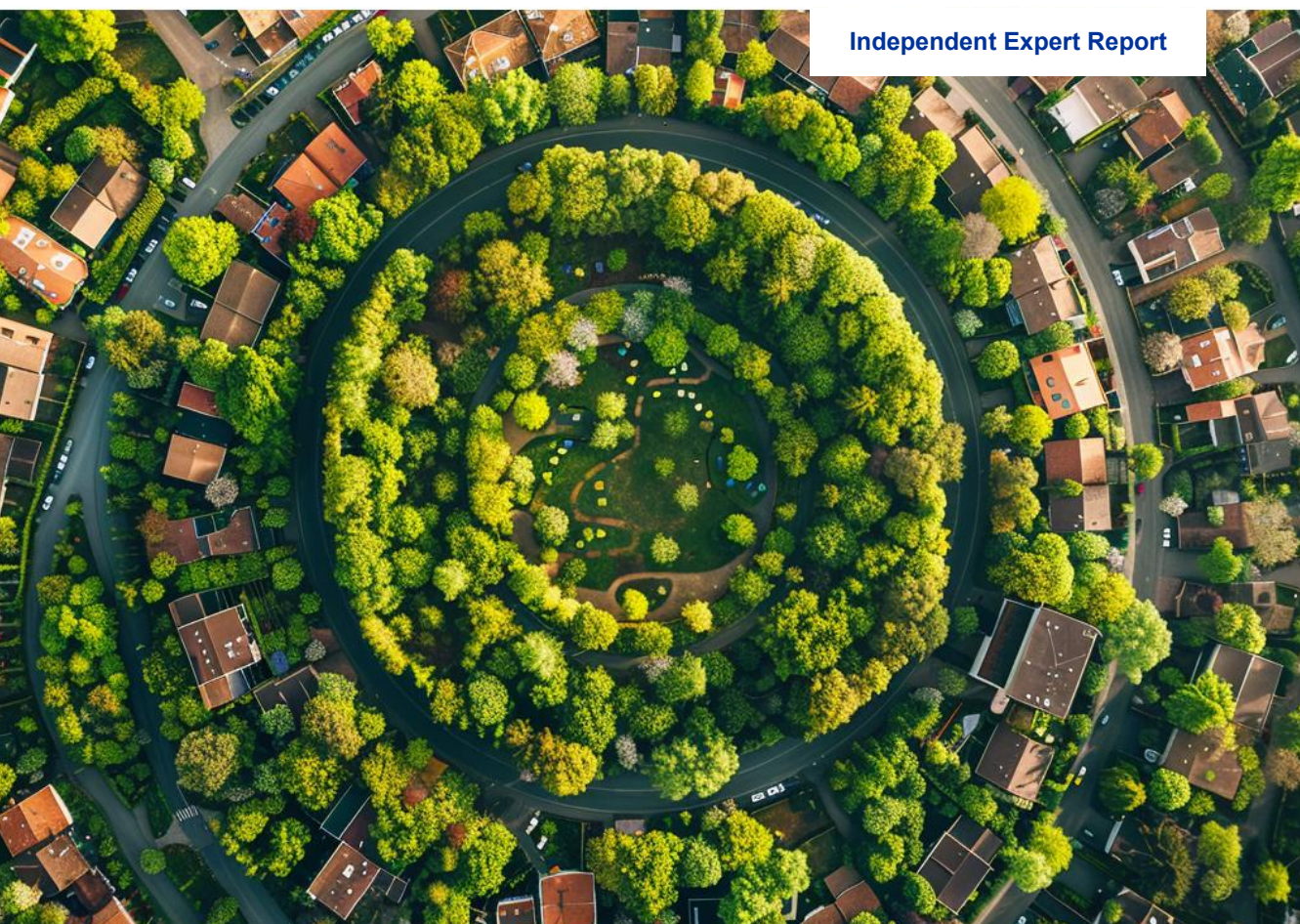


Research & Innovation projects supporting the Circular Economy Act

Focus Area: Waste electric and electronic equipment and
recovery of critical raw materials



Independent Expert Report

Research & Innovation projects supporting the Circular Economy Act
Focus area: Waste electric and electronic equipment and recovery of critical raw materials

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Focus area: Waste electric and electronic equipment and
recovery of critical raw materials

Adj. Prof. Dr. Ajay B. Patil

Contents

Executive Summary	4
Glossary	6
1. Scope and policy relevance	7
1.1. Problem definition	7
1.2. Link to CE Act objectives and related EU legislation.....	9
2. Methodology and analytical framework	10
2.1. Analytical logic	10
2.2. Sources and evidence.....	10
2.3. Project portfolio attribution and assessment method	10
3. R&I Project Portfolio scope & overview.....	11
3.1. Portfolio overview	11
3.2. Portfolio characterisation	13
3.3. Key challenges addressed.....	13
4. Outcomes and impacts across the portfolio	13
4.1. Tangible results and knowledge generated.....	13
4.2. Impact assessment	20
5. Success and failure analysis	21
5.1. Enabling factors	21
5.2. Hindering factors.....	22
5.3. Common features of successful solutions.....	23
6. Upscaling, replication and transferability	24
7. Regulatory insights for the Circular Economy Act	26
7.1. Regulatory gaps identified.....	26
7.2. Legislative and administrative burdens.....	27

8.	Policy recommendations.....	27
8.1.	Prioritisation logic.....	27
8.2.	Prioritised recommendations	28
9.	Conclusions	30
10.	Annexes	31
10.1.	Annex I: Full Project Portfolio Matrix.....	31
10.2.	Annex II: Individual Project Analysis Insights.....	31

Executive Summary

The Circular Economy Act (CE Act) addresses key intervention areas, including waste electrical and electronic equipment (WEEE) and the recovery of critical raw materials (CRMs).

An analysis of 23 research and innovation (R&I) projects – covering WEEE, CRMs, batteries, photovoltaic (PV) panels, energy-intensive industries, advanced manufacturing, and digital circular solutions – revealed that these were multi-stakeholder consortium initiatives, focusing on technology development, legislative compliance, validation, and SME engagement.

Key findings across the portfolio:

- Successes: Effective solutions integrated reverse supply chains, reliable feedstock availability, appropriate technologies, and value chain frameworks, enabling multi-step circular value creation and utilisation.
- Challenges: Inconsistent feedstock quality, waste losses in the value chain, insufficient recognition of tangible circular economy benefits by industry stakeholders, conflicting waste management and circularity regulations, a disposal-centric value chain, and a disconnect between market demand for circular resources and EU-based manufacturing and handling processes.

Top policy recommendations and estimated EU-wide impacts:

Expanding WEEE recycling to include a broad range of feedstocks (e.g., battery waste, PV panels, industrial slag, and digital solutions) presents significant untapped potential. However, this requires coordinated action under the CE Act, EU Green Deal, Battery 2030+ Directive, and Net Zero Industry Act, alongside a manufacturing-focused framework addressing waste-resource interfaces, value allocation, and carbon footprint management. State-supported or subsidised mechanisms could enhance EU competitiveness and sustainability, ensuring measurable benefits from the CE Act.

The 23 analysed projects demonstrated strong potential in technology, manufacturing, business, and sustainability, which could be leveraged through the CE Act in synergy with the CRM Act and EU Green Deal initiatives.

WEEE recycling technologies are being developed based on strategic and demand-driven considerations, rather than traditional waste management approaches.

The circular economy (CE) field in the EU has evolved from initial scoping and statistical studies into complex engineering processes, value chain optimisation, regulatory frameworks, and behavioural adaptations. These elements will be critical in shaping future CE regulations, aligning with the Critical Raw Materials Act and waste management policies at both EU and UN levels.

As an advanced economy with strong technological adoption, the EU is an ideal market for developing reverse supply chains, innovative processes, and CE expertise – provided there is strategic alignment and profitability. Public funding mechanisms could support new CE processes and product development (even if initially cost-negative), enhancing overall sustainability and making Europe a more attractive investment hub.

However, a lack of coherence and understanding persists, leading to insufficient large-scale engineering processes. Recent EU projects have significantly advanced CE knowledge, with some providing clear pathways for expansion, wealth creation, and business opportunities.

Urban mining through WEEE recycling could effectively drive CRM circularity and criticality, but success depends on feedstock availability, technical and business process capacity, and knowledge dissemination. The EU must align reverse supply chains with supportive legal

frameworks to facilitate feedstock and value exchange, ensuring the viability of circular economy models (see Figure 1).

