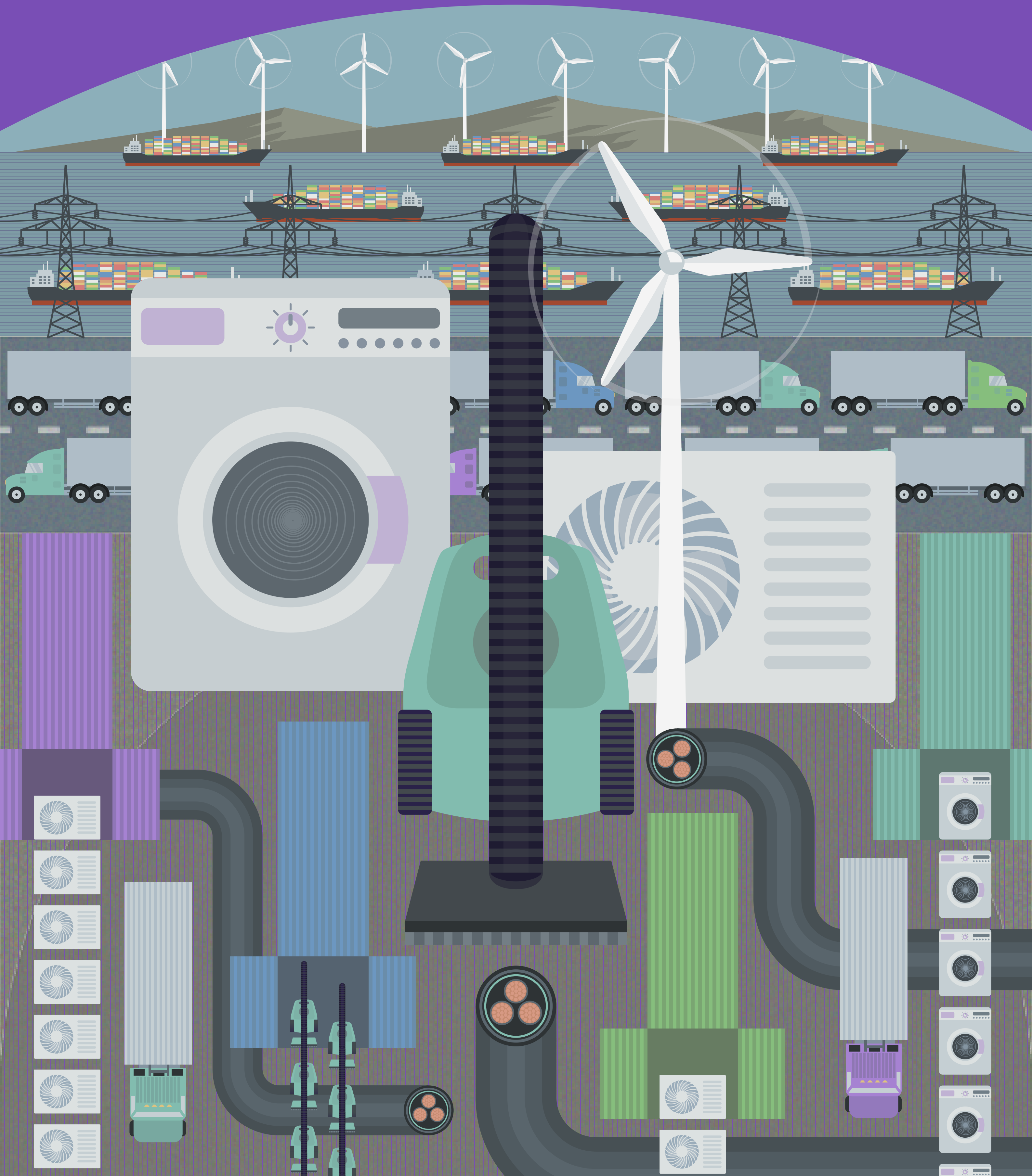
# Design for Security of Supply

## IMPACT OF CIRCULAR DESIGN STRATEGIES ON CRITICAL RAW MATERIAL DEMAND



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# Colophon

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# Index

# Executive summary

Disruptions in the supply of critical raw materials (CRMs) have accelerated in recent years, with direct consequences for European and Dutch manufacturing and energy sectors. China's 2025 export-licensing controls on rare earths and NdFeB permanent magnets caused temporary production stoppages at automotive suppliers. The EU Critical Raw Materials Act (CRMA) focuses primarily on building European production, processing, and recycling capacity. This report examines a complementary approach: reducing demand for primary CRMs through circular product design. Using dynamic Material Flow Analysis across six product groups, it models how changes in design parameters at the product level aggregate into reductions in material demand when applied across the market.

## Quantitative Results

Modelled reductions in CRM demand range from 27% to 78% across six product groups: washing machines, cables, heat pumps, vacuum cleaners, heavy transport, and wind turbines. For NdFeB permanent magnets, where China dominates production and processing, combined strategies achieve demand reductions of up to 75%. The strategy with the highest impact differs per product group.

The modelled strategies span product-level design changes, technology substitution, and system-level operational measures. For washing machines, we find that product lifetime can be doubled from 12 to 24 years, which nearly halves CRM demand. For heat pumps, replacing copper boiler tanks with steel strongly reduced copper demand, and combined strategies reduce cumulative CRM demand by almost 80%. For wind turbines, adopting NdFeB-free generator technologies (geared, electrically excited, and ultimately high-temperature superconducting designs) could in principle eliminate NdFeB demand by 2050, provided R&D investment and procurement frameworks support these technologies. In cables, the product is already highly optimised; gains of over one third come from higher utilisation intensity at the system level through improved insulation and reduced reserve capacity requirements.

The lifetime extension scenarios assume that products designed for longer life are actually kept in use longer. In practice, consumer behaviour, evolving product functionality, and the economics of repair versus replacement all affect whether technical durability translates into longer use. The modelled reductions should be read as optimistic scenarios conditional on these factors being addressed.

## Policy Analysis

Material efficiency and lifetime extension deliver the largest CRM demand reductions across product groups. Neither is adequately supported by current policy. Existing Ecodesign regulations do not address material efficiency for CRMs at the product level. The ESPR and Right-to-Repair Directive support some repairability requirements, but the business case for repair remains weak without stronger warranty enforcement and fiscal reform. In many product groups, the CRM-containing component is not the life-limiting factor: extending product life by servicing non-CRM wear parts preserves the material already in the product.

Recycling receives more policy attention and also supports EU industrial capacity-building. However, higher recycling rates do not automatically reduce import dependence. European NdFeB manufacturers currently cannot produce the highest magnet grades from recycled material, and the EU lacks the production chains to convert recycled CRMs into semi-finished products at scale. Across EU WEEE from 2006 to 2021, 56% of element mass was never formally collected, and specialty metals (including most listed CRMs) had a recovery rate of 2%. Mass-based WEEE collection targets do not create incentives to recover low-quantity, strategically important materials.

Demand-side strategies can reduce demand before new supply chains become operational. Lifetime extension reduces demand once longer-lived products remain in use past the point where shorter-lived versions would have been replaced. Material substitution can be deployed rapidly if the preliminary R&D is in place. For some product groups, the most effective interventions are operational rather than design changes (e.g. higher cable utilisation intensity, AI-based route optimisation in heavy transport), and fall outside the scope of Ecodesign regulation.

## Recommendations

At European level, the report recommends: setting minimum durability requirements in Ecodesign delegated acts, benchmarked against lifespans already achieved by best-in-class products; introducing product-specific CRM efficiency thresholds where technically feasible; requiring mandatory removal of CRM-containing components before shredding in the upcoming WEEE revision, with per-material recovery rates rather than weight-based targets; and directing R&D funding toward CRM-free motor and generator technologies. The Batteries Regulation is a good model for structuring product-specific CRM requirements: material-specific recycled content mandates with escalating timelines, combined with a digital passport for composition transparency.

At national level, the report recommends: adjusting the fiscal treatment of repair labour relative to virgin materials; lengthening statutory warranty periods and enforcing them more effectively; embedding CRM reduction and durability requirements in public procurement; and implementing progressively stricter requirements in procurement concessions and tenders to give manufacturers a predictable investment timeline. The six product groups were selected to cover a range of conditions: mature and slowly innovating versus rapidly developing; gram-scale CRM content versus hundreds of kilograms; and product-level design as the main path versus system-level or operational changes. Across all six, material efficiency and lifetime extension produce the largest demand reductions.

# 01

# Introduction

# INTRODUCTION

Disruptions in the supply chains of critical raw materials are occurring more frequently, with major consequences for the European and Dutch economy. The Critical Raw Materials Act (CRMA) focuses most of its attention on building European production, processing, and recycling capacity. A complementary approach is to reduce demand for primary critical raw materials (CRMs) through product design measures. In this report we will explore the quantitative impact that these design measures can have on overall CRM demand.

## Supply and demand side strategies for critical raw materials

Critical and strategic materials (hereinafter: CRMs) underpin the transition to sustainable energy technologies, electric transport, and the electrification of industry (European Commission, 2023b). Rapid growth is also visible in defence, digitalisation, and aviation.

The extraction and processing of raw materials is geographically concentrated. The Netherlands is dependent on imports of raw materials, semi-finished products, and end products containing CRMs.

Increasing geopolitical tensions have made this dependency more problematic. Risks are materialising into actual disruptions. For example, the export restrictions on permanent magnets composed of neodymium, dysprosium, iron, and boron (NdFeB) in April 2025. These magnets are applied in wide range of applications, from sensors to motors and generators (including wind turbines) to magnetic separation technologies. China's export-licensing controls on rare earths and related magnets contributed to automotive supply-chain disruptions, including temporary production stoppages at some suppliers (Reuters, 2025).

The CRMA is intended to secure the supply of CRMs at the European level through diversification, substitution, mining, processing, and recycling. By 2030, part of the extraction, processing, and recycling of CRMs should take place within Europe (European Commission, 2024c). Various initiatives are underway for the Netherlands to contribute to the CRMA. Since the potential for conventional mining in the Netherlands is very limited (NMO & TNO, 2025), the Dutch Ministry of Foreign Affairs is working on supply partnerships with resource-rich countries. There is also significant potential for locally extracting critical materials through urban mining (van der Voet et al., 2025).

Although supply agreements and urban mining offer alternatives for extraction, the capacity for refining and semi-finished product manufacturing also remains insufficient in Europe.

A mismatch between supply and demand can be solved by improving supply and by reducing demand. This study focuses on the demand side of the equation, specifically on circular product design: using fewer critical materials while maintaining functionality, through material efficiency, lifetime extension and recycling.

There is precedent for product-level design changes producing large system-level effects. The EU Ecodesign regulation for vacuum cleaners, which capped motor power at 900 W from 2017 while maintaining cleaning performance requirements, is estimated to save 12 TWh of electricity per year by 2020 and 15 TWh by 2030, a 52% saving compared to a scenario without Ecodesign measures. The European Commission (2024b) notes that "the 2030 savings are 0.49% of the total EU27 electricity consumption in 2020, and close to the annual electricity consumption of Croatia.

This study applies a comparable logic to CRMs: it models how changes in design parameters at the product level aggregate into reductions in material demand when applied across the market. This report is an adapted translation of Copper8 & Delft University of Technology (2026a, 2026b), which were commissioned by the Dutch Ministry of Infrastructure and Water management.

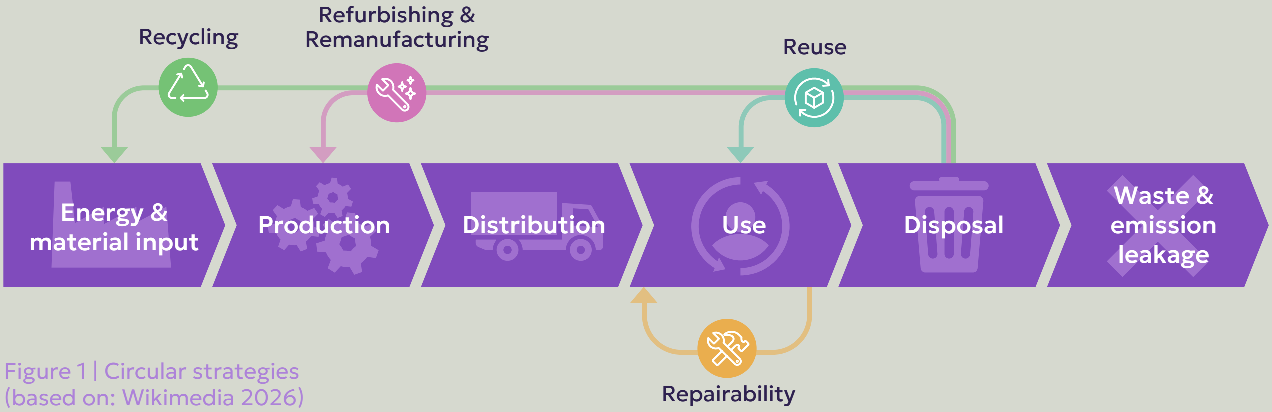



Figure 1 | Circular strategies
(based on: Wikimedia 2026)

## Circular strategies explored in this report

Several circular strategies exist to extend the lifetime of products and their materials, based on the phase in which they are restored. Circular design implements these circular strategies in the manufacturing, use, and end-of-life of products. Business and revenue models ensure economic viability, while policy frameworks incentivize circular design by creating level playing field market conditions for circular and linear businesses.

### Durability & Reuse

**Durability:** The capacity of a product to maintain its functional and physical integrity over an extended period, resisting wear, tear, and obsolescence. Durable products sustain their functional value (technical performance), physical value (material robustness), and aesthetic value (appearance) throughout their extended lifespan. Design for durability involves selecting robust materials, using high-quality components, and ensuring long-term software support.

**Reuse:** The practice of using a product again in its original form and function by another user, either directly (second-hand use) or after minimal intervention such as cleaning or repairs. Reuse maintains the product's identity and purpose. The strategy extends product lifetime by enabling additional use cycles beyond the original owner's period of use, whether through resale, donation, or other forms of redistribution. In this report, reuse explicitly excludes refurbishment activities involving systematic testing, grading, or proactive component replacement.

### Refurbishment & Remanufacturing

**Refurbishment:** Brings products back to good working condition for resale through inspection and replacement of broken or deteriorated components. Any company with part-exchange capability can perform refurbishment using original or third-party parts. The process is less standardized than remanufacturing (see next section) and typically does not involve complete disassembly to component level. Quality refurbishment should provide warranty comparable to new products.

**Remanufacturing:** A standardized industrial process that completely disassembles products to the component level, restores them to original as-new (or upgraded) condition and performance, and produces fully warranted products for resale meeting specific technical specifications and testing standards. The process involves complete disassembly, inspection, cleaning, component replacement where needed, reassembly, and rigorous testing. OEMs are typically best positioned for remanufacturing due to their access to original specifications and technical knowledge.

### Repairability

The process of restoring a malfunctioning product to working condition by fixing or replacing broken components. The repair process involves diagnosing the failure, disassembling the product, replacing or fixing defective components, reassembling, and testing functionality. Design for repair focuses on making products easy to disassemble and reassemble, with accessible components, available spare parts, repair information (manuals or guides), and consideration for safety and software updates. Repair can be performed by the user themselves (DIY repair), professional repair services, or manufacturers.

### Recycling

The process of converting end-of-life products into secondary raw materials that can be used in new products. Design for recycling aims to make products suitable for the complete recycling value chain, ensuring all materials can be retained in the highest possible quality to maximize reuse. The recycling process typically involves collection, depollution (removal of hazardous materials), shredding, automated sorting using various technologies (image recognition, magnets, induction, density sorting), and material reprocessing. In Western European contexts, most electronics are shredded rather than manually disassembled due to labor costs.

## Relevant policy

### Dutch National Programme Circular Economy (NPCE)

The Dutch National Programme for the Circular Economy (NPCE) 2023–2030 sets the government's agenda for moving the Netherlands toward a fully circular economy by 2050, including national goals and interim targets (Rijksoverheid, 2025). It links circular economy policy to reductions in $CO_2$ emissions, land use, and water consumption, and treats security of supply as a core rationale alongside environmental impacts.

### Dutch National Raw Materials Strategy

The Dutch national raw materials strategy (Rijksoverheid, 2022) aims to improve the security of supply of critical raw materials through five priority areas:

- Circularity and innovation
- Sustainable European mining, refining, and stockpiling
- Diversification of supply and partnerships
- Increasing sustainability of international supply chains
- Knowledge development and monitoring

These areas are linked to both the CRMA and the NPCE. Circularity and innovation (point 1) is connected to existing government initiatives including mission-driven innovation policy, and procurement policy for solar panels and wind farms. Under point 5, the Netherlands Materials Observatory (NMO) was established to map and monitor the Netherlands' dependencies on critical raw materials.

### EU Critical Raw Materials Act (CRMA)

The CRMA entered into force 23 May 2024 (currently under amendment) and is aimed at securing the supply of Critical and Strategic Raw Materials (European Commission, 2024c). The act also sets benchmarks by which Europe should diversify its supply. By 2030:

- Extract at least 10% of European consumption of SRMs in Europe
- Process at least 40% of European consumption of SRMs in Europe
- Recycle at least 25% of European consumption of SRMs within Europe
- Import no more than 65% of European consumption of CRMs from any single third country

The CRMA requires large companies that use strategic materials to carry out a risk assessment of their supply chains at least once every three years. Permanent magnets are a priority for increasing circularity. Manufacturers and importers placing permanent magnets on the market are required to label their products indicating whether a product contains permanent magnets, along with the chemical composition and location of those magnets. Minimum recycled content in NdFeB magnets is to be set via delegated acts by 31 Dec 2031.

The CRMA provides for the acceleration of 'strategic projects', including permitting procedures and assistance linking strategic projects to public or private financing. The RESourceEU Action Plan (European Commission, 2025b) builds on this by establishing a new 'financing hub' mobilising close to €3 billion by end of 2026, leveraging national and regional funding, and further simplifying permitting.

## EU Ecodesign for Sustainable Products Regulation (ESPR)

The ESPR forms the central regulatory framework for Ecodesign measures for product groups, with product-specific measures elaborated through delegated acts (European Commission, 2024e). The regulation entered into force on 18 July 2024 and promotes more sustainable and circular products in the EU. It covers all physical products, including those with permanent magnets. Only a few categories are excluded, such as vehicles as defined in Regulations 167/2013, 168/2013, and 2018/858.

