Potential of permanent magnet recovery from Dutch waste: the case of Hard Disk Drives

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Strategic material recovery from Hard disk drives

Hard Disk Drives (HDD)

contain valuable parts, such as the aluminum casing, PCBs and permanent magnets

Neodymium & Dysprosium

are significant Strategic Raw Materials (SRMS) present in the permanent magnets of Hard Disk Drives. They are currently not recovered.

These magnet materials are crucial for the

Energy Transition, Data infrastructure and Aerospace

1,7% Nd
0,8% Dy

Of the Dutch raw material demand can be met by recovering SRMs from the 58 tonnes of magnets from Dutch waste. This contributes to the EU SRMs goal of 25% recycling.

1,7 million EUR

Is the estimated revenue of recovering these CRM.

TNO identified the following barriers in exploiting the potential of Nd from HDD:

- Overall Dutch collection levels for small IT are below EU targets and the performance in other EU countries.
- Shredding HDD completely is the cheaper option for safe data removal, in comparison with careful robotic and/or human dismantling.
- The European Nd recycling industry is still in the pilot phase.

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Glossary

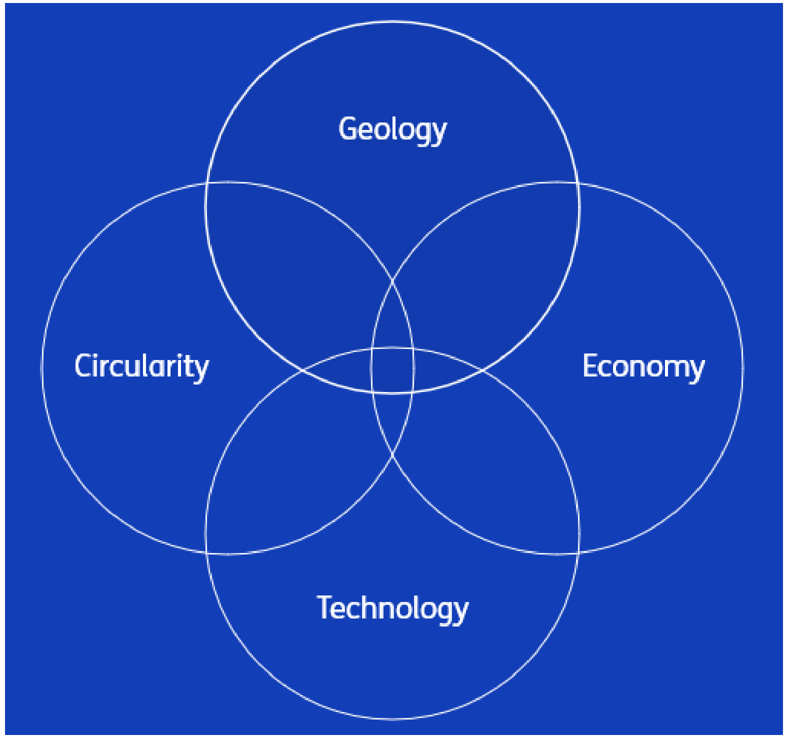
- **Critical raw materials (CRMs)**: CRMs are those materials with a high supply risk and high economic importance for the EU. As defined in the CRMA 2024.
- **Final processing / smelting**: A process (either pyrometallurgical or hydrometallurgical), involves bringing about physical and chemical transformations in the materials to enable recovery of valuable metals.
- **LAP3:** Landelijk AfvalbeheerPlan
- **Official collection**: Waste which has been formally collected and reported by the nominated parties.
- **PoM**: Put on Market refers to products that have been placed on the Dutch (and EU) market in a specific year.
- **Pre-processing**: A process which encompasses all forms of pre-treatment of waste products, including manual or mechanical disassembly into smaller fractions and material streams, ready for final processing.
- **Recovery**: 'Recovery' means any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy. Defined in the Waste Framework Directive (2018).
- **Recycling**: 'Recycling' means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations. Defined in the Waste Framework Directive (2018).
- **Stock**: Stock refers to the accumulated quantity of a specific product or material that is either in use, e.g. functionally used by a person or business, or unused or broken, e.g. in a household or business.
- **Strategic raw materials (SRMs)**: Also 16 CRMs, as outlined in the CRMA, for which demand is projected to increase significantly in the coming years. This includes the addition of Copper and Nickel (previously not classified as CRMs).
- **WEEE**: Waste electrical and electronic equipment as defined in the WEEE Directive (2012).
- **WEEE generated**: WEEE (see above) which has left the stock.

This research is part of the NMO

Nederlands Materialen Observatorium

The Nederlands Materialen Observatorium is housed within TNO and has the following scope:

- Acquiring, collecting, managing and providing data, information and insights on the current and future demand, supply and availability of critical raw materials within the Netherlands.
- Gain insight into the dependency on critical raw materials and processed materials throughout the value chain.
- Determining the effects of circular policies on the supply and demand of critical raw materials, processed materials and finished products.
- Evaluation of supply risks and measures taken by governments.
- Evaluating technological innovations relevant to the supply and demand of critical raw materials and processed materials.



Background, Problem definition and Goal

- The EU seeks to greater strategic autonomy and increase its long-term competitiveness of its industry by enhancing access to critical materials, specifically by harnessing "the potential of domestic resources through mining, *recycling* and innovation in alternative materials" (Draghi, 2024, p.54).
- In this vein, the Critical Raw Material Act (CRMA) (EU, 2024) sets recycling benchmarks for the EU for **meeting 25% of the EU's annual demand** for strategic raw materials from secondary sources, e.g. recycling, by 2030. This currently applies to the aggregated quantity of all strategic materials for the EU.
  - Article 26 of the CRMA, point C states that member states should "*increase the collection, sorting and processing of waste with relevant critical raw materials recovery potential, including metal scraps, and ensure their introduction into the appropriate recycling system, with a view to maximising the availability and quality of recyclable material as an input to critical raw material recycling facilities"*
    - *Point 5 states "Member States shall identify separately, and report, the quantities of components containing relevant amounts of critical raw materials removed from waste electrical and electronic equipment and the quantities of critical raw materials recovered from such equipment."*
  - The CRMA states that circularity of permanent magnets is a priority, as it used in many technologies. Articles 27 and 28 are specifically aimed at permanent magnet recycling, in stark contrast to other components or CRM that do not have own articles.

Problem definition

In previous studies, hard disk drives (HDDs) in waste electrical and electronic waste (WEEE) have been recommended as a product containing critical and strategic materials such as neodymium, dysprosium and praseodymium. These are not currently recovered in quantity and are mostly shredded with the CRM contents ending up in mixed or ferrous fractions (CEWASTE, 2021; TNO, 2024). The EU's recycling input rate and processing capacity for these elements is currently low to non-existent (see next slide), meaning the waste processing for SRMs is not sufficiently well organised.

Goal

The goal for the Netherlands is to find concrete and actionable ways to contribute to the overall EU CRMA benchmarks. This research examines the extent to which waste HDDs can contribute to the CRMA benchmarks and targets, given economic, technological or policy considerations and developments.

The recycling input rate is low or non-existent for certain strategic materials, which provides motivation to push for increased recovery from waste sources

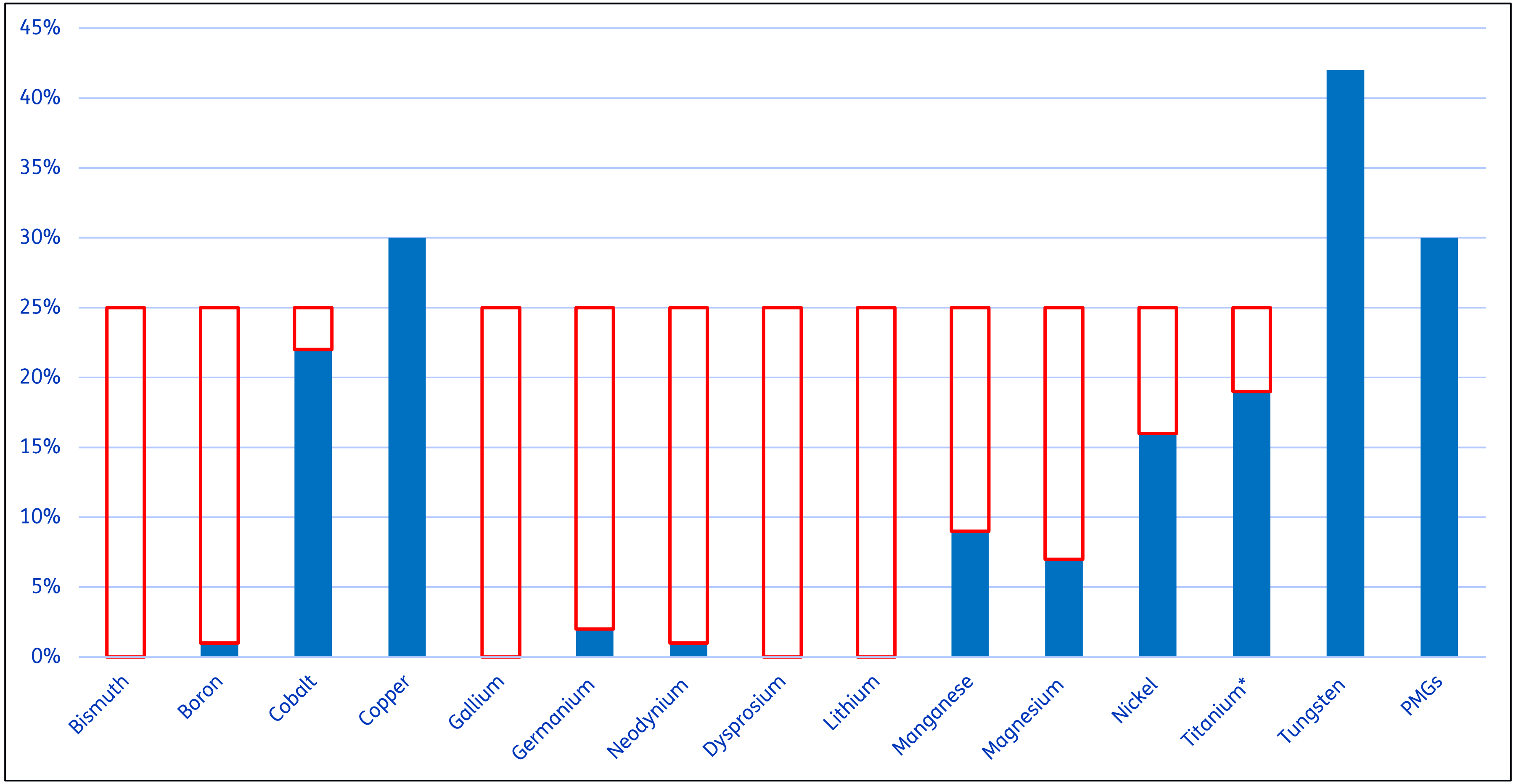


Fig. 1 Recycling input rate in the EU as a share of own consumption. Source European Commission, 2024. * uses data from Boba et al., 2018.

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Rationale for the study

Policy rationale

The CRMA outlines an overarching recycling benchmark of **meeting 25% of the EU's annual demand** for strategic raw materials from secondary sources by 2030. In addition, the European Commission is exploring whether to apply separate targets to specific waste streams in the coming years. **In the future, specific targets might apply to individual materials and waste streams depending on the technological and economic feasibility**. Permanent magnets recycling is specifically mentioned in Articles 27 & 28 of the Act.

Scoping rationale

Previous studies have outlined the presence of CRMs in various EU waste streams, including cars, waste electrical and electronic equipment (WEEE), batteries, extractive waste, and landfills (JRC, 2018). Moreover, a Horizon 2020 research project (FutuRaM, 2024) is currently examining six waste streams: cars, WEEE, batteries, Slags & Ashes, mine tailings and construction and demolition, to determine and classify the CRM potential in each.

In the Netherlands, a previous study by TNO (2023), as preparation for an update of the national waste management plan (circulair materialenplan (CMP) due in 2025), outlined additional waste flows to those indicated by the EU: shredder waste and waste from metal recycling (TNO 2023).

