product passport

15

Circularity index for product design: a case study of car-based mobility

Gabriel Carmona

Kai Whiting

Jonathan Cullen

First IRTC conference – 17th Feb 2023

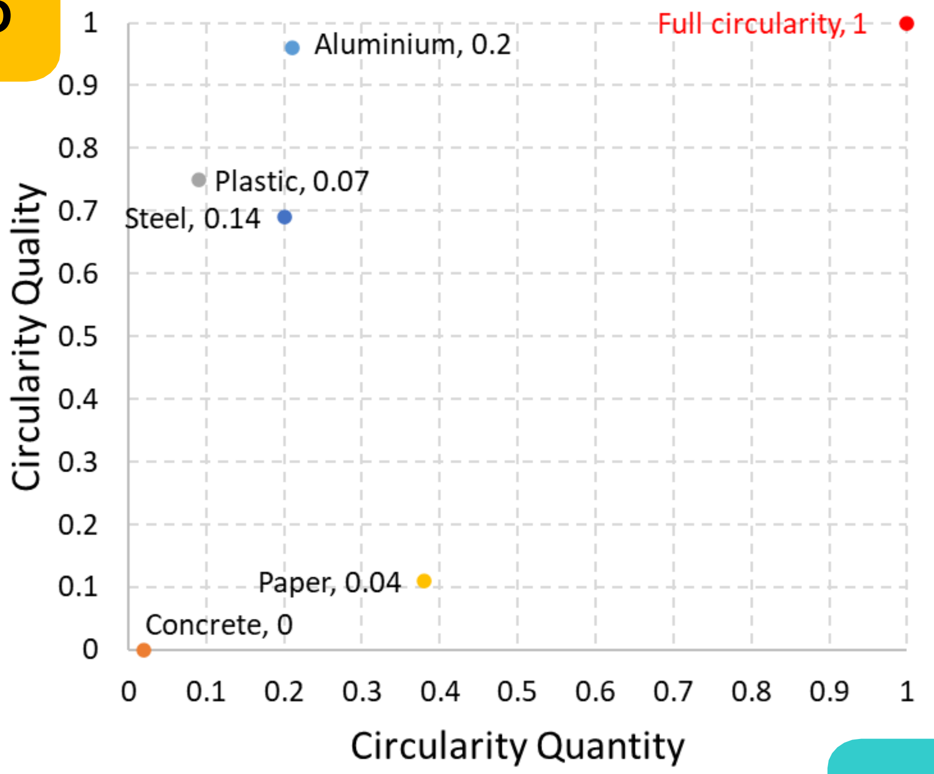
How far are we from full circularity?

Circularity Index CI = α x β

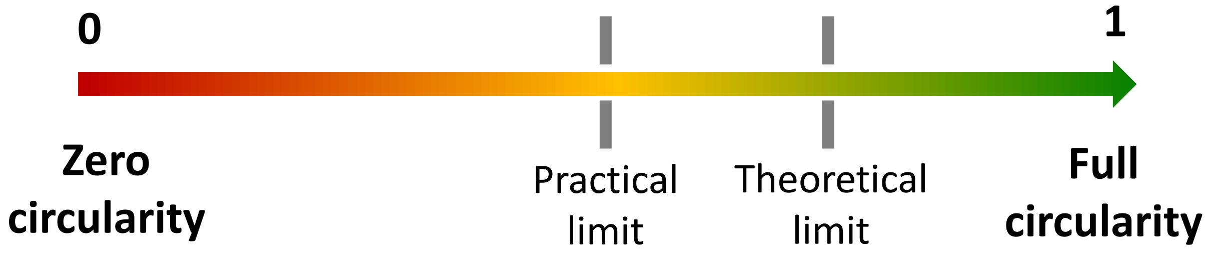
$$\alpha = \frac{recovered\ EOL\ material}{total\ material\ demand}$$

$$\beta = 1 - \frac{energy\ required\ to\ recover\ material}{energy\ required\ for\ primary\ production}$$

