Trendreport Leitprojekt ORCHESTER

Trends für ein digitales Ökosystem für eine resiliente und nachhaltige Versorgung mit funktionssicheren Werkstoffen

Ort: Karlsruhe

Datum: 13.02.2026

Status: Version 2

Impressum

Trendreport Leitprojekt ORCHESTER

Verantwortlich für den Inhalt des Textes

Ewa Dönitz, ewa.doenitz@isi.fraunhofer.de; Björn Moller, bjoern.moller@isi.fraunhofer.de

Beteiligte Institute

Fraunhofer-Institut für Werkstoffmechanik IWM
Fraunhofer-Institut für Werkstoff - und Strahltechnik IWS
Fraunhofer-Institut für Zerstörungsfreie Prüfverfahren IZFP
Fraunhofer-Institut für Werkzeugmaschinen und Umformtechnik IWU
Fraunhofer-Institut für System- und Innovationsforschung ISI
Fraunhofer-Einrichtung für Wertstoffkreisläufe und Ressourcenstrategie IWKS

Bildnachweis

Zitierempfehlung

Dönitz, E.; Moller, B. (2025): Trendreport Leitprojekt ORCHESTER. Trends für ein digitales Ökosystem für eine resiliente und nachhaltige Versorgung mit funktionssicheren Werkstoffen. Karlsruhe: Fraunhofer-Institut für System- und Innovationsforschung ISI

Veröffentlicht

Februar 2