The main provisions of the ESPR include: delegated acts promoting durability, repairability, upgradability, disassembly, refurbishment, and recyclability; mandatory digital product passports for regulated product groups (expected 2026–2027); energy efficiency requirements; provisions against premature obsolescence; a prohibition on destroying unsold consumer products; and mandatory Green Public Procurement (GPP) rules to encourage demand for sustainable products.

## EU Batteries Regulation

The Batteries Regulation (Regulation (EU) 2023/1542) entered into force on 17 August 2023 and is the first EU regulation to cover the full lifecycle of a product category with binding, material-specific requirements for critical raw materials (European Parliament and Council, 2023). It applies to all batteries placed on the EU market and sets mandatory minimum recycled content shares for cobalt (16% from 2031, rising to 26% from 2036), lithium (6%, rising to 12%), and nickel (6%, rising to 15%) in industrial, EV, and SLI batteries. It also sets material recovery targets from recycling (95% for cobalt and nickel, 80% for lithium by 2031) and requires a battery passport with composition, carbon footprint, and recycled content data from 2027.

The Batteries Regulation establishes a regulatory precedent: product-specific, material-specific CRM requirements with binding targets and escalating timelines are achievable at EU level. The combination of recycled content mandates, composition transparency through a digital passport, and material recovery targets provides a tested template for what the CRMA aims to achieve for permanent magnets, and for what this report recommends for other CRM-containing product groups.

## EU Right-to-Repair Directive (R2RD)

The Right-to-Repair Directive (Directive (EU) 2024/1799, from here onwards R2RD) entered into force on 30 July 2024. Member States must adopt it into national law by 31 July 2026, after which the obligations apply to product groups for which repairability requirements exist under EU law. The R2RD applies to a wide range of consumer electronics, including household washing machines, tumble dryers, dishwashers, refrigeration equipment, electronic displays, vacuum cleaners, mobile phones, tablets, and products with batteries for light transport. The main provisions are:

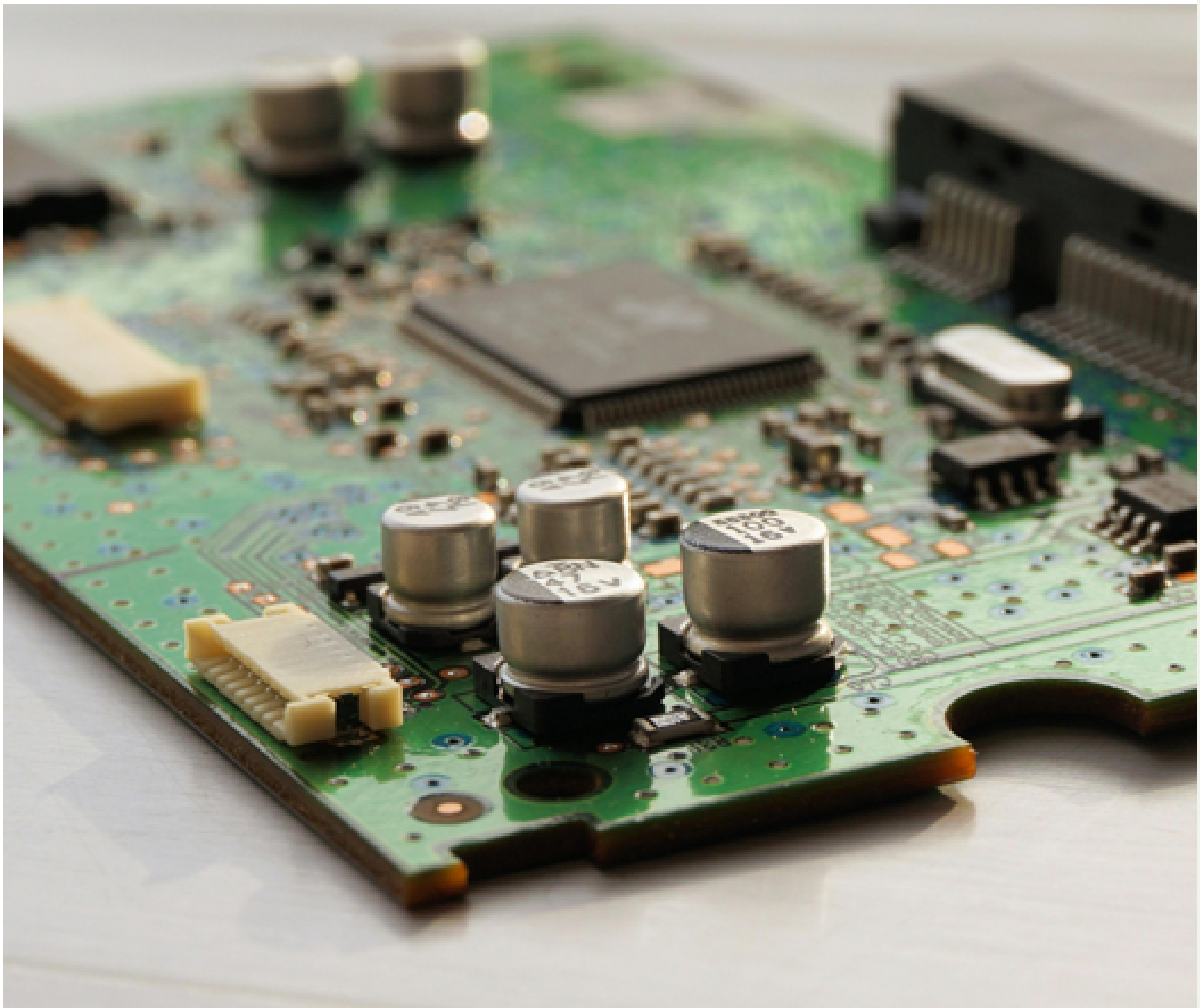
- Manufacturers must ensure products are repairable
- Spare parts, repair information, and software tools for diagnosis must be made available to both manufacturers and independent repairers
- The statutory warranty period is extended by one year when a consumer chooses repair instead of replacement
- Repairers must inform consumers via the standardised European Repair Information Form

The effectiveness of the R2RD depends heavily on transposition into national law, which can vary per member state.

### Waste from Electrical and Electronic Equipment Directive (WEEE)

The WEEE Directive has three objectives (European Commission, 2012): preventing waste from electrical and electronic equipment (EEE), promoting reuse and recycling of secondary raw materials, and supporting the efficient use of raw materials incorporated in EEE. Although primarily focused on the waste phase, it also has implications for product design: member states are required to promote cooperation between recyclers and manufacturers so that Ecodesign practices lead to products that can be better reused, disassembled, and recovered.

Critical and strategic raw materials are not addressed in the current WEEE Directive. An environmental and socioeconomic impact assessment will determine whether the WEEE Directive will be revised in late 2026. This revision offers an opportunity to include the mandatory removal of components containing CRMs, comparable to the requirements in the Batteries Regulation (European Parliament and Council, 2023).



## Overview of current CRM supply and demand, and End-of-Life recovery

Based on CBS (2025), the Netherlands plays an important distribution role in the European market for critical materials, primarily through the Port of Rotterdam. In 2024, the Netherlands imported €22.3 billion worth of critical materials in total. Of that total, €17.2 billion and 18.5 million tonnes concerned imports from non-EU countries, which made the Netherlands the EU's largest importer from non-EU countries. Of that €22.3 billion, €9.8 billion, or 44%, consisted of quasi-transit: goods that pass through the Netherlands while remaining in foreign ownership. Excluding quasi-transit, Dutch imports of critical materials amounted to €12.5 billion in 2024.

While the import weight grew by ~40% over the period from 2002 to 2024, the economic value more than tripled in that same period.

CBS also reports €12.8 billion of critical-material imports entering Dutch economic ownership (note that this is calculated for 2023, using a slightly different method from the above figures, based on economic ownership rather than physical border crossings). Of this €12.8 billion, 57.8% was re-exported, meaning that the goods temporarily entered Dutch ownership before being exported again with little or no processing. Another 41.1% was processed by firms in the Netherlands, of which 17.0% was processed for domestic expenditure and 24.1% for export. Only 1.1% was directly intended for domestic expenditure, which CBS notes mainly reflected inventory formation: firms purchasing critical materials for use at a later moment.

The largest shares of imported materials, excluding quasi-transit goods are attributed to coking coal, aluminium, phosphate ore and phosphorus, accounting cumulatively for 80% of import weight. By value aluminium, copper, nickel and coking coal are the dominant materials, accounting together for around 76% of import value. For critical materials imported for further processing, the main sectors include the basic metals industry, construction, metal products, energy supply and chemicals.

On the EU level, substantial quantities of critical materials in end-of-life products are lost instead of re-entering the European economy via recycling. Pauliks et al. (2025) quantify element flows across 54 WEEE product categories in the EU-27 from 2006 to 2021. Of the cumulative element mass generated over that period, 56% was never formally collected. A further 9% was removed during pre-treatment, and only 28% was recovered. Specialty elements, a group that includes 21 of the European Commission's listed CRMs, had a recovery rate of 2%. Collection rates rose from 27% in 2006 to 60% in 2021, but 35 of the 59 elements tracked are not recycled from WEEE at all.

For several CRMs, the quantities lost in the WEEE system are large relative to European imports. Unrecovered gallium in EU WEEE corresponds to 40% of annual EU imports, tantalum to 23%, magnesium and tungsten each to 12% (Pauliks et al., 2025; all 2021 figures). These are theoretical maxima that assume full recovery, which is not technically or economically feasible for all elements, but they indicate the order of magnitude of secondary material potential foregone in current collection and recycling practices. Reducing demand for CRMs through product design (the focus of this report) and improving end-of-life recovery through design-for-recycling (which is discussed in Sprecher et al., 2026) are complementary strategies.

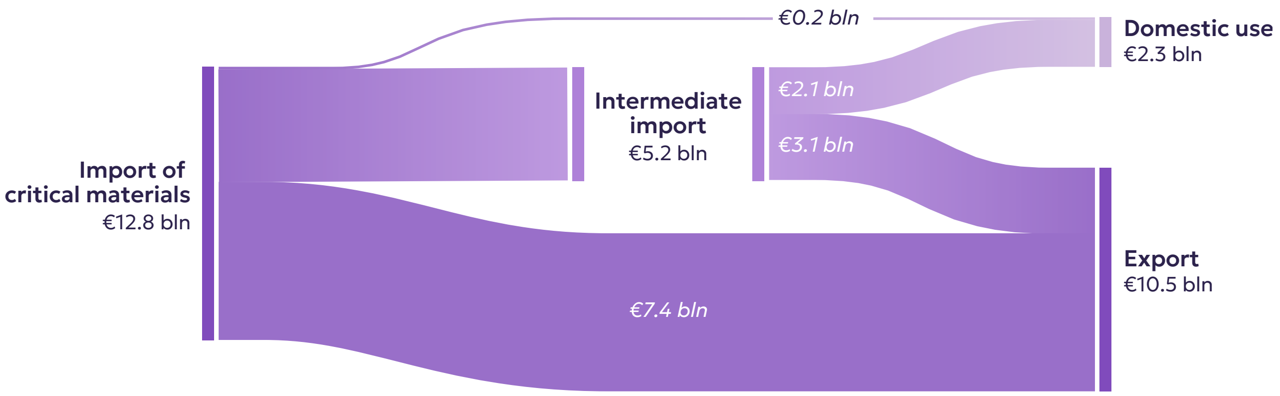



Figure 2 | Destination of imported CRMs in 2023 (CBS, 2025).

02

# Research Aims and Methodology

# RESEARCH AIMS AND METHODOLOGY

The aim of this study is to examine how selected circular design strategies affect demand for critical and strategic raw materials in six product groups up to 2050, with particular attention to NdFeB permanent magnets. It compares business-as-usual and intervention scenarios to estimate the potential size of demand reductions. On that basis, it identifies the policy implications for European and Dutch efforts to improve security of supply through circular design.

## Scope

Six product groups have been selected for analysis. The first set of three products examines the effect of circular design strategies on demand for CRMs broadly, covering washing machines, cables, and heat pumps. The second set focuses specifically on NdFeB permanent magnet demand for vacuum cleaners, heavy transport, and wind turbines.

The products were selected on the basis of relevance to policymakers, total demand volumes, and expected demand growth (at least stable, if not increasing). Data availability was also a leading factor, as for many product groups there is still insufficient publicly available information on the use of critical materials, whether in the form of Bills of Materials or otherwise. The selection of clearly different product groups strengthens the applicability of policy recommendations in Chapter 4 to product groups not covered here.

This study focuses on strategies that can be implemented through design decisions and closely related operational choices at the product level. Broader system-level measures such as product sharing are excluded, as these require different policy adaptations across multiple policy domains.

## Analytical Framework

### Circular Design Strategies

This report analyses three circular design strategies to reduce the use of critical materials:

**Material efficiency** focuses on reducing the quantity of critical materials per product, through either design optimisation or substitution with less risky alternatives. In practice, the two often overlap. The use of neodymium in permanent magnets, for example, can be reduced through careful adjustments to the electric motor, combining design modifications (optimising magnet positioning) and substitution (using higher-quality electrical steel around the magnet).

**Lifetime extension** encompasses design choices focused on durability, repairability, and reuse, so that products containing critical materials need to be replaced less frequently. This reduces the net inflow of new materials at equivalent use levels.

**Recycling** covers design for high-quality material recovery, for example by designing products so that components containing critical materials can be properly disassembled and recovered at end-of-life.

These three strategies correspond to the Narrow the Loop, Slow the Loop, and Close the Loop framework used in the NPCE 2023–2030 (Rijksoverheid, 2023). The remainder of this report refers to the individual design strategies directly.

| NPCE Framework | Design Strategy | Description |
|---|---|---|
| **NARROW THE LOOP** (Material efficiency) | Material substitution | Replacing critical materials with less risky alternatives (e.g. NdFeB-free motor types, copper-to-steel boiler tanks) |
| | Material intensity reduction | Reducing the quantity of critical material per product through design optimisation (e.g. magnet geometry, higher-quality materials) |
| **SLOW THE LOOP** (Lifetime extension) | Durability | Designing products for longer functional lifetimes |
| | Repairability | Enabling access to critical components, spare part availability, repair guide availability |
| | Reuse, refurbishment, remanufacturing | Extending product or component life through second-use cycles |
| **CLOSE THE LOOP** (Recycling) | Design for recycling | Designing products for easy disassembly and high-quality material separation |
| | Disassembly for component recovery | Enabling removal and recovery of specific critical material components (e.g. permanent magnets, PCBs) |
| | Recycled content | Incorporating secondary materials into new products (e.g. recycled NdFeB in permanent magnets) |

Table 1 | Narrow the Loop, Slow the Loop, and Close the Loop framework used in the NPCE 2023–2030 (Rijksoverheid, 2023)

## Research Methodology

For each of the six product groups, several scenarios were developed. The scenario parameters are based on insights from 17 semi-structured interviews with manufacturers and suppliers in the sector, sectoral organisations, and academic experts. Follow-up questions were used to explore specific topics or verify information from other interviews. An overview of interviewed parties can be found in Appendix II. The baseline data (sales projections, material intensity per unit, and material composition) was based on desk research and can be found in Appendix III.

For three product groups we calculated the full set of CRMs (washing machines, cables, and heat pumps), and for a further three product groups (vacuum cleaners, heavy transport, and wind turbines), we focused on NdFeB, one of the most geopolitically sensitive materials.

The modelled scenarios are not forecasts of future material flows, but rather they are intended to visualise the extent to which system-level demand can shift when individual design parameters change, and to identify which strategies have the largest effect.

Results are calculated using a dynamic Material Flow Analysis (dMFA) model, which is based on Python code and data provided by the Leiden University Institute of Environmental Sciences (CML). The advantage of using a dMFA model is that it allows to track deployment over time of new units with e.g. updated material composition or lifetime.

03

# Impact of Design Strategies on Material Demand

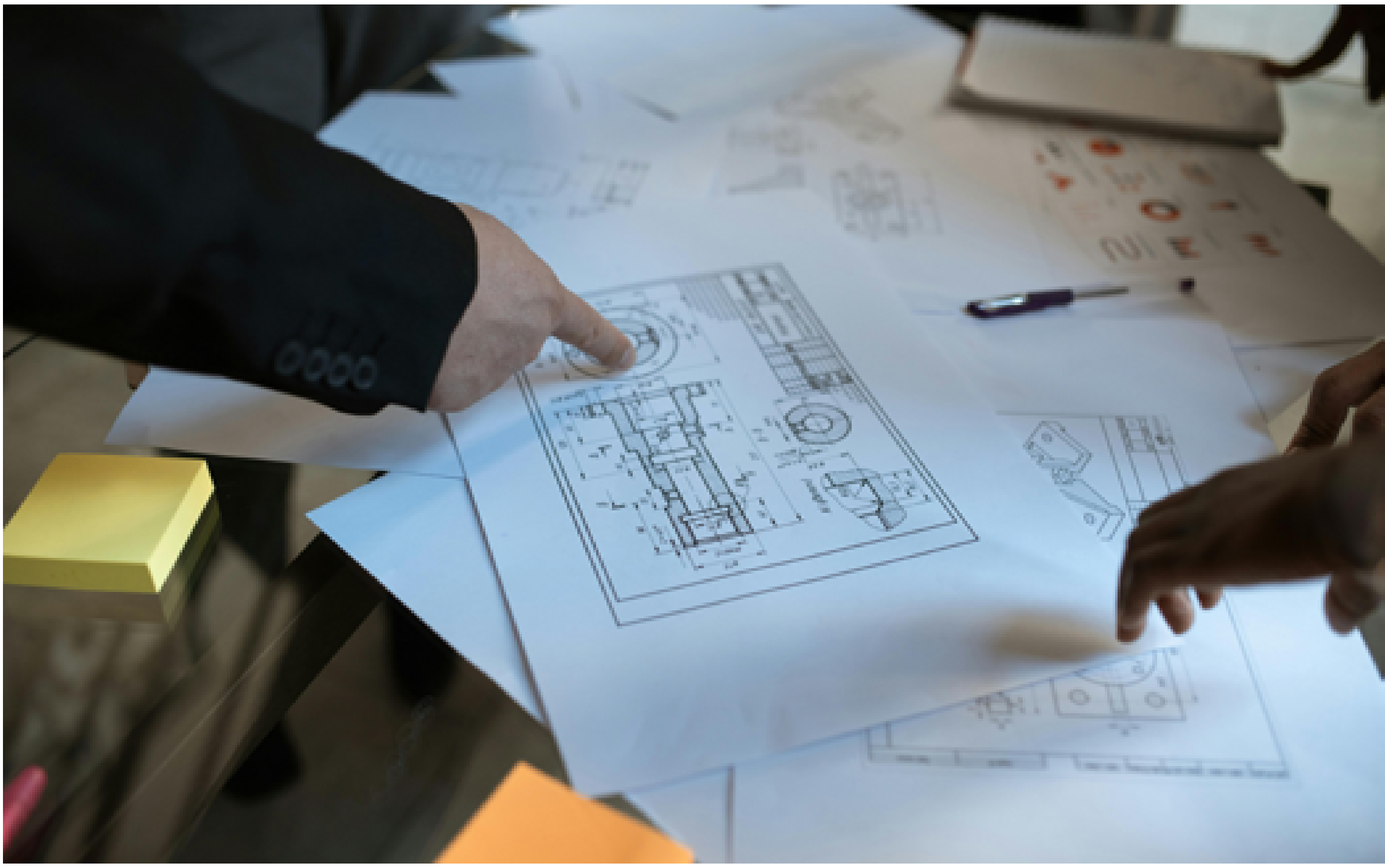
## IMPACT OF DESIGN STRATEGIES ON MATERIAL DEMAND

Circular design can have a major impact on the demand for critical materials. Across the products and CRMs, reductions range from 27% to 78%. For NdFeB permanent magnets, the combined effect of the design strategies examined reaches up to 75% demand reduction.