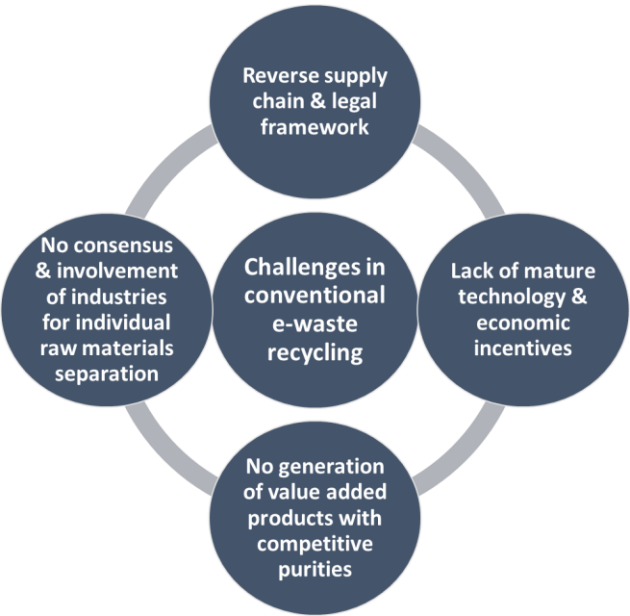


Figure 1: Challenges with conventional recycling of e-wastes¹

¹ Circ.Econ.Sust. 3, 1127–1140 (2023). <https://doi.org/10.1007/s43615-022-00204-7>

Glossary

CE: Circular economy

CRM: Critical Raw Materials

DPP: Digital product passport

EV: Electric Vehicle

EoL: End-of-Life

KCC: Key CRM containing component

KCE: Key CRM containing equipment

NdFeB: Neodymium Iron Boron magnets

PCBs: Printed circuit boards

PGM: Precious group metals

PV: Photovoltaics

REE: Rare earth elements

WEEE: Waste electronics and electrical equipment

PET: Polyethylene terephthalate

LCA: Life cycle assessment

PCBA: Printed circuit board assemblies

Front end market: Primary resources-based production without additional expenses or operational expenses related to waste management in comparison to the non-EU companies

1. Scope and policy relevance

1.1. Problem definition

With the advent of smart, green and hybrid electronic technologies, human life has reached another tech revolution. As a by-product of this, humans have generated 62 million tonnes (t) of e-waste by 2022 with 6.1 kg/person waste generation. Every day, 416,000 mobile devices and 142,000 computers are being discarded globally. This is expected to rise at 82 million t by 2030. Estimated raw material loss with this e-waste is equivalent to 55 million Euros in 2016 with only 20% recycling rate.²

However, the established recycling nowadays mainly just concern dismantling and crushing the e-waste into smaller volumes. Most of the by-products (except plastic, glass and ferrous metals) and secondary wastes are landfilled. Instead, by following the principles of circular economy, we can assure sustainability of raw materials resources and that of the dependent technologies. Recycling of e-waste could save 658 million t of greenhouse gas per 10⁵t of e-waste. Following the Minamata and Basel conventions and the Paris agreement, in most of the EU countries, it is mandatory to process the generated e-waste within the state boundary and decrease the landfilling (**Figure 2**).³

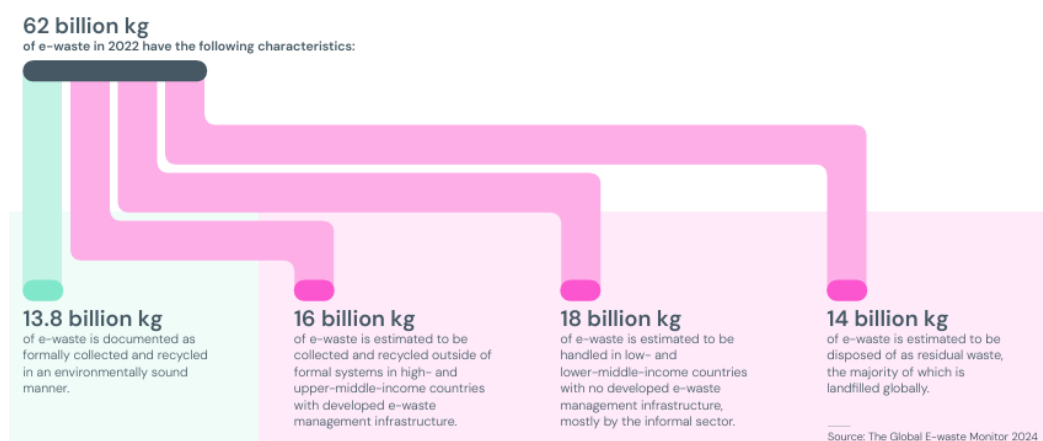


Figure 2: Fractions of informal collection and loss of e-waste (credits: global e-waste monitor and WEEE Forum) i.e. 62 million tonnes (Mt) of e-waste was produced in 2022, Up 82% from 2010; On track to rise another 32%, to 82 million tonnes, in 2030.⁴

In 2022, the e-waste generated globally contained 31 billion kg of metals, 17 billion kg of plastics and 14 billion kg of other materials (minerals, glass, composite materials, etc.).⁵ Most of the IT companies and electronics suppliers are subject to extended producer responsibility for the appliances they sell.⁵ With the newly adopted legislations, this implies that computer and smart

² The Global E-waste Monitor 2024

³ <https://www.basel.int/>

⁴ <https://weee-forum.org/key-figures/>

⁵ Refer to intervention area EPR

phone manufacturing companies must provide means to customers through which they can return the e-waste for recycling at the end of life. Therefore, the IT industries in the EU (and beyond) need mature and economic processes to keep these expenses lower, so that they can be competitive in front-end markets (i.e. primary resources-based production without additional expenses or operational expenses related to waste management in comparison to the non-EU companies). In addition, the conventional recyclers and dismantlers cannot ease this situation by recycling only glass, plastics and ferrous substances and leaving behind precious and critical raw materials in landfills.⁶

Overall adoption of the good practices in e-waste management by society is dependent on the self-sustainability and economic viability or better incentives for recycling activities. The focus of the upcoming CE act should be to enable and stimulate the creation of such value chains in the EU. Another major focus of the CE Act should be to generate a conducive framework along with the CRM Act, to enable the recovery technology for rare earths (RE) as raw materials from IT industry e-wastes. However, economically viable technology to achieve the individual purities of such CRMs from e-waste by urban mining does not exist up to date. Therefore, to make the EU self-sustainable with supply of such materials, it is indispensable to cater to the ever-growing technology needs involved.

Major process difficulties in the production or recycling of such raw materials are due to challenging separations of the REs from each other and their diluted content in e-waste streams. The diversity and inhomogeneity of waste materials make their recovery challenging, and once mixed with other raw materials, their separation is most difficult. Therefore, if not produced in the front-end industry itself, such recycled materials have a rather low market value that makes a successful implementation of a recycling technology very challenging as demonstrated in projects CEWaste, DICE and CloseWEEE. Therefore, it is necessary to develop robust separation technologies for achieving high-grade secondary raw materials as well as components from e-waste. With sustainablySMART project, the entire range from technology development to the business application is covered (targeted Technology Readiness Level (TRL) from 3-7 until technology development, demonstration, process economics and market research).

WEEE matters most because of its accessible urban mining potential, which could be unlocked by the legal intervention like a successful implementation of CE act. It would give a solution to one of the largest growing and the most complex waste feed as evident from the target feeds in the assessed projects. The complexity could be understood by organic and inorganic nature of components also in mineral and metallic forms with diverse feedstock types such as WEEE (Gadgets and IoTs), PVs/solar panels, battery wastes, composites and metal alloys, water resources, wearables and diagnostic devices, etc. Also, the key interventions required for the deployment of successful CE strategies includes digital marketplace, digital product passport and information and circular business model developments, as targeted by the projects CircThread, C-Servees, Treasure and Sophia. This needs to be complemented by policy, standardisation and legislative integration and adaptations with technology pilot demonstration, to see e-waste as a resource for urban mining (CEWaste, DICE, FREE4LIB, ENCIRCLE and CircThread).

⁶ CRM Act EU 2023

1.2. Link to CE Act objectives and related EU legislation

The key and quality context here would be the objectives of the CE Act and EU legislations like the EU CRM Act, EU Net Zero Industry Act, EU Green Deal, Battery 2030+ Strategy as well as to the United Nations Sustainable Development Goals.

- Responsible consumption and production of resources from primary and secondary origin.⁷
- Converting the EU value chains and businesses and if possible, way of life from linear to circular ways to create sustainable and smart cities.⁸
- In terms of the WEEE, providing integrated waste and resources management solutions to the complex feedstocks management.
- Harnessing the new opportunity of business in manufacturing, value chain, regulations, use of sustainable materials in advanced manufacturing and overall carbon footprint management along with resources sovereignty of the EU.⁸
- Strong integration of the CE Act and the CRM Act in terms of new reverse supply chain and front-end market generation for metals, minerals and nutrients in the European products.^{1,8}
- Generation of new know-how, supply chains (forward and reverse), integration of primary production, waste management and the CE to achieve necessary scale of businesses/feedstock in the EU along with necessary businesses and revenue pipeline. Consequently, the EU has the opportunity to convert such revenue into more jobs, and improve its capacity to invest in further R&D to generate next generation processes and feeds on trace content and traceability levels.³



Figure 3: Generation of strategic know-how for the circular economy of less harnessed feeds and process solutions³

⁷ UN Sustainable Development Goals

⁸ ENCIRCLE strategy to convert linear to circular models

2. Methodology and analytical framework

2.1. Analytical logic

Present invention has expanded the logic to understand what types of feeds are available in terms of the WEEE categories, and what types of processes, technologies and value chains are available. This has been further extrapolated to feasible or circular direction enablers. The identification of scalable and strategic solutions is key priority and also in terms of feedstock and complexity the priority was given to WEEE and they were compared with different projects in terms of batteries, photovoltaics/ PV, advanced materials, energy intensive processes as well as CE and digital solutions. Project Melodiser was included to have water and nutrient circular economy represented.

2.2. Sources and evidence

Key information and evidence were sourced primarily from the SYGMA, CORDIS and project / project partners websites, scientific literature or previous or follow up projects or companies of different partners. Other literature was used such as thesis databases, websites of global e-waste monitor, International Resources Panel, the SCREEN project, and carbon credit compensation agencies/authorities. Some insights have been added, reflected or corelated by the reviewer based on his involvement in the assessment of CRM Act projects in terms of technology, scalability, business and sustainability benchmarking without going into confidential details but only following the analytical logic and resources. Some of them are mentioned below:

Resources and link for the CE act evaluations

<https://www.resourcepanel.org/the-panel>

<https://screen.eu/>

<https://ewastemonitor.info/the-global-e-waste-monitor-2024/>

<https://jojneconnect.com/>

<https://mettop.com/en/products/5>

<https://www.goldstandard.org/consultations/consolidated-methodology-for-recovery-and-recycling-materials-from-solid-waste>

2.3. Project portfolio attribution and assessment method

RTD has kindly provided the access to the total of 33 projects. Reviewer requested access to 5 more projects to have granularity of WEEE topic as a priority. E.g. composites as well as digital or LCA based aspects were balanced with that of technology and business model demonstration. Finally, the decision was taken to review the 23 projects in total focusing on different urban secondary feeds, advanced manufacturing and CE solutions or validations. The assessment method involved the priorities of feedstock i.e. WEEE, PVs, batteries and other market / business portfolios such as energy intensive industries, advanced manufacturing, CE and digital solutions based on the scope discussed in consensus with RTD team.