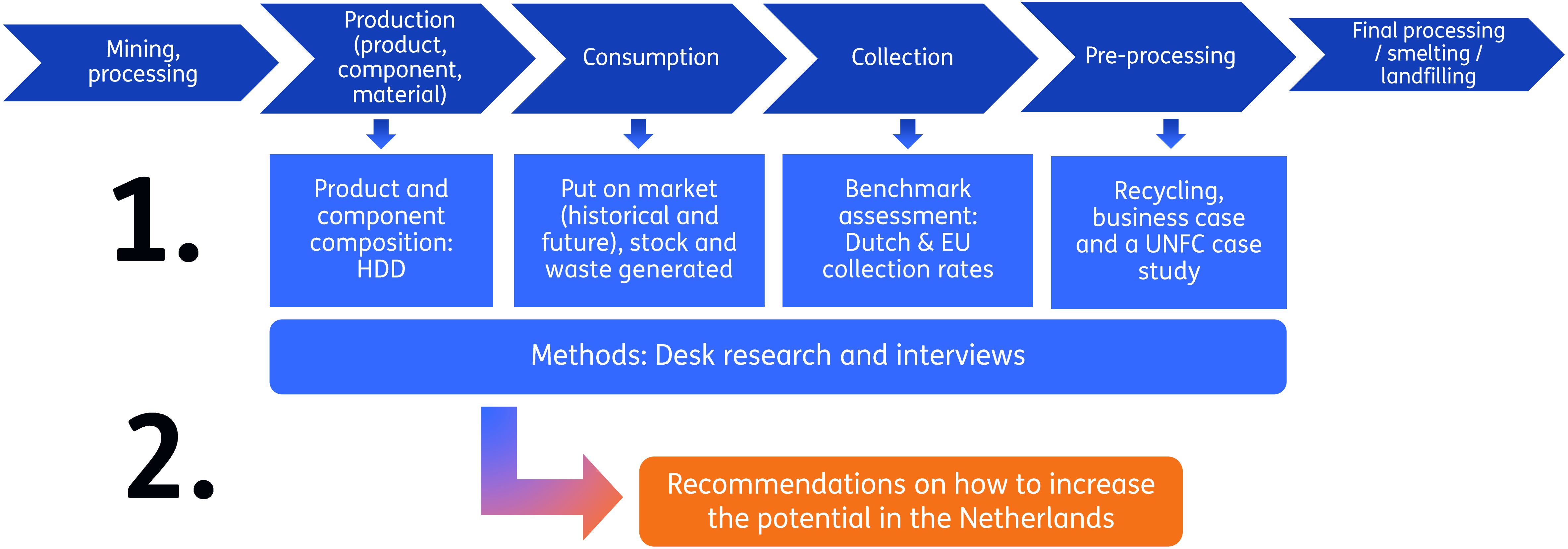
These waste streams provide the context for the NMO activities that focus on how the Netherlands can contribute to the CRMA recycling objectives. To support this ambition, the NMO explores the ***low hanging fruit***: recycling use cases where we expect relatively large amounts of CRMs and/or value chains in which the Dutch government can intervene with relative ease.

HDDs

For one of the first recycling use cases TNO selected wasted hard disk drives (HDDs). Previous studies (CEWASTE, 2021; TNO, 2024) have pointed to wasted HDDs as being a rich source of CRMs that could be separated from waste. The complex functions of HDDs require specific electronic components that contain CRMs, specifically the well know neodymium permanent magnet. Additionally, the recycling state of the art is shredding, followed by pyrometallurgical recovery of probably only high value metals such as gold, silver and copper. This offers a clear opportunity for circularity, as the HDDs components can be disassembled and reused or recycled for specific metals. An alternative for safe data destruction is also available in the form of magentization.

Approach and methods

Point of departure: Since there is no mining and final processing of the strategic materials from HDD in the Netherlands we begin from the production stage. See the annex for an in-depth description of the method.



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The scope of this research is the 'potential' of permanent magnet (in HDDs (containing Nd, Dy)) separation from within Dutch E-waste.

- Increasing the EU's strategic autonomy for materials requires examining different supply sources that are socio-economically viable and technologically feasible to recovery.
- **The focus of this study is to examine the potential (socio-economic and technical) to separate permanent magnets (contained in HDD) into a separate and concentrated fraction for subsequent processing (of SRMs)**
  - Socio-economic entailed examining the related business case around CRM recovery from Dutch e-waste and whether an on-going project is socially desirable. In essence, the social and economic viability.
  - Technological entailed verifying the technological feasibility of recovering SRM components (HDDs) from Dutch e-waste

This study was made possible by the input and feedback by the following people

Interviewees

Jan Visser – Mirec

Alfred Jager – Mirec

René Eijsbouts – Stichting OPEN

Lorenzo Glorie – Recupel

Robin Ronceray – Ecologic

Kees Baldé - UNITAR

Reviewers

Ton Bastein (TNO)

Elmer Rietveld (TNO)

Marina von Vietinghoff (DERA)

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Hard disk drives contain many strategic raw materials, such as neodymium, praseodymium and dysprosium, in the permanent magnets

- HDDs were invented as data storage devices in the 1960s. They're mainly used in desktops, laptops, home servers, external hard disk, gaming consoles, automotive vehicles, surveillance cameras and data centres.
- The main components that contain SRMs are the aluminium casing, PCBs (which contain palladium) and the permanent magnets (which contain neodymium and dysprosium)
- In 2014, between 6-16% of global neodymium use was for HDDs (Peeters, 2018) .This number has decreased since, as Nd magnets in HDDs have become smaller and the share of other product groups such as windmills has increased.
- An average HDD contains small quantities of neodymium, dysprosium and praseodymium in the magnet and PCB.
- In recent years, solid state drives have risen in popularity due to their larger storage funds and faster processing speeds. It is expected that HDDs will be phased out in laptops, but will still find usage in other household appliances and data centres. The waste generated is expected to be stable (Statistics Netherlands, 2024).

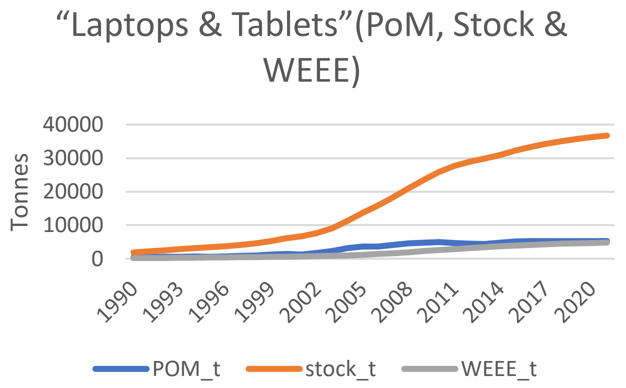
Consumption of HDDs is expected to decrease from household IT, e.g. laptops, but to increase overall due to applications in data centres

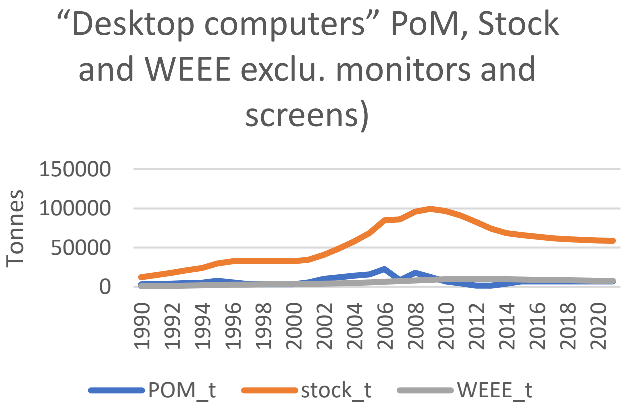
Historical perspective

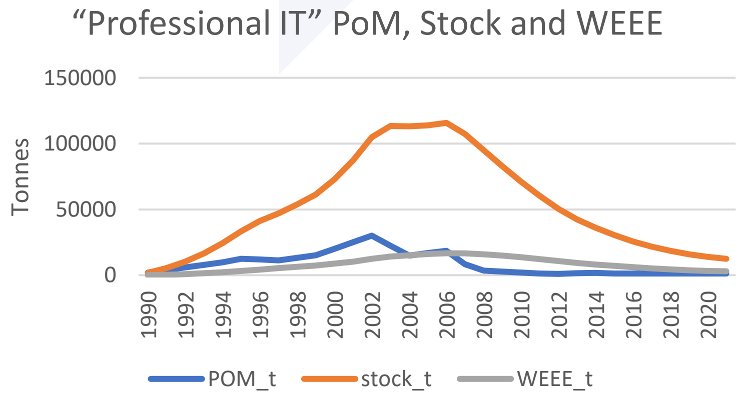
- The assumes lifespan of HDD is 5 years.
- There is an estimated over a thousand tonnes of HDDs in Dutch stock in 2020, with stable quantities being placed on the market and becoming waste.
- HDDs are found in many different laptop brands. The most popular brands sold in the Netherlands (in 2018) were Dell and HPE.
- There is estimated to be 281 data centres in the Netherlands, providing a rich source of future HDD.

Future perspective

- Overall HDDs use in the EU is projected to increase in coming eight years (Market Research Future, 2024). As such, the HDD waste stream is projected to increase on the short term as well.
  - However, the use in consumer equipment, such as laptops, is projected to decrease, owing to their replacement by solid state drives.
  - The increase is likely to come from their continued use in other applications, such as data storage.







Source: (Van Straalen et al., 2017).
The historical data on specific quantities of HDDs in the Netherlands only extends to 2020 and is estimated from the years 2016-2020 (Huisman, 2017).

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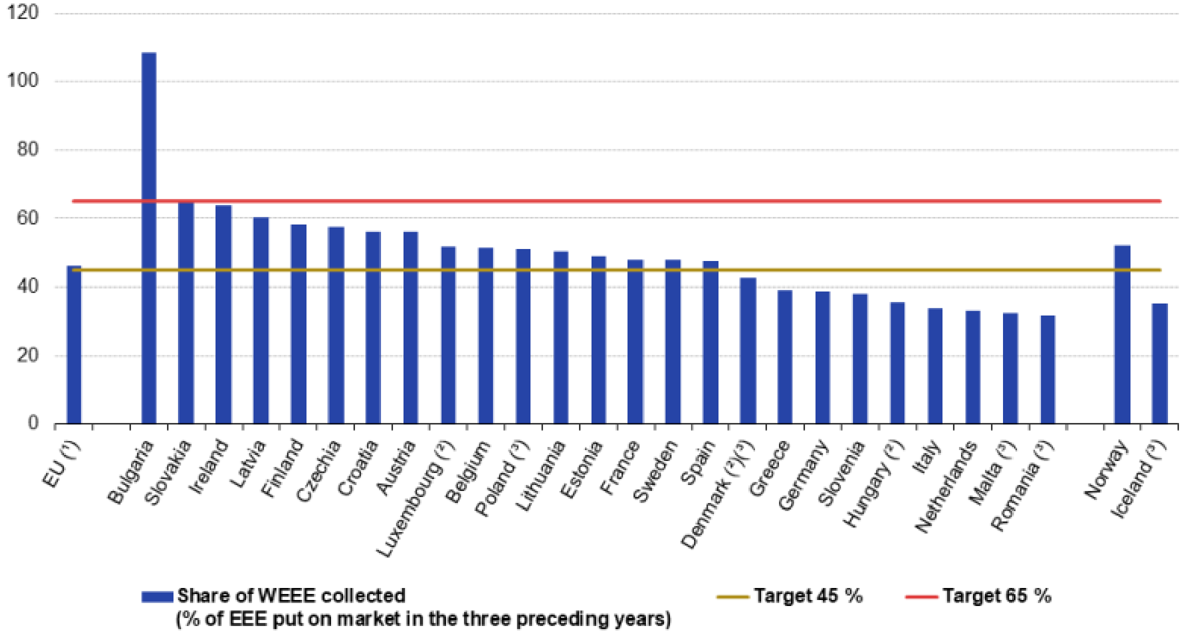
Dutch collections levels of WEEE are below EU targets and behind counterparts, increasing them would raise the supply of waste HDDs for CRM recovery

- The policy and organisational context for WEEE in the Netherlands is complex, with many actors involved.
- Across the EU, collection levels for WEEE are lower than the official target (65% based on the average weight of put-on market from the previous three years).
- The Netherlands performs worse than EU counterparts such as Germany, Belgium (for small IT) and France (for large and small IT). See figure opposite for 2021 (the most recent year with complete EU data);
- Key differences between the Netherlands and neighbouring countries that could explain the difference in collection, include the separation at source (Belgium) and long standing B2B strategy (France) (see Annex for descriptions)

Total collection rate for waste electrical and electronic equipment (EEE), 2021

(% of average weight of EEE put on the market in the three preceding years)



(¹) Eurostat estimate.
(²) 65 % target not applicable. Country applies calculation methodology based on WEEE generated: see Figure 2b.
(³) 2020.
Source: Eurostat (online data code: env_waseleeos)

eurostat

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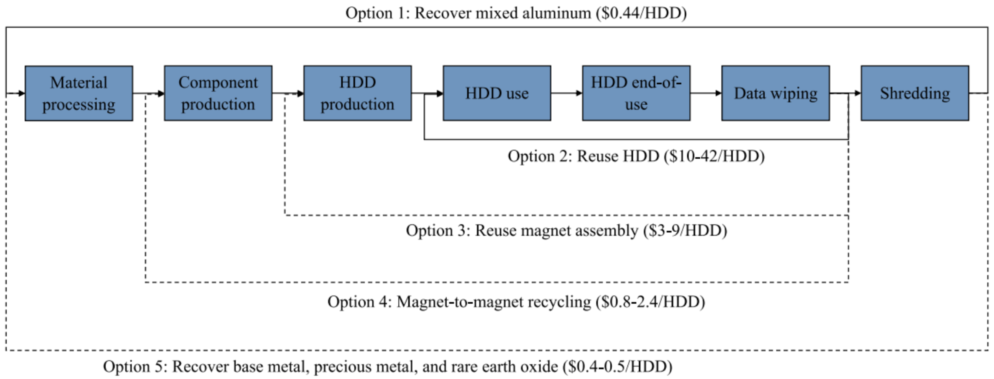
Recycling HDD is technically possible, but currently is not pursued in the EU due to a preference for shredding for efficiency and data concerns

- Roughly speaking, there are five options in recovering HDD, as shown in the figure on the right.
- Each recovery option results in different product, component or material streams that can be valorised. Reuse options or magnet-to-magnet recycling are (theoretically) the most profitable and result in lower emissions per kg HDD.