β

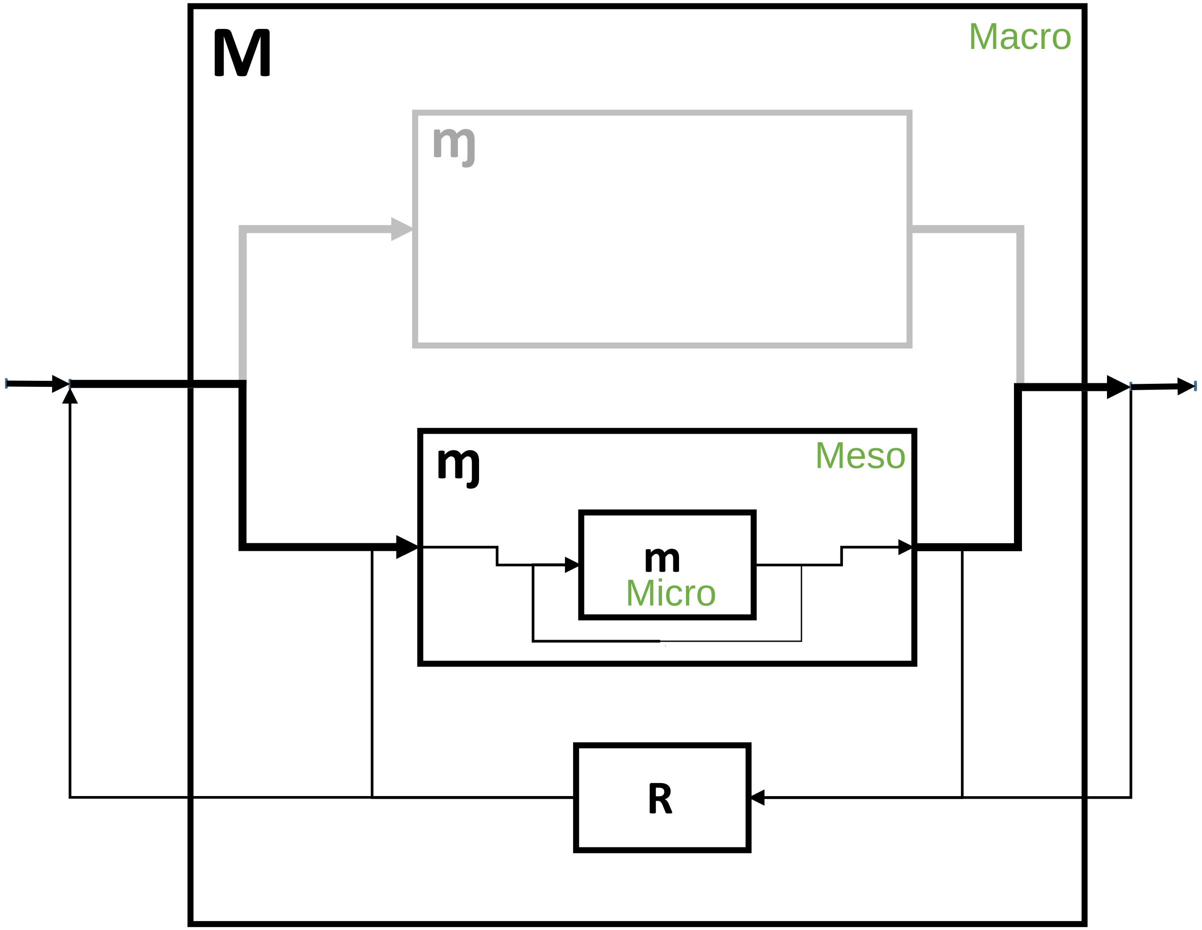


α



Adapted from Cullen, 2017

Alpha index