Reviewer gave specific attention to the methods in terms of engineering and separations: sensing and digitalisation, sorting and mechanical processing, separations and purifications, value chain-based interventions, and recovery output in terms of the polymers, metals and composite mixtures.

3. R&I Project Portfolio scope & overview

3.1. Portfolio overview

Scope	No.	ID	Project	Budget in M Euros	Scope
CRMs WEEE	1	641747	CloseWEEE	5.92	WEEE and battery recycling
	2	781060	Metallica	0.07	WEEE recycling for Cu, Au & PGM metals
	3	820859	CEwaste	1.92	Voluntary certification scheme for waste treatment
	4	680604	sustainably SMART	7	Sustainable Smart Mobile Devices Lifecycles through Advanced Re-design, Reliability, and Re-use and Remanufacturing Technologies
	5	958302	PEACOC	11.2	Pre-commercial pilot for the efficient recovery of Precious Metals from European end-of-life resources with novel low-cost technologies
PV	6	101122277	APOLLO	5.33	Sorting, recycling and testing technologies Ingot for Si and integrated Al and Ag recycling and DPP
	7	101122298	QUASAR	7.12	Heading towards a circular economy for the solar PV industry/integrated processes and sorting decision making
BAT	8	101069685	RHINOCEROS	8.94	Validation, dismantling metals and graphite recovery
	9	101069789	RELIEF	6	Li recovery from mine waste, residue slags, brine solutions, relithiation agent and other products
	10	101104204	REINFORCE	5	Battery recycling business modelling process validation

	11	101069890	FREE4LIB	9.28	Battery recycling and production/battery passport/robotics technology
	12	101058124	ENICON	6.02	Battery metal production from laterite ores
Energy Int.	13	101058089	EuReComp	8.903	large composite components recycling
	14	101058694	HIYIELD	5.47	Steel recycling / increased yield with low environmental impact
	15	101138747	RecAL	10.65	Recycling Technologies for Circular Aluminium
Ad Manu	16	101058636	ABSolEU	8.08	ABS (Acrylonitrile Butadiene Styrene) polymer recycling
	17	101091915	MEloDISER	8.26	water circular economy with sustainable membranes with biobased and cheaper ingredients
	18	101178230	ENCIRCLE	5.99	digital twin and circular models' marketplace for circular economy business opportunities
CE and Digital	19	101182162	SOPHIA	6	Human and robotics environment interface for CE applications
	20	101003587	TREASURE	4	Recycling and circular economy of auto components and digital tools
	21	776714	C-SERVEES	7.94	Circular business models for electronics and electrical sector
	22	958448	CircThread	9.88	Building the Digital Thread for Circular Economy Product, Resource & Service Management
	23	101060184	DICE	9.21	E-waste from health industry/logistics and business model aspects
Total				158.183	

3.2. Portfolio characterisation

The intervention area is focused on WEEE processing and recycling. The projects CloseWEEE, Metallica, CEwaste, sustainablySMART, PEACOC had key focus on the WEEE, batteries and PV recycling using physicochemical processes and validation methodologies. Projects APOLLO and QUASAR focused on PV recycling. There were five projects each on the battery/battery materials, circular economy and digital solutions (RHINOCEROS, RELIEF, REINFORCE, FREE4LIB and ENICON). Three projects were dedicated to energy intensive industries such as large composites recycling (EuReComp), sustainable steel recycling (HiYield), and circular aluminium and aluminium alloys (RecAL). Projects ABsolEU zoomed into ABS polymer recycling from LEGO, ENCIRCLE aims to digitise and circularise heavy industries such as zinc coating/production. Project Melodiser focuses on the membrane distillation technology for water and nutrients recovery. Together, these three projects address the scope of energy intensive industries. The final category was of circular and digital solutions (5 projects). Here, SOPHIA developed human and robotics interfaces, TREASURE focused on CE for car components with digital tools, C-SERVEES on CE business models for the electronics and electrical appliances-based waste streams. CircThread aimed at building information threads for resources and service management, and DICE investigated the health industry related wastes reverse logistics and product passports.

3.3. Key challenges addressed

The key challenges addressed by the current scoping study were identifying right feedstock for circular economy technology and the implementation of key circular economy processes. That involves process flowsheet development for detailed characterisation, mechano-chemical processing, possible process integration and scale up, and fitting into boundary conditions for the regulatory, financial, life cycle assessments and social and behavioural barriers. The key challenge addressed was navigating through the complexity of such WEEE to find the right manufacturing and CE process and to address the polymers and metal recovery.^{9,10}

4. Outcomes and impacts across the portfolio

4.1. Tangible results and knowledge generated

Following technologies and priority feedstock has been demonstrated and validated. Details could be found in Annex on project specific datasets.

Sensing and digitalisation

The project CloseWEEE integrated different interlinked research and innovation areas for an improved, resource-efficient recycling of polymer materials and critical raw materials from electrical and electronic equipment (EEE): (1) Efficient and effective disassembly of EEE is key for high quality material fractions, separation of materials but also for reuse of components and parts. Appropriate & eco-friendly upgrading of recovered materials to second-life applications such as alternative flame-retardant systems and their impact on processing, fire, thermal and mechanical properties of recovered plastic compounds have been studied. High quality black plastic like ABS and high gloss compound has been produced with a mixture of virgin materials, recycled materials, suitable impact modifiers and thermal stabilisers. Different kind of analytics

⁹CEwaste requirements for improving CRM recycling from WEEE and waste batteries, pages 70-72

¹⁰Methodology - consolidated methodology for recovery and recycling of materials from Solid wastes, GOLD Standard, Geneva

methods such as XRD, XRT, NIR i.e. X-ray and infra-red based technologies were studied and demonstrated on the conveyer-based plants.¹¹

Sorting and mechanical processing

The processes for increasing range and yields of recovered materials from WEEE streams, increasing energy efficiency of recycling processes, reduced environmental footprint measured by qualitative and quantitative indicators: Recovery efficiencies of PC-ABS and ABS fractions, as well as the target additives and minerals from brominated plastic fractions, and End-of-Life (EoL) vehicles, respectively have been established.^{12, 13}

Economic and environmental validation of the products and processes developed in CloseWEEE. An initial evaluation of the capital and operational expenditures was made for the plastic recovery fraction. Initial results on the Environmental impacts of PC-ABS and ABS recovery were obtained and analysed and efforts were made to scale it up, though the TRLs of 4-5 could be reached for most of the technologies.¹³

Separations and purifications

One of the success stories in separation and purification has been provided by the Metop technology called urbanGold. It is now available at the TRL 7-9 and with customised plants and consulting options by the Austrian consulting company. The focus is on hydro- and pyrometallurgical options for copper (Cu) and gold (Au) recovery (via project Metallica).¹³ It was short one partner SME project. It has given quite tangible results for gold and precious metals recycling from the WEEE and resulted in spin-off-based implementation afterwards. This technology has reached TRL 7-8 and is commercialised at the moment.

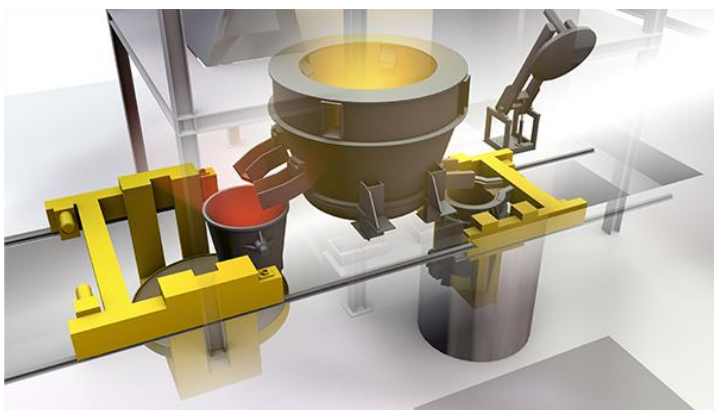


Figure 4: Henry smelter developed for the precious metals recycling from WEEE.