However, shredding is most common option in the Netherlands and EU

- Smashing and shredding of HDDs is the norm, driven by a focus on safe data removal, the policy landscape, which focuses on mass and not specific materials (see slide 11) and uncertainties in the HDD qualities and reuse business case for 'outdated' equipment.
  - Dutch **sorting** companies offer a price of € 1,35 per HDD kg.
  - Shredded HDD are separated for ferrous, non-ferrous and plastic recyclate fractions by magnets, eddy currents, floatation and centrifuges. The resulting metal fractions are recycled by **pyrometallurgy, where only the** valuable Gold, Palladium, Silver is recovered and SRMs like silicon and Neodymium are lost.
  - Alternative recovery routes that include hydrometallurgical leaching are possible from a technical point of view (see figure on the right), but business case insight is lacking. The same accounts for manual disassembly of magnets instead of shredding.



Enterprise HDD recovery options with recovered values in US dollars (iNEMI, 2019)

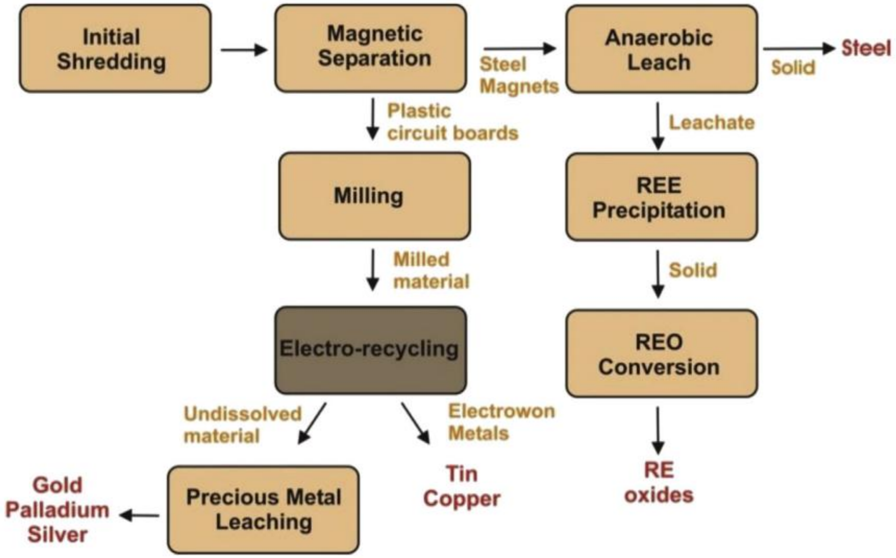


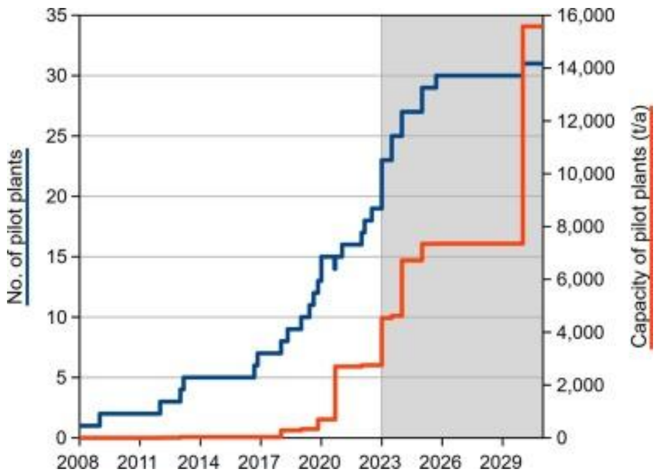
Fig. 2. Flow diagram for the comprehensive recovery of value and critical materials from electronic waste.

Flow diagram for the recovery of CRM from e-waste (Mengyao, 2018)

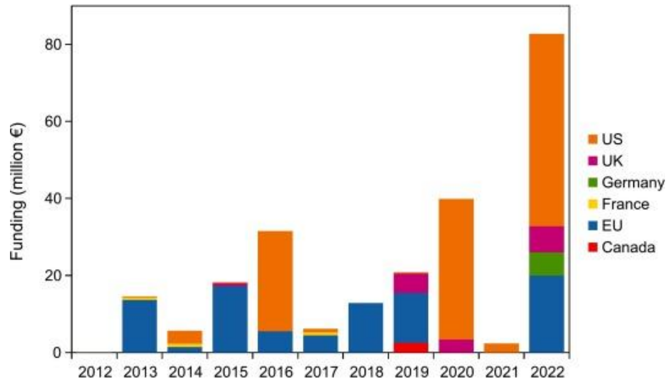
Magnet recycling capacity is projected to oversupply the European Nd demand

- A recent study by the Leiden University group of René Kleijn (Koese, 2025) has mapped the global entrepreneurial activities on magnet recycling. Based on announcements, they expect the capacity to increase from 2750 t/a in 2022 to 15.578 t/a in 2030. This would imply an EoL recycling rate of 17 % of the estimated 90 Mt. global NdFeB waste. Additionally, they conclude that between 2012 and 2022, more than 230 MEUR was invested into EoL REPM recycling, mostly by the US.
- The EU has the second largest recycling capacity, after Canada. TNO has mapped the EU initiatives that are currently active in the table below. Half of these are the result of European funded projects like Horizon. REEPRODUCE is such a project that is still active.
- The currently planned total EU recycling capacity is 3430 tonnes. With an recycling rate of 90% and an Nd content of 30%, this would result in ~900 tonnes of secondary Nd supply, exceeding the current EU demand of 120 tonnes. However, this might change in the next decade as a response to the push for more strategically autonomous European Industry.
- An interesting note is that there are multiple EU magnet trading companies who collect and possibly shred magnets and then send them to Asia for Recycling. One of these (Newland magnetics, France) is even Chinese owned.

country	city	company	Asset/Process Type	Asset/Process Type specifications	Project Category	Status	TRL level	Capacity (ton)
Belgium	Brussels	**JGI Hydrometal**	Hydrometallurgy	nd-of-life Nd-based permanent magnets and obtain high-quality REEs-oxalates.	Project	Active project	7	NA
Germany	Bitterfeld-Wolfen	**Heraeus REMLOY GmbH**	Melt spinning	Recycling EoL magnets to powder	Company	operation	9	600
Germany	Pforzheim	**HyProMag GmbH**	Hydrogen decrepitation	Recycling to magnetic powder and magnet production. Collaboration with UK sister company in Tyseley.	Company	planning	7	100-330
France	Grenoble	**MagREEsource**	Hydrogenation	From recycled metal powders to new magnets	Company	operation	9	50
France	Lyon	**Carester**	Hydrometallurgy	hydrochloric & nitric based hydrometallurgy, Dismantling	Company	production scheduled in 2026	8	2000
Greece	Polygono	**Monolithos Ltd**	Hydrometallurgy	Existing production plant	Project	pilot	7	630
Italy	Ceccano	**Itelyum**	Hydrometallurgy	Existing pilot plant from FENIX project	Project	pilot	7	NA
Norway	Kristiansand	**Elkem**	High temperature electrolysis	Ionic Liquid Extraction	Project	probably non operational	4	NA
Slovenia	Ljubljana	**Magneti ljubljana**	Hydrogen-based Processing of Magnet Scrap	Hydrogen-based Processing of Magnet Scrap	Project	operation	8	50



Number of new plants (blue) and their total recycling capacity (red) for REE magnet recycling (Koese, 2025)



Funding and investments provided to magnet recycling development and deployment, by country of destination and award date (Koese, 2025)

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Pre processing

Business case for HDD magnet recycling in the Netherlands: theoretical availability

Estimated annual Dutch HDD magnet volume = 58 tonnes (UNITAR personal communication)
Assumed average magnet weight = 27,2g (Nguyen, 2017)
→ Estimated amount of annually wasted HDD magnets = 58 Mg / 27,2g = 2,13 million

Average Dy in magnet = 0,06g (Danczak, 2017)
Average Nd in magnet = 1g : (Danczak, 2017)

Annual Dutch Dy consumption = 15 tonnes (Grondstoffenscanner, 2024)
Annual Dutch Nd consumption = 121 tonnes (Grondstoffenscanner, 2024)

→ Estimated Dy potential = 0,06g * 2,13 million = 0,128 tonnes
= 0,8% of Dutch consumption

→ Estimated Nd potential = 1g * 2,13 million = 2,13 tonnes
= 1,7% of Dutch consumption

Conclusions

State of the art of CRM-recovery from HDD

- HDDs contain several CRM: **In theory, recycling HDD could contribute to 1,7% of the Dutch Nd demand and 0,8% for Dy.** However, these components are not recovered in the Netherlands due to challenges of disassembly, sensitivity over data and the financial business case.
  - The most common route is shredding, followed by sorting and pyrometallurgy.
  - Focused data removal and magnet disassembly is technically possible, as demonstrated by different literature.

Collection

- Collection levels for small and large IT- waste are low in the Netherlands. Learning from France and Belgium, collection could be increased by separation at source (Belgium) and/or a long standing B2B strategy (France).

Magnet recycling:

- There is no rare earth recycling of neodymium and dysprosium or such magnets in the Netherlands. In Europe, magnet material recycling is only now in the pilot or start-up phase, with a couple of past EU projects and the current construction of a few plants in France, Germany and UK. The added capacity of these projects already exceeds the European demand for magnet powders.
  - For the short term, the Netherlands could therefore play a role as a feedstock supplier for recovered magnets to EU companies with better pre-treatment, e.g. manual and mechanical separations and processing.
  - On the long term, the Netherlands could develop its own recycling capacity, exploiting its position as a major (waste) logistics hub. This would require further research on creating a hydrometallurgical industry in the Netherlands, and broader feedstock sources beyond HDDs.

Policy recommendations to stimulate reuse and recycling

Policy recommendations:

1. **Regulatory options** to demand the targeted separation and preprocessing of HDDs instead of current (wasteful) shredding activities. Regulatory options could include posing separate *collection, separation and CRM recycling targets* for actors within the value chain, or *banning the shredding* of HDDs (following the examples of wastes that were banned due to hazardous properties, e.g. asbestos)

2. **Subsidy options** to finance the development and adoption of new circular technology, such as reuse aimed data wiping, automated (magnet) disassembly or hydrometallurgy or melt spinning. These technology themes could be incorporated into the current extensive subsidy landscape, specifically the subsidies aimed at Technology Readiness Level 4-6.

3. **Collaborative options** to ensure a successful and continued exploitation of new circular value chains for recovering, recycling and reusing HDD magnets in the EU. Options could include facilitating purchase agreements between EU magnet recyclers, feedstock suppliers (in the Netherlands) and eventual off-takers.