The six product groups show that the specific design strategy with the highest impact differs per product group. For washing machines, the greatest opportunity lies in lifetime extension, which can nearly halve CRM demand. For cables, the product is already highly optimised and conductor material can barely be reduced without loss of function; the biggest gains come from higher utilisation intensity at the system level. For heat pumps, both material efficiency and lifetime extension are relevant, with the replacement of copper boiler tanks with steel almost eliminating demand for copper. For vacuum cleaners, all three strategies together can reduce NdFeB demand by roughly 80%. For heavy transport, magnet optimisation and partial motor substitution can collectively achieve a 75% reduction. For wind turbines, the adoption of NdFeB-free generator technologies could eliminate NdFeB demand entirely within the modelling horizon.

In practice, different circular strategies can strengthen or work against each other. Lifetime extension through repairability and design for recycling sometimes pull in opposite directions: screw connections make repair easier, while snap fits are better suited for shredding at end-of-life. The report Rewiring Consumer Electronics: Reducing Demand for Critical Raw Materials by Design (Sprecher et al., 2026) maps specific design strategies against circular outcomes and goes into depth on what design decisions matter where.

There is also a strong European ambition to establish NdFeB recycling capacity. European NdFeB manufacturers currently cannot produce the highest magnet grades from recycled material, which means that recycled magnets from, for example, a truck will not automatically substitute virgin NdFeB in heavy transport applications. A detailed examination of this issue is outside the scope of this report but should be noted for where recycling is discussed.



# Washing machines

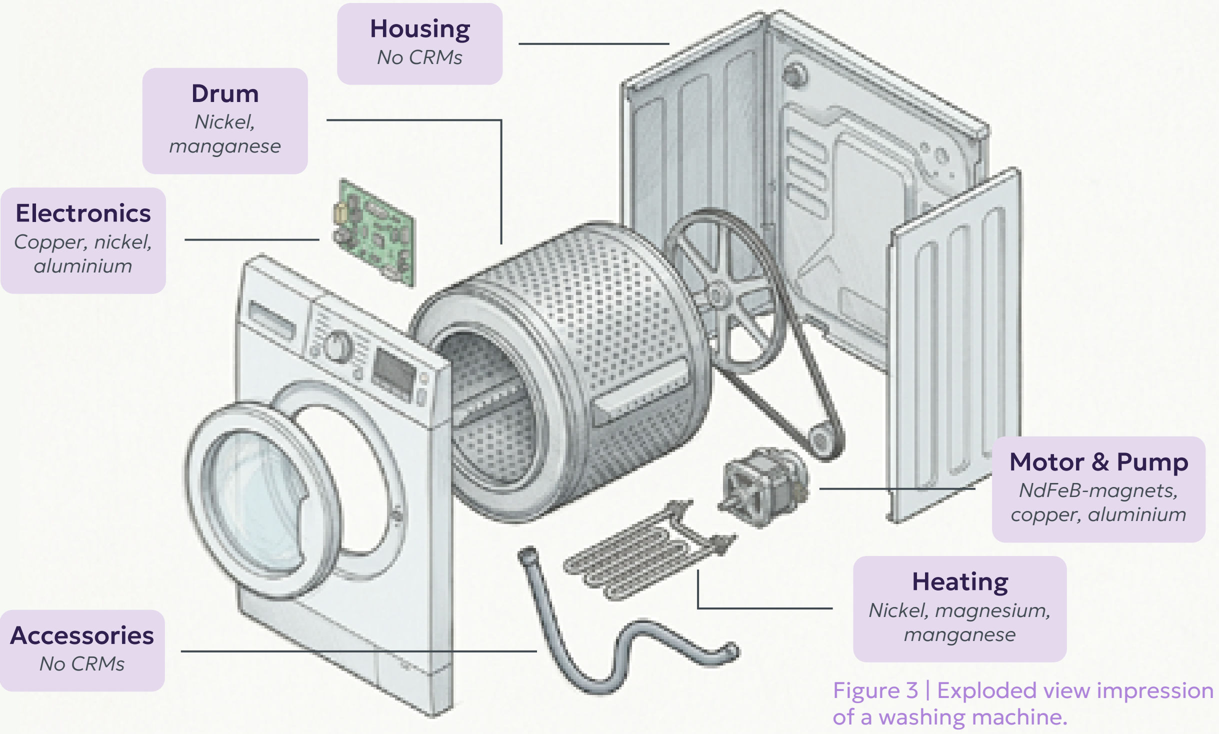



Figure 3 | Exploded view impression of a washing machine.

A typical washing machine consists of six main components. The electrical components (including Printed Circuit Boards) and the electric motor are the main sources of critical material content. Most households already own a washing machine. In the baseline scenario, annual sales numbers increase very slowly, reflecting the projected increase in number of Dutch households.

## Circular Design Strategies

Material efficiency strategies for washing machines focus on optimising the electromagnet in the motor, using a different motor type, and eliminating certain electrical components. Lifetime extension strategies address product architecture, repairability, and component replaceability. Recycled material application is also included, based on the expected availability of EU-manufactured NdFeB magnets with recycled content from 2035 onwards. The strategies and parameters are detailed in Figure 4 and Table 2.

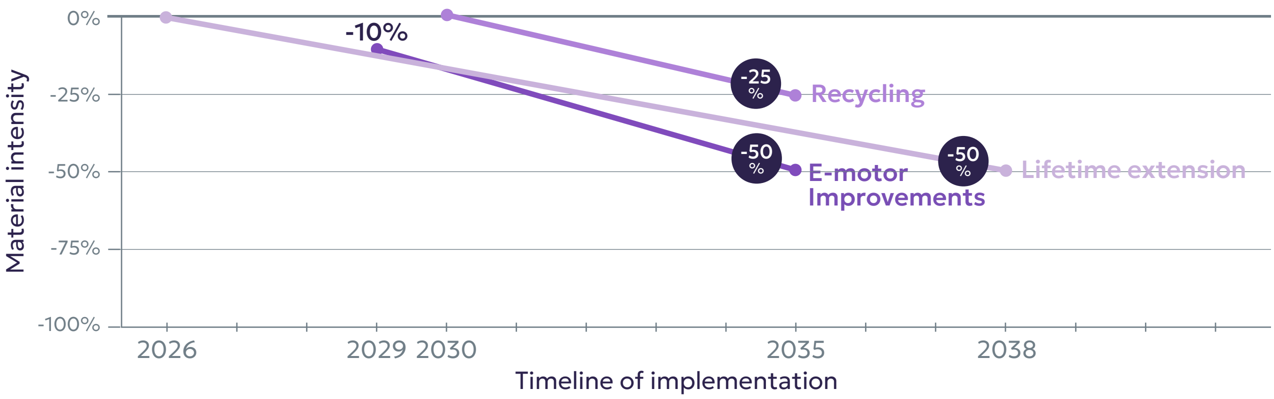



Figure 4 | Timeline of implementation and material intensity reduction per strategy for washing machines.

| Description | Component | Effect | Year | Explanation |
|---|---|---|---|---|
| **Optimisation of electric motor leading to reduced magnet content, and alternative motor type** | Electric motor and Magnet (NdFeB) in electric-motor | -10% to -50% | 2029–2035 | Through use of more and higher-quality electrical steel and optimisation of magnet grade, NdFeB weight per washing machine can be reduced by 10% by 2029. Further reduction through new motor types reaches 20% by 2032. Introduction of an entirely new motor type reaches 50% by 2035. |
| **Lifetime extension from 12 to 24 years** | Whole product | 0% to -50% | 2026–2038 | A washing machine currently has an average lifetime of 12 years. High-end models have a lifetime of 20 years. This can be further extended through more robust design, design for repairability, and availability of spare parts. From 2026 only best-in-class washing machines are sold, doubling the average lifetime over the period 2026–2038. |
| **Recycling** | Whole product | 0% to 25% | 2030-2035 | Through improved infrastructure and design measures, recycled content of washing machine components increases by 25% in 2035. Modelled as reduction in material inflow. |

Table 2 | Circular design strategies for washing machines.

New washing machines often carry more electronics than strictly required for washing, such as Wi-Fi modules, touchscreens, and microcontrollers instead of mechanical dials. Removal would reduce material use, but manufacturers have little reason to simplify, since these features support product differentiation and premium pricing. Insufficient component-level data on material composition is publicly available, so we did not include a scenario modeling savings from product simplification.

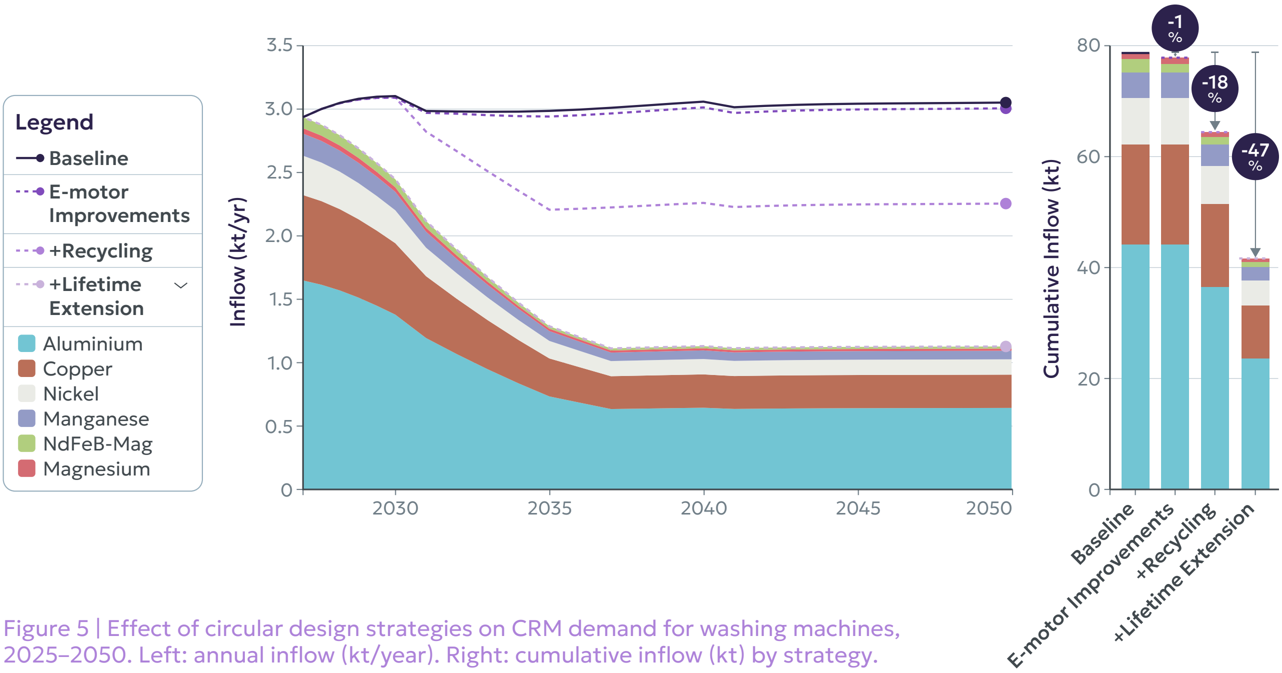



Figure 5 | Effect of circular design strategies on CRM demand for washing machines, 2025–2050. Left: annual inflow (kt/year). Right: cumulative inflow (kt) by strategy.

## Effect on CRM Demand

Lifetime extension has the greatest effect because it applies to the entire product (Figure 5) and nearly halves the demand. Washing machine prototypes with a technical service life of 50 years already exist (E15, interview). The feasibility of lifetime extension depends on product architecture: when critical components can be easily replaced, repair, refurbishment, and reuse can be addressed within a single design. Tools such as disassembly maps help designers identify where interventions are most needed (E5, E6, E15, interviews).

Reductions of 10% to 20% in NdFeB use per motor are technically feasible through combined design of electrical steel, copper, and magnet geometry (E1, interview). Further reduction requires new motor types or different magnet technologies, which may have negative consequences for compactness, noise levels, or energy efficiency (E2, E14, interviews). NdFeB-free motor types are modelled to become available in the 2032–2035 timeframe.

Most washing machines are discarded after 10–15 years, even though the technical service life is often 18 years (E17, interview). Only high-quality washing machines from premium brands tend to enter a second use cycle. Design improvements alone do not yield better outcomes if the behavioural factors driving early disposal are not addressed. In consumer electronics, lifetime expectations directly influence replacement timing: products that appear sturdy through material choice and form factor lead to longer lifetime expectations regardless of actual technical durability (Sprecher et al., 2026). For modelling purposes, the lifetime extension scenario assumes a doubling of average service life from 12 to 24 years, based on a mix of current high-quality machine performance and emerging prototype lifetimes.

# Cables

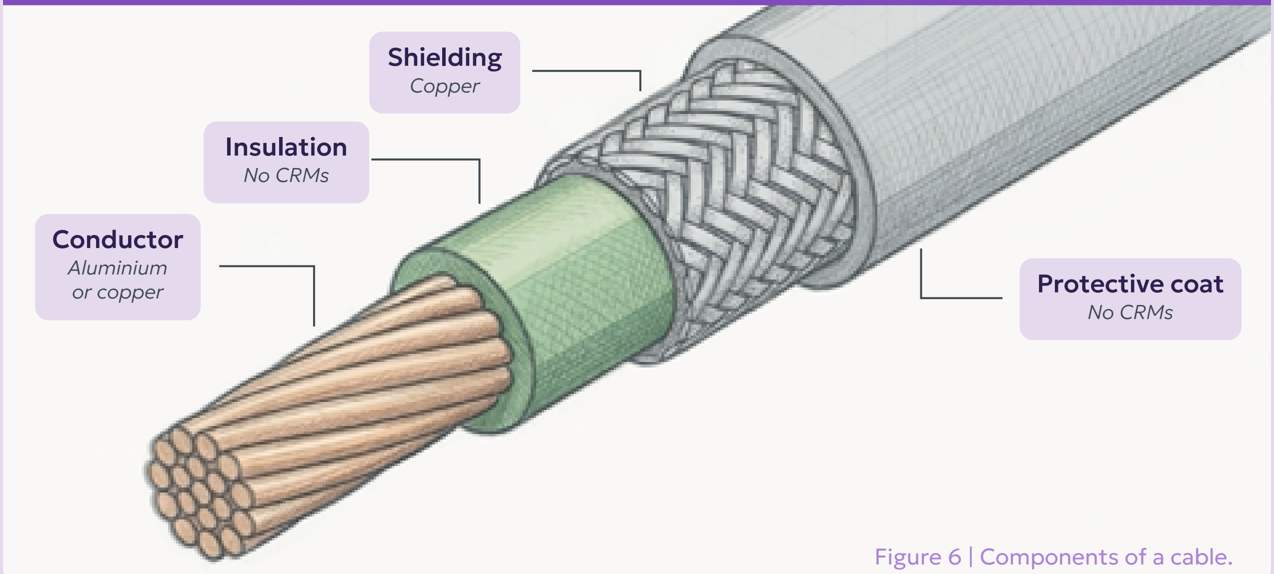



Figure 6 | Components of a cable.

A cable has four main components, of which the conductor can be made of copper or aluminium, and the shielding contains a copper mesh. In the Netherlands, most high and medium voltage cables have aluminium conductors, but globally copper conductors are still widely used.

In the baseline scenario, the expansion of energy infrastructure and the energy transition leads to a significant demand for cables (Agterhuis et al., 2024). Based on discussions with grid operators, we assume a constant rate of new cables being installed at the maximum installation capacity, leading to a steady annual inflow of materials into the system.

## Circular Design Strategies

Cables are a mature product. Manufacturers have been applying material efficiency for decades (E12, interview), driven by cost and sustainability considerations. Cable conductors are already highly optimised: reducing conductor material directly worsens conductivity and increases grid losses. Applying recycled material in conductors at scale also carries risk, as impurities reduce conductivity and increase grid losses (E12, interview).

The modelled strategies therefore do not target the conductor material directly. Instead, they focus on the wider application of insulation materials that allow higher operating temperatures (increasing current-carrying capacity per kilometre), and better utilisation of existing infrastructure by reducing spare capacity reserves. Lifetime extension was examined but falls outside the modelling scope, as cables already have service lives of 80 or more years and the effect would only materialise after 2050. The strategies and parameters are detailed in Figure 7 and Table 3.