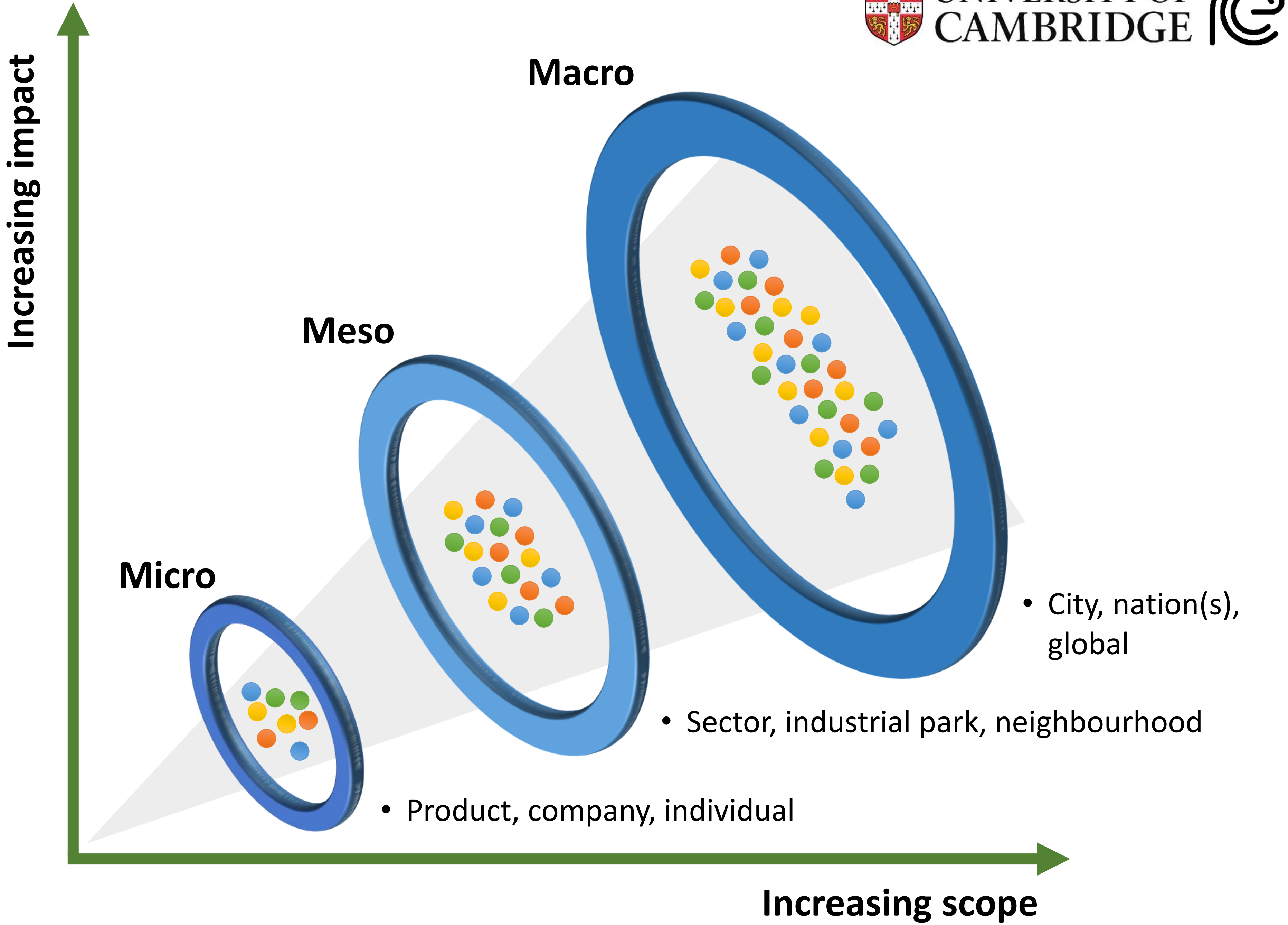
$$\alpha = \frac{recovered\ EOL\ material}{total\ material\ demand}$$