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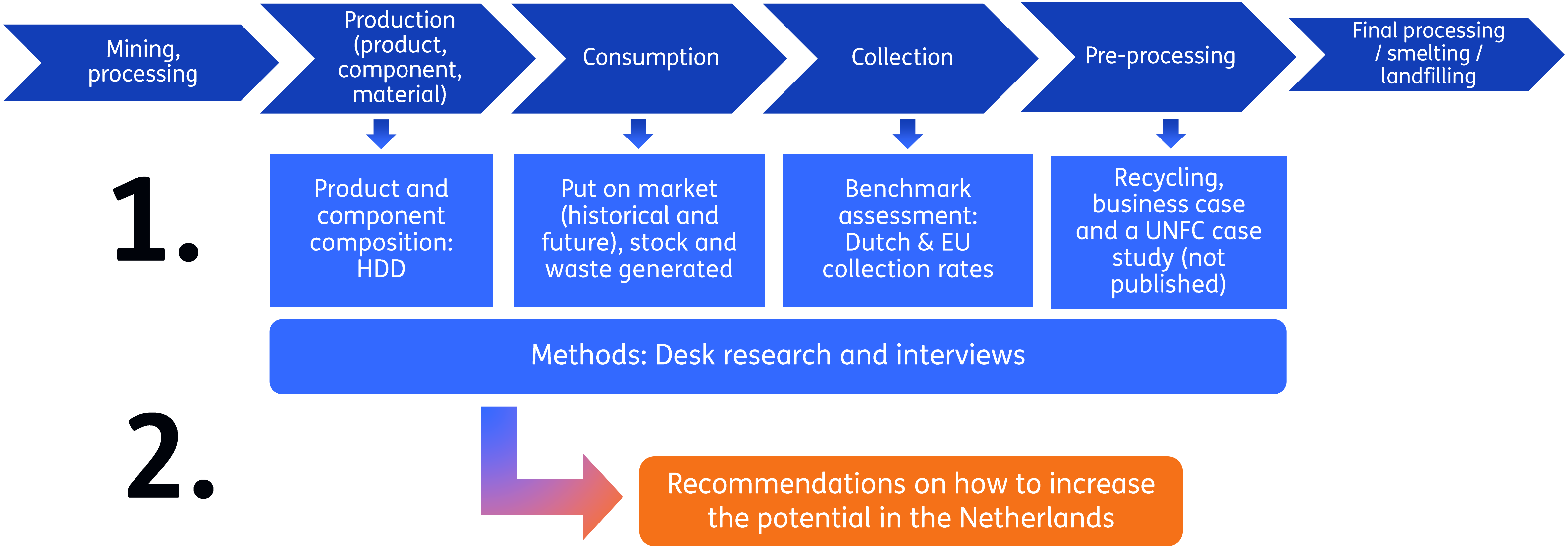
Annex

Approach and methods

Point of departure: Since there is no mining and final processing of the strategic materials from HDD in the Netherlands we begin from the production stage. See the annex for an in-depth description of the method.



Method and approach explanation

Approach

To examine the extent to which waste HDDs in the Netherlands can contribute to the recycling ambitions of the CRMA, this study followed an in-depth case study approach. Such an approach allows for a detailed exploration and understanding of a singular case in a bounded system. In this instance, examining the potential (economic, technological, or policy) to increase CRM recovery in the Netherlands.

This research followed a four-step approach. First, examining the product and material compositions of HDDs. Second, a quantitative description of HDDs in the Netherlands (using historical data to the most recent available). This included HDDs (and their respective waste category) that were put on the Dutch market, currently in stock, and generated as waste. Third, we analysed the current collection and recycling system, including creating an overview of the relevant actors, collection, and recycling rates. The performance of the Netherlands was benchmarked against three nearby countries (France, Belgium, and Germany), where the Netherlands has a lower collection rate. Based on this benchmark, we interviewed the Dutch, French, and Belgian organizations involved in the collecting and recycling. We approached the respective German organization but had no response to our requests. This interview data allowed us to gain insight into potential reasons why the Netherlands' collection rates were lower, and how this could possibly be improved. Finally, we examined the existing business case for recovering magnets containing CRMs from HDDs to illustrate the potential of CRMs available from Dutch waste. We examined a specific organization that had explored recovering them using robotic technology. This we classified using the United Nations Framework Classification for Resources (UNFC).

Methods

This research used a combination of desk research and five semi-structured interviews with four organizations (see acknowledgements slide). In addition, it combined market data on material prices against volumes of CRMs in Dutch waste flows containing HDDs to create a Sherwood plot. This is presented in the subsequent annexes. Finally, the UNFC was used to classify a specific project in the Netherlands. Due to confidentially reasons this was not published.

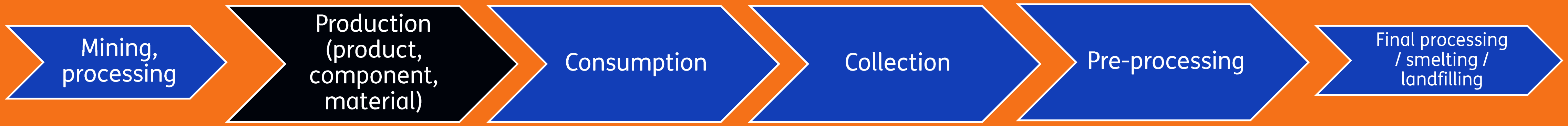
Data Used

Scientific literature, EU policy and market literature on HDDs, EU policy, and waste dynamics in the Netherlands. Quantitative data came from Eurostat, the Dutch Bureau of Statistics (CBS), S&P data, and ProSum. All references are listed in the reference slide.

Limitations

This research is primarily limited due to the number of interviews (N=5), which only allowed a more general understanding of the contrasts between the Belgium, Dutch, and French systems. In addition, the ProSUM data, which contains the best insights on HDD quantities in the Netherlands, only extends to 2020. Thus, the data misses the previous three years and does not provide insights into the exact future trends. Such limitations should seek to be improved on in subsequent studies.

Product and component material composition



Hard disk drives contain many strategic raw materials, such as neodymium, boron and dysprosium, in the permanent magnets

- HDDs were invented as data storage devices in the 1960s. They're mainly used in:
  - Desktops and laptops (the HDDs in desktops are larger than those in laptops);
  - Network Attached Storage (NAS): 'home servers' in other words;
  - External hard disk for computers and gaming consoles,
  - Automotive vehicles;
  - Surveillance cameras;
  - Data centres / Cloud storage (use higher quality HDD, with larger magnets).
- The main components that contain SRMs are the aluminium casing, PCBs (which contain palladium) and the permanent magnets (which contain neodymium, boron and dysprosium)
- In 2014, between 6-16% of global neodymium use was for HDDs.
- In recent years, solid state drives have risen in popularity due to their larger storage funds and faster processing speeds

Hard Disk Drives components

Common desktop class- HDD sizes for consumer goods are either 3,5” (desktop) or 2,5” (laptop). Components are:

- **Casing**: for protection
  aluminium and stainless steel
- **Platter**: to store magnetised bits
  aluminium, glass or ceramic, with thin magnetic coating (e.g. Ruthenium)
- **Spindle**: rotates the platter with 5400 to 1500 rpm. Also contains a permanent magnet.
- **Write head**: writes or reads the information on the disk with an electromagnet
- **Printed Circuit Board**: controls and powers the electronics
  gold, silver, palladium
- **Air filter**: controls the air pressure in the HDD so that the write heads glide on the correct flying height.
- **Actuator arm**: extension for the write heads
- **Actuator**: moves the arm with an electromagnet (iron, copper) and a permanent nickel plated neodymium magnet ($Nd_2Fe_{14}B_2$)

Enterprise HDD have a similar architecture as desktop class HDD. The individual parts are however generally larger (e.g. larger magnets), improving stability and speed. Also, they contain more electronics for extra control of the operation.

Table 1. The average mass (g) of HDDs components

	The average mass (g)	
	3,5" HDD	2,5" HDD
Total mass	517.3 ± 64.2	108.2 ± 24.3
Top cover	111.6 ± 40.4	12.6 ± 5.3
Mounting chassis	242.0 ± 46.1	56.2 ± 7.2
Electronics card	41.3 ± 19.3	12.8 ± 2.6
Platters	31.0 ± 15.5	8.4 ± 4.2
Platter’s mounting	5.9 ± 2.9	3.5 ± 1.2
Spindle	53.3 ± 14.6	
Read/write head with the arm	18.9 ± 5.9	
Screws	7.2 ± 1.7	2.0 ± 1.0
Magnet assembly of actuator	48.6 ± 21.9	12.6 ± 5.8
Remainings	2.6 ± 2.2	5.5 ± 4.5

Fig. 3. The examples of magnets assembly of actuator from different hard disk drives (HDDs)

Source: (Nguyen, 2017)

HDD CRM content

There are multiple studies done on the CRM content of HDDs. The table on the right gives a summary of 3 relevant studies. Since the used HDD samples differed, so do some of the results on for instance Al, Cu and Pd.

Looking at the current recovery rate of these elements, noticeable gaps are found at the rare earths Nd, Pr and Dy. This indicates a clear potential in the recovery of these CRM from HDD.

Element	g per HDD unit (Cucchiella,2015)	*Financial worth of CRM ($)* (Cucchiella, 2015)	Concentration (mg/kg) (Buechler, 2020)	Weight composition (Nguyen, 2017)	Recovery rate business as usual (without rare earth hydromet) (Nguyen,2017)
Al, aluminium	441,000	1,06	60.911	54,89%	100%
Cu, copper	15,000	0,11	137.825	5,47%	79,47%
Dy, dysprosium	0,060	0,02	105	0,12%	0%
Au, gold	0,005	0,40	136	0,002%	96,5%
Nd, neodymium	1,000	0,05	1992	0,92%	0%
Pd, palladium	0,003	0,23	6608	0,002%	60%
plastics	44,000				
Pr, praseodymium	0,145	0,01	332	0,08%	0%
Ag, silver	0,031	0,03		0,06%	83,93%
Fe, steel/iron	62,000	0,01	41.567	22,5%	95,07%

Danczak performed a study on the composition of NdFeB magnets specifically. A screenshot is provided on the right.

Table 6. The results of chemical analysis of NdFeB magnets (values in weight %)

No. of sample	B	Fe	Ni	Dy	Nd	Pr	Co
1	0.867 ± 0.019	53.3 ± 0.3	3.37 ± 0.10	1.42 ± 0.04	28.7 ± 0.6	2.05 ± 0.09	3.61 ± 0.05
2	0.871 ± 0.040	61.9 ± 0.1	1.92 ± 0.06	0.818 ± 0.003	26.4 ± 0.2	11.3 ± 0.2	0.540 ± 0.025
3	0.848 ± 0.009	55.3 ± 0.6	6.38 ± 0.03	1.33 ± 0.09	24.9 ± 0.8	12.8 ± 0.2	0.486 ± 0.008
4	0.959 ± 0.056	55.2 ± 0.2	2.79 ± 0.02	0.080 ± 0.002	26.2 ± 0.2	11.3 ± 0.5	1.01 ± 0.07

Source: (Danczak, 2017)

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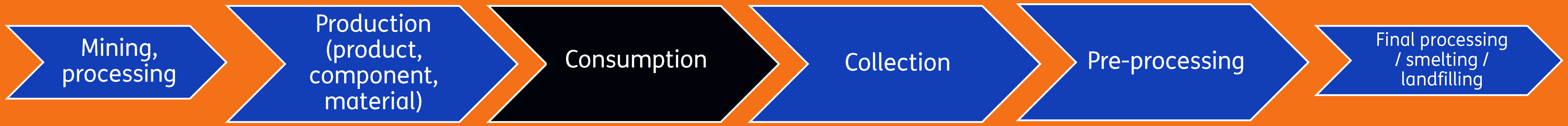
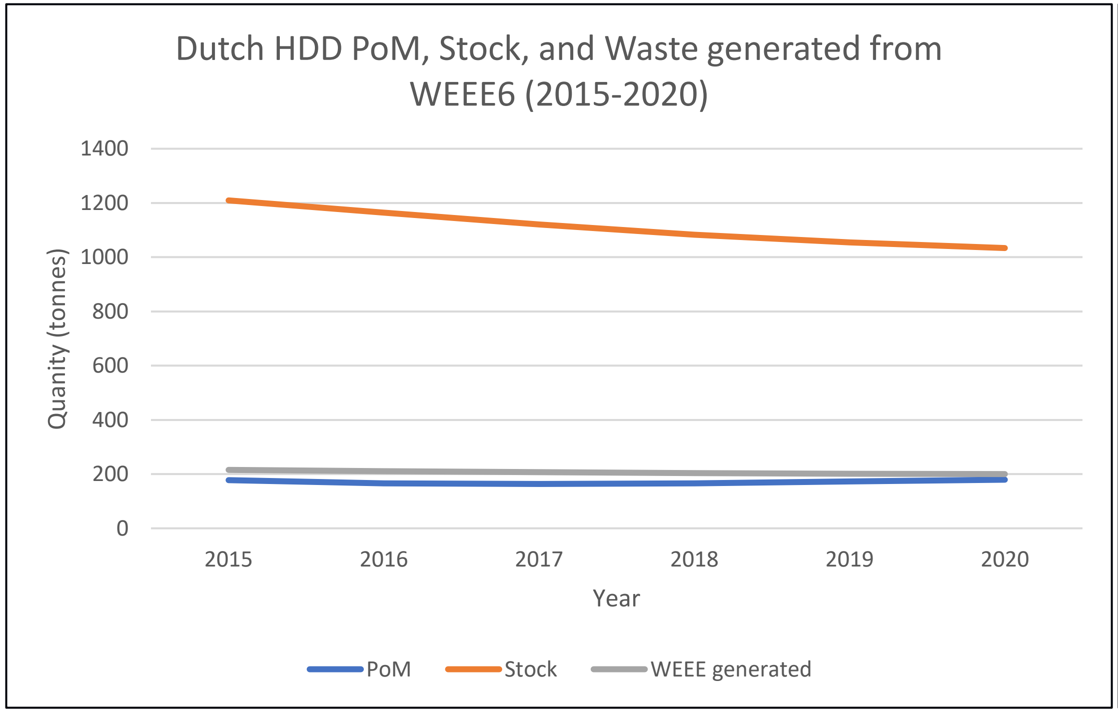
Consumption