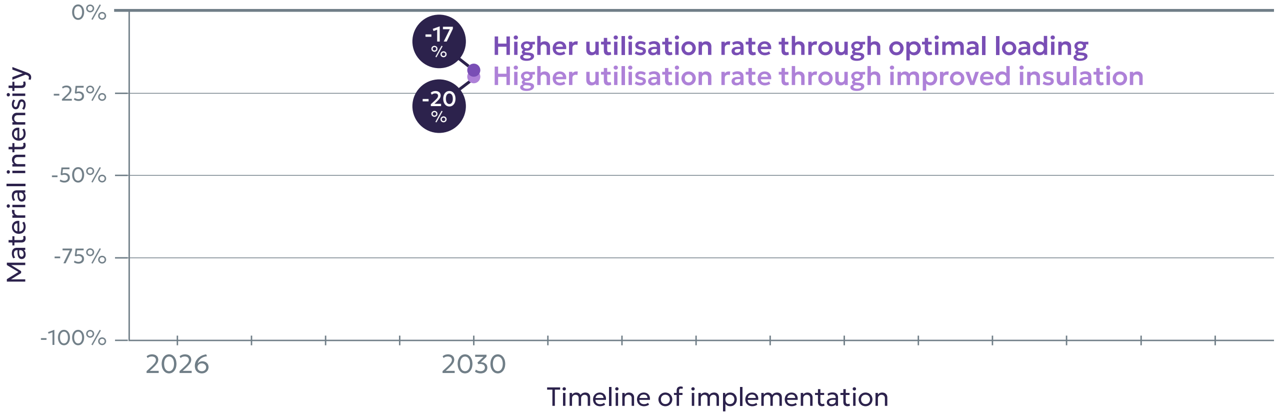



Figure 7 | Timeline of implementation and material intensity reduction per strategy for cables.

| Description | Component | Effect | Year | Explanation |
|---|---|---|---|---|
| **Higher utilisation rate through improved insulation material** | Insulation | -20% | 2030 | The more current flows through a cable, the warmer it becomes. Maximum capacity is determined by the maximum permitted temperature. By using an innovative material such as P-laser in the insulation layer, the cable can safely operate at a higher temperature, gaining higher capacity with the same amount of conductor material. In theory, capacity can increase by approximately 20%. Modelled as a one-time switch in 2030, with 20% lower material intensity as a result. |
| **Higher utilisation rate through optimal loading of electricity infrastructure** | Conductor | -17% | 2030 | Electricity infrastructure can be more optimally loaded. This can increase capacity by 10% to 20%. This heavier loading can be achieved, for example, by loading transformers more heavily or by allowing more loading during colder periods. This study assumes an increase of 17%. |
| **Lifetime extension** | Whole product | n/a | n/a | Cables can remain in use for very long periods, provided some wear components such as couplings and end fittings are periodically replaced. Not modelled because the effect would not occur before 2050. |

Table 3 | Circular design strategies for cables.

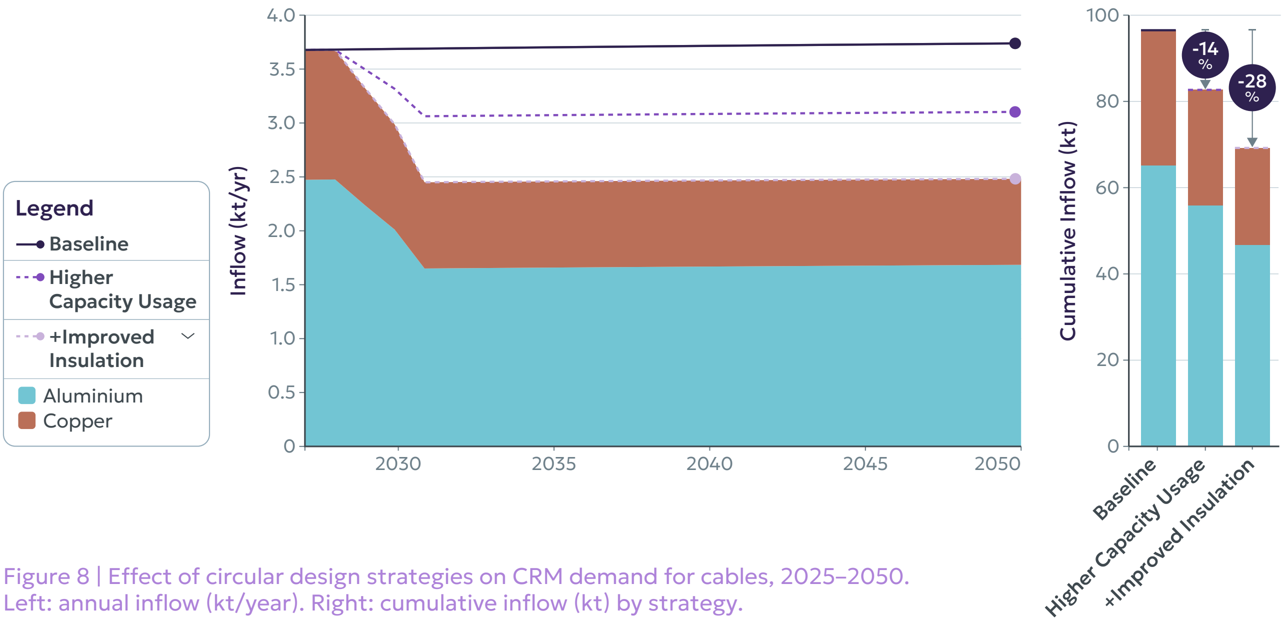



Figure 8 | Effect of circular design strategies on CRM demand for cables, 2025–2050.
Left: annual inflow (kt/year). Right: cumulative inflow (kt) by strategy.

## Effect on CRM Demand

The two modelled strategies to increase utilisation reduce CRM demand for cables by over one third (Figure 8). By increasing utilisation intensity, fewer cables need to be laid, reducing total CRM demand at the system level. Note that in practice, in the Dutch case, demand for increased grid capacity is large enough that the cable installation rate would likely remain at the same elevated level, with increased utilisation absorbed by unmet demand rather than reducing installation volumes.

The first strategy is the application of insulation material that allows cables to operate safely at higher temperatures, so that a cable with the same conductor material can carry more power, resulting in fewer cables being needed to achieve the same capacity (assumed here to be a 20% improvement in utilisation rate). P-laser insulation from Prysmian, already applied on a limited scale in the Netherlands, is an example. Note that higher temperatures also lead to slightly higher transmission losses, which is not accounted for here.

The second strategy is a higher utilisation of electricity infrastructure. The Dutch energy system has a significant back-up capacity, up to 2/3rds of total installed capacity is reserved as back up. Relaxing these back-up requirements allows for more of the reserve capacity to be used at peak-demand moments. An improvement potential of between 10% and 20% was identified by the Ministry of Climate and Green Growth (Agterhuis et al., 2024). This study assumes 17% increase in utilisation rate. Optimal loading could, however, shorten service life if cables or supporting components require earlier replacement. Further research into this is needed.

## Heat pumps

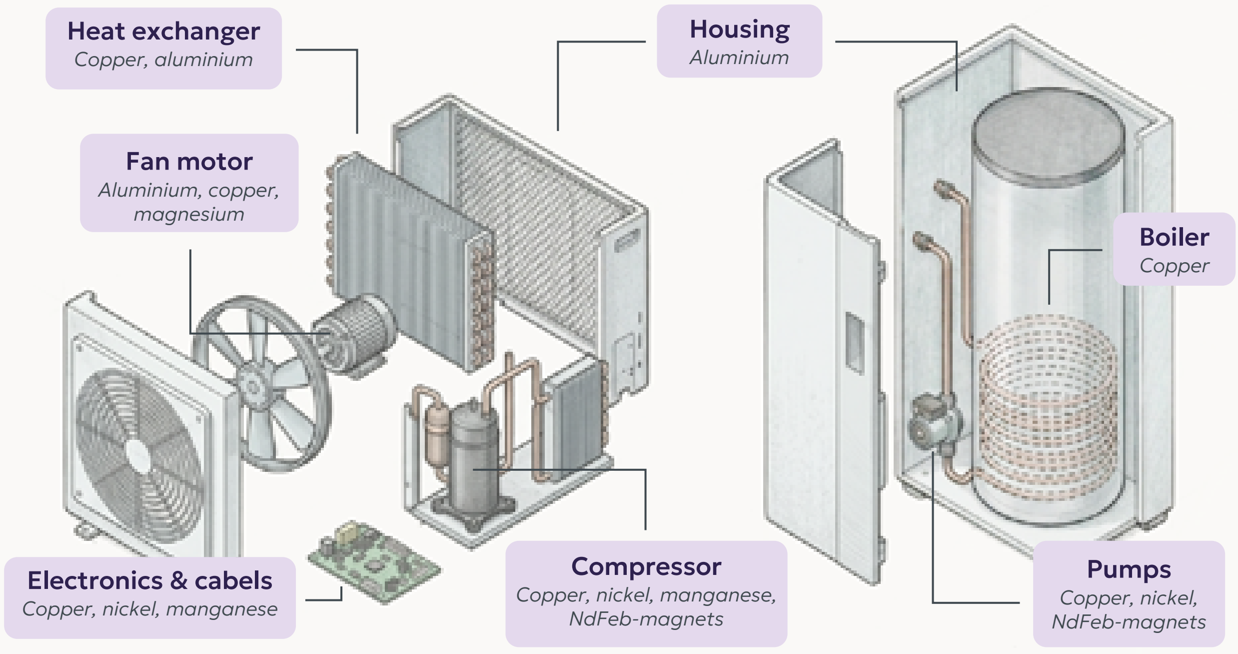



Figure 9 | Exploded view impression of a heatpump: outdoor unit (left) and indoor unit (right).

A heat pump consists of eight main components. In the baseline scenario, significant growth is expected, driven by the role of heat pumps in the energy transition. From 2040 onwards, replacement demand from earlier installations adds to sales volumes.

The compressor is the heart of the heat pump and contains an electric motor with permanent NdFeB magnets. The magnets themselves are almost never the life-limiting factor. Even after 30 years, they continue to function well unless the coating has been damaged, for example by a saline environment (E2, interview). Typically, the bearings wear out first, then the encoder systems, and only lastly to the rotor with magnets (E1, interviews). The critical materials in the compressor could therefore in principle outlast the current average service life of the heat pump by a wide margin, provided that it is possible to service the bearings and encoder systems.

### Circular Design Strategies

Five design strategies have been modelled for heat pumps, spanning material substitution, motor optimisation, and two life-extension approaches. The replacement of copper boiler tanks with steel is already underway in practice, partly driven by Environmental Performance of Buildings (in Dutch: *milieu prestatienorm gebouwen, MPG*) requirements in the Dutch construction sector (E11, interview). The strategies and parameters are detailed in Figure 10 and Table 4.

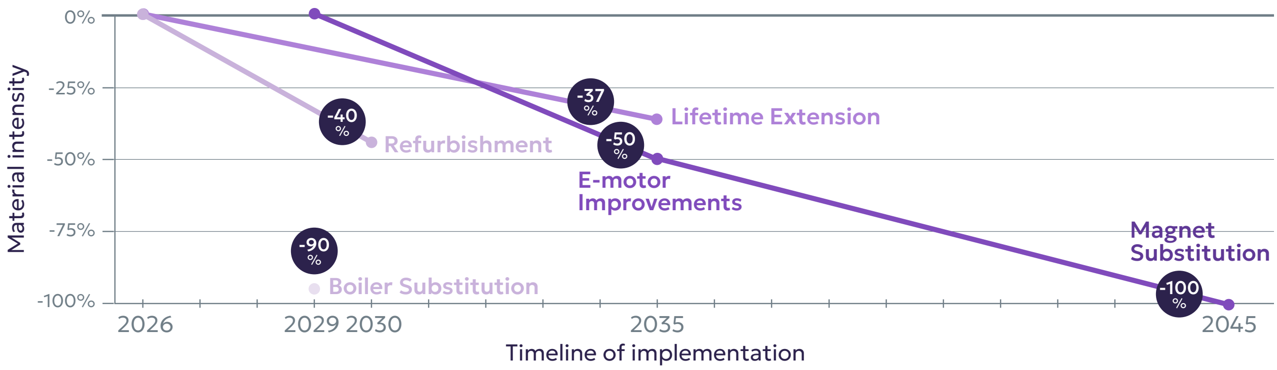



Figure 10 | Timeline of implementation and material intensity reduction per strategy for heat pumps.

| Description | Component | Effect | Year | Explanation |
|---|---|---|---|---|
| **Lifetime extension through modularisation** | Whole product | -37% | 2026–2035 | The average lifetime of a heat pump as of 2025 is 17 years. Through improved repairability via modularisation, the lifetime is extended by ten years to 27. This is assumed to be fully implemented by 2035. Note that in practice, heat pump replacement is often coupled with major home renovations. How frequently Dutch households renovate and whether renovation timelines would lead to early replacement regardless of product condition is not accounted for here. |
| **Refurbishment and resale leading to material intensity reduction** | Whole product | -40% | 2026–2030 | Heat pumps approaching the end of their lifetime are refurbished and resold instead of discarded. This reduces demand for new heat pumps and the associated material inflow. |
| **Substitution from copper to steel boiler tanks** | Boiler tank | -90% copper | 2029 | Copper in heat pump boiler tanks is substituted with steel, reducing copper use from 16 kg to 1 kg per heat pump. Based on a three-year design cycle, this transition is fully implemented by 2029. |
| **Optimisation of electric motor, followed by magnet substitution** | Magnet (NdFeB) in electric motor | -50% (2035)<br><br>-100% (2045) | 2029–2045 | Higher-quality electrical steel and optimisation of magnet geometry, followed by implementation of new motor designs with up to 50% less NdFeB at equivalent performance. Full replacement of NdFeB magnets with alternative technologies by 2045. |

Table 4 | Circular design strategies for heat pumps.

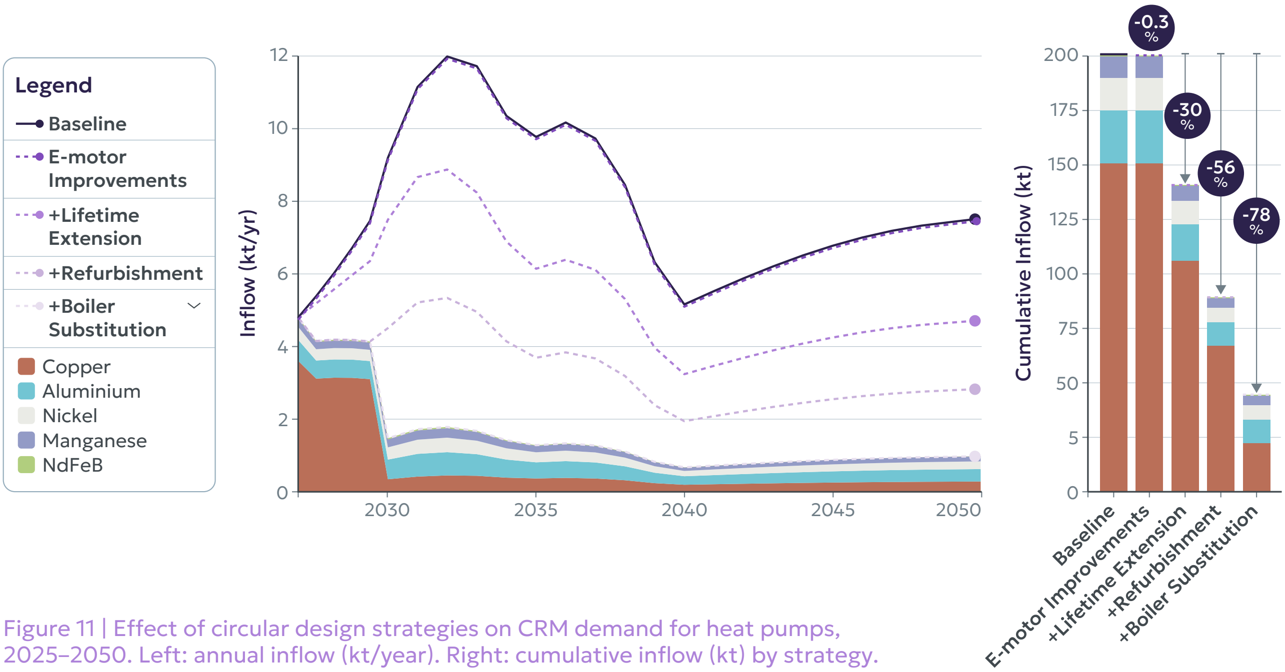



Figure 11 | Effect of circular design strategies on CRM demand for heat pumps, 2025–2050. Left: annual inflow (kt/year). Right: cumulative inflow (kt) by strategy.

## Effect on CRM Demand

For heat pumps, both material efficiency and lifetime extension lead to large reductions in CRM demand. The two lifetime extension strategies together lead to more than a halving of CRM demand (Figure 11). The material efficiency strategy (copper-to-steel boiler tank substitution) also delivers a large reduction, primarily because of the large mass involved. Cumulative demand falls by almost 80% when all strategies are implemented. Note that lifetime assumptions are based on current use conditions. Increasing heating and cooling demands due to climate change could affect both the adequacy of installed equipment over its modelled life and the intensity of use, which may reduce effective lifetime in years even if operating-hour durability remains unchanged.

# Vacuum Cleaners

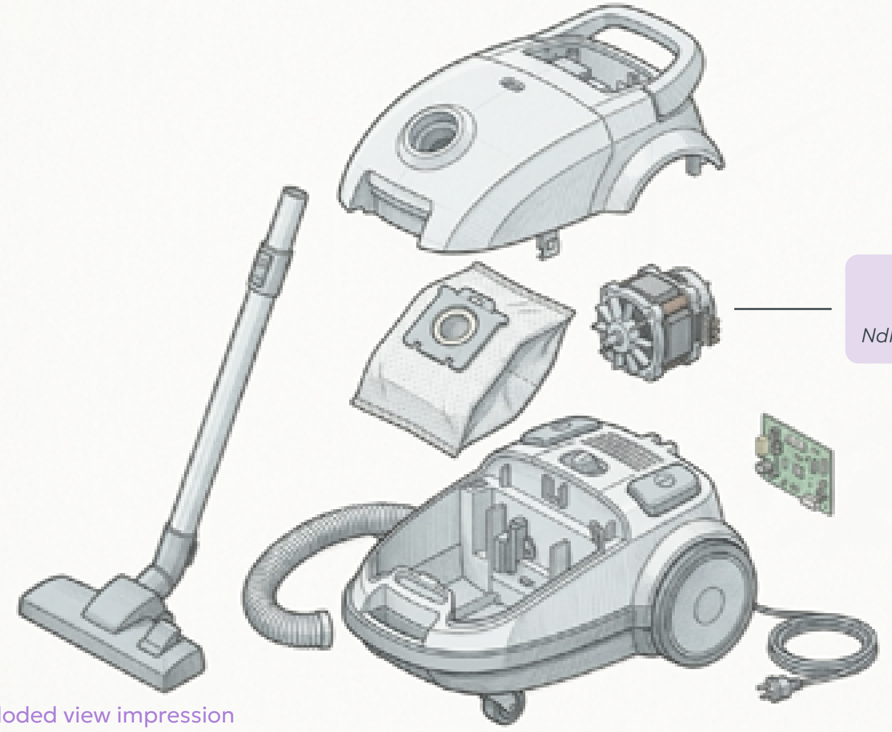



Figure 12 | Exploded view impression of a vacuum cleaner.