- Meso and micro scale: inputs and outputs might have different levels of circularity.
- Circular/recovered flows do not necessarily re-re-enter the same system.
- Supply vs demand imbalance.
- Metal pollution constrains.

$$\alpha_{inflow} = \frac{circular\ inflow\ (recycling, repurposing, reuse)}{total\ material\ inflow}$$

$$\alpha_{outflow} = \frac{circular\ outflow\ (recycling, repurposing, reuse)}{total\ material\ outflow}$$

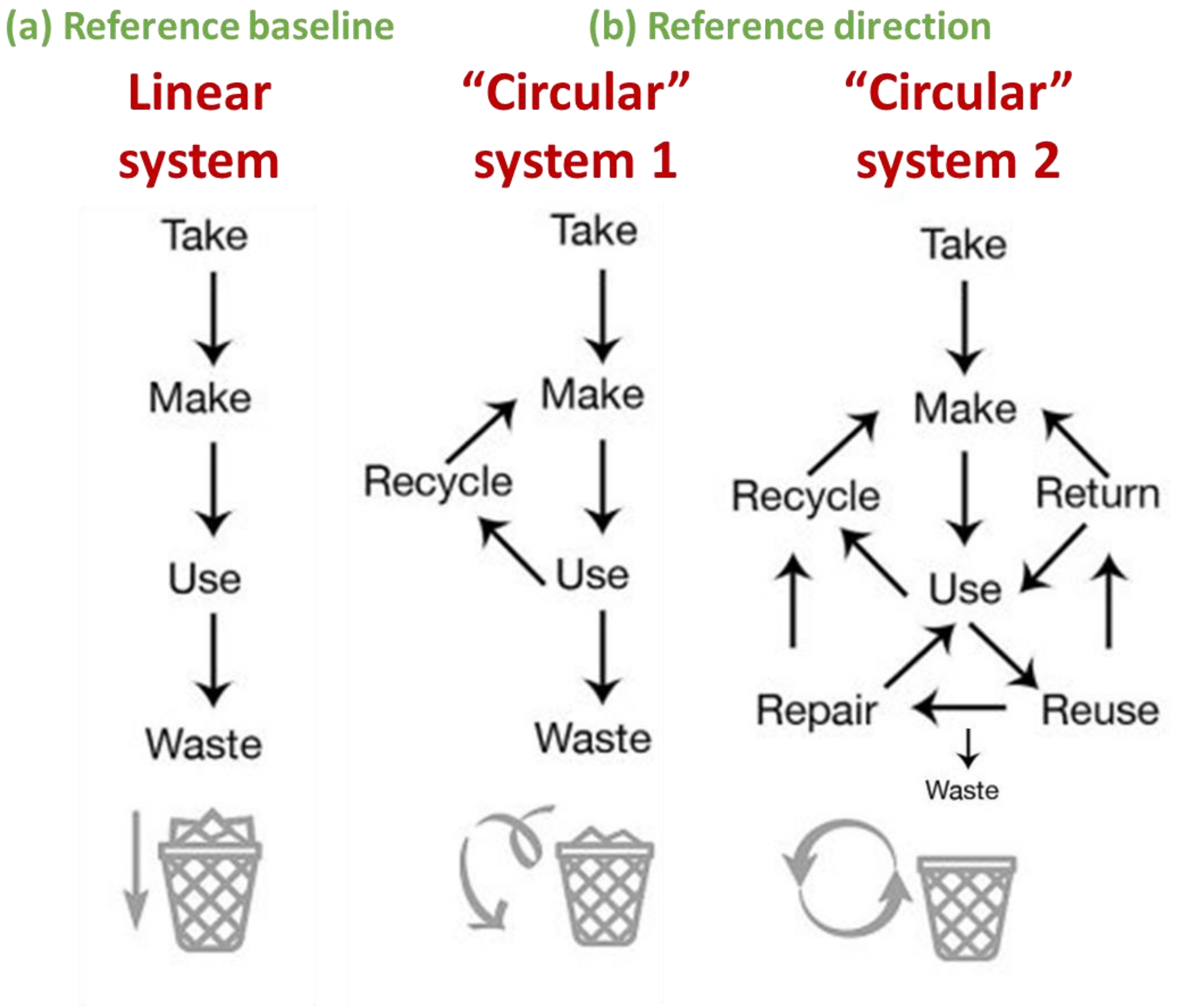
Scale


Increasing impact
Macro
Meso
Micro
• City, nation(s), global
• Sector, industrial park, neighbourhood
• Product, company, individual
Increasing scope

Beta index

$$\beta = 1 - \frac{life\ cycle\ emissions\ of\ circular\ system}{life\ cycle\ emissions\ of\ linear\ system}$$

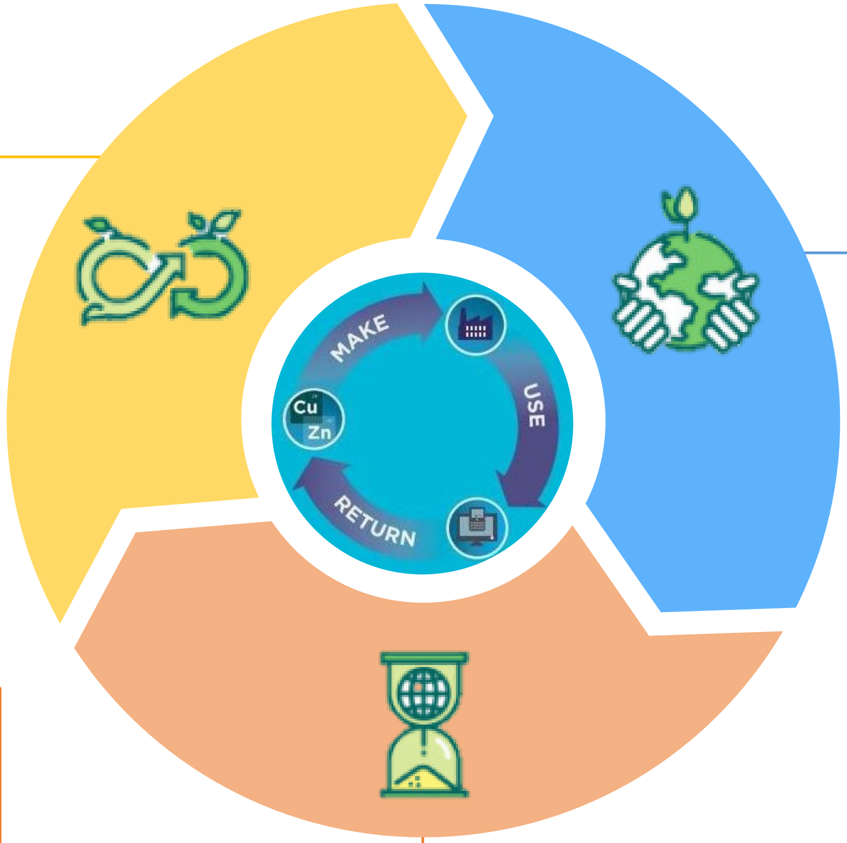
- Defining the reference point and reference direction.
- From energy to environmental impact (e.g. carbon emissions).
- Life cycle approach (environmental trade offs and burden shifting).
- Service approach (mobility, shelter/housing, nutrition, etc.)