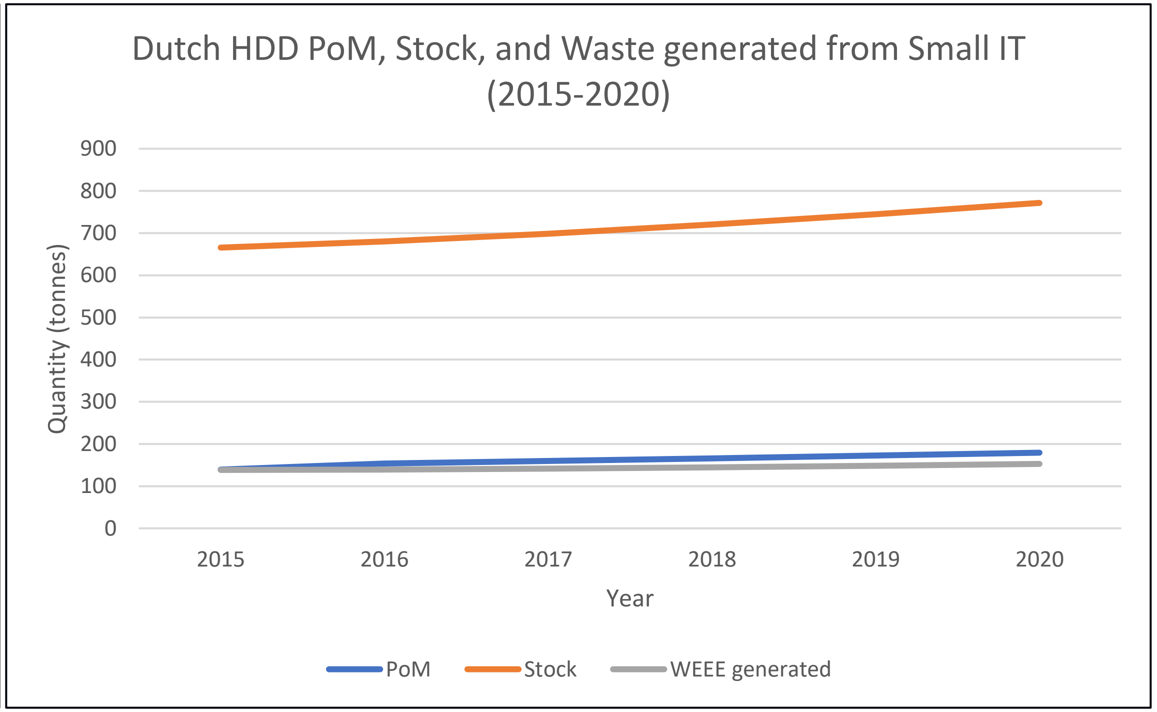


WEEE Directive (2012) product category overview

Category	Examples
1. Temperature exchange equipment	Refrigerators, Freezers, Equipment which automatically delivers cold products, Air conditioning equipment, Dehumidifying equipment, Heat pumps, Radiators containing oil and other temperature exchange equipment using fluids other than water for the temperature exchange.
2. Screens, monitors, and equipment containing screens having a surface greater than 100 cm^2	Screens, Televisions, LCD photo frames, Monitors, Laptops, Notebooks.
3. Lamps	Straight fluorescent lamps, Compact fluorescent lamps, Fluorescent lamps, High intensity discharge lamps - including pressure sodium lamps and metal halide lamps, Low pressure sodium lamps, LED.
4. Large equipment	Washing machines, Clothes dryers, Dish washing machines, Cookers, Electric stoves, Electric hot plates, Luminaires, Equipment reproducing sound or images, Musical equipment (excluding pipe organs installed in churches), Appliances for knitting and weaving, Large computer-mainframes, Large printing machines, Copying equipment, Large coin slot machines, Large medical devices, Large monitoring and control instruments, Large appliances which automatically deliver products and money, Photovoltaic panels.
5. Small equipment	Vacuum cleaners, Carpet sweepers, Appliances for sewing, Luminaires, Microwaves, Ventilation equipment, Irons, Toasters, Electric knives, Electric kettles, Clocks and Watches, Electric shavers, Scales, Appliances for hair and body care, Calculators, Radio sets, Video cameras, Video recorders, Hi-fi equipment, Musical instruments, Equipment reproducing sound or images, Electrical and electronic toys, Sports equipment, Computers for biking, diving, running, rowing, etc., Smoke detectors, Heating regulators, Thermostats, Small Electrical and electronic tools, Small medical devices, Small Monitoring and control instruments, Small Appliances which automatically deliver products, Small equipment with integrated photovoltaic panels.
6. Small IT and telecommunication equipment (no external dimension more than 50 cm)	Mobile phones, GPS, Pocket calculators, Routers, Personal computers, Printers, Telephones.

Dutch historical HDD put on market, stock and waste indicates an overall decrease in quantity across all categories, but rising in Small IT.





Source: (Statistics Netherlands, 2024; Huisman et al., 2017).

WEEE6 refers to all product categories in the WEEE Directive (see slide 26). Small IT covers all the equipment covered by that product category (see slide 26).

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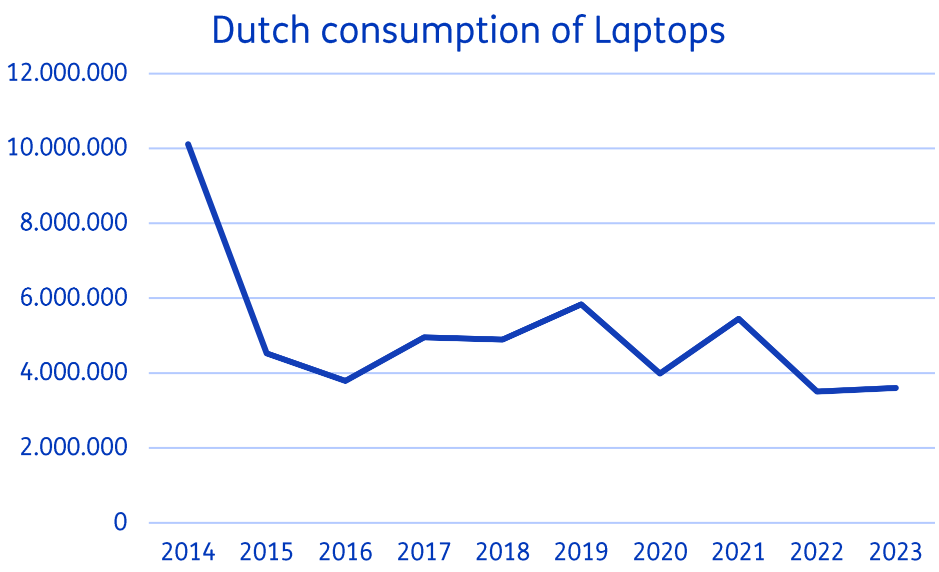
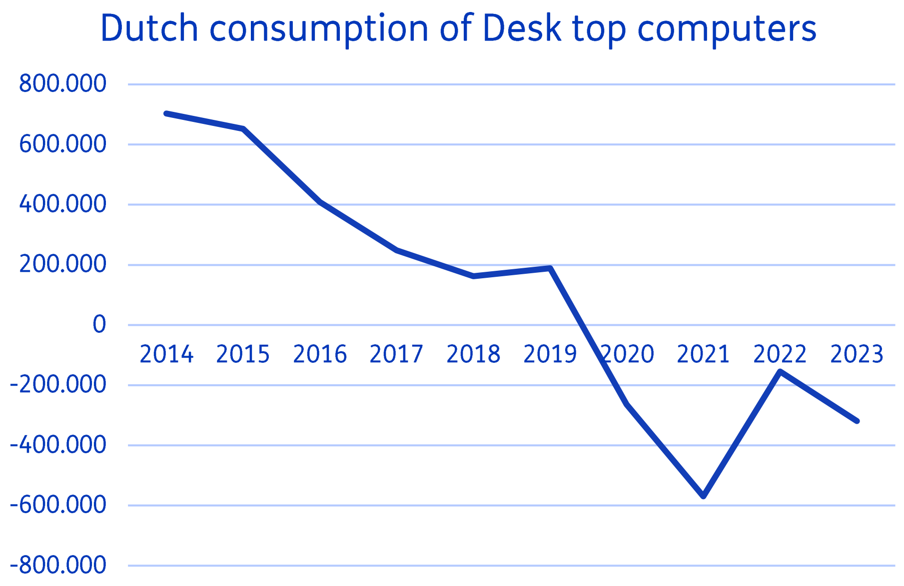
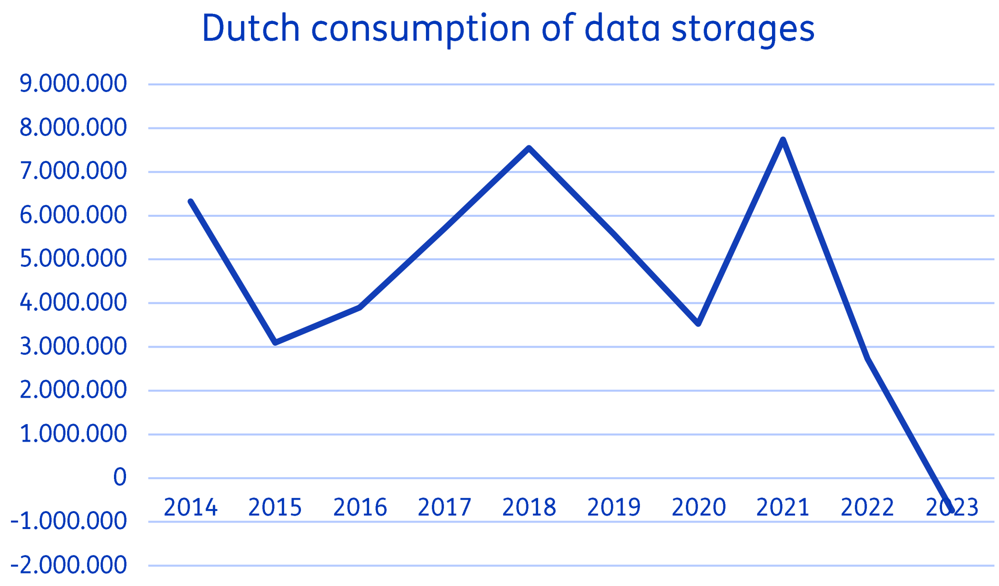
Dutch historical consumption of products containing HDDs



- Dutch consumption (import + production – export) has stabilized: 4 million units per year in 2023
- Since 2020, more desktop computers are exported from the Netherlands (shift away from desktop computer monitors).
- Data storage units were exported more in 2023 (for the first time), from previously high levels of consumption.
- Coupled with previous page, laptops consumption has stabilized, meaning 'stock' is increasing. Desktop stock and consumption is inconclusive (but likely decreasing) and data storage is likely decreasing.