The permanent magnets in a vacuum cleaner are located in the electric motor, which generates the suction. In the baseline scenario, low growth in newly sold vacuum cleaners is expected, reflecting the projected increase in number of Dutch households.

## Circular Design Strategies

Magnet optimisation focuses on reducing NdFeB content in the electric motor through combined adjustment of electrical steel, copper, and magnet geometry. Lifetime extension relies on design principles such as higher-quality components, screw connections instead of adhesive, disassembly with standard tools, and clear product documentation (E4, interview). A comparison of two functionally identical vacuum cleaners with different product architectures found that disassembly time for the motor assembly went from 6.5 minutes to 60 seconds, because of better component positioning and fastener choice (Sprecher et al., 2026).

Recycled material application is also included, noting that EU production of high-quality NdFeB from recycled material is still in early stages at the time of writing (E3, interview). Here, we assume that around 2035 an NdFeB production facility becomes operational in the EU that can process recycled material and produce qualitatively sufficient NdFeB magnets, which is technically feasible but requires supportive policy (Koese et al., 2025). Environmental impact and system-level CRM inflows are also reduced, but less so because recycling activities are not without losses and environmental impacts (van Nielen et al., 2024).

The average lifetime of a vacuum cleaner is currently 6 years. Through modular design and design for repairability, this can be doubled to 12 years (E5, interview). Assuming a 3-year design cycle beginning in 2026, the first effects start in 2029. From 2035 onwards, the halved replacement rate yields a 50% reduction in NdFeB magnet inflow. The strategies and parameters are detailed in Figure 13 and Table 5. Note that this scenario applies to conventional vacuum cleaner types, where incremental functional improvement is modest. Robot vacuum cleaners are a faster-moving product category where new functionality may generate replacement pressure independent of technical condition.

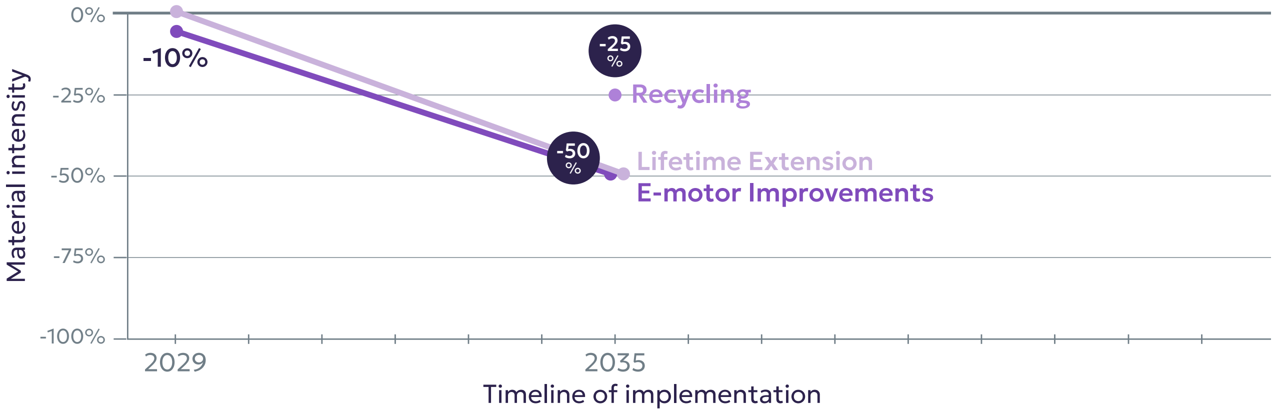



Figure 13 | Timeline of implementation and material intensity reduction per strategy for vacuum cleaners.

| Description | Component | Effect | Year | Explanation |
|---|---|---|---|---|
| **Recycled material use** | Magnets (NdFeB) in electric motor | -25% | 2035 | EU-manufactured NdFeB magnets with 25% recycled content are expected to reach the market around 2035. Modelled as a 25% reduction in (virgin) material inflow. |
| **Optimisation of electric motor leading to reduced magnet content, and alternative motor type** | Magnet (NdFeB) and electric motor | -10% to -50% | 2029–2035 | Through use of more and higher-quality electrical steel and optimisation of magnet grade, NdFeB weight per vacuum cleaner can be reduced by 10% by 2029. Further reduction through new motor types reaches 20% by 2032. Introduction of an entirely new motor type reaches 50% by 2035. |
| **Lifetime extension from 6 to 12 years** | Whole product | 0% to -50% | 2029–2035 | A vacuum cleaner has an average lifetime of 6 years. Through modular design and design for repairability, vacuum cleaners can last twice as long (E5, interview). Assuming a 3-year design cycle, effects start in 2029. From 2035 onwards, the halved replacement rate yields a 50% material reduction. |

Table 5 | Circular design strategies for vacuum cleaners.

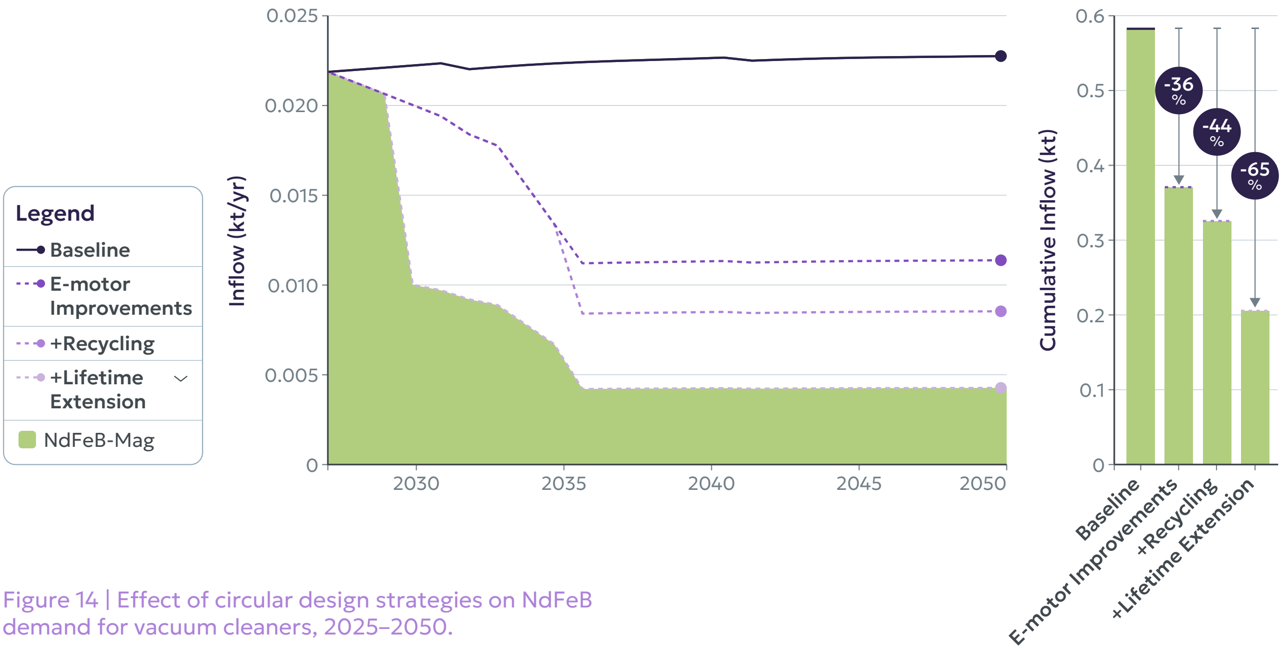



Figure 14 | Effect of circular design strategies on NdFeB demand for vacuum cleaners, 2025–2050.

## Effect on CRM Demand

Circular design strategies for vacuum cleaners can reduce NdFeB demand by up to roughly 80% through to 2050 (see Figure 14). The three strategy types all contribute: magnet optimisation, lifetime extension, and recycled material application. Reductions of 10–20% in NdFeB per motor are technically achievable through combined motor design optimisation (E1, interview). Further reductions require new motor types, which may affect compactness, noise, and energy efficiency. Lifetime extension depends on relatively straightforward design choices and can be improved with simple interventions. Repair design interventions only translate into reduced NdFeB demand if they are accompanied by real-world repair activity, supported by information and spare parts availability.

Heavy Transport

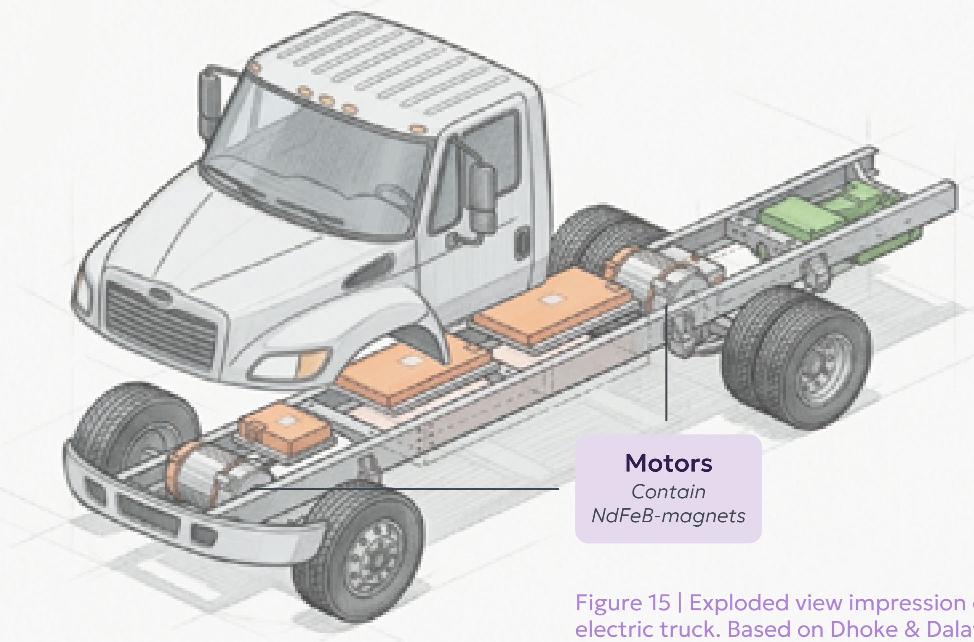



Figure 15 | Exploded view impression of an electric truck. Based on Dhoke & Dalavi (2024).

Neodymium magnets are highly useful in heavy transport drivetrains due to superior technical performance, but are not strictly necessary. The design strategies modelled assume a technological pathway that preserves the technical characteristics of NdFeB-based motors as much as possible. Electric vehicles also contain numerous smaller NdFeB-based motors, such as those in electric windows and windscreen wipers. These are not included in this analysis.

## Circular Design Strategies

Three strategies have been modelled for heavy transport, all focused on material efficiency: optimisation of existing NdFeB motors, partial replacement of NdFeB motor power with motors using no permanent magnets, and increased vehicle utilisation intensity through autonomous driving technology. Lifetime extension and recycling have not been modelled: the former because data on design-driven lifetime changes in heavy transport is limited, the latter because it is unclear if magnet quality requirements for heavy transport applications are too demanding for current EU recycled material production.

Magnets recovered from heavy transport vehicles can be used as raw material for less demanding applications, such as vacuum cleaner motors. Recyclers note that it is difficult to recover magnets profitably from electric vehicles. Design measures that reduce adhesive use and more clearly separate magnetic from non-magnetic material could improve the economics of recovery. The strategies and parameters are detailed in Figure 16 and Table 6.

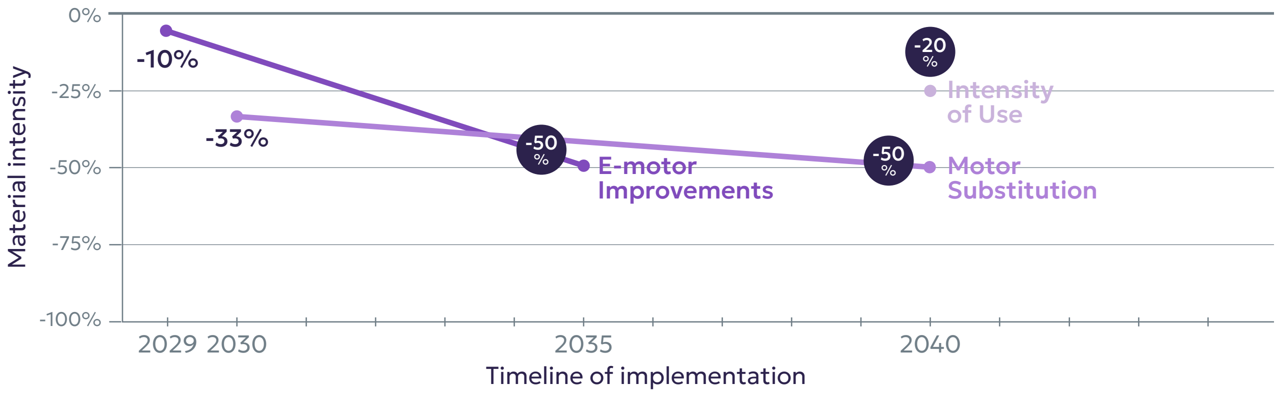



Figure 16 | Timeline of implementation and material intensity reduction per strategy for heavy transport.

| Description | Component | Effect | Year | Explanation |
|---|---|---|---|---|
| **Optimisation of electric motor leading to reduced magnet content** | Magnet (NdFeB) in E-motor | -10% to -50% | 2029–2035 | Through use of more and higher-quality electrical steel and optimisation of magnet grade, NdFeB weight per vehicle can be reduced by 10% by 2029 (E1, interview). Further reduction through new motor types reaches 20% by 2032. Introduction of an entirely new motor type with minimal NdFeB content reaches 50% by 2035. |
| **Partial substitution of NdFeB motor power** | Motor | -33% to -50% | 2030–2040 | A large NdFeB motor can be replaced with a combination of motor types. The Tesla Model 3, for example, uses a combination of an NdFeB motor and an alternative electric motor to maintain optimal efficiency across different driving conditions (E3, interview). Further substitution of NdFeB motor power with NdFeB-free alternatives reaches 50% by 2040. |
| **Increased utilisation intensity through AI** | Whole product | -25% | 2040 | Unlike passenger cars (parked 95% of the time), trucks are used as intensively as possible. AI and autonomous driving innovations could further increase utilisation intensity, reducing the total fleet needed (E9, interview). |

Table 6 | Circular design strategies for heavy transport.

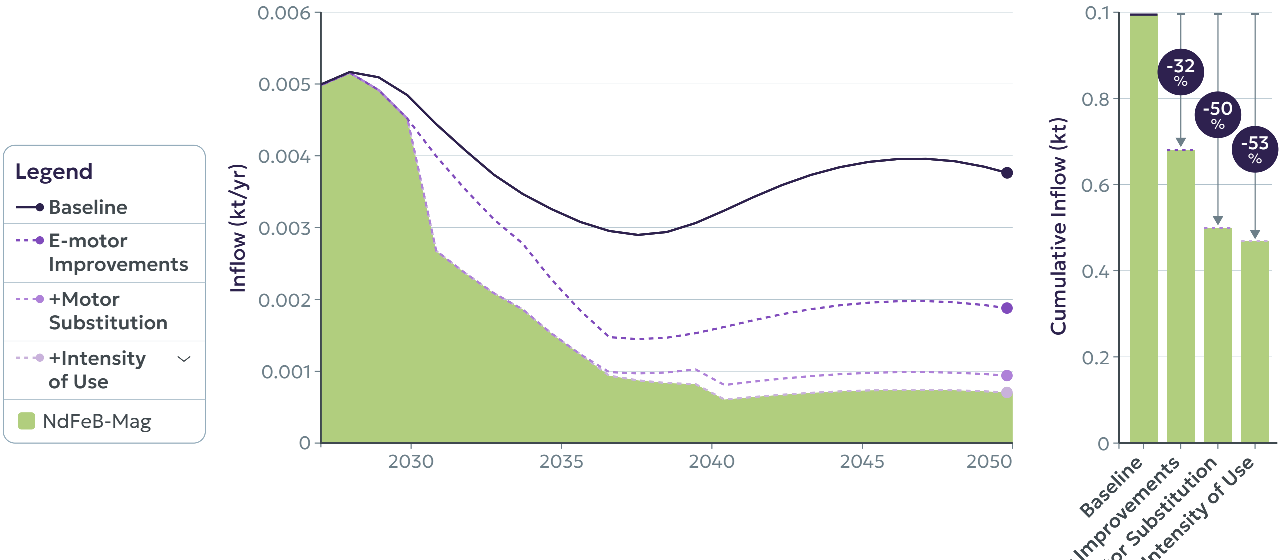



Figure 17 | Effect of circular design strategies on NdFeB demand for heavy transport, 2025–2050.

## Effect on CRM Demand

The design strategies can lead to an overall 75% reduction in NdFeB demand for trucks and public transport buses (Figure 17). Motor optimisation through the balance between electrical steel, copper, and magnet geometry achieves up to 20% reduction per motor. Partial structural substitution, where part of motor power is delivered by motors without permanent magnets, achieves further reductions. This approach is already applied by Audi and Volkswagen in passenger vehicles (Audi USA, n.d.; Volkswagen, 2023). Full substitution away from neodymium motors, accepting a limited loss of efficiency, could in principle bring demand to near zero within a relatively short timeframe. Deployment of AI for route and load optimisation could reduce the total truck fleet needed by up to 25% in the longer term (E9, interview), with corresponding reductions in fleet level material intensity per service unit.