In CloseWEEE, thorough process flowsheet has been developed for the battery or black mass recycling as shown in Figure 5. This has integrated recovery of CRMs like lithium (Li), cobalt (Co), nickel (Ni), Graphite and copper (Cu) powder and process model has been developed for the 2000t scale.¹⁴

¹¹ CloseWEEE-WP2-DEL-D2.4-GAI-20170601.doc, page 7

¹² ABSolEU Deliverable 1.4: Report on wABS characterisation, page 6

¹³ Metallica, <https://mettop.com/en/products/5>

¹⁴ CloseWEEE-WP4-DEL-D4.5-AC-20171206-v01.doc

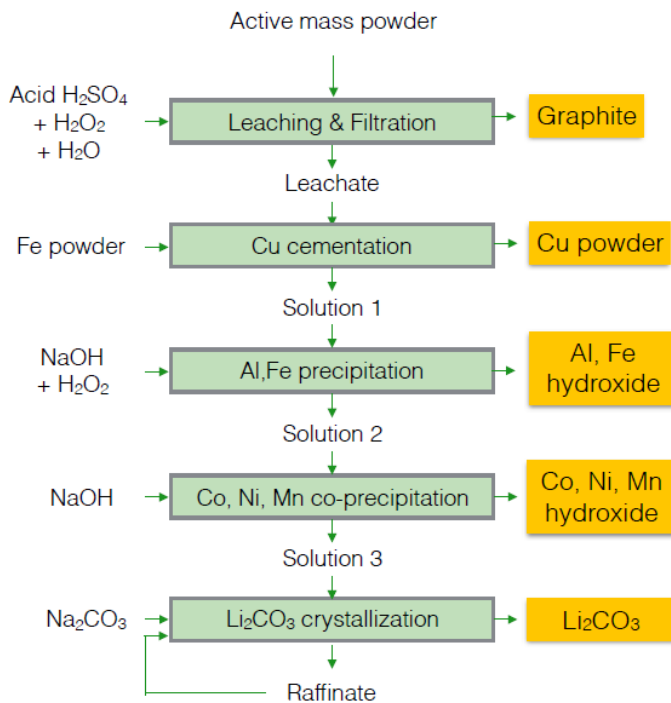


Figure 5: battery recycling process combining the metals productions with different applications and battery manufacturing for which the CloseWEEE partner Accurec have done the process model development up to 2000 tonnes.¹⁴

Value chain-based interventions

The reviewed project portfolio clearly demonstrates that the polymers/plastics, water/nutrients, battery, photovoltaics and energy systems, WEEE, auto and mobility components needs to be harvested. The extended producer responsibility-based aspects and sometimes incentivised processing programmes have helped a lot. For instance, in the PV industries as well as in the WEEE recycling, recollection could be studied as a classic case enabled by the EPR regulation/ VAT exemption which could be further used to strengthen the CE value chains.^{11,15,16} CEwaste also recommended the overcoming of barriers as well as avoiding the contradicting effects of CE business models. For example, incorporation of resources information with electronics by making 26 CENELEC standard¹⁷ binding for publishing standards in the electrotechnical engineering field.¹⁵ DICE also emphasised the paradox of e.g. planned obsolescence in circular business models whereby customers are forced to buy new products. This leads to achieving a circular business model on behalf of a circular ecosystem by exclusively dealing with specialised components and not promoting overall CE, circularity for circularity's sake e.g. with renting models more polluting due to transportation costs.^{16b}

Polymers separation: Ethyl acetate as solvent to set a benchmark for future up-scaled experiments. An alternative solvent has been achieved for the ABS recycling and recovery purpose. Also tracing based approach has been developed. Unique fingerprinting models can be translated into the existing ISO standard 10303. It has been developed (Via ABSolEU) Jotne

¹⁵CEwaste: D 4.4- Roadmap for the long-term sustainability of the scheme, page 33

¹⁶DICE: Resources, Conservation & Recycling p. 208 (2024) 107719, ^{16b} CE paradox policy paper

¹⁷https://docbox.etsi.org/workshop/2012/201206_eeworkshop/02_STANDARDIZATION_INITIATIVES/IEC_CEN_ELEC_Legnani.pdf

and TNO has started creating a unique fingerprint model for ABS. Its major technical specification is to differentiate between different ABS types.¹⁸

In CloseWEEE ABS recycling process has been achieved again using special solvent mixtures and has been now commercialised as the Creasolv process.

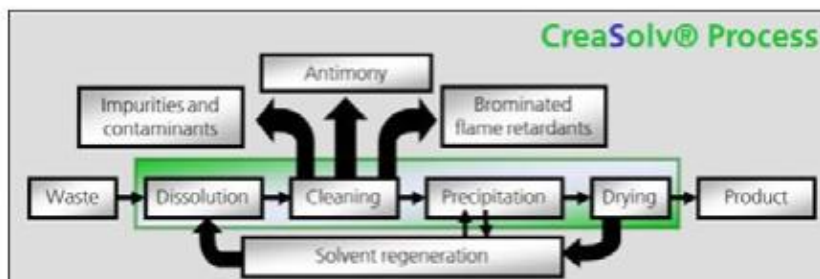


Figure 6: Creasolv process for polymer recovery.¹⁹

WEEE recycling process validations: The WEEE Directive currently sets mandatory recycling targets that are based on a percentage of the material recovered from the total mass of the product. The attainment of the recycling target is calculated via dividing the weight of the WEEE that enters the recovery facility (after proper treatment) by the weight of all separately collected WEEE for each category (Annex V of the Directive), expressed as a percentage. The targets vary slightly across different WEEE categories, from 75 % to 85 %, generally with larger equipment having higher recovery targets. This choice is most likely due to the larger equipment (such as freezers, washing machines and musical equipment), which tend to be more homogenous in their material composition. However, as CRMs may constitute only 1 % of a device's weight or less, there is little incentive to recycle them unless they can be extracted easily (economically). As a consequence, there is almost no market drive for CRM recycling.

In addition, the recovery targets create specific demands for WEEE recycling technology and drive it down certain development paths. Hereby developers of recycling technologies are encouraged to think first and foremost on how to recycle the base metals in large amounts in order to reach the mandatory targets, whilst giving no incentive to focus on the valuable materials of low concentrations which also may be difficult to extract. Flat recycling rates do not take into account the properties of a poly-substance/metallic waste stream that contain wide plethora of materials that have different environmental, economic and technological impacts.²⁰

Good cooperation between collectors, recyclers, auditors for the EPR schemes and also metal/plastic recovery entities Vs management or energy harvesting is needed; so that both economic as well as calorific value for WEEE could be harvested. Also, possible integration and correlation with primary mining and the Carbon crediting-based methodology is available and has to be thought of during CE Act drafting. It has been studied for the long-term viability of metal and polymers recovery from the WEEE.¹²

On cross functional levels, innovation has been demonstrated using sustainable materials like wood and recycling metal frames modules. It will make a change to the life cycle of mobile information and communication devices by **developing new product design approaches**

¹⁸ABSolEU: D 2.3a Intermediate Report on fingerprinting model for ABS, page 8

¹⁹<https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7829830>

²⁰EU Legislation on WEEE Recycling and its Failure to Close The Loop of Critical Raw Materials, Uni Helsinki, May 2020, Matias Penttila, page 53

(including enhanced end-of-life performance, re-use and re-manufacturing aspects; i.e. implementing “Design for a Circular Economy”).

This is relevant particularly for smartphones and tablet computers on the product and printed circuit board level, and by new re-/de-manufacturing processes with improved resource efficiency. Viable solutions include: (1) **enhanced sorting capabilities and speed** (optimised sorting efficiency), (2) **automated disassembly** of mobile IT devices for extraction of reusable components / modules, better material separation and depopulation of end-of-life devices (increase value creation out of discarded devices significantly to create an economic advantage over shredding processes), and (3) **high-quality performance testing** (batteries) and **rework** (semiconductors and modules) of reusable components/modules (creating a market push for reusable parts through enhanced availability for repair and cascade reuse).²¹

The cases of Fairphone and puzzlephone were validated in terms of modularity. In term of validated technology, one partner has assembled a pilot batch of 30 units of the D4R tablet to demonstrate the feasibility of such a small-scale production through partnering with other production environments (for wood and metal working respectively). The PCB of a voice recorder has been redesigned to accommodate four distinct modules, including a backbone board, a processor module, a power module, and an USB connector module being produced as prototypes and merged in a joint assembly. This was TRL 6 development.²¹

For the critical and precious metal recovery sophisticated electrochemical process has been demonstrated such as green solvent medium demonstrated on multiple feeds such as PV, auto catalysts, slags and PCB wastes. The refining stage was based on two novel low-cost technologies: microwave (MW) assisted leaching and gas diffusion electro crystallisation (GDEx). In addition to current PEACOC project, the PLATIRUS R&I project in the past as well and selected by the PLATIRUS consortium as the most promising ones out of 9 other technologies for direct precious metals (PMs) or metal oxide recovery routes from waste materials containing PMs. TRL 7 was successfully achieved and integrated process.²²

The valorisation concept considers single PMs streams through the Deep Eutectic Solvents (DES) extraction, by reutilising the obtained PMs from the PEACOC process in the production of new components such as new auto catalysts or 3D printed products. They have demonstrated the processes at TRL7 using novel concentration technologies (Magnetic Density Separation (MDS), NOVA, and Ultra-Fast Sorting (UFS) able together to increase the concentration of PMs by up to 100 times from low and mid-grade PCBAs.²³

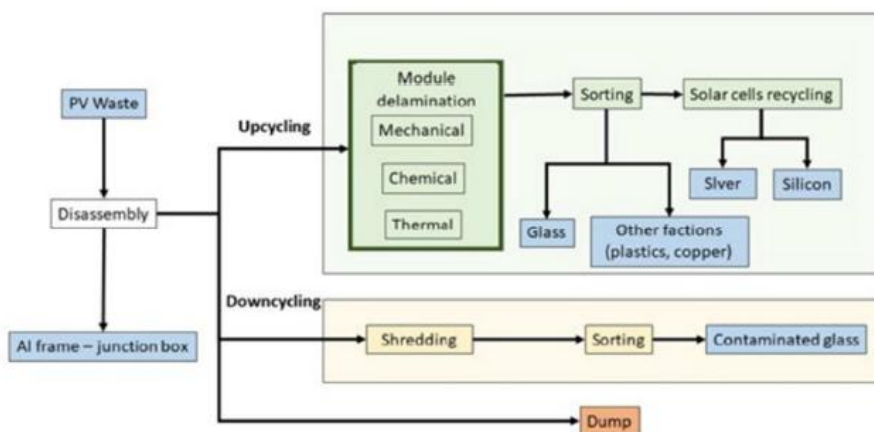


Figure 7: Demonstrated upcycling of the PVs for upcycling aspects

²¹sustainablySMART D1.9 D4R tablet: Pilot batch (30 units)

²²PEACOC D6.10. Commissioning Activities

²³PEACOC D3.6 – Best concentration flowsheet for various EOL PCBA grades

In terms of potential of recycling business model/feed value validation, specific comparison was proposed e.g., ~ 100 t of Ag (worth ~ 70 M€) were not recovered from PCBA in 2015. Also, it has been estimated that Ag can be present in PV panels, in concentrations of about 600 g/t in crystalline PV modules. Moreover, EoL PV panels are expected to undergo significant expansion in the coming decade increasing from 43 kt in 2017 (i.e., 25.8 t of Ag) to more than 1.2 Mt in 2030 and to 60 Mt in 2050. Their recycling is expected to generate around 720 t to 3.6 kt Ag in 2030 and 2050 respectively, worth ~0.5 B€ and 2.6 B€.