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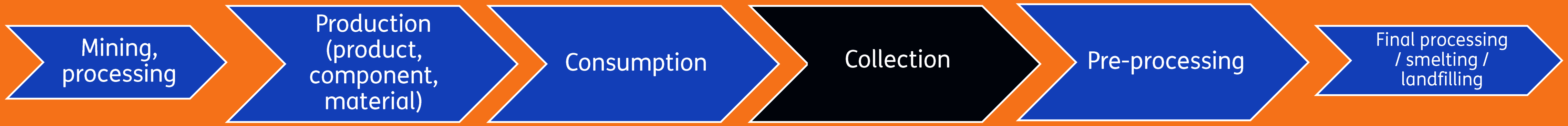
Collection


Mining, processing
Production (product, component, material)
Consumption
Collection
Pre-processing
Final processing / smelting / landfilling

The policy and organisational context for WEEE in the Netherlands is complex, with many actors involved

- E-waste (WEEE) is regulated under the WEEE Directives (EU, 2008) and which is currently under review, and modified by the WFD (2008, 2018). Directive deploys the principle of **extended producer responsibility**, where the producer (defined as any actor who brings the product onto the member state’s market) must contribute to organising and financing the collection and recycling;
- ‘Producers’ must collect up **to 65% of the weight/mass of waste products** each year and recover, e.g. reuse, recycle and incinerate for energy, up to 85% of what is collected. This is reported to the Dutch and EU governments (WEEE Directive, 2012).
- In the Netherlands, this is translated to sector plan 71 (Afgedankte elektrische en elektronische apparatuur) of the national waste management plan (Landelijk afvalbeheerplan 3). This deploys a technological minimum processing standard for WEEE.
- In the Netherlands, organising the collection and recycling is organised on behalf of the ‘producers’ by a third party – Stichting OPEN. A non-exhaustive overview of key actors in the value chain is shown here.
- **Recovering CRMs is not a part of the WEEE Directive or the Dutch LAP3**. They only focus on mass or bulk processing and reporting. However, reporting CRMs from WEEE is now part of the CRMA. Stichting OPEN collects data on the SRMs Copper and Aluminium.

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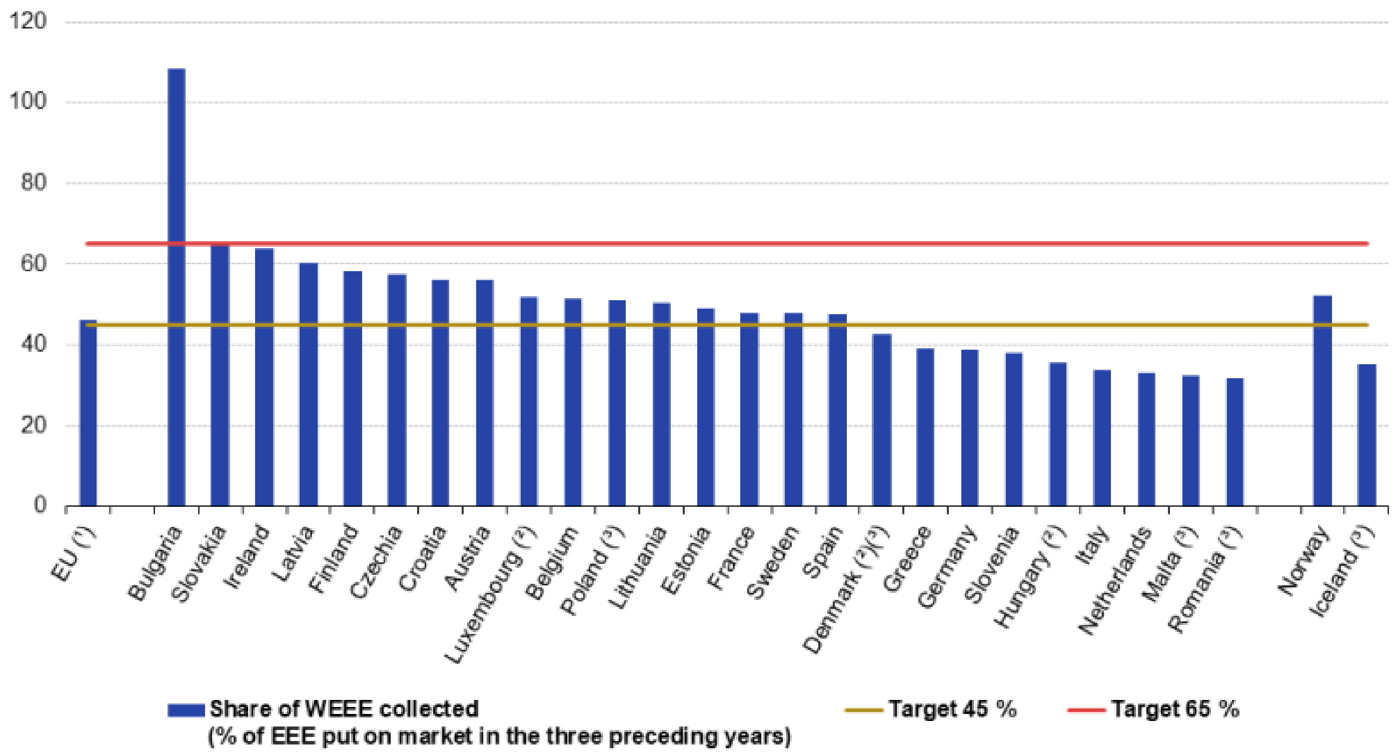
Dutch collection levels are below EU targets, and lower than neighbouring countries

Total collection rate for waste electrical and electronic equipment (EEE), 2021
(% of average weight of EEE put on the market in the three preceding years)



(¹) Eurostat estimate.
(²) 65 % target not applicable. Country applies calculation methodology based on WEEE generated: see Figure 2b.
(³) 2020.
Source: Eurostat (online data code: env_waseleeos)

eurostat

- Dutch collection levels dropped in 2021 to 33% from 44% in 2020*, likely due to the Covid pandemic.
- Overall Dutch collection levels are below the EU targets
- Collection levels are also lower to countries with comparable levels of consumption and maturity of systems, e.g. France, Belgium and Germany.
- The Netherlands collected 17% less than Belgium in 2021.

*this includes PV panels. Without PV, Dutch collection goes above 50% in 2020.

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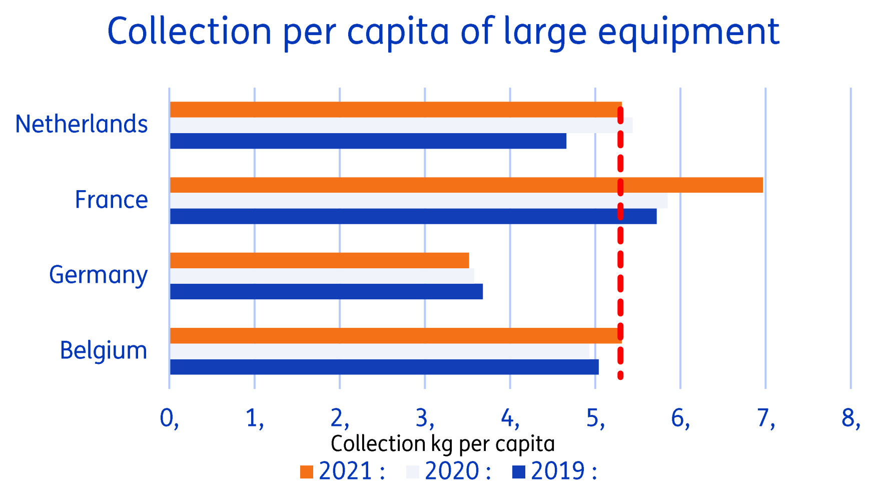
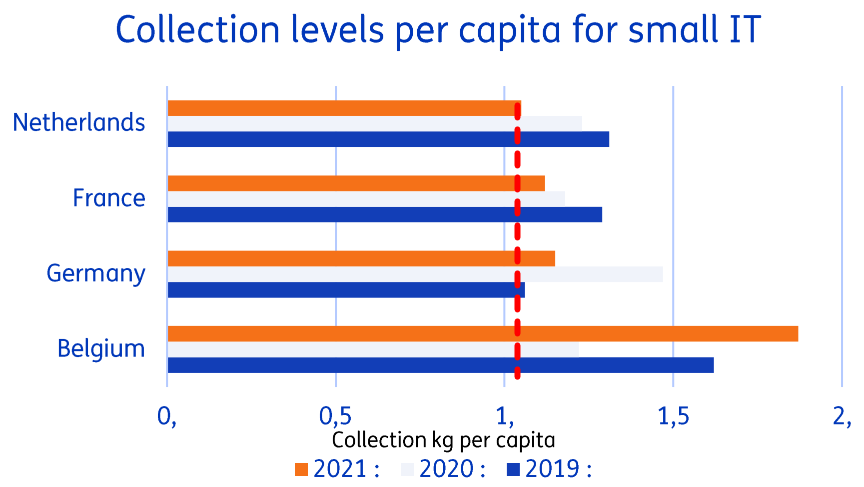
Collection levels for the waste streams containing HDD are also lower against EU counterparts





Baseline assessment: On a per capita basis, the Netherlands has lower collection levels for waste streams containing HDDs compared to EU counter parts.

For Small IT, France collects roughly 0,05 kg per capita more, while Belgium collects roughly 1 kg more.

For Large equipment, France collects more per capita.

Note: the data here only includes publicly disposed products (households and businesses). HDDs disposed of privately, or resold are not included here.

Source: (Eurostat, 2024)

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EU collection levels additional data

TIME	2012		2013		2014		2015		2016		2017		2018		2019		2020		2021	
GEO (Labels)																				
European Union - 27 countries (from 2020)	38.6	s	:		:		:		:		:		46.8	s	48.8	s	46.2	s	:	
Belgium	39.4		38.8		38.6		41.4		47.9		46.1		49.4		51.2		50.7		50.2	
Bulgaria	72.8		67.8		78.8		106		97		79.4		73.4		81		92.2		108.3	
Czechia	30.4		31.4		33		42		:		58.3		48.7		54.2		57		57.5	
Denmark	52.5		50.1		50.8		50.3		47.9		44.9		44		43.3		42.7		:	
Germany	40.9		42.2		42.9		42.5		44.9		45.1		43.1		44.3		44.1		38.6	
Estonia	42.4		32.9		42		50.5		59.8		59.1		62.6		64.2		61.5		53.8	
Ireland	42.3		45.6		50.1		:		:		:		64.6		61.3		60.4		63.8	
Greece	20.5		24.6		33		36.8		41.4		42.4		44.6		47.3		40.9		39.1	
Spain	22.5		:		:		:		:		48.2		50.7		55.2		52.3	e	47.8	
France	29		29.4		32.5		39.3		45.3		44.7		46.1		45.7		42.4		48.1	
Croatia	37.6		35.5		37.2		60.1		94.1		81.6		83.5		72.9		69		56.2	
Italy	48.4		43.6		34.5		39.4		41		40.8		42.8		39.4		36.5		33.8	
Cyprus	14.1		14.5		18.2		28.5		28.7		57.1		36.3		25.3		32.1		28.6	
Latvia	30.2		30.3		29.3		27.7		26.3		49.8		49.5		51.1		41.8		57.5	e
Lithuania	58.3		62.1		81.6		55.8		43.4		42.1		44.1		47.7		45.6		50.6	
Luxembourg	31.8		33.4		40.2		48.9		52.2		51		50		54.2		53.6		53.8	
Hungary	35.9		45.6		54.8		60.8		63.5		60.6		59.3		52.2		44.3		35.6	
Malta	10.8		12.2		11.9		13.2		16.3		21.8		27.5		40.1		32.1		25.6	
Netherlands	198.6		78		61.1		45.8		47.9		49.6		48.9		48.5		43.8		33.5	
Austria	47.7		47.6		49.1		50.2		50.1		62.4		57.6		62.1		62.1		56.5	
Poland	36.2		34.7		35		40.2		45.6		45.4		44.7		72		61.8		63.3	
Portugal	28.7		37.1		49.1		53.6		55.8		53.9		51.9		33		32.9		26.9	
Romania	17.2		24.2		24.4		30.1		31.5		29.3		31.5		38.1		34.5		:	
Slovenia	33		29.7		33.7		36.2		46.2		39.1		40.2		42.1		38.8		38.1	
Slovakia	48.3		47.3		48.7		47.6		55.7		52.1		51.1		56		62.4		65.1	
Finland	36.3		40.3		47.1		46.7		47.3		53.5		54.8		57.9		63.3		54.7	p
Sweden	74.1		77.5		62.7		61.7		66.4		56.3		54.5		58.5		50.9		48	
Iceland	35.7		33		44		46.6		47.2		48.5		37.6		:		:		:	
Liechtenstein	:		:		157.1		174.1		153.3		111.7		123.1		:		:		:	
Norway	58.4		57		58.3		57.7		57		54.7		53		55.8		55.9		52	

Qualitative insights on international collection rate and strategies

Netherlands

- 13.000 collection points in the country.
- No specific collection measures for product groups containing HDD. HDDs are cannibalised / sold due to value from consumer streams due to value. Main challenge is getting it into the official streams.
- Overall, the main obstacle for the higher collection of WEEE (as stated by the PRO) is from B2B. Consumer level is high, but B2B is work in progress. In two years (60,000 tonnes missed).
- 6.25% of operating budget goes on consumer campaigns / consumer awareness.
- Interview: Stichting OPEN