Framework: Low carbon and circular economy

Keep products and materials in use

EOL recovery, reuse and repurposing



Phase out waste and pollution

Long-term decarbonisation

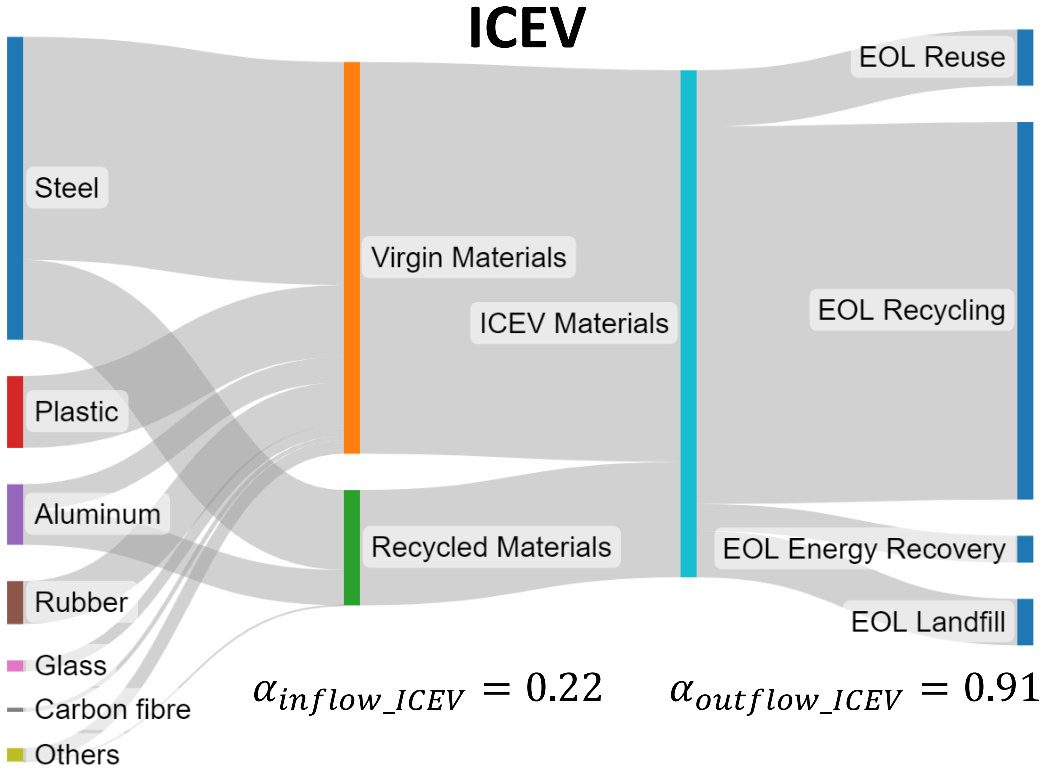
Decouple resource use to allow regeneration of natural systems

Service efficiency

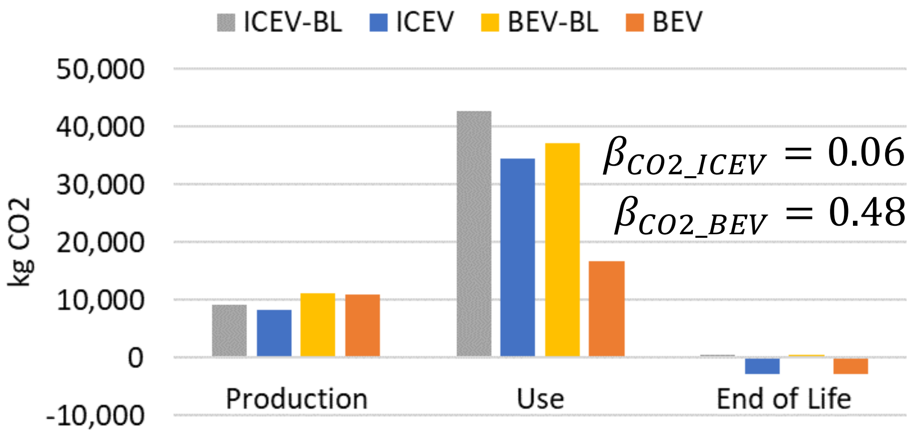
Bridging service systems, circularity and decarbonisation

Adaptation of Circular Economy Principles from EMF (2013)