To conclude, there is a significant untapped potential for recycling of Au and Ag from EU resources such as increasing EoL products that are not yet effectively valorised (e.g., low/mid-grade PCBA and PV panels).

Another possible technology supplement specifically to PV modules has been demonstrated for the Etching technology. The efficiency of DES in etching silver (Ag) from solution was demonstrated including experiments for Ag extraction on multiple cost-efficient and commercially available metal substrates by electrodeposition methods.²⁴

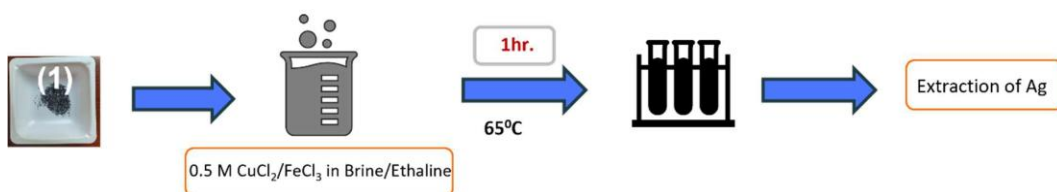


Figure 8: Example of the etching process/leaching principle for recovery of metals²⁵

Also, it was demonstrated that the separation of technology-critical metals (TCMs) through the design and sequential integration of sonication processes into a continuous integrated pilot line, ensuring scalability and process continuity, though the final plant could be run only on the 8ml/min capacity afterwards as per the information given in the Apollo project.²⁵

Also, some of the projects like RELIEF, RHINOCEROS, REINFORCE, FREE4LIB and ENICON considered comprehensive battery recycling technology demonstration and battery materials production using plethora of technologies in integrated and the isolated unit process forms. The RELiEF project has developed and validated innovative processes for extracting high-purity, battery-grade lithium from non-conventional secondary sources. Solvent extraction was performed as a liquid–liquid separation technique in which target ions in an aqueous phase are transferred into an immiscible organic phase containing selective extractant(s). In this task, the extractant system is HBTA (4,4,4-trifluoro-1-phenyl-1,3-butadione) and TOPO (trioctylphosphine oxide) in an organic diluent (Exxsol D80). The process selectivity is governed by extractant composition, phase ratio (Organic/Aqueous, O/A), residence time, and counter-current staging. Digital solution for the battery health calculations based on number of cycles on TRL 4 scale has been demonstrated.²⁶

²⁴PEACOC D9.2. LCA and LCC of the PEACOC technologies at laboratory

²⁵APOLLO: D2.2 TCM Separation Process

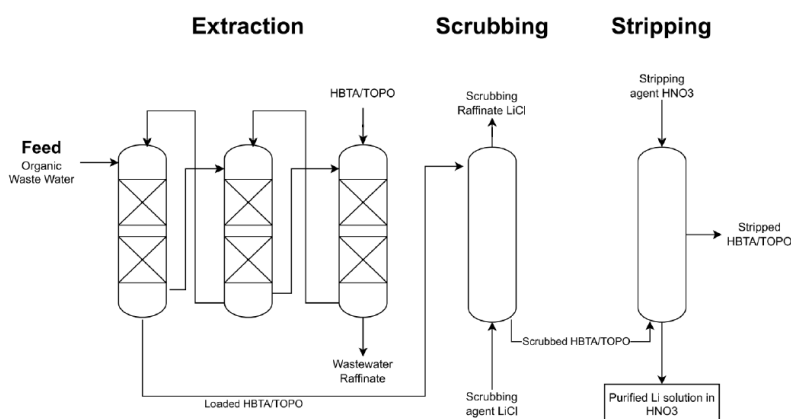


Figure 9: Demonstrated pilot extraction system for Li recovery in continuous mixer settler extraction plant of multiple 100s of ml capacity²⁶

Project like CEwaste considered multiple areas of scope such as verification scheme for recycling, control and optimisation of the recycling processes from multiple feedstocks, possibility of digital circular economy solutions and marketplaces, its integration with the design for recycling and the advanced manufacturing options. Comprehensive certification system is available as the project outcome for the WEEE and battery recycling. Comprehensive legal framework, traceability, up and downstream monitoring requirements and necessary documentation has been discussed, and possible treatment methods have been collected and established.

They have also corelated the business model related aspects such as covering the net cost of treatment for the recovery of metals which may have a lower value and may not be run as stand-alone circular economy operations.

Net treatment costs = Fractions positive value – Operating Costs (labour, energy, depreciation, others) – Fractions negative value – Profit Margin Plant

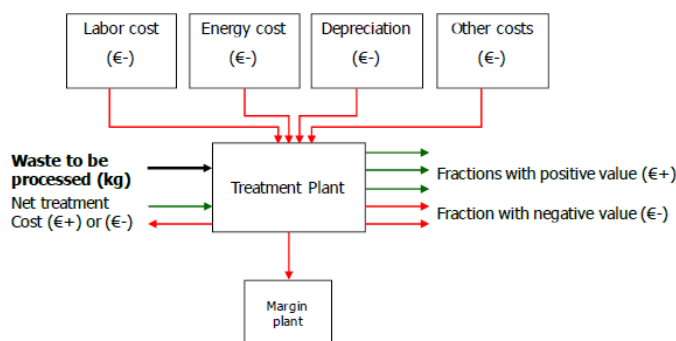


Figure 10: Net treatment cost principle utilised in the Europe as EPR model which can be extended further to CE operations²⁷

²⁶RELIEF: D7.2 Report on Demonstrator Process, page 21

²⁷CEwaste: D4.4 Roadmap for the long-term sustainability of the scheme, page 26

Profitability with respect to the scale of operations has clear effect on validated business model scenarios such as described in CloseWEEE. It was not profitable on 200 t scale but can be incentivised via ERP, however profitable on the 2500t/y level.²⁸

CAPEX	€	6,000,000.00 €		Production (t/yr)	Price (€/t)
Annualized CAPEX	€/yr	1,197,648.75 €	ABS	893.65	1,040
OPEX	€/yr	1,366,693.63 €	Sb2O3	19.98	13,000
Annualized costs	€/yr	2,564,342.39€	Br	36	50
Income	€/yr	3,544,532.00 €	PC/ABS	1,479.74	1,432
Benefit	€/yr	980,190.07€	PS	750	720

4.2. Impact assessment

Many projects in WEEE scope considered impact assessment and also benefits of circularity in details and with variety of point of views. As part of the project CloseWEEE, detailed mapping of the ecoefficiency assessment was proposed which can help with taking the decisions based not only on economic viability or environmental sustainability but also by combining both of them.

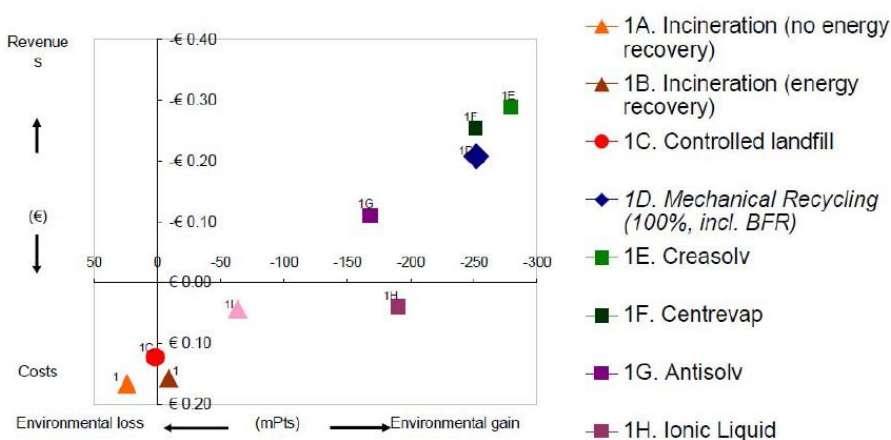


Figure 11: Ecoefficiency approach considering the economic and environmental impact of different competing process.²⁹

This comparison among different competing and traditional technologies shows the superiority of the developed processes like Creasolv. Important to note here is that the incineration and landfilling are not suitable options at all showcasing the need for circular economy solutions.

In case of circular economy solutions, both the mechanical processing as well as separations and product manufacturing can cause substantial environmental impact. E.g. The “modularity parts” make up 2 to 13 % of the production phase impacts depending on the impact category and are for most impact categories mainly connected to the additional PCB area.³⁰ More than 40% of the life cycle carbon footprint of a tablet is related to the production of electronics parts

²⁸CloseWEEE D4.4-DEL-D4_4-IVV-20170623_v2.doc

²⁹CLOSEWEEE-WP3-DEL-D3.3-VTG-v03-20171130.doc

³⁰sustainablySMART D7.3 Life Cycle Assessment studies

and assembly. Clearly dominating is the flash memory (storage) with 20% of the total carbon footprint. The overall GHG emissions related to the D4R tablet were of 64,68 kg of CO₂ equivalent. The most impactful phase is production, taking up around 60 % of the emissions followed by the use phase with 30 %. Additionally, the end-of-life phase has a notorious benefit representing -10 % of the final impacts.^{31,31}

The analysis of the environmental and economic implications of the use of different novel technologies for the extraction of PMs from diverse waste streams has yielded some preliminary insights. It showed that the factors such as energy usage, waste treatment and resource consumption significantly influence the sustainability of each technology. Understanding these details is essential for decision-making that considers environmental impacts in a potential upscaling.