# Wind Turbines

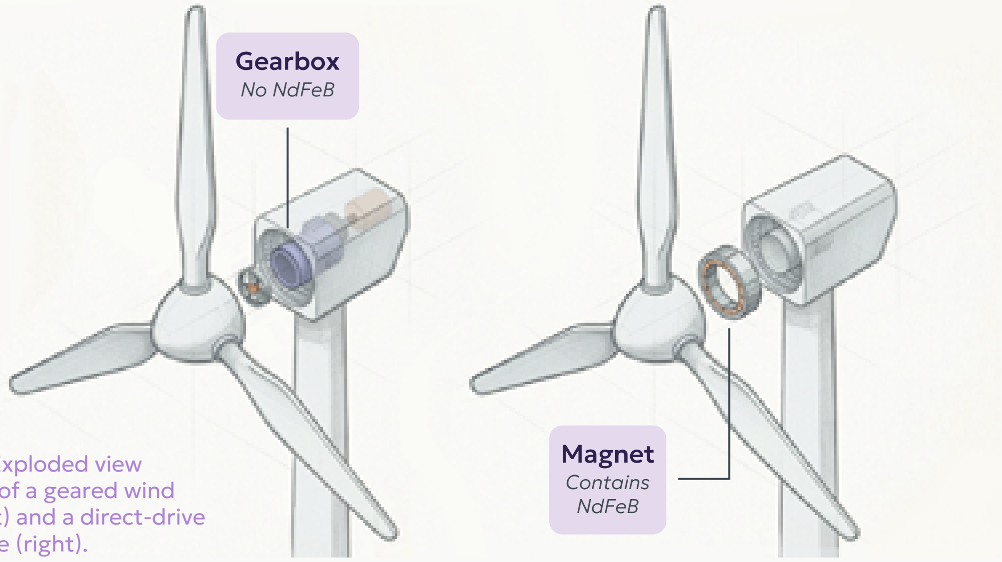



Figure 18 | Exploded view impression of a geared wind turbine (left) and a direct-drive wind turbine (right).

NdFeB magnets are convenient for wind turbines, especially offshore, because they reduce maintenance needs. Offshore turbines in Europe rely almost entirely on NdFeB-based generators, and the literature commonly assumes 650 kg of permanent magnet per MW of installed capacity (Liang et al., 2022). For onshore turbines, the majority use geared generators, which do not need NdFeB.

NdFeB demand from wind turbines can potentially be eliminated entirely through the adoption of NdFeB-free generator technologies. The timing depends on the pace of R&D, industrial investment, and whether procurement frameworks actively select these technologies. In principle, a switch to NdFeB-free geared offshore turbines is possible in the near term, but with significant technical limitations (including lower efficiency) for current large-scale designs (Carrara et al., 2025). In this report, we model a pathway to eliminate NdFeB that assumes technological developments to maintain or improve on the technical capacities of current offshore generator designs.

## Circular Design Strategies

The primary strategy modelled for wind turbines is the transition to NdFeB-free generators, with gradual implementation of alternative technologies delivering comparable technical performance.

Lifetime extension strategies have been inventoried but not modelled, as effects would only materialise after 2050 given the already long operational lifetime of wind turbines. Recycling faces the same time horizon constraint: sufficient high-quality recycled material would need to come from decommissioned wind turbines, and meaningful volumes will not be available before 2050.

The modelled pathway follows three technology generations: geared turbines replacing direct-drive NdFeB generators from 2030 (33% reduction), electrically excited generators from 2035 (66% reduction), and high-temperature superconducting turbines from 2040 (100% reduction). This trajectory is ambitious but consistent with a recent JRC report (Carrara et al., 2025). The strategies and parameters are detailed in Figure 19 and Table 7.

Because the NdFeB-magnets are a large fraction of the Bill of Materials, the design of magnet-assemblies is already highly optimized (E1, E2, interviews). The use of heavy rare earth elements such as dysprosium has been reduced since 2011 through grain-boundary diffusion techniques (Seo & Morimoto, 2014), and overall magnet quality has improved through better production process control. Further NdFeB reduction per MW is achievable mainly through alternative generator concepts: geared solutions, electrically excited generators, and in the longer term possibly high-temperature superconductivity.

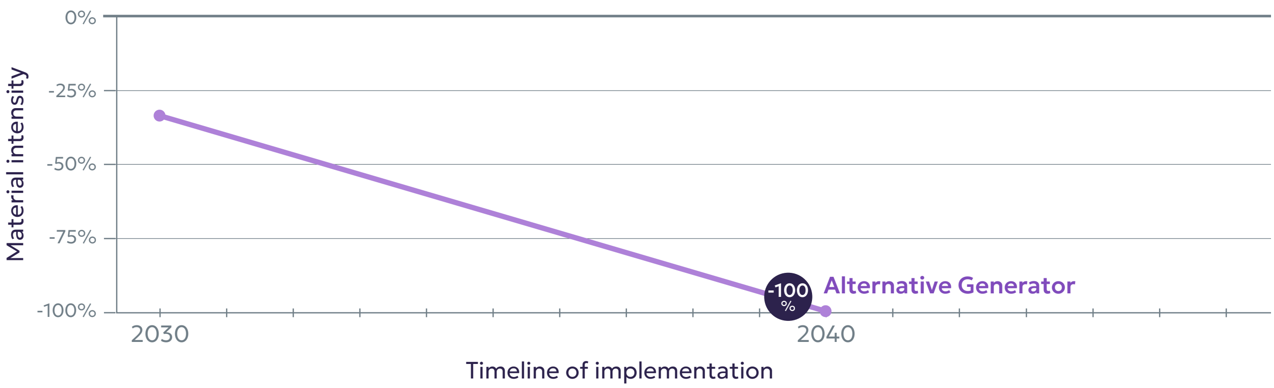



Figure 19 | Timeline of implementation and material intensity reduction per strategy for wind turbines.

| Description | Component | Effect | Year | Explanation |
|---|---|---|---|---|
| **Transition to NdFeB-free alternative generators** | Generator | -33% to -100% | 2030–2040 | By 2030, 33% reduction through adoption of geared turbine designs. By 2035, 66% reduction through electrically excited generator designs. By 2040, full elimination of NdFeB through high-temperature superconducting turbine technology (Carrara et al., 2025). |
| **Lifetime extension** | Whole product | n/a | n/a | Not modelled: the original lifetime of wind turbines (27 years) already falls outside the model period, so extension to 40 years would have no effect before 2050. |
| **Modular magnets for reuse** | Magnets (NdFeB) | n/a | n/a | NdFeB magnets can be mounted modularly on the rotor, enabling direct reuse. Not modelled due to long turbine lifetime placing the effect beyond 2050. |

Table 7 | Circular design strategies for wind turbines.

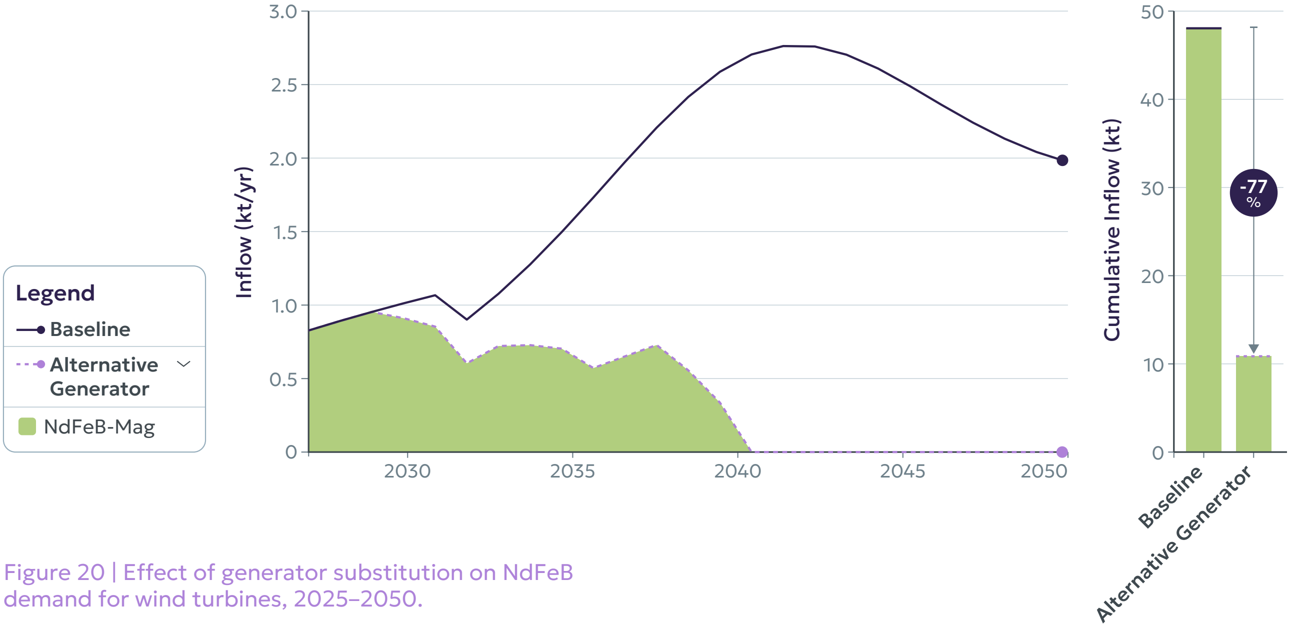



Figure 20 | Effect of generator substitution on NdFeB demand for wind turbines, 2025–2050.

## Effect on CRM Demand

NdFeB demand can reach zero (Figure 20), but this is only feasible when R&D investment, industrial capacity development, and a stable procurement policy framework that incentivises these technologies are pursued simultaneously (E8, interview).

04

# Policy Analysis

# POLICY ANALYSIS

The preceding chapters show that material efficiency and lifetime extension can lead to large reductions in CRM and NdFeB demand. Existing policy is strongest on recycling and secondary material use. This chapter examines opportunities for additional policy to support the broader set of circular strategies, starting with an overview of cross-cutting preconditions that affect whether the modelled demand reductions can be achieved in practice. Recommendations are subsequently presented in Chapter 5. A full overview of the policy analysis can be found in Appendix I.

## Efficient Use of Materials

Existing policy does not yet actively encourage the reduction of CRM use, either at the system level or at the product level. Indirect incentives exist in some sectors. For example, the Environmental Performance of Buildings (*milieuprestatie gebouwen, MPG*) requirement in the Dutch construction sector has been an indirect driver for at least one heat pump supplier to switch from copper to steel boiler tanks. This kind of signal only affects materials present in large quantities and where the CRM has a higher environmental impact than the substitute, making it relevant primarily for strategic materials such as copper and aluminium rather than for CRMs present in smaller quantities.

Higher utilisation rates are not a free lunch. For example, higher cable utilisation intensity would require revisiting the 99.9% grid reliability target currently set by the ACM (Sigüenza et al., 2021), which is a political choice. Increasing utilisation of heavy transport assets requires further optimisation of logistics, in a sector that already is focused on increasing efficiency as much as possible.

A precondition for improving material efficiency is that manufacturers and importers have adequate insight into their own Bills of Materials. Many do not know the exact composition of the components they purchase from abroad. The CRMA already requires large companies to conduct supply chain risk assessments (European Commission, 2024c), but this is difficult to execute without visibility into component composition. The Digital Product Passport (DPP) under the ESPR could facilitate this, for compliance and for design decision-making.

## Supply Chain Diversification

A central objective of the CRMA is to diversify supply chains for critical materials to increase security of supply (European Commission, 2024c). Table 8 shows the scoring criteria for supply chain resilience from the draft Nederwiek-I-A tender (Ministerie van Klimaat en Groene Groei, 2025).

As with secondary material use, the market will not voluntarily bear the economic costs of supply chain diversification without requirements imposed through regulation or procurement. Procurement criteria in individual tenders do not provide the long-term predictability needed for industry to invest in diversified supply chains.

We also note that higher recycling rates do not automatically translate into reduced import dependence. In practice, CRMs are often critical because the applications in which they are used demand very high material quality, and the required advanced processing capacity exists only in very limited number of locations. Recycling in the current

| Criterion | Assessment standard | Points |
|---|---|---|
| 5.1 Supply chain resilience of magnets. Long-term resilience and diversification of the supply chain is maximised by ensuring that refining of ores, metallisation of metals, and/or production of magnets in the wind turbine generators is not predominantly carried out in a single third country. The applicant demonstrates that the submitted percentage for the production step(s) is plausible given the actual and complex production chain for magnets. | For the magnets used in the wind turbine generators of the wind farm, more than 95% of refining, metallisation and/or magnet production is carried out in a single third country. | 0 |
| | More than 85% and no more than 95% of refining, metallisation and/or magnet production is carried out in a single third country. | 4 |
| | More than 75% and no more than 85% of refining, metallisation and/or magnet production is carried out in a single third country. | 8 |
| | More than 65% and no more than 75% of refining, metallisation and/or magnet production is carried out in a single third country. | 12 |
| | Less than 65% of refining, metallisation and/or magnet production is carried out in a single third country. | 16 |

Table 8 | Scoring criteria for supply chain resilience of permanent magnets, from the draft Nederwiek-I-A tender (Ministerie van Klimaat en Groene Groei, 2025).

end-of-life system typically degrades quality, a phenomenon known as downcycling. The EU currently lacks the production chains to convert recycled raw materials back into semi-finished products and new components at scale. For now, recycling is not an effective standalone strategy for reducing import dependence on foreign critical and strategic materials.

### Market expectations & material choice

The shift from ceramic magnets to NdFeB in vacuum cleaners was driven by consumer demand for compact, powerful appliances (E2, interview). The motor optimisation scenarios (modelled at 10 to 50% NdFeB reduction) partly depend on R&D into NdFeB-free motor types that can match these expectations. Without such R&D, reducing NdFeB content means accepting trade-offs in size, noise, or performance that the market does not currently reward. This applies beyond vacuum cleaners: wherever NdFeB-magnets enable miniaturisation, material substitution requires either technological alternatives or a shift in what consumers expect from a product.

## Lifetime Extension

The ESPR working plan announces that from 2027 onwards (European Commission, 2025a), Ecodesign will give more attention to repairability, which will support lifetime extension strategies. This is already partially visible in the product-specific Ecodesign regulation for washing machines (European Commission, 2019). The upcoming regulation for heat pumps has not yet included concrete repairability or lifetime requirements.

Policy requirements alone are not sufficient to make repair scale in practice. The business case for repair is not strong enough for most companies (E4, E5, E11, E14, interviews). Consumers are also underinformed about their existing rights: in the Netherlands, the statutory warranty period is not two years (as many consumers believe) but as long as can reasonably be expected for the product to last. This right is rarely invoked (E13, interview). Extending and enforcing warranty periods is one of the most direct ways to strengthen the business case for durable design, because manufacturers then bear the financial consequences of premature failure rather than the consumer. Sprecher et al. (2026) propose mandatory warranty periods of 12 to 15 years for washing machines, a range that exceeds the current average lifetime while remaining achievable by best-in-class manufacturers.

### Lifetime extension & the innovation curve

Policies aiming for substantial lifetime extension are most relevant where successive product generations offer diminishing functional improvement, because the cost of keeping an older product in use is low relative to what a new one would add. Washing machines and vacuum cleaners are relatively mature product categories where this applies. For products where each generation is substantially better than the last, extending product life means locking in older technology. Heat pumps are still in a phase of rapid development, and a refurbished unit may be less energy-efficient than a new one. The lifetime extension scenario for heat pumps therefore carries more uncertainty than for washing machines or vacuum cleaners.

## Consumer behaviour & early replacement

The lifetime extension scenarios also assume that products designed for longer life will actually be used longer. Washing machines are discarded after 10 to 15 years on average, even though their technical service life is often 18 years (E17, interview). Only premium brands tend to enter a second use cycle. Products that appear sturdy through material choice and form factor lead to longer lifetime expectations regardless of actual technical durability (Sprecher et al., 2026). Design for durability alone is therefore insufficient. The modelled reductions depend on whether longer-lived products are actually kept in use, which is partly a question of consumer perception and partly of economic incentives for repair versus replacement.

Critically, steady technical functionality may not suffice, as the replacement (and thus lifetime) of consumer facing products is also affected by the evolving social context of consumption and use (Krych & Pettersen, 2025). For example, newer models may offer new functionalities not present in aged products (e.g. digital screens and new programs in washing machines; robotic vacuums that have longer battery life, can navigate a messy bedroom, and also mop the floor). Relatedly, new more fashionable designs may come to market.

So, while the technical performance of products stays steady, consumer expectations of the functionality provided may lower willingness to repair as well as lead to premature product replacement (Makov and Fitzpatrick, 2021).

Changes in use intensity can also affect lifetime duration. For example, changes in washing frequency habits: Krych & Pettersen (2025) note that the average Norwegian family went from two to eight weekly washing cycles between 1960 to the 2020s. More washing cycles per year would lead to shorter lifetimes than expected. Similarly, changing weather patterns could affect use intensity of heat pumps and subsequently their overall lifetime. Products may also be prematurely replaced as part of renovations, home décor fashions, or life changes (e.g. marriage, divorce, etc.). Finally, longer-lasting products may not lead to a 1:1 decline in purchases of newer products as rebound effects may also come into play (Maldini et al., 2025; Makov & Font-Vivanco, 2018).

## Recycling and End-of-Life

Existing policy gives considerable attention to recycling and transparency requirements at end-of-life. The CRMA will require certain product groups to (i) have a label stating whether permanent magnets are present and, if present, the magnet type (e.g., NdFeB, SmCo, AlNiCo, or ferrite), and (ii) link to a unique product identifier that provides detailed information on magnet weight, location, chemical composition, and instructions for access and safe removal. Large companies using strategic materials, including copper in heat pumps and cables and NdFeB in electric motors, are also required to map strategic material use and assess supply risks.

Upcoming revisions of product-specific Ecodesign regulations and the WEEE Directive are the main opportunities to integrate CRMA-level information requirements into more product and material groups. The proposed revision of the regulation on circularity requirements for vehicle design (European Commission, 2023a) is a good model: it expands extended producer responsibility for end-of-life vehicles to buses and trucks, and introduces mandatory removal of components containing critical raw materials. The Batteries Regulation (European Parliament and Council, 2023) goes further: it sets binding, material-specific recycled content targets with timelines, mandatory material recovery rates, and a digital passport with composition and recycled content data. This combination of transparency requirements and binding targets provides a template for other CRM-containing product groups, including those covered in this study.