CI of current car-based mobility

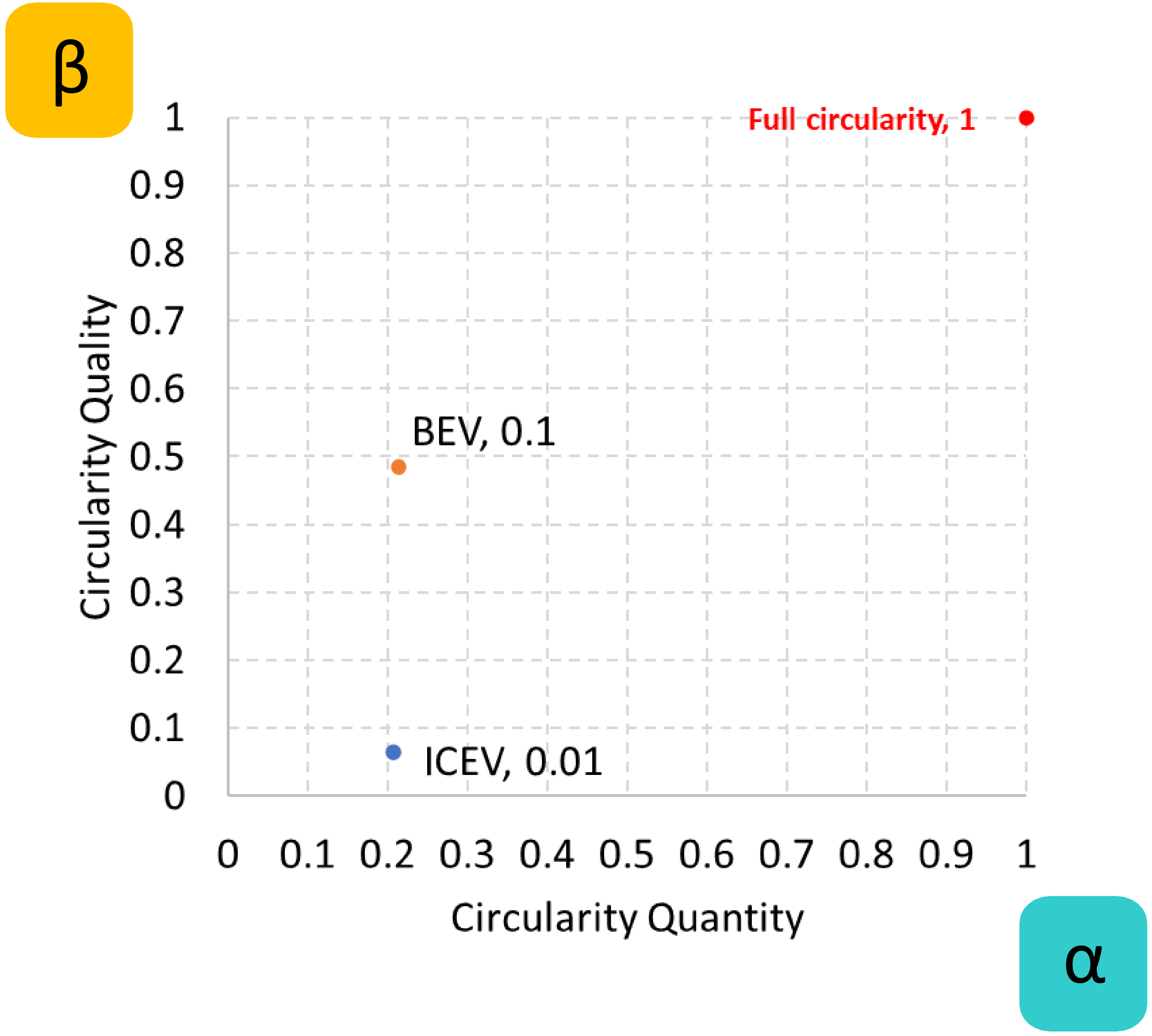


$\alpha_{inflow\_ICEV} = 0.22$ $\alpha_{outflow\_ICEV} = 0.91$



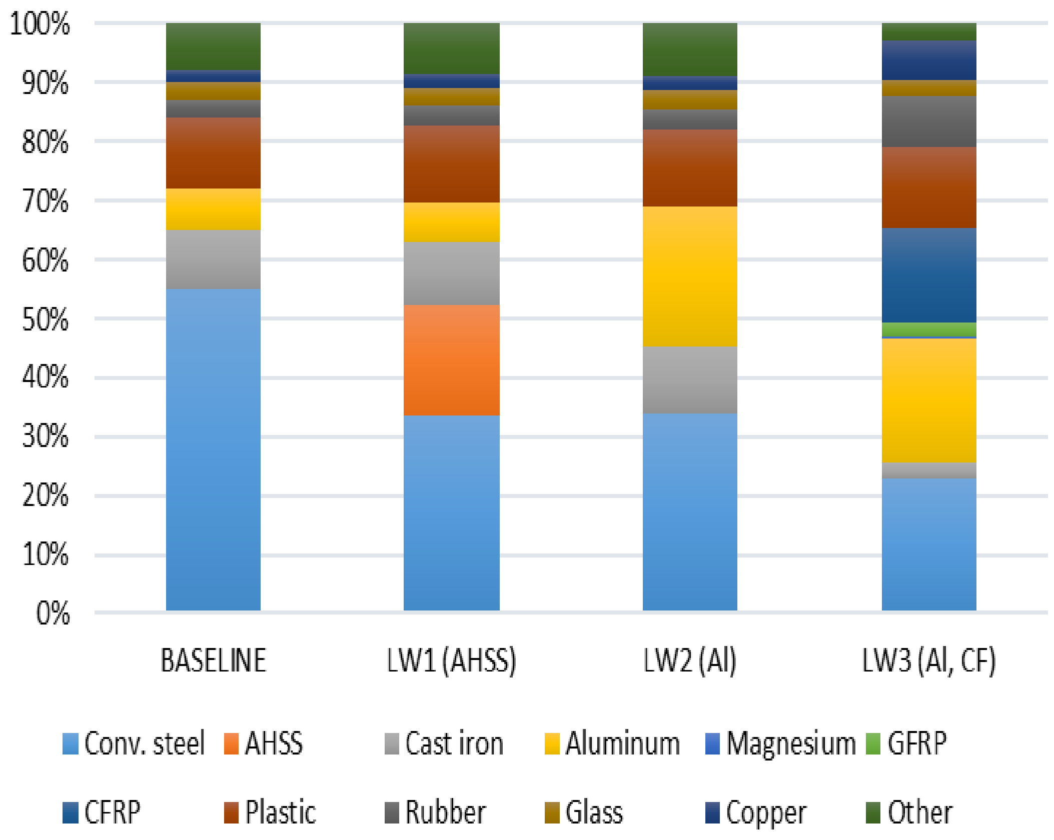
$\beta_{CO2\_ICEV} = 0.06$

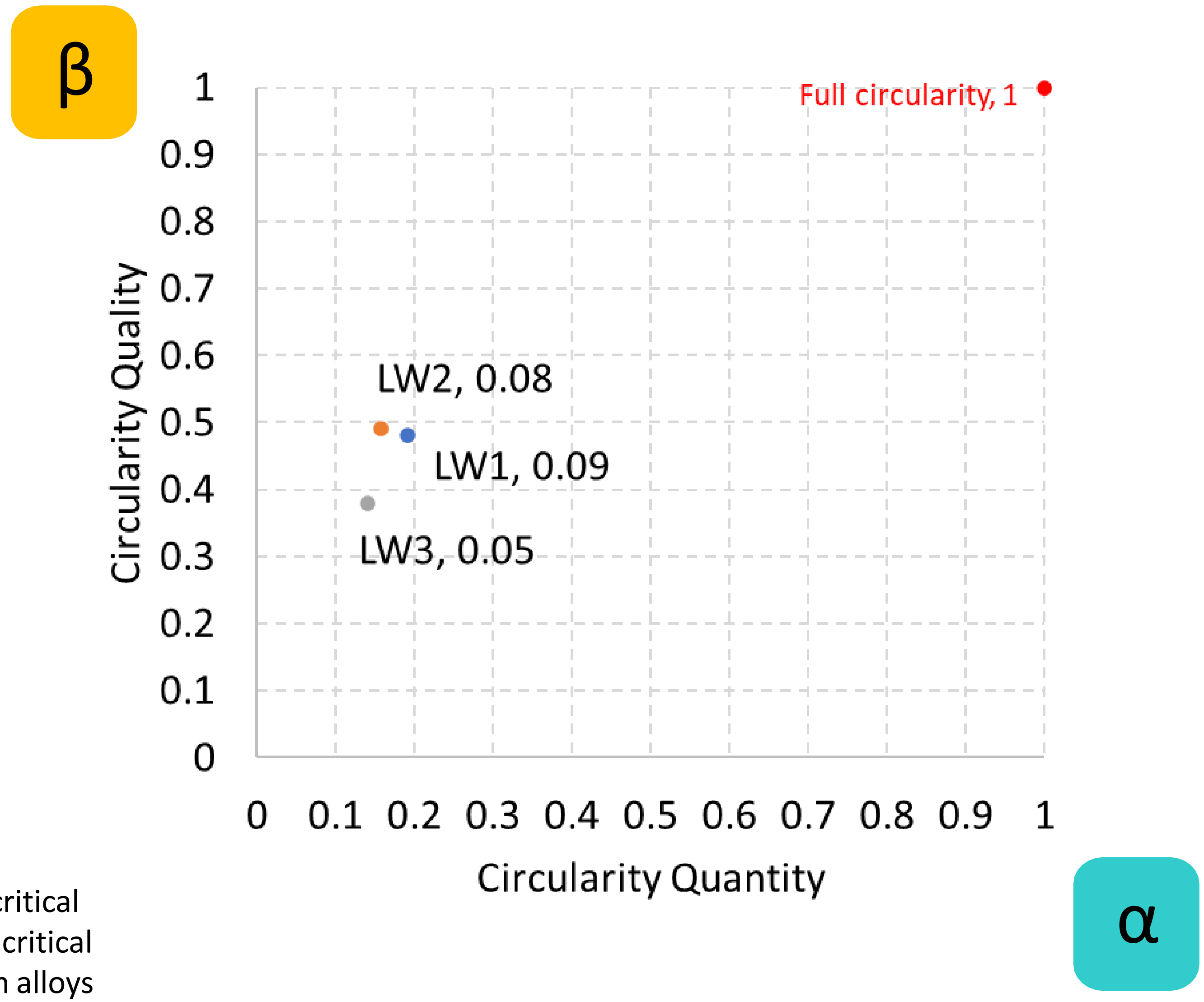
$\beta_{CO2\_BEV} = 0.48$



UK data from Carmona et al (2021) and Rodrigues et al (2023)

CI of lightweighting





LW1: advanced high strength steel (AHSS)
LW2: Aluminium (Al)
LW3: Aluminium and carbon fibre (CF)

Not considered critical but they require critical elements to form alloys & composites

Criticality considerations from Bobba et al (2020)