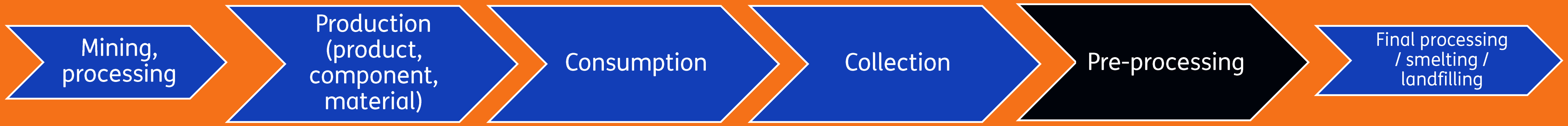
France

- 12.000 Collection points in France (lower per capita and square km basis). France has, since its WEEE policy inception, focused on B2B campaigns, specifically for ICT. 1-2% of operating budgets are spent on R&D.
- No specific measures for product groups containing permanent magnets (aside from specific campaigns for ICT in general). There is competition between actors for ICT due to commercial value in the reselling market. Interviewee indicated that they have explored Nd in HDD magnets, but see lower quantities compared to other WEEE sources, e.g. e-bikes and vacuum cleaners.
- Main challenge for collection is getting the right information to consumers at the right time and getting them to think.
- Interview: Ecologic

Belgium

- 11.729 collection points in Belgium (higher per capita and on a square km basis). Belgium does WEEE separation at the collection point, not via sorting as in the Netherlands.
- Belgium separates waste at source, not via collection centres. No specific measures for product groups containing permanent magnets. However, there is a separate measure for operators to remove PCBs. Company policy is not to communicate budget spent on consumer campaigns.
- Main challenge for collection is to tackle the secondary informal market.
- Interview: Recupel

Pre-processing



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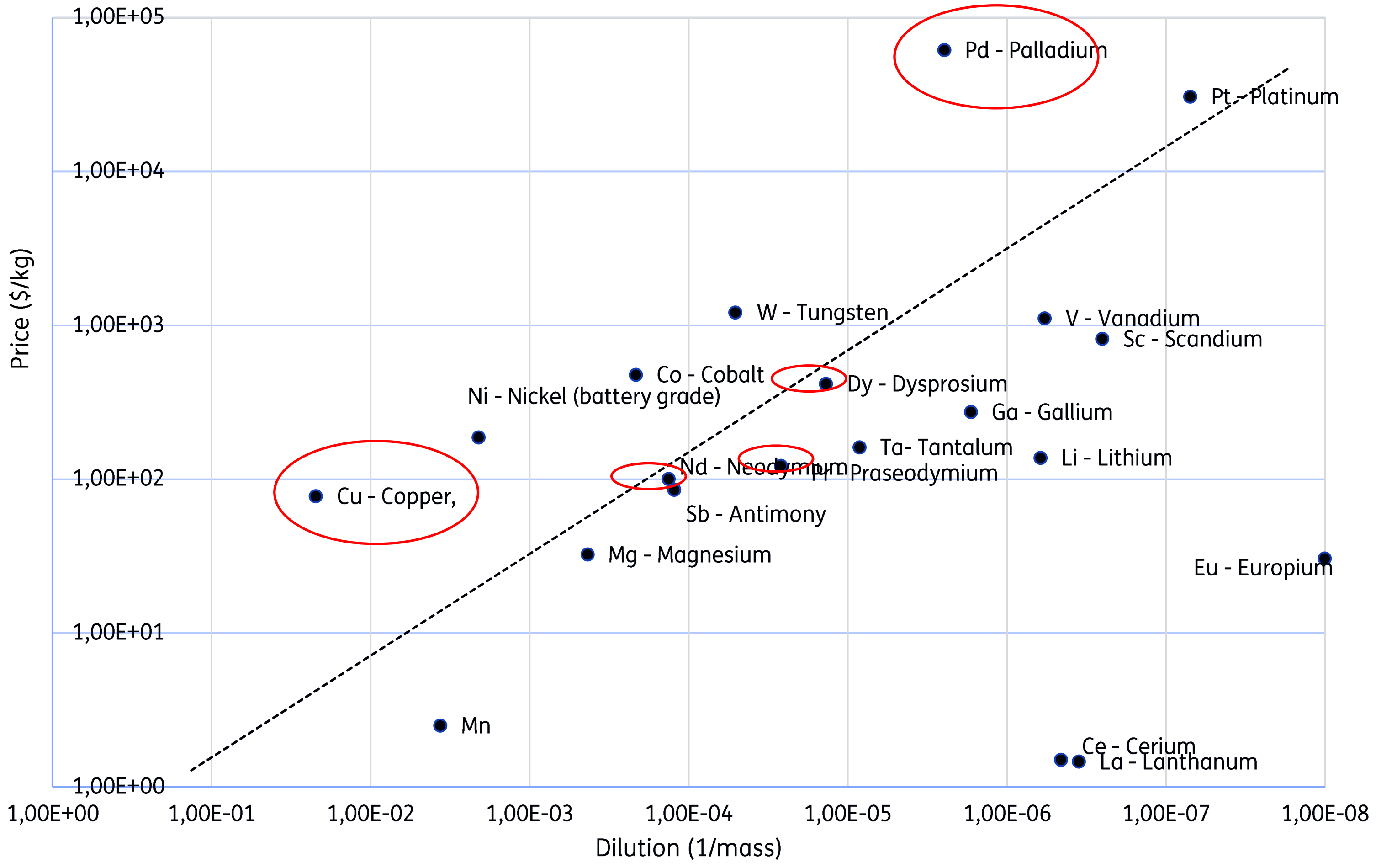
A Sherwood plot for materials in all Dutch waste IT

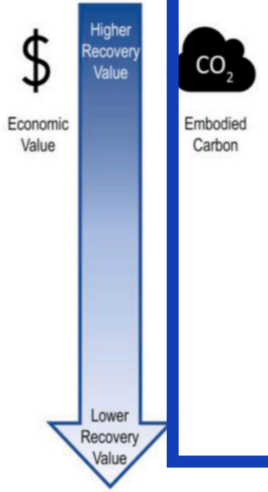
By plotting the price and dilution of materials present in waste, we can map the (potential) profitability of recovering that material. The diagonal dotted Sherwood line gives a rough indication of that profitability. Materials above the line are generally recoverable, while the materials below are too diluted or have a too low price point for economic feasibility.

CRMS with a red circle are those present in HDDs. Pd and Cu are known to be recovered in existing processes, neodymium, dysprosium and praseodymium are not. However, dysprosium and neodymium are at the edge of the line. This indicates that the better pre-processing and concentration of the magnets would make the material recovery of these materials (theoretically) profitable combined with hydrometallurgical recovery (see slide 24). This implies there is either a financial, technological or regulatory push is needed to achieve this.



HDD R-strategy options

Table 1
The HDD & RE magnet value recovery cascade. The table was summarized from Frost et al., (2020). These are listed in order from highest to lowest economic and environmental value.



Value Recovery Option	Description of Technology/Process	Barriers/Opportunities for Circular Business Model
HDD reuse	Secure data wiping and internal company reuse or sell to secondary markets	Highest value recovery option and most environmentally beneficial. A common practice of shredding HDDs for data security reasons precludes other downstream uses.
HDD component reuse (e.g. magnet assembly)	Disassemble, recover and reuse or remanufacture HDD components	Requires active collaboration among end users (or ITADs) and HDD manufacturers. Currently limited by placement within similar drive model
Intact magnet recovery for non-HDD Use	Magnets are punched out of HDD and reused as intact magnets for axial gap motors	Technology is theoretically viable*, but motors must be designed with reusing HDD magnets in mind.
Magnet-to-magnet recycling*	Process HDD RE magnets into new sintered magnets with magnetic properties similar to HDD magnets	Magnets need to be certified in HDDs to close the loop, locked in linear supply chains for RE magnets. Need sufficient volumes of HDD RE magnets
Making RE Oxides from HDD magnets and other precious metals recycling	HDD magnets can be processed into high purity RE oxides* for open or closed loop recycling	Process needs to be scaled beyond pilots, traceability of RE oxides is difficult; locked in linear supply chains

*See Handwerker and Olson (2019) for detailed technology description.

Complete reuse of HDD saves up to 69% of global warming impact (Jin, 2020).

Smashing and shredding of the HDDs is still most common, since the volume of waste HDDs is uncertain and the business case for recovering other materials is uncertain.

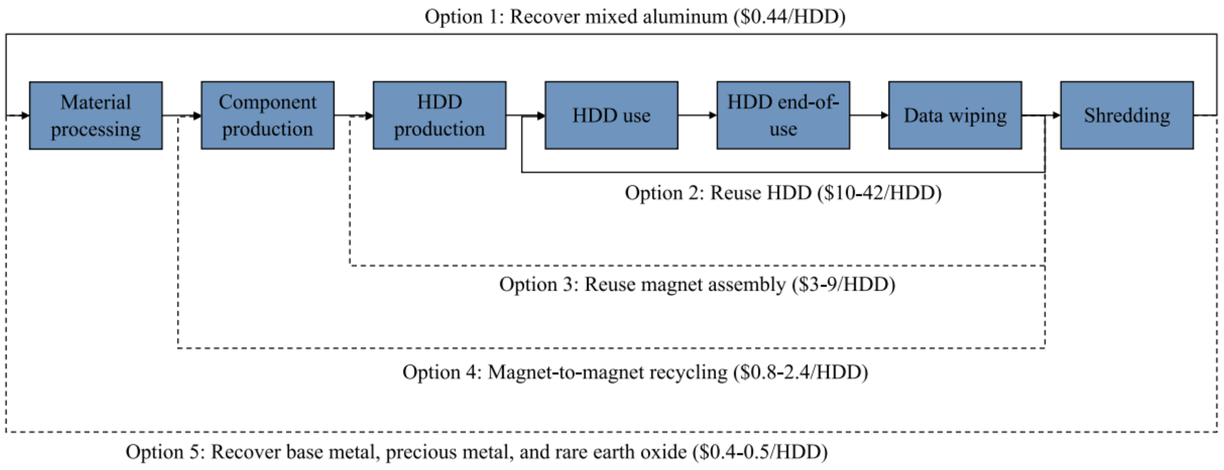


Fig. 1. Enterprise HDD recovery options with recovered values shown in US dollars in parenthesis (iNEMI, 2019)

Magnet disassembly (and reuse)

Due to the generated magnetic fields and layer of glue keeping the magnets into position, sintered NdFeB magnets are difficult to separate from the metal plates. One option is demagnetization through either an opposite magnetic field or heating above the Curie temperature (585K). (Danczak, 2018) *. Another option is applying force through the use of tweezers and spludgers.*

The Peiró study assessed the needed time to disassemble the PCB and Permanent Magnets (PM).

Table 2
The time (seconds) and the economic cost (€) to separate the PCB and the PMs contained in HDDs.

Target parts		2.5″ HDD units		3.5″ HDD units	
		Time (Seconds)	Cost (Euros)	Time (Seconds)	Cost (Euros)
PCB	Min	13	0.04	10	0.03
	Max	16	0.05	16	0.05
PM1	Min	22	0.07	15	0.05
	Max	30	0.09	31	0.09
PM2	Min	37	0.11	28	0.08
	Max	51	0.15	55	0.16
PM3	Min	82	0.25	59	0.18
	Max	103	0.31	115	0.35
PCB + PM1 + PM2	Min	49	0.15	39	0.12
	Max	63	0.19	71	0.21
PCB + PMs	Min	94	0.28	70	0.21
	Max	116	0.35	131	0.39

Frost performed a LCA on the dismantling of 6100 magnet Assemblies (MA) from data center HDD in the USA and then reusing them at a HDD producer in Thailand. This resulted in a 86% decrease in global warming potential in comparison to the Business As Usual production of Nd magnets from virgin resources. Magnet assemblies (MA) contribute to 8% of HDD total materials impacts.