Across EU-27 WEEE from 2006 to 2021, the main source of material loss was not recycling technology but collection: 56% of element mass was never formally collected (Pauliks et al., 2025). Specialty metals, including most listed CRMs, had a recovery rate of only 2%, because recycling technologies for these elements either do not exist or are not economically viable. The mass-based collection targets in the current WEEE Directive do not create incentives to recover low-quantity elements, even where those elements have high strategic or economic value. The NdFeB magnets, PCBs, and other components discussed in this report contain precisely this type of material.

The current EPR tariff structure provides insufficient incentives for better design. Companies pay a uniform rate to Producer Responsibility Organisations such as Stichting OPEN, regardless of how recyclable their products are. Differentiating EPR tariffs by recyclability (known as ecomodulation) would create a direct financial incentive for designs that facilitate high-quality material recovery (E6, interview). This approach has a policy precedent in the existing differentiation of packaging waste fees under the EU Waste Framework Directive (Directive 2018/851, Article 8a(4)(b)).

### Recycling quality and scale

European NdFeB manufacturers currently cannot produce the highest magnet grades from recycled material, which means that magnets recovered from demanding applications (e.g., heavy transport, wind turbines) may need to cascade into slightly less demanding ones (e.g., washing machine pumps) rather than being recycled into equivalent products. The economics of recovery also vary with the quantity of magnet material per unit: wind turbine magnets, at 650 kg per MW, are worth recovering; small consumer electronics magnets are much more challenging with current product design and recycling infrastructure (E3, interview). At the same time, the strong magnetic fields of large turbine magnets create safety and handling constraints that require dedicated dismantling procedures and infrastructure beyond what product design alone can address (E3, interview). A uniform recycling policy will not be equally effective across these product groups.

## Recycled content requirements

The CRMA sets requirements for Original Equipment Manufacturers (OEMs) regarding the use of secondary material in permanent magnets weighing 0.2 kg or more, from 2031 onwards (European Commission, 2024c). The Batteries Regulation (European Parliament and Council, 2023) already sets comparable requirements for cobalt, lithium, and nickel in batteries, with mandatory minimum recycled content from 2031 and higher thresholds from 2036.

As an example of how this could be done, we replicate here the relevant sections of the draft tender for the Nederwiek-I-A offshore wind farm, where award criteria were included for supply chain resilience (Table 8) and for secondary raw material use in magnets (Table 9) (Ministerie van Klimaat en Groene Groei, 2025). Note that these criteria were removed following market consultation. To the authors of this report, this indicates the risk of overly relying on industry input on matters of long-term industrial policy, in instances where there is tension between short-term compliance costs and long-term industrial resilience. Roadmaps with increasing recycled content requirements over time could address this.

The market is not expected to substantially increase secondary material use in NdFeB magnets without stronger direction. Award criteria in individual tenders are likely insufficient on their own to affect system change, partly because the economics of secondary material in magnets are not yet favourable and partly because turbine manufacturers are not yet set up for this. Without a longer-term framework, neither turbine manufacturers nor magnet manufacturers have the certainty needed to invest in processing capacity.

| Criterion | Assessment standard | Points |
|---|---|---|
| 4.1 Use of secondary raw materials in magnets. The use of secondary raw materials from post-consumer magnets in the production of magnets within the wind turbine generators is maximised. | The percentage of secondary raw materials from post-consumer magnets used in the production of magnets within the wind turbine generators for the wind farm is less than 20%. | 0 |
| | The percentage is 20% or more and less than 30%. | 3 |
| | The percentage is 30% or more and less than 40%. | 6 |
| | The percentage is 40% or more and less than 50%. | 9 |
| | The percentage is 50% or more. | 12 |

Table 9 | Scoring criteria for secondary raw material use in permanent magnets, from the draft Nederwiek-I-A tender (Ministerie van Klimaat en Groene Groei, 2025).

## Cross-cutting Preconditions

Certain cross-cutting preconditions must be in place before circular product design strategies can scale. Sprecher et al. (2026) examines these issues in more depth.

**Absence of economic incentives:** Economics are often cited as the main barrier to circular product design. Without hard performance indicators or statutory requirements for material efficiency or repairability, these strategies are generally not prioritised (E15, interview). Economic pressure also drives cost reduction and miniaturisation, making products technically harder to repair (E5, E11, interviews). Economic pressures, consumer behaviour, skill erosion, and institutional structures reinforce each other, and lock the sector into linear models. Effective interventions should target points where a single change propagates through multiple barrier categories (Sprecher et al.,2026). When successive product generations deliver meaningful reductions in operating costs (e.g., through improved energy efficiency) consumers also have an incentive to replace a functioning product, which works against lifetime extension even in the absence of any product fault.

**Infrastructure and friction costs**: The lifetime extension and recycling scenarios assume that products are actually repaired, returned, or recycled at the rates modelled. In practice, logistics for intake, handling, and return flows limit what can be achieved. Existing collection points are often unsuitable for larger products, making actual return flows uncertain. Low product prices make professional repair uncompetitive with replacement, removing the incentive for manufacturers to design for repairability (Sprecher et al., 2026). These friction costs could limit the real-world impact of close-the-loop strategies below levels modelled in this report.

**Manufacturers need the correct information to be able to act**: Realising the modelled lifetime extension scenarios requires that manufacturers understand which components fail, under what conditions, and which design changes would be most effective. In practice, manufacturers have limited visibility into actual use patterns, fault reports, and repair histories (E16, interview). Repair operations and product development teams are typically separate organisations, so failure mode data does not reach designers (E15, interview). Sprecher et al. (2026) documents this pattern across consumer electronics and identifies the organisational separation as a structural cause. Without feedback from the field, design teams lack the information to prioritise interventions, and lifetime extension remains an aspiration rather than an engineering target.

**Knowledge and skills gaps**: Much of the design knowledge needed to adapt product architectures for circularity has been lost through decades of production outsourcing. Manufacturers often lack adequate knowledge of the material composition of the components they source abroad. Recovering these skills requires serious and effective investment in research and education.

# 05

# Conclusions and Recommendations

# CONCLUSIONS AND RECOMMENDATIONS

This study set out to explore the extent to which circular design strategies can reduce demand for critical and strategic raw materials, and to identify where European and national policy can do more to support these strategies. The combined effect of the strategies examined can reduce NdFeB demand growth by up to 75% across the product groups studied. For individual product groups, lifetime extension alone can already halve annual CRM demand. The underlying design knowledge, manufacturing methods, and business model frameworks to achieve this already exist. However, while the technical basis is already in place, the policy and economic conditions for broad implementation are not.

## Conclusions

**The strategies with the largest modelled demand reductions receive the least policy attention.** Material efficiency and lifetime extension deliver the largest reductions in CRM demand. Lifetime extension is particularly effective because it reduces demand for all CRMs in a product simultaneously. Material efficiency is not yet addressed by any product-specific Ecodesign regulation in the context of critical materials. Some of the lifetime extension strategies are supported through repairability requirements in the ESPR and the Right-to-Repair Directive, but the business case for repair remains weak in the absence of stronger warranty enforcement and fiscal reform.

**Demand-side strategies can reduce CRM demand before new supply chains are operational.** Building European production and recycling chains and diversifying supply chains requires years to decades. Demand-side strategies can begin producing results sooner. Lifetime extension affects demand as soon as it takes effect, because in-use products last longer. Substitution can be implemented rapidly if the situation demands it, provided the preliminary design work is already done. Timely R&D investment in CRM-free alternatives is a precondition for rapid response and resilience.

**CRM-containing components often outlast the products they are installed in.** In heat pumps, NdFeB magnets can function for 30 years or more; bearings and encoder systems fail first, and the rotor with magnets last (E1, E2, interviews). Cables have service lives of 80 years or more. Where the CRM-containing component is not the life-limiting factor, extending product life through servicing other components preserves the material investment already embedded in the product. This reinforces the case for lifetime extension as a CRM strategy: each additional year of use defers the demand for new critical materials without requiring any change to the CRM-containing component itself.

**Different product groups require fundamentally different circular strategies.** The highest impact design strategies differ by product group. Effective policy needs to accommodate this variation rather than default to recycling-focused measures across all categories. In some product groups, lifetime extension produces the largest effect. In others, material substitution dominates. When the product is already highly optimised, gains come from system-level utilisation rather than product design.

**Higher recycling rates do not reduce import dependence without European capacity to process recycled material into components.** Current recycling processes typically degrade material quality, and the EU lacks the production chains and knowledge base to convert recycled CRMs back into semi-finished products and components at scale.

**Current end-of-life systems lose the majority of CRMs before they reach a recycler.** Pauliks et al. (2025) find that 56% of elements in EU WEEE were never collected between 2006 and 2021, and specialty elements, which include most listed CRMs, had a recovery rate of 2%. Mass-based collection targets do not incentivise recovery of low-quantity, strategically important materials. The demand reductions modelled in this report complement rather than replace better end-of-life systems: they reduce the total volume of CRMs that collection and recycling infrastructure needs to handle. A tonne of NdFeB that is never placed on the market cannot be lost in the waste stream.

**For some product groups, the most effective interventions are operational rather than design changes.** For cables, the product itself is already highly optimised, and conductor material cannot be reduced without loss of function. The modelled reductions come from higher utilisation intensity through improved insulation materials and relaxed reserve capacity requirements. For heavy transport, increased vehicle utilisation through AI-based route and load optimisation reduces fleet size and therefore aggregate NdFeB demand. These interventions fall outside the scope of Ecodesign regulation and require coordination with e.g., grid infrastructure standards and transport policy.

**Manufacturers and regulators lack the material composition data needed to act on CRM reduction.** For washing machines, a material efficiency strategy targeting electronics (touchscreens, Wi-Fi modules) could not be modelled because the CRM composition of these components is not publicly available. For heavy transport, lifetime extension and recycling strategies were excluded due to insufficient data. For cables, the effect of recycled conductor material on grid performance is poorly understood. These methodological limitations of this study reflect the broader absence of publicly available Bills of Materials data for CRM-containing products, which also limits the ability to make informed decisions about substitution and efficiency.

**The policy conclusions are relevant beyond the six product groups analysed.** The six products were chosen to cover different conditions: mature and slowly innovating (washing machines, cables) versus rapidly developing (heat pumps, heavy transport); gram-scale CRM content (vacuum cleaners) versus thousands of kilograms (wind turbines); product-level design as the main path (washing machines, vacuum cleaners) versus system-level or operational changes (cables, heavy transport). Across all six, material efficiency and lifetime extension produce the largest demand reductions. The same pattern likely holds for other CRM-containing products.

## Recommendations

National governments can act as legislator, as contracting authority, and as participants in EU-level regulatory processes. Several of the recommendations below are directed at the EU level, where national governments need to push for stronger integration of circular design strategies into product regulation. At the national level, governments can use procurement to create market conditions that regulation alone has not yet achieved, and can act directly on fiscal policy and enforcement. A full policy analysis table with product-specific detail can be found in Appendix I.

**Pursue minimum durability requirements in product-specific Ecodesign regulations, based on lifetimes already achieved by best-in-class products (EU, lifetime extension).** Ecodesign regulations should also require that non-CRM wear components (bearings, seals, encoders) be accessible and replaceable without disturbing the CRM-containing assembly, since these components often fail before the CRM-containing parts do.

**Pursue fiscal reform that makes repair economically competitive with replacement (national, lifetime extension).** The current fiscal treatment of repair labour relative to virgin materials is a consistently cited barrier to realising the lifetime extension scenarios in practice. At the national level, better enforcement and communication of existing warranty rights would reinforce these requirements: in the Netherlands, the statutory warranty period extends well beyond the two years most consumers assume, but this right is rarely invoked.

**Set product-specific material efficiency thresholds for CRMs in upcoming Ecodesign delegated acts (EU, material efficiency).** Begin with the product groups where substitution is already technically feasible. Set clear R&D roadmaps for product groups where there are technical challenges.

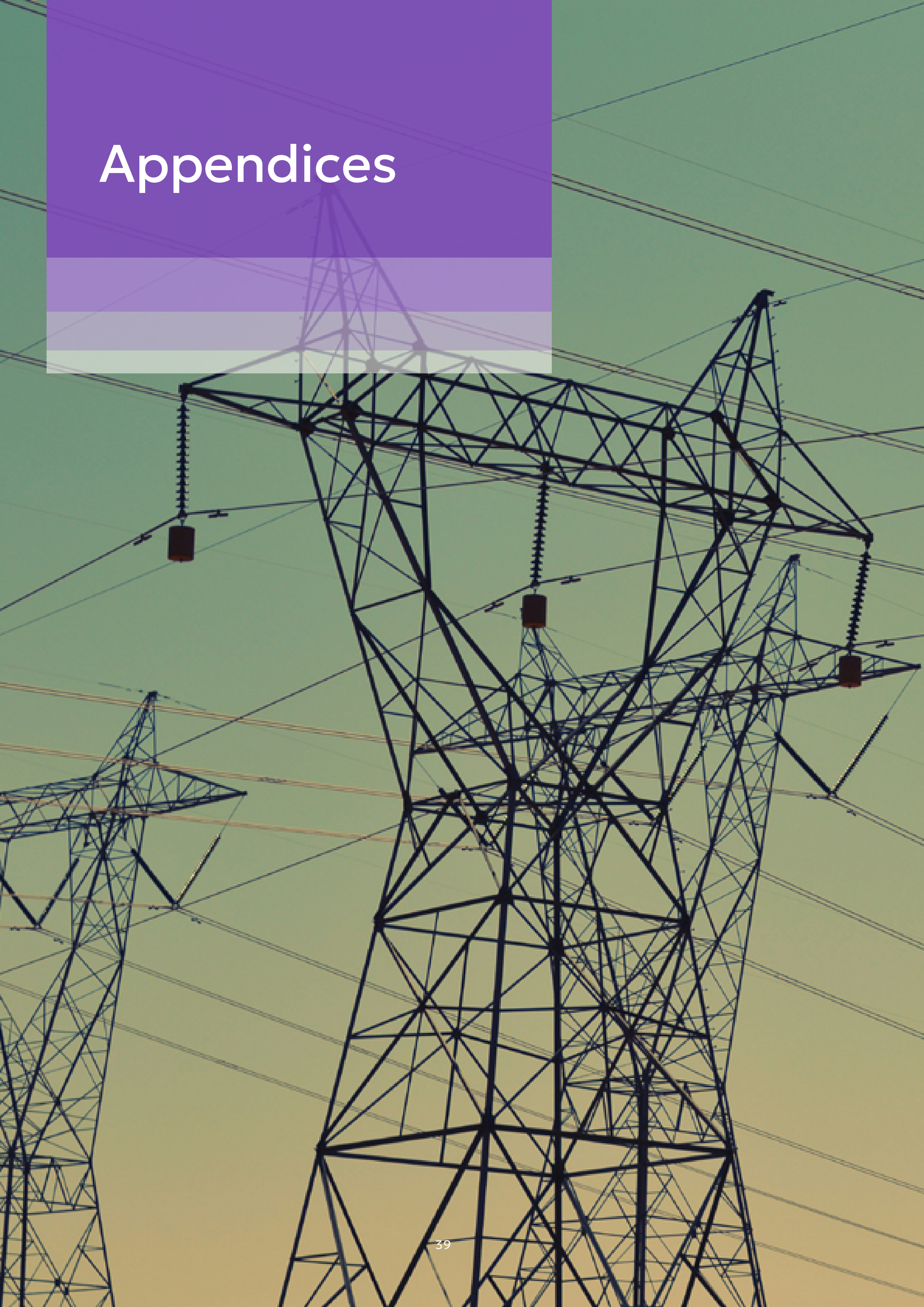
**Require mandatory removal of CRM-containing components prior to shredding in the upcoming WEEE revision, and set per-material recovery rates rather than weight-based targets (EU, recycling).** The Batteries Regulation (European Parliament and Council, 2023) provides a template for structuring product-specific CRM requirements more broadly: material-specific recycled content mandates with escalating timelines, combined with a digital passport for composition transparency.

**Direct R&D funding towards CRM-free technologies (EU and national, technology development).** Several of the modelled scenarios assume that alternative motor types and generator technologies reach the market within the next decade. Without sustained investment, these alternatives will not reach the market in time.

**Embed CRM reduction requirements in public procurement (national procurement, material efficiency).** Procurement criteria should reward technologies that reduce reliance on critical materials, including alternative designs and reductions in CRM content. Award criteria could include secondary material use and supply chain resilience measures.

**Include material efficiency and durability requirements in public procurement concessions and tenders (national procurement, lifetime extension).** Requirements that become stricter over time would give manufacturers a stable horizon for planning and investment.

# Appendices



APPENDIX I.