CI of low energy and material demand

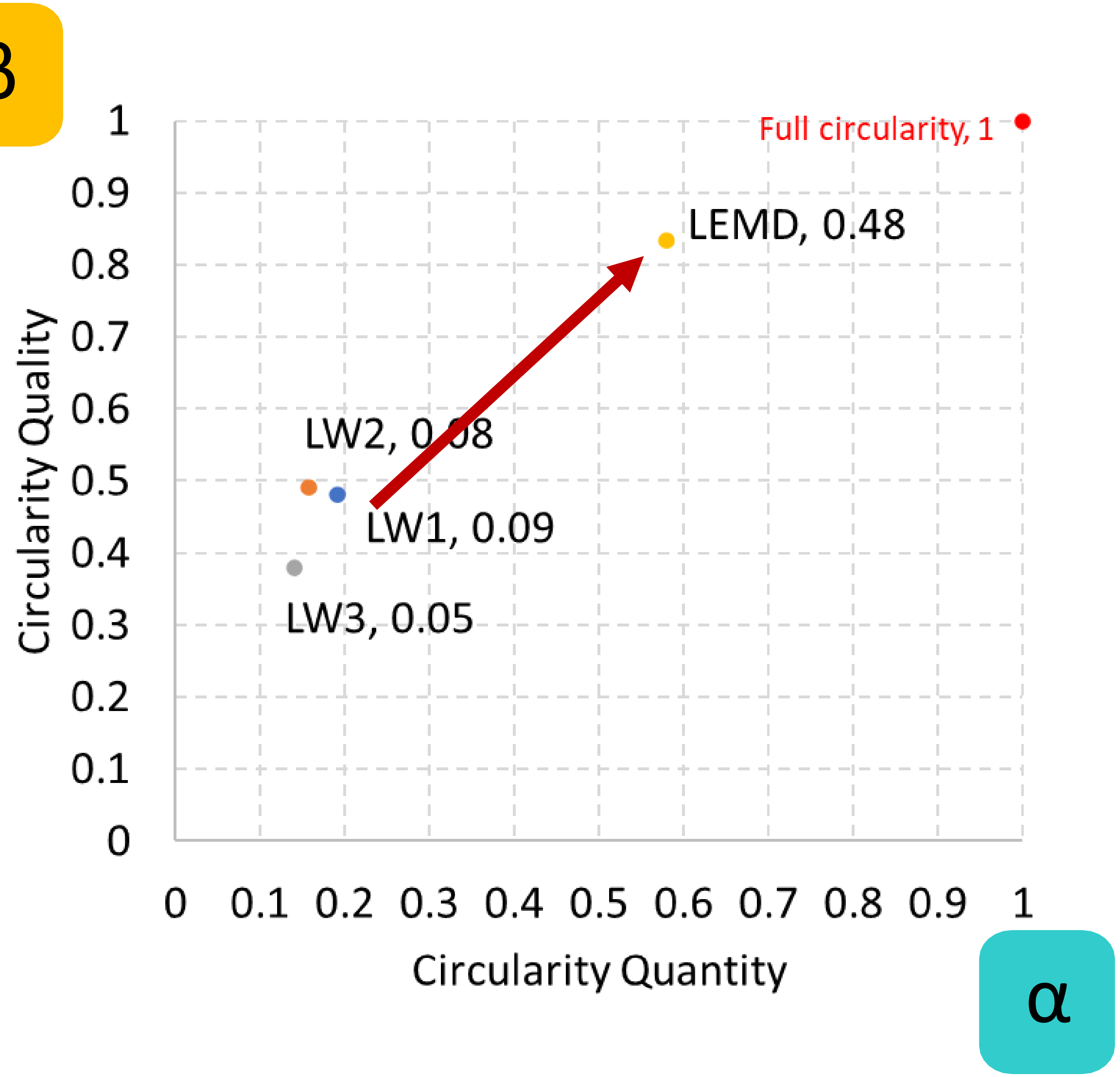
UNIVERSITY OF CAMBRIDGE
resource efficiency collective

nature energy | ANALYSIS
https://doi.org/10.1038/s41560-018-0172-6

A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies

Low Energy and Material Demand (LEMD):

- Increase industry's resource efficiency:
  - dematerialisation by 89%
  - material efficiency by 72% .
- Vehicle fuel efficiency reaches 0.7 MJ/pkm (50%)
- Stock efficiency increases to 25,383 pkm/veh (40%):
  - Shared mobility, MaaS
  - Compact/transport oriented urbanisation



LEMD scenario assumptions from Grubler et al (2018)

Final thoughts

Some guiding questions to ask when assessing CE strategies include:

- What could be the theoretical benchmark for the CE?
- What other scenario narratives and strategies could be proposed?
- What are the implications for other transport modes (bus, train) and infrastructure?
- What is the acceptance of such indicators by industry?
- To what extent reducing material demand decreases resource criticality?

Thank you!

Gabriel Carmona

lgc29@cam.ac.uk

This research receives the financial support of the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 101027892 and the Fonds de la Recherche Scientifique – FNRS under Grant No CR40001149.

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Carmona, L. G., Whiting, K., & Cullen, J. (2022). A stock-flow-service nexus vision of the low carbon economy. Energy Reports, 8, 565-575.

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Rodrigues, B., Carmona, L.G., Whiting, K., & Sousa, T. (2022). Resource efficiency for UK cars from 1960 to 2015: From stocks and flows to service provision. Environmental Development, 41, 100676.