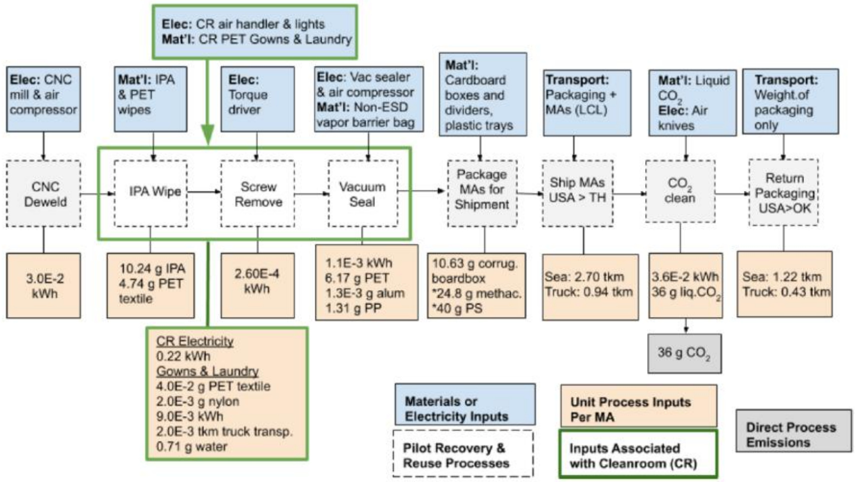
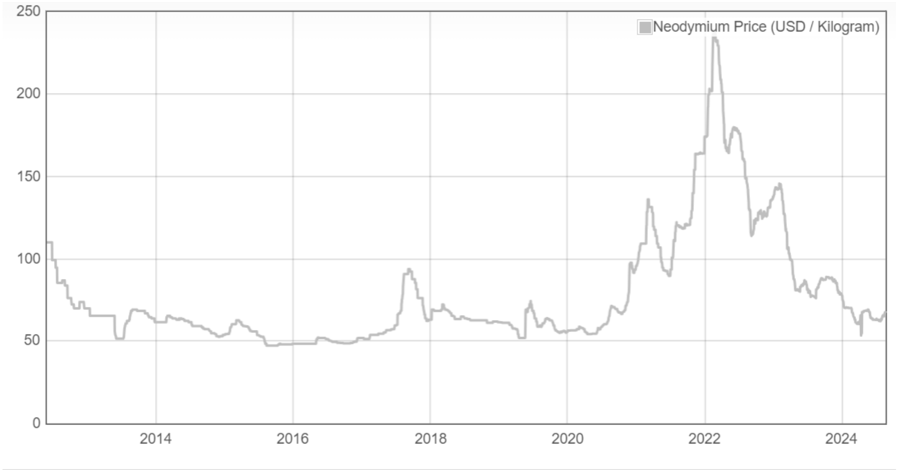
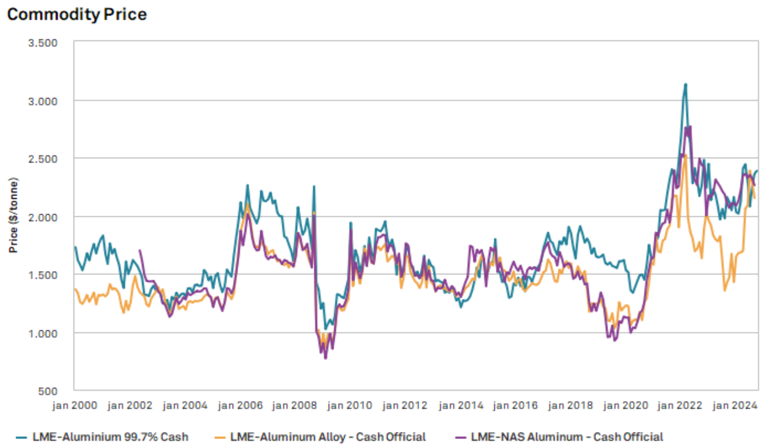


Fig 3. Material and energy inputs, direct emissions, and associated unit process data for the MA recovery process of the MA set from one HDD (Model Number ST16000NM003G). IPA= isopropyl alcohol, PET= polyethylene terephthalate, CNC= computer numerical controlled, methac. = methacrylate, PS= polystyrene, Non-ESD = non-electrostatic discharge, PP = polypropylene. Material and electricity inputs associated with operation of the cleanroom (CR) are highlighted separately in the green boxes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Value of main SRMs in HDDs peaked in 2022, and have stabilized since



Neodymium prices (USD/kg). 70$/kg (Daily Metal Price, 2024)



Historical Aluminium prices. Source SSP Global

Palladium prices (USD/kg). 3000$/kg

Source: Daily Metal Price: Neodymium Price (USD / Kilogram) Chart for the Last Max

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Pre-processing for recycling

Dutch **sorting** companies offer a price of € 1,35 per HDD kg. The most important activity is the safe destruction of present data by shredding, following data protection regulations (WEEELABEX). Data wiping alternatives to shredding are melting, drilling and degaussing (magnetisation). Shredded HDD are then separated for ferrous, non-ferrous and plastic recyclate fractions by magnets, eddy currents, floatation and centrifuges.

After sorting, the resulting waste streams are then recycled by **pyrometallurgy** companies that recover only the valuable high concentration elements (Gold, Palladium, Silver). Silicon metal and Neodymium are oxidized and then lost in the pyrometallurgical process.

Hydrometallurgical routes for PCBs could be considered to recover Si and other valuable metals (PMs, Cu). In this case, the preparation processes (dismantling and separation) must be optimised within the design to enhance the economics of the process

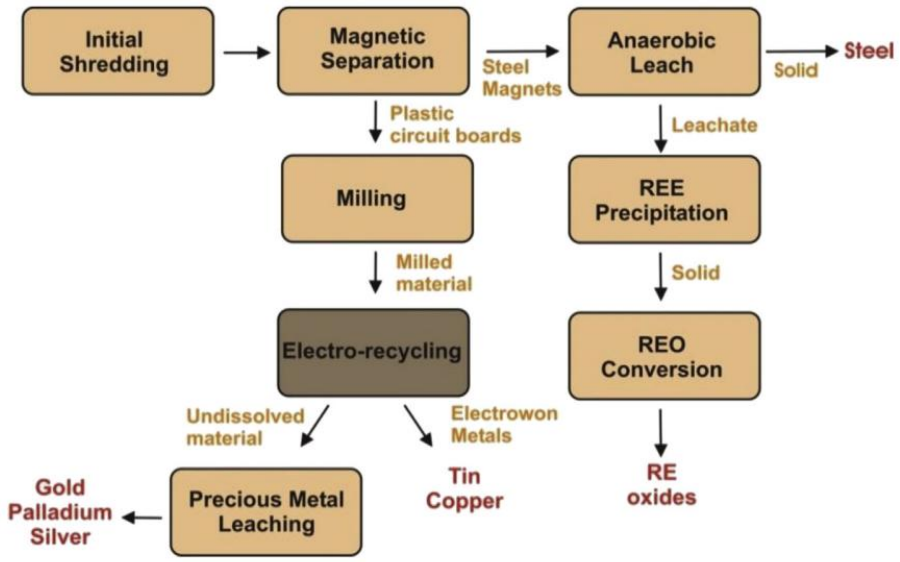


Fig. 2. Flow diagram for the comprehensive recovery of value and critical materials from electronic waste.

Source: Diaz

A pilot in Barcelona dove deeper into this feasibility of using **nondestructive processes to harvest PCBs and permanent magnets (PMs)** to recycle them more efficiently. They concluded **that separating PCBs and PMs from HDDs is economically profitable.** Since the economic costs of non-destructive separation and harvesting the PCBs and PMs are lower than the economic value of the gold, silver, and palladium contained in the PCB [Peiró].

TNO Nederlands Materialen Observatorium

There is a secondary market for complete HDDs, and varying prices for specific components, e.g. PCBs

- Class 1-A PCBs are old PCBs with galvanically gold-plated contacts. **13,84 €/kg up to 1t**
- Class 1-B PCBs are PCBs from computers / industrial equipment which have visible gold-plating and numerous chips. **10,38 €/kg up to 1t**
- Class 1-C PCBs are colourful motherboards without attachments from computers. **3,11 €/kg up to 1t**
- Class 2-A PCBs are PCBs from industrial equipment which, however, unlike class 1 PCBs, have hardly any visible gold contacts. **3,11 €/kg up to 1t**
- Class 2-B PCBs are PCBs from industrial equipment which, however, unlike class 1 PCBs, have hardly any visible gold contacts. **1,66 €/kg up to 1t**
- Class 3 PCBs are boards with large components such as capacitors, transformers, heat sinks and only a few components / chips or contacts containing precious metals. **0,76 €/kg up to 1t**

Hard disks

Description:

Hard disks / computer hard disks with control board and aluminium housing without other attachments.

Purchase price 22.08.2024

1,23 €/kg up to 1t

Prices for special or larger lots on request / after material inspection

Source: (Precious-metal services, 2024)

Closed loop recycling initiative

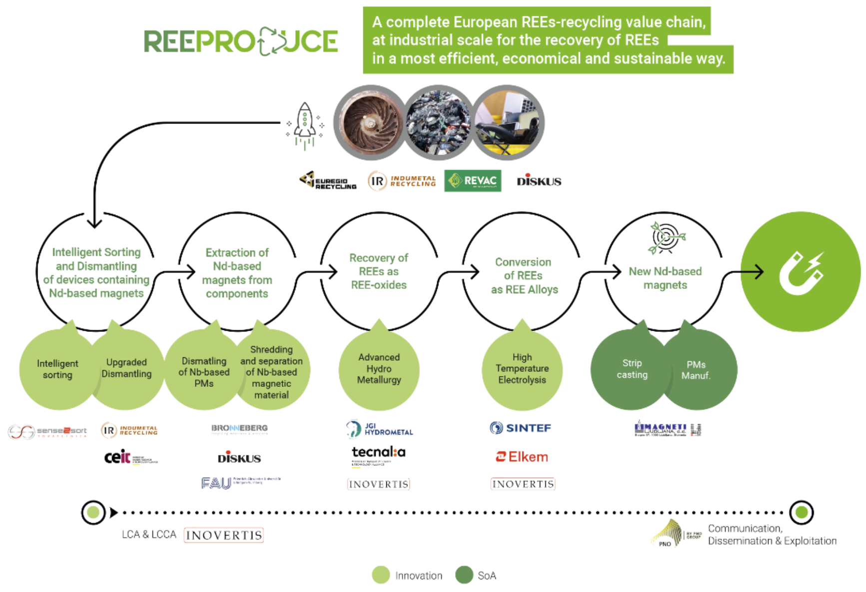
- Dell, Teleplan and Seagate successfully introduced a closed-loop recycling process for HDDs. -> RBACompassAwardsCaseStudies2019.pdf (responsiblebusiness.org)

State of the Art Nd magnet recycling in the EU

In Europe most HDD are shredded and then sorted into several material streams. Neodymium is not specifically sorted in this step.

- In 2019, the Horizon project REE4EU finished, demonstrating their high temperature electrolysis cell to produce RE oxide ingots from discarded magnets and magnet production scraps (called swarf).
- In 2022, a part of the REE4EU consortium continued into the REEPRODUCE Horizon project. This project runs until 2026 and aims to set up the first sustainable and complete European REEs-recycling value chain at industrial scale, able to produce REEs from EoL products at competitive cost and with environmentally friendly technologies. Achieving this goal will secure an important and strategic value chain for Europe’s green transition.
- In 2022, another Horizon project called REEsilience has started. The REEsilience project partners will categorise Rare Earth Elements by geographic locations, quantities, chemical composition, ethical and sustainable indicators, ramp-up scenarios, and pricing, considering all value streams from virgin to secondary material to achieve the goal. TU Delft and Leiden University are partners in mapping the waste flows and doing LCA-studies.
- n 2023, a French spin-off called MagREEsource from the CNRS Institute was funded 5 million to build 50 tonnes pilot for magnet recycling. This appears to be the first magnet recycling plant in Europe.
- In 2023, the LIFE project called INSPIREE has started to build the first industrial scale plant for REE recovery from permanent magnets by Itelym in Ceccano, Italy.
- The French company Carester is planning a 2000 tonnes recycling plant called Caremag to be ready in 2026.

(DERA, 2024) poses a overview of the magnet recycling industry state of art, including opportunities and boundaries for exploitation. One main conclusion is that the quality of reused or recycled magnets is very important for the technical feasibility and thus the business case.



State of the Art HDD recycling – Worldwide

Outside EU:

- UK based company HyProMag Ltd aims to produce 100 tonnes per annum of NdFeB mangets from recycled magnets in 2023 and in Germany in 2024 (Hypromag GmbH). No further information available on website.
- US company ReElement recovers and refines to magnet and battery grade materials, in what appears to be a pilot scale since 2022. It uses a chromatographic approach.
- US company REEcycle recycles Nd magnets from different sources. Recycling steps include removing the nickel plating, crushing, leaching and crystalizing and filtration. It then sells a Nd/Dy mixture to magnet producers.
- Okon recycling offers direct magnet reuse to original equipment makers (OEM) after demagnetizing and dismantling.
- It is reported that Hitachi has developed a mechanical dismantling and separation technique for NdFeB magnets in HDDs and air conditioners, using a rotational dram.
- UK based company Ionic Technologies uses ionic fluids in a 30 t/year pilot demonstration in Belfast.
- The largest Japanese chemical company Shin Etsu has industrial hydro metallurgy capacity in Japan and Vietnam.
- US magnet producer Noveon Magnetic recycles its own cuttings (swarf) using powder metallurgy.