The preliminary cost evaluation demonstrates that the costs associated with PMs recovery extend beyond the direct expenses of the processes. Incorporating waste management and disposal costs provides a more comprehensive view of the financial aspects and where the technology could be improved in terms of performing economic results. This information aids in understanding the long-term economic sustainability of each technology.

Key findings highlight the significant carbon footprint of high-purity silicon production, emphasising the need for regulations to promote recycling and reduce emissions. Economic opportunities in recovering valuable materials like silver and silicon support circular business models in the PV sector.²⁶ Attempts were also observed to establish a strategic dialogue with the TRANSENSUS LCA project, creating a vital link between RELiEF's material-level assessments and TRANSENSUS's product-level LCA standardisation for electric mobility.²⁷

Additional information: Detailed recommendation including USB type C chargers and not allowing individual socket or adapter with it has been implemented in the EU.³² Main policy challenge is to require or incentivise not to sell new adapters with every new smartphone has been considered as the way to mitigate substantial environmental impact.^{32,33}

In a cross-sectional area of different projects, the clear understanding has been established that circular economy processes will need information, feed, energy, mechanically and chemically processed fractions. This will need processing and production capacities and will result in generation of byproducts. Therefore, carbon impact must be calculated and interpreted not to jeopardise the potential opportunities in circularity.¹¹

5. Success and failure analysis

5.1. Enabling factors

The important factors of the successful circular solutions are as follows:

One of the keys enabling factors in case of the WEEE is that it is one of the largest growing municipal waste categories at the moment which needs tangible and rational management solution. Also, due to increasing permitting issues of new mines, decreasing overall mining ore qualities as well as need of closer feeds to non-mining countries, e-waste functions as the urban mining resource.^{4,11,13,14,15,16}

Raw materials criticality and the Critical Raw Materials Act: geopolitical supply chains and strong demand for resources by technological and high-tech industry, clean energy and mobility

³¹ https://www.fairphone.com/wpcontent/uploads/2016/11/Fairphone_2_LCA_Final_20161122.pdf

³² <https://www.europarl.europa.eu/news/en/press-room/20220603IPR32196/deal-on-common-charger-reducing-hassle-for-consumers-and-curbing-e-waste> ; SEIPOG

³³ JRC policy brief on materials circularly in phones

transition and the targets of about 30-60% local production and recycling targets by the newly enacted CRM Act provides a guideline and mandate to produce in the EU. Therefore, circular economy of WEEE as a key waste and resource management issue comes on the forefront of it.^{34,35}

Sustainability and clean transition: These megatrends not only need the high tech and critical metals and minerals but also to retain the high sustainability and cleanliness of such an energy resource, circular use of the raw materials is needed. In case of WEEE, it is important as electronics and electrical equipment are used everywhere in energy generation, energy transmission, energy utilisation and energy saving pathways.^{15,16,27}

Important business, innovation and job opportunities: In Europe, mass production capacities around mining, metal and component productions are lost to global south due to economic and political reasons. However, EU retains competitive edge on highly innovative businesses. The CE solutions provide such a suitable opportunity to develop highly innovative, complex and integrated processes and business and job opportunities can be developed around it, in the EU. As per the Eurostat, it is expected that CE will generate nearly 2.3 million new jobs in the EU in the near future.^{3,10,16}

5.2. Hindering factors

Key hindering economic factors are as follows:

Lack of market drivers making CRM recycling economically unavailable. Without proper economic and market incentives, the recycling of CRMs makes no economic sense. To enable recovery of CRM, an attractive market environment must be created so that investments are profitable and risks are acceptable.^{15,16,17,21}

Lack of information on where CRMs can be found. The lack of information indicating that a product contains CRMs can lead to wrong disposal of materials by consumers, which means products do not reach the correct recovery facilities. The lack of information can also lead to incorrect recovery by recyclers, as they are unaware of where or which CRM can be found in the disposed items.³⁶

Absence of recycling and recovery technology for specific CRMs. Despite the fact that recovery of CRMs is technologically possible, few techniques have gone beyond the proof-of-concept stage, due to several reasons. In some cases, like fluorescent powders, the technology works on a pilot scale, but due to marketing problems in the final treatment, development has stopped. Specific final treatment technologies, for instance of NdFeB (Neodymium Iron Boron) magnets and Li, are not yet available for pre-treatment operators. Therefore, recovery of these materials is not yet happening. The main issues behind recovery challenges are the lack of development of specific technology, the complexity and the high costs behind it.^{11,34,35}

The process of CRM recycling also faces technical, technological and organisational limitations, such as: The technology used for the recycling and recovery of specific components is not yet widely available at an industrial level, and is also complex. In many cases, the risks related to low demand are hampering the development process and the investment in new processes.^{11,34}

The technology used for the recycling and recovery is usually expensive.

It is difficult to achieve high-quality secondary materials that are suitable to be incorporated into new products. This is due to market challenges, such as ensuring economic feasibility of the process, and proper market conditions for the supply and demand of materials, and

³⁴ENICON policy brief

³⁵DICE policy brief on CE act public consultation

³⁶CircThread: D6.5 Circular Design Recommendations Tool Overview and Technical Description, page 5

technological challenges, such as the difficulty in separating different components in the recovery process.^{11,18} Projects like EuReComp, HiYield and RecAL has provided the upcycling, controlled alloy development and smart feed characterisation and mixing strategies.^{37,38,39}

Difficulty in accessing components containing CRMs in products is due to (for example) the design of products not considering the end-of-life phase and resulting in, for instance, glued components. This might also be linked to trends like miniaturisation and increasingly complex material mixtures which make separation inefficient or even technically impossible. Insufficient separate collection of WEEE further dilutes the CRMs over collected WEEE stream. It should be noted that usually CRMs are present in very low concentration in individual products, so it is paramount to consolidate feeds and the resulting fractions for the end-processing. Difficulty for some CRMs to achieve high-quality secondary materials suitable to be incorporated in new products needs to be acknowledged. Access to a comprehensive knowledge base is essential. Such knowledge might not only be linked to recycling operations (i.e., where are the CRM and in which concentration) but also can be used for planning investments in recycling infrastructures.^{34,37-39} Lag between use of CRM in products and availability for recycling (long-life assets) might sometimes influence the time to market for technological innovations.^{14,16,27}

The present economic framework conditions (i.e., market demand for CRM obtained from recycling, volatility of prices and difficulties to concentrate enough input fractions to obtain economies of scale for CRM recovery) makes the recycling of CRMs other than PGMs not viable or attractive. Most modern waste management would not be economically feasible if it was not financed by taxes, fees paid by consumers, or by producers in the course of obligations arising from extended producer responsibility as stipulated (such as the management of WEEE in the WEEE Directive).¹¹

Legal constraints and limiting factors:

Waste management regulations many times compete with the circularity solutions and can cause loss of important critical raw materials such as the rare earth metals due to presence of small amount of Mercury or Lead.

Recycling of WEEEs specifically affected by the Basel convention and Minamata convention-based regulation which hinders the transboundary movement of WEEE to achieve higher scale in one of the EU member states as well as processing permits for heavy metal containing wastes.^{4,5,10,16,35}

5.3. Common features of successful solutions

Following factor related to the WEEE provide the successfully solutions. As evident in the assessed projects and literature, key and minimum enabling condition is the availability of feedstock and information about its composition. The successful solutions were able to demonstrate the technologies and integrated process flowsheets which can access the value of the raw materials in such feedstock. E.g. Gold and copper content as demonstrated by the Urban gold technology and also by the Creasolv technology for the plastic recovery and also important aspects to decontaminated Br and F containing plastic fractions.^{15,20}

Second enabling factor is the choice of technologies and process steps, if they are able to take care of value and contaminants with minimal and integrated steps then the tangible economic and environmental sustainability could be achieved.

Scalability of ingredients or engineering design deployable around the world/EU 27 is a very important factor as well. The process needs to be based on easily accessible or scalable

³⁷EuReComp: D5.1 – Naval & Construction Demo Case: ROCCA demonstrator introducing recycled fibres with infusion process

³⁸HiYield: D 2.1 Database of suitable scrap types as process feedstock, page 23

³⁹RecAL: D13.1 Range of ideal recycling rate as a function of 6xxx to 1xxx alloy admixture

reagents, scalable and manageable machinery and finally as the replicable mechanism around the world so that larger market and quality acceptance could be reached.^{15,16,24,26,27,35}



Figure 12: Intervention in utility designs/ design for circularity^{40, 41}

Lastly, it is necessary to achieve high purity or required quality of the output from complex WEEE which should have market acceptance and also the needed manufacturing and digital market solutions needs to be available and enabled. This needs to be complemented by the legal framework which pushes for circularity, feed collection and reverse supply chain but also avoid conflict between waste management and circular solutions.^{16,35}

In terms of the design principle of the maximum utilisation, if possible, across the sectors needs to be considered. This has been very well implemented by the charging infrastructure by the IoT industry where the connection has been harmonised and multiple adapters are not sold anymore to support long term and the durable usage.⁴¹

6. Upscaling, replication and transferability

WEEE processes and circular economy has a strong replication potential in the EU. This is possible because EU is the highly industrialised, digitalised and electrified continent. Therefore, in terms of raw materials utilisation as well as the e-waste generation per capita, EU is one of the leading economic zones. Therefore, circular economy of WEEE has a huge potential in the EU. The regulatory frameworks in the EU are also effective in terms of the enforcement and also for the incentivisation.^{15,16,41}