# Policy Analysis

The table below presents the policy analysis for the six product groups covered in this report. The first section covers cross-cutting policy instruments that apply to multiple product groups. The second section covers policy that is specific to individual product groups or sectors.

| Policy Instrument | Existing Policy | Analysis and Recommendations |
|---|---|---|
| ESPR and product-specific Ecodesign regulations | The ESPR Framework Regulation describes recovery of critical raw materials as a general parameter. Product-specific Ecodesign regulations exist for washing machines (European Commission, 2019) (revision forthcoming) but not yet for heat pumps or vacuum cleaners. | Upcoming product-specific Ecodesign regulations and revisions are the primary vehicle for integrating CRM considerations into product design. For each product group, regulations should include: CRM content rules for encouraging material efficiency; accessibility and disassembly requirements for components containing permanent magnets and PCBs; secondary material requirements in line with the CRMA; minimum durability requirements based on lifetimes already achieved by best-in-class products. |
| Digital Product Passport (DPP) | The mandatory DPP under the ESPR is expected in 2026–2027. It will require transparency on material composition, disassembly instructions, and CRM content. | The DPP is an enabling instrument for multiple recommendations in this analysis, including material composition transparency, disassembly guidance, and CRM traceability. Postponement of the DPP is not desirable. Applies to all product groups covered in this report. |
| CRMA: transparency and supply chain risk assessment | The CRMA (European Commission, 2024c) requires transparency regarding permanent magnet use and supply chain risk assessments for large enterprises using strategic materials. For products with permanent magnets weighing over 0.2 kg, the share of secondary material must be publicly disclosed by May 2027, with minimum shares to be set via delegated acts by December 2031. | It is unclear to what extent manufacturers of washing machines, heat pumps, and other products are aware of these requirements. Better information provision regarding the CRMA is needed, including through sector-specific entry points such as the Roadmap Circular Climate Installations (Circulaire Maakindustrie, 2025) for heat pumps. |
| CRMA: recyclability of permanent magnets | The CRMA requires recyclability of permanent magnets. The ESPR describes recovery of critical raw materials as a general parameter. | Product-specific Ecodesign regulations can operationalise this requirement: accessibility and disassembly of components containing permanent magnets; transparency on the location and chemical composition of magnets via the DPP. Applies to all product groups containing NdFeB magnets. |
| WEEE Directive | The WEEE Directive (European Commission, 2012) states that proper processing preserves valuable raw materials, but CRMs are not specifically named. A revision is expected part of the Circular Economy Act by end 2026. | The WEEE revision should include targeted processing of critical materials (referencing the European Commission list) with a minimum retention percentage. Mandatory removal of CRM-containing components should be considered, analogous to the upcoming end-of-life vehicles regulation (European Commission, 2023a). Applies to washing machines, heat pumps, and vacuum cleaners. |
| Right-to-Repair Directive | The Right-to-Repair Directive (European Commission, 2024a) provides a basis for lifespan extension of consumer electronics, including spare part availability and consumer access to repair. | The government can support implementation through clear consumer communication about warranty rights and repair options. Consumers are often unaware that the statutory warranty period in the Netherlands extends beyond two years. Applies primarily to washing machines and vacuum cleaners. |

| | | |
|---|---|---|
| **Batteries Regulation (precedent)** | The Batteries Regulation (European Parliament and Council, 2023) sets binding, material-specific recycled content targets (cobalt, lithium, nickel) with escalating timelines (2031, 2036), material recovery targets from recycling, and a battery passport with composition and recycled content data from 2027. It does not apply directly to the product groups in this study, but is the most advanced EU instrument combining CRM-specific product requirements with transparency obligations. | The regulatory structure of the Batteries Regulation provides a tested model for CRM-specific product requirements in other sectors. Its combination of mandatory recycled content, escalating timelines, and a digital passport could be adapted for permanent magnets in Ecodesign regulations and for copper-intensive product groups. The CRMA secondary material requirement for permanent magnets (from 2031) follows a similar logic but with less specificity. |
| **Product- and sector-specific policy** | | |
| **Cables: NEN standards and grid utilisation** | Existing NEN standards for cable load capacity and electricity supply reliability as set by the ACM result in unused overcapacity on the grid. | Raising the load capacity of the grid, as discussed in (Agterhuis et al., 2024), also leads to lower CRM demand in the short and medium term. The trade-off with potentially additional outage minutes should be made part of the policy discussion on grid congestion. |
| **Heat pumps: Roadmap Circular Climate Installations** | The Roadmap Circular Climate Installations (Circulaire Maakindustrie, 2025) includes actions on data availability, supply security, lifetime extension through EPR, and end-of-life ownership and responsibilities. | The Roadmap actions are described in fairly general terms and should be strengthened on CRM-specific measures. Increasing data availability can help reduce strategic material use (e.g. steel instead of copper boiler vessels). The EPR contribution should be linked to lifetime extension and reuse, not solely to weight and recycling targets (ecomodulation). Ecomodulation is not yet part of the new general binding rules. |
| **Heavy transport (buses): Circular public transport Covenant** | The Circular public transport Covenant (Convenant Circulair Openbaar Vervoer, 2025) provides a basis for decentralised public transport authorities and concession holders. | A roadmap with over time increasing requirements for secondary material share in permanent magnets and supply chain diversification can provide producers with a stable planning horizon. Programme of Requirements and Procurement Guidelines should include CRMA-aligned criteria. |
| **Heavy transport: EU vehicle circularity regulation** | The EU Regulation on circularity requirements for vehicle design (European Commission, 2023a) (provisional agreement reached December 2025) extends EPR for end-of-life vehicles to trucks and buses. | This regulation provides good integration of existing policy: mandatory declaration of recycled materials including CRMs; authority to set mandatory recycled content targets; mandatory removal of CRM-containing components. The approach is a good model for other product groups. |
| **Wind turbines: offshore wind procurement** | In the Nederwiek-I-A offshore wind tender (draft), NdFeB measures were explicitly included as award criteria. These were removed after market consultation (Ministerie van Klimaat en Groene Groei, 2025). | Future tenders should create coherence between circular design strategies and CRMs; pursue longer wind park lifetimes; include transparency on permanent magnet use per CRMA; include requirements (not just criteria) for secondary materials and supply chain diversification. A schedule of progressively stricter requirements is recommended to give industry long-term predictability. |
| **Wind turbines: end-of-life management** | No EPR exists for end-of-life wind turbines. An industry guideline exists for onshore decommissioning (WindEurope, 2020). | The government can pursue an EU-wide end-of-life management system for wind turbines (analogous to the EPR system for electronics), including mandatory declaration of recycled CRM content and mandatory removal of permanent magnets. The onshore guideline can be adopted and extended to offshore. |

Table 1 | List of consulted experts

## APPENDIX II.

# Consulted Experts

| Code | Background | Product Groups |
|---|---|---|
| E1 | Active at a major multinational that produces electric motors and magnetic assemblies | All product groups |
| E2 | Asian manufacturer of NdFeB permanent magnets | All product groups |
| E3 | Active in the recycling and manufacturing of NdFeB permanent magnets | Vacuum cleaners, heavy transport, wind turbines |
| E4 | Product designer in a major commercial chain that purchases and sells consumer electronics, including vacuum cleaners | All product groups |
| E5 | Researcher in design for repair and circular economy | All product groups |
| E6 | Researcher in product lifetime extension and circular economy | All product groups |
| E7 | Representative of an organisation in the heavy transport manufacturing industry | Vacuum cleaners, heavy transport, wind turbines |
| E8 | Active in an organisation that generates and supplies energy in Europe | Vacuum cleaners, heavy transport, wind turbines |
| E9 | Expert in logistics innovation | Vacuum cleaners, heavy transport, wind turbines |
| E10 | Development and production of pumps | All product groups |
| E11 | Developer and producer of heat pumps | Washing machines, cables, heat pumps |
| E12 | Active in the cable industry | Washing machines, cables, heat pumps |
| E13 | Researcher in design for sustainable behaviour and consumer rights | Washing machines, cables, heat pumps |
| E14 | Researcher in design for recyclability | Washing machines, cables, heat pumps |
| E15 | Researcher in design for sustainability and circular economy | Washing machines, cables, heat pumps |
| E16 | Researcher in circular economy and consumer electronics | Washing machines, cables, heat pumps |
| E17 | Expert in the collection and recycling of WEEE | Washing machines, cables, heat pumps |

Table 2 | List of consulted experts

# APPENDIX III.
# Baseline Data per Product Group

This appendix provides the baseline data underlying the demand projections in Chapter 3, including both sales forecasts and material composition per product group. For the CRM product groups (washing machines, cables, and heat pumps), the baseline scenario parameters are based on the dynamic Material Flow Analysis (dMFA) model developed by CML at Leiden University. For the NdFeB product groups (vacuum cleaners, heavy transport, and wind turbines), the projections are based on desk research and the sources cited below.

## Washing Machines

The forecast for washing machines is based on washing machines sold in recent years, the ownership rate, and the development of the number of households. Since 98% of households already own a washing machine, the forecast through 2050 is primarily linked to changes in the number of households, which rises slightly each year CBS (2022, 2024).

Between 2020 and 2024, the number of newly sold washing machines fluctuated, mainly because during the COVID years of 2021 and 2022 sales dropped by nearly 10% (APPLiA, 2023, 2025). This deviates sharply from the change in other years. For projections through 2050, we therefore use the average change from more stable periods: 0.15 new washing machines are sold per additional household. This results in a slight increase in sold washing machines over time.

| Material | Weight (kg) |
|---|---|
| Product: Washing machine | 70 (total) |
| Aluminium | 2.45 |
| Copper | 1.001 |
| Nickel | 0.462 |
| Manganese | 0.026 |
| Magnesium | 0.060 |
| Magnet (NdFeB) | 0.130 |

Table 3 | Critical and strategic materials in washing machines (Steunenberg, 2021; Sigüenza et al., 2021; Torrubia et al., 2023).

## Cables

The forecast for cable volumes is based on the scenarios from Netbeheer Nederland (2024). Three cable types are distinguished, each with a different growth projection for 2050 relative to 2023:

- **Low-voltage cables (LV):** 20–30% more cables relative to 2023
- **Medium-voltage cables (MV):** 35–45% more cables relative to 2023
- **High-voltage cables (HV):** 20–33% more cables relative to 2023

This report uses the average of the forecasts per cable type, with the total number of cables increasing linearly from 2023 through 2050. The annual number of new cables can be derived from this projection. Material composition data is based on the cable products most frequently purchased by Dutch network operators (Enexis, Stedin, personal communication, 2025). For LV cables, these are the 4x6 mm$^2$, the 4x16 mm$^2$ (both with copper conductors), and the 4x150 mm$^2$ with aluminium conductor. For MV cables, these are the 1x240 mm$^2$, 3x240 mm$^2$, 1x630 mm$^2$, and 1x800 mm$^2$, all with aluminium conductors. For HV cables, this is the 1x800 mm$^2$ with aluminium conductor (E12, interview). Cable product specifications are drawn from TKF Connectivity Solutions (n.d.a, n.d.b, n.d.c, n.d.d, n.d.e, n.d.f, n.d.g) and itsme (2026).

Cable material intensity values per cable type are shown below.

| Cable type | Aluminium (kg/m) | Copper (kg/m) |
|---|---|---|
| Low-voltage cables | 0.54 | 0.48 |
| Medium-voltage cables | 1.61 | 0.44 |
| High-voltage cables | 2.16 | 0.72 |

Table 4 | Critical and strategic materials in cables (TKF Connectivity Solutions, n.d.a, n.d.b, n.d.c, n.d.d, n.d.e, n.d.f, n.d.g; itsme, 2026). Values represent weighted averages of the most frequently purchased cable products by Dutch network operators.

## Heat Pumps

The forecast for the number of heat pumps is based on the scenarios from Netbeheer Nederland (2024). Warmte365 subsequently converted these scenarios into the number of homes per year with heat pumps (Jansen, 2023). The analysis focuses on heat pumps with boiler (hybrid heat pumps), as these make up the largest share and the design strategies have the greatest effect on them. This covers:

- **Hybrid air-source heat pumps** (gas)
- **Hybrid air-source heat pumps** (hydrogen)

This report uses an average of the scenarios, with the number of heat pumps in use increasing linearly between the data points. Heat pumps need to be replaced after a number of years, generating additional replacement demand from approximately 2040 onwards.

| Material | Weight (kg) |
|---|---|
| Copper | 16 *(of which boiler tank: 15)* |
| Aluminium | 5.2 |
| Nickel | 1.8 |
| Manganese | 0.3 |
| Magnet (NdFeB) | 0.25 |

Table 5 | Critical and strategic materials in heat pumps (hybrid air-source heat pump).

## Vacuum Cleaners

The forecast for the number of vacuum cleaners is based on vacuum cleaners sold in recent years and the development of the number of households. The forecast through 2050 is linked to the change in the number of households, with the number of households rising slightly each year, from 8.47 million in 2025 to 9.25 million in 2050 (CBS, 2024).

A distinction has been made between three types of vacuum cleaners with the following trends (APPLiA, 2023, 2025), which have been applied to the years through 2050:

- **Canister vacuum cleaners:** this is the traditional vacuum cleaner, for which newly sold units in 2020–2024 fell by an average of 0.61 per additional household
- **Robot vacuum cleaners:** for this type, the number in 2020–2024 increased by an average of 0.28 per additional household
- **Stick vacuum cleaners:** for this type, the number in 2020–2024 increased by an average of 0.61 per additional household

The permanent magnets in a vacuum cleaner are located in the electric motor. A standard vacuum cleaner contains approximately 16.8 grams of NdFeB magnet material (van Nielen et al., 2023; Liang et al., 2022).

| Product | NdFeB magnet intensity (kg) |
|---|---|
| Vacuum cleaner | 0.0168 kg/unit |

Table 6 | NdFeB magnet intensity in vacuum cleaners (van Nielen et al., 2023; Liang et al., 2022).

## Trucks and Buses

The forecast for the number of trucks is based on background data for the Climate and Energy Outlook from 2024 (Revnext, 2024). This provides a forecast through 2040, distinguishing four categories of trucks:

- **Light trucks:** with a total weight (truck + cargo) between 3.5 and 10 tonnes
- **Medium trucks:** with a total weight between 10 and 20 tonnes
- **Heavy trucks:** with a total weight above 20 tonnes
- **Heavy trailers:** all types of trailers with a total weight above 3.5 tonnes

For the years between the data points from the reference, linear interpolation is assumed. The number of electric trucks increases sharply through 2035. Between 2035 and 2040, the increase is lower. For the forecast after 2040, an annual increase as seen between 2035 and 2040 is assumed.

NdFeB magnets in heavy transport vehicles are used in the electric drivetrain motors. The magnet intensity for trucks and buses is approximately 2.55 kg per vehicle (van Nielen et al., 2023; Liang et al., 2022).

| Product | NdFeB magnet intensity (kg) |
|---|---|
| Heavy transport vehicle (truck/bus) | 2.55 kg/vehicle |

Table 7 | NdFeB magnet intensity in heavy transport vehicles (van Nielen et al., 2023; Liang et al., 2022).

## Wind Turbines

The forecast for wind turbines is based on targets from the Regional Energy Strategy (RES) documents. Total installed capacity in megawatts (MW) is used rather than the number of turbines, as wind turbines come in many different variants with large differences in capacity. The amount of magnets is also determined based on capacity rather than unit count.

Offshore wind turbines use NdFeB magnets in their direct-drive generators. The magnet intensity is approximately 650 kg per MW of installed capacity (Liang et al., 2022). Onshore wind turbines in Europe predominantly use generator types that do not require NdFeB magnets.

| Product | NdFeB magnet intensity (kg) |
|---|---|
| Offshore wind turbine | 650 kg/MW |

Table 8 | NdFeB magnet intensity in offshore wind turbines (Liang et al., 2022).

APPENDIX IV.

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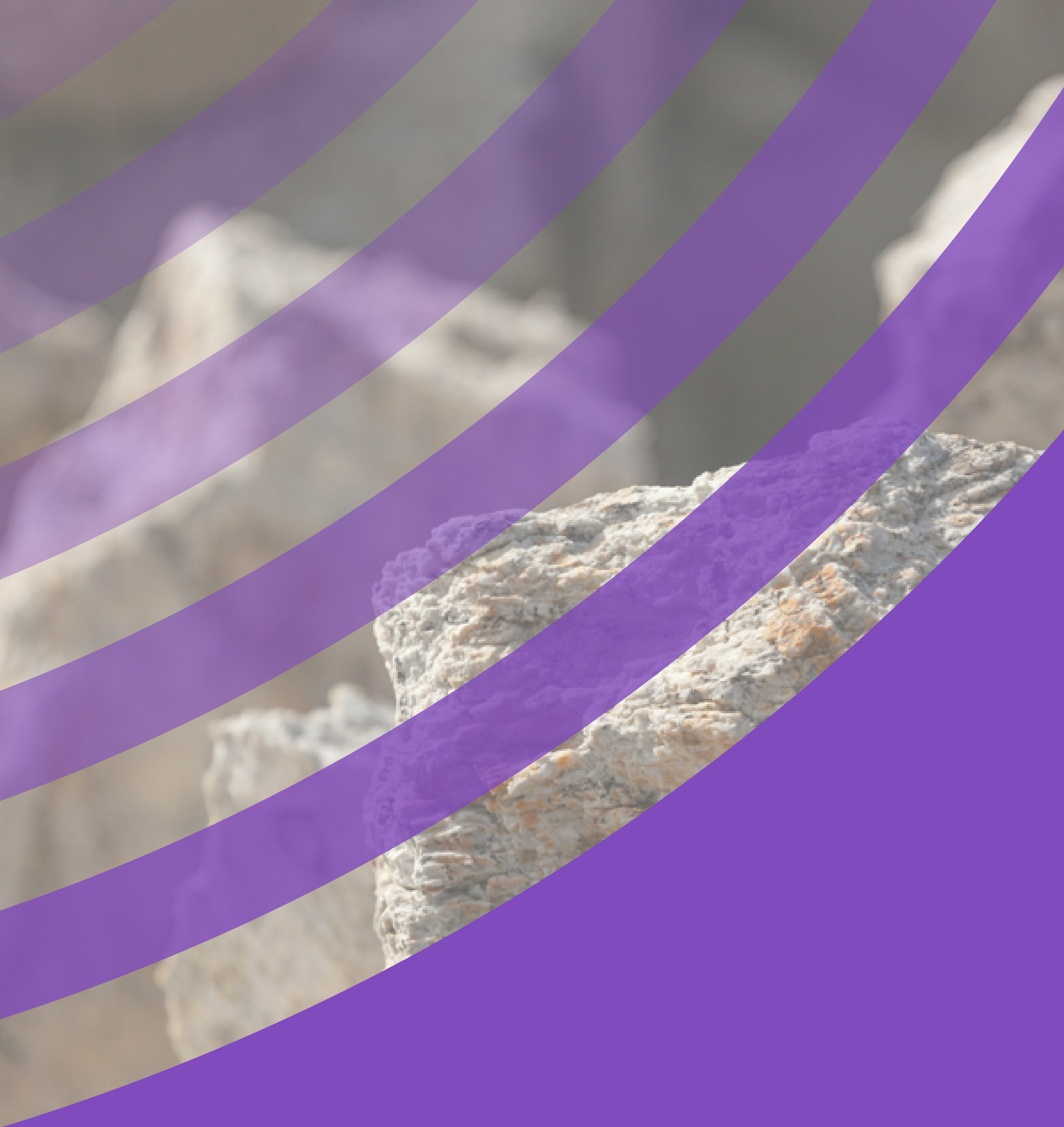

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