The important success story for it is the PET recycling programme enacted by the EU countries. This example can be further translated into the WEEE case to address one of the key issues of financing the reverse supply chain as well as to cover the costs of recycling metals whose competitive markets doesn't support the CE solutions.^{16,42}

⁴⁰Accenture's Circular Electronics Design Guide; SEIPOG

⁴¹C-Servees: D6.1 guidelines for ecodesign, page 46

⁴²<https://www.economia.rs/how-the-deposit-return-scheme-for-packaging-works>

The models and approaches proposed by the CEwaste project can also support in attaining the scalability and viability in terms of the combination of recycled feed with primary processing and also agreeing on the standards with which the materials could be used in the remanufacturing and circular design approaches. However, these holistic and theoretical approaches need to be practiced in engineering terms by developing the processes and solutions.^{15,16}

Ecodesign guidelines with good performance: successful examples: Senseo coffee machine, Signify lighting, CISCO packaging, Fairphone, Philips healthcare, production at Samsung facilities, We wash washing machine facility and Olivetti printing services, Circ4life ICT tool for circular economy business models, Sunpower battery charger.⁴¹

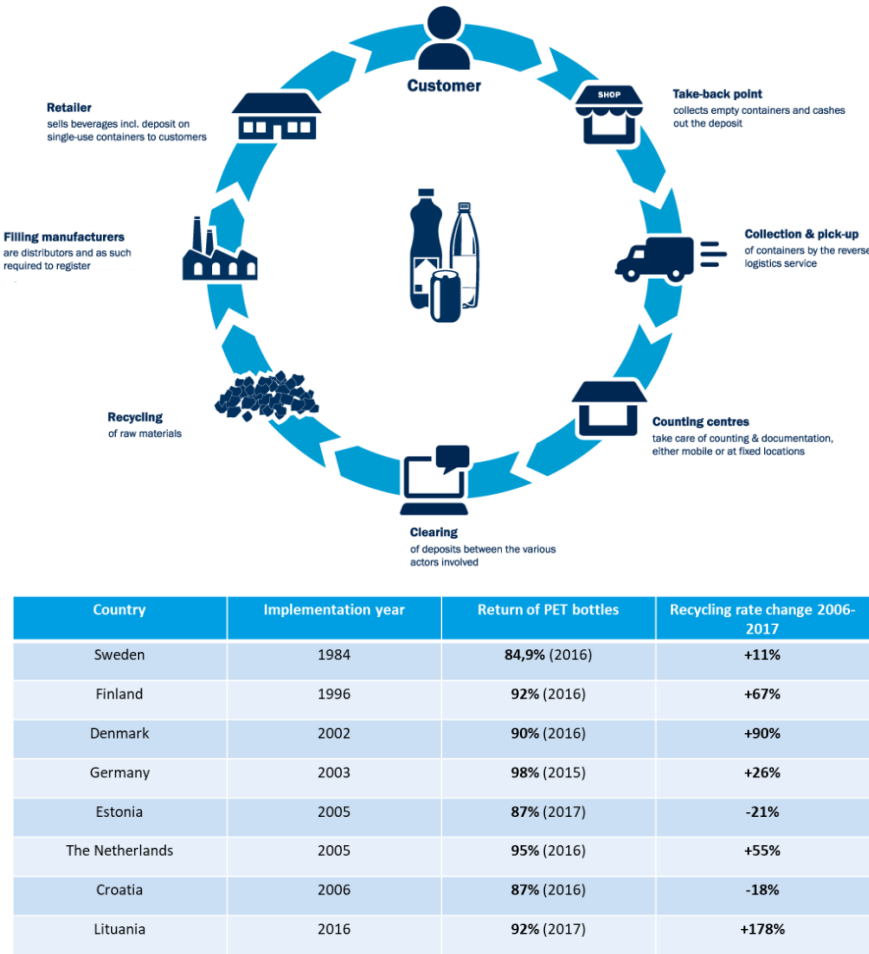


Figure and Table 13: Figure depicting the PET recycling financing mechanism and impact of it in increasing the PET circular economy reflected in the table⁴²

In assessed projects the scalability of the process steps on large scale/ TRL levels was a key issue e.g. GDex process could operate on small scale. Electrodialysis and solvent extraction processes in the RELIEF were successful however its processing need to be demonstrated using larger metallurgy infrastructure or hubs available in rest of the Europe. Transboundary movement of the e-waste for specific recyclers will help in attaining the required scalability and amortisation of the CAPEX and OPEX.

Such feasibility of the CE pilots has been tested also by CEwaste project.¹⁵

Key risk and bottle neck was the lack of information between the recycler and processing companies at different level of the value chain, this make the materials to be landfilled, moved to other geographies or lost. Therefore, informed value chain is needed.^{16,36}

The EU can certainly run the plants for PCB, PV, lamp, batteries and magnet recycling which could achieved necessary scalability using the assessed technologies subject to the optimisation of technical and value chain-based aspects.^{16,43}

7. Regulatory insights for the Circular Economy Act

7.1. Regulatory gaps identified

As depicted in above mentioned sections there are gaps in the existing regulatory and waste management framework of the WEEE. There are issues with the implementation of waste management and environmental laws. There are examples of e-waste treated as hazardous waste as they contain metals that are categorized/defined as toxic or harmful. Therefore, it is necessary to outline the content and type of e-wastes and WEEE, to avoid such a misrepresentation and strict enforcement which in the current setting is promoting the linear economy with massive resource burden as well as the transfer of the WEEE to geographies outside the EU causing serious feedstock availability issues in the EU zone.^{15,16}

Therefore, WEEE recycling and circular economy needs to be allowed in the new legal framework. Also, the transboundary movement inhibited by the implementation of Basel convention, Minamata convention, other cantonal and national environmental and waste management regulations in the EU zone, needs to be opened with necessary compliance for scalable and ethical operations.^{15,16,35,36,41}

Contrary to this, the transboundary movement outside the EU zone needs to be strictly banned so that WEEE feeds as well as CRMs are not lost.

Another tangible gap is about the financing of self-insufficient CE processes. They should be covered in the EPR, tax credits or via incentives mechanisms. Initial value chain must be installed by using tax credits, direct support, covering by piloting projects and low-cost funds to the CE companies.^{16,27}

This needs to be done with the alignment of the CRM Act so that necessary targets for recycling and manufacturing can be objectively supported and achieved, e.g. by providing the urban mining feedstock for recycling within the EU, and making its output available to manufacturing companies as CRMs. Mandatory local resourcing portions or tax incentives are at the moment absent and thus the demand pool is not there in the EU.^{8,16,41}

The possibility of achieving scale by combining different primary and secondary resources is practiced and allowed at the moment to only some extent. It is essential that this be revised so that multiple WEEE can be processed in integrated pathways to make them viable and operational. These mixing restrictions exist because of the in-homogeneity of mining and WEEE feeds and toxic metal contents, which however can be addressed in the development of appropriate CE processes.^{16,35}

There is potential gap in availability of information about WEEE, their composition and key stakeholders. There is no mechanism to enable stakeholder dialogues as well labelling and information sharing about the value and CRM contents as current manufacturing enables performance parameters exchange instead of resources and compositions.³⁶ Lack of awareness and incentives i.e. many organisations remain tied to their legacy systems and are reluctant to

⁴³ PEACOC D6.10. Commissioning Activities

embrace new business logics. Often, executives misinterpret circularity as simply an advanced form of recycling, missing its full potential.⁴⁴

7.2. Legislative and administrative burdens

Majority of issues applied to mining and chemical industry permitting, toxic materials transport and related to the feed transport and its customs restriction are resulting into the massive legal burden on the CE operations in the EU.¹⁶

On one side, many SMEs specialised in the CRMs and CE operations struggle for the feedstock in the international market. As for the gold and PGM containing feeds the global south-based companies are giving very good pricing rendering the EU companies non-competitive due to high energy and labour costs as well as higher compliance and related additional expenses.^{3,15,16,44}

This needs to be brought on level playing field by providing the tax credits or case-to-case, WEEE, or target CE metal specific pathways and mechanism has to be established to support downstream manufacturing which current legal burden impedes, as also confirmed by CRM recycling stakeholders.^{16,41}

The mentioned case of lamp waste due to Hg content is subject to reporting every three months, which small companies cannot adhere to or comply due to low resources availability and also the other burning priorities for them related to business development and expansion.⁴⁵

Another legal burden is due to the supply chain due diligence or sanctions contradictions which avoids the exchange of recyclates and values between the markets. Heavy compliance effectively leaves the EU resources and CE company isolated and alone with expectation of high labour, environmental, operational and profit requirements. This inhibits further capital and market flows giving non-EU companies the advantage of the access to feeds, partners as well as buyer manufacturing companies.⁴⁶ E.g. EU companies have difficulty to import Co bearing minerals due to designation of conflict mineral affecting primary and secondary production and thus downstream battery manufacturing value chain is getting substantially affected.

Overall legal burden inhibits conditions where heavy industry and metallurgy companies could run operations without worries in the EU. This is also resulting in downstream supply chain and competitiveness constraints in the manufacturing sector. In the long term, this is causing irreversible losses of know-how and industrial capacities, which should be avoided. This was evident in the CEwaste stakeholder pilot, where value or compliance was lost as the individual recyclers were not aware about the other processes and which value needed to be retained.^{3,15}

8. Policy recommendations

8.1. Prioritisation logic

Following prioritisation has been proposed to support the increase in CE in the EU.

The prioritisation based on the derisking of the CE value chain and its organic establishment in the context of the WEEE and the CRM recovery aspects. This concerns first the access to feed and related information. Making front end electronics usage and the back-end recycling

⁴⁴ DICE: Circular Business Models_ More than Recycling; Circular Business Models_ Unpacking the Paradoxes

⁴⁵ J Environmental Chemical Engineering, 10 (6), 2022, 108915

⁴⁶ <https://verfassungsblog.de/csddd-the-unintended-consequences-of-mandatory-due-diligence>

synchronised and protect the specialised companies and production environment along with related know-how in the EU.^{35,41,44,47}

1. Feedstock and labelling information.
2. Closing the loophole in WEEE transfer within/outside the EU.
3. Market access and the financing to promote less profitable CE processes.
4. Industrial infrastructure, framework, and know-how generation.
5. Derisking in terms of piloting and financing early capital.
6. Legal and eco-design-based adaptation to promote WEEE recycling.
7. Tracing and compliance for fair competition.
8. Balance between waste management and CE pathways and finding new avenues for the EU competitiveness.

8.2. Prioritised recommendations

Following actionable recommendations are provided to ensure the CE Act's envisaged impacts as well as the complete and robust coverage in the EU. These recommendations could be implemented standalone as well as in synergy with the CRM Act, Battery Directives and the Net Zero Industry Act.

1. Access to feedstock and related composition and volume information/restriction of feed transfer out of the Europe. New collection models clustering CRM-rich products. Inclusion of information in Digital Product Passport. Development of solid criteria to assess CRM presence. **Legal obligation to dismantle Key CRM containing components (KCC) and recover CRM.**^{15,16,44,47}
2. Making 26 CENELEC standard binding in European Standardisation Organisations. It is responsible for publishing standards in the electrotechnical engineering field. CENELEC maintains close relationships with the International Electrotechnical Commission (IEC) and the European Committee for standardisation (CEN). Through its Technical Committee TC 111X "Environment", CENELEC addresses the generic environmental standardisation needs of the electrotechnical sector, especially in support of European legislation.¹⁷
3. Access to market by value chain creation in consensus with the CRM Act and the achievable framework and targets in waste management. **Mandatory recycled content of key CRM containing equipment (KCEs) including CRM, such as batteries.** Creation of a market for CRMs E.g. website secondtrade.com, mandatory incorporation of CE resourced content in the new projects and protecting their cost and economic viability by tax, EPR and financing-based aspects, VAT and Tax credits as well as the gate fees to cover the costs of CE for CRMs.^{15,16}
4. Access to technologies, upstream suppliers and downstream buyers.^{34,35}
5. Access to industrial and manufacturing as well information and digital infrastructure.⁴¹
6. Necessary manpower and know-how, nurturing and growing.³
7. **Pilot of promising process flowsheets from the EU projects where tangible high TRL and scalable progress have been seen through recycling HUBs and Boosters.** Locating and forming new clusters for plastics, chemistry, and metallurgy related fields.^{15,16,34}
8. Taking care of the legal burden, giving opportunity to SMEs to convey the impact of downstream, administrative support and easy + time efficient tools.^{15,16,41,47}

⁴⁷ C-Servees: D6.2 position paper

9. Eco-modulation fees or extended EPR coverage to cover the costs of CE operations, thus giving them strategic and national importance.^{15,16}
10. Increasing tracing and CE based incentives schemes and additional promotion of CE processes. This has been successfully adapted in the plastic recycling industry.^{15,35,41,47}
11. Improve critical infrastructure for recycling of specific CRMs and products.³⁴
12. Resolve the conflict between waste management and CE scenarios.^{15,16b}
13. Robust financing and integrated process development and deployment pathways.^{15,41}
14. Provide clear framework for emerging and untapped WEEE resources e.g. Optical fibre cables, micro-e-mobility devices, industrial byproducts and slags, reminding of the land-filled WEEE and the related feed and composition information flows.^{10,27,34,35}
15. The CE based products needs to be adapted for acceptable recycle qualities as well as the possible carbon compensation or carbon credit-based financing to cover the related costs.^{13,15,35,44}
16. Broadening the CE Act Beyond Recycling: Embedding a Hierarchy of Circular Strategies
17. [The Clean Industrial Deal](#) recognises that products must stay in circulation for as long as possible, but its proposed measures place most emphasis on recycling. To achieve its objectives, the CE Act should extend its scope to other circular strategies. [Hoveling et al. \(2024a\)](#) mapped best circular practices and identified gaps for medical devices.^{16,16b,48}
18. **Harmonised Terminology: The CE Act should establish clear and harmonised terms & definitions to ensure consistent use.** DiCE highlighted the value and need of a unified glossary to be able to communicate along the value chain. It is revealed that key actors were unclear how circularity applies to them, and which strategies may be used. Therefore, DiCE's consolidated [Terms & Definitions](#) can serve as the basis and be adopted by the CE Act for promoting a common understanding among value chain actors and regulatory bodies, reduce fragmentation, and support coherent application of the legislation.^{16,48}
19. Expanding CE Metrics Beyond Circular Material Use Rate (CMUR): Relying only on the CMUR is too narrow to capture the full circularity. While useful, CMUR misses aspects like product design, repairability, durability, and recyclability at end-of-life. To ensure comprehensive monitoring, the Act should add indicators such as recycled content, recyclability metrics (e.g. recycling rates) and repairability index, among others. This broader framework would track progress across product lifecycles more effectively, helping policymakers to target interventions where it matters and positioning the EU as a global leader in circularity monitoring.^{41,44,48}
20. Advancing Circularity and Social Sustainability through Awareness and Cooperation: The CE Act should focus on awareness-raising and fostering collaboration among actors and change agents as these are key enablers of circularity and social sustainability. Engaging all stakeholders, including the public, can boost WEEE collection rates and speed up acceptance and adoption of circular practices. Engagement can lower the (perceived) health & safety risks when circularising medical devices and supporting social benefits such as skills development and the creation of new jobs, particularly within Europe. Finally, citizen engagement is an essential component to enable closed loops. Integration of behavioural science through e.g. co-

⁴⁸DiCE: D2.1 Barriers and opportunities to circularising digital health devices and an inventory of best practices

creation and motivational strategies is critical to ensure that products designed for closed-loop systems are returned and can be recirculated.⁴⁸

21. Harmonise the Net Zero Industry Act article 25 and CRM act article 29 with recycled content and circular economy definitions with CE act.^{16,35}

9. Conclusions

Circularity will provide the conversion of waste and resources management including those for the critical raw materials in the potential economic, and sustainable business opportunity.

The portfolio of projects assessed in current evaluation assures clear promise that there is technical, value chain, sustainability and market prospects which could be utilised. The technologies required for tapping the potential of the complex WEEE feedstock needs different physicochemical and data management approaches such as clear access and understanding of the feedstock. Understanding of value and contamination or impurities. Designing and demonstration of feedstock and target metal specific process flowsheet is required as the nature of WEEE will continue to evolve in future. Wherever possible, promotion of the possibility of minimal mechanical, high-temperature and chemical processes is necessary. However, in case high value and circularity can be achieved such processes should not be avoided, as the overall carbon impact can be decreased and amortised by multiple use of resources as well as the integrated waste, primary and secondary resources management by considering the overall broad picture.

It is evident from the assessment that the complexity of WEEE feeds and therefore their process flowsheets is very high, therefore, there is need of multiple separation technologies such as leaching, electrodialysis, etching, solvent extraction, electrowinning, filtration, precipitation, electrowinning, pyrometallurgy and the electrowinning to get access to critical, precious and technology metals. This makes the process integration and the scale up very difficult. Therefore, combination of decentralised and centralised approach could be utilised i.e. creation of concentrates and products which can be part of the scaled purification and concentration operations which are usually costs and impact intensive. Along with this strong metallurgy infrastructure and know-how needs to be generated.

The successful example of the Cresolv process for plastics and the urban gold process from Metallica showed the possibility of the scale-up. However, also highlighted the status-quo that there is need of EPR support or presence of highly incentivising gold or PGMs in the WEEE feeds to make processes viable and scalable. Also, the content of CRMs needs to be clearly indicated in WEEE and component information in terms of the resources content. It will help in better disassembly, concentration and purification processes as evident in DICE, CircThread and C-Servees observations.

Key drivers for a circular economy approach in WEEE are the fast-growing nature of such waste types, the need to access and retain the critical raw materials within the EU, and awareness of new business and job opportunities this sector will offer in years to come. However, the key barriers are lack of feeds and reverse supply chains and information about their resources and CRMs content; lack of processes and technologies especially metallurgy to achieve high purity metals. Lack of scalability, economic viability as well as contradicting waste management regulations which mandates the disposal/transfer/management of the wastes. It doesn't provide possibilities to utilise them in circular pathways.

Therefore, the creation of reliable feed, reliable technologies, a reliable and scalable production/manufacturing environment, economic or regulatory support for reliable projects and also an enabling legal framework and financing mechanisms are needed, which could all be provided by the upcoming CE Act.

10. Annexes

10.1. Annex I: Full Project Portfolio Matrix

The table attached above and also separately includes the list, website, budget and key findings/scope in 1-2 lines.

10.2. Annex II: Individual Project Analysis Insights

Key information extracted from specific projects has been provided by the expert in form of metadata, project data matrix and leaderboard file of crude data used for synthesis of present report. It has been compiled as the leaderboard document and made accessible to DG RTD. Specific references to project deliverables documents or other literature sources are provided in footnotes.

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This report presents key findings from a project portfolio analysis conducted to generate evidence-based recommendations for the Circular Economy Act (CEA), with a specific focus on waste electrical and electronic equipment (WEEE) and the recovery of critical raw materials (CRMs). The analysis shows that regulatory hurdles, a disposal-centric value chain, and a disconnect between market demand for circular resources and EU-based manufacturing hinder the deployment of circular solutions. The report provides targeted recommendations in support of integrated reverse supply chains, reliable feedstock availability, appropriate technologies, and value chain frameworks, enabling multi-step circular value creation and utilisation.

Studies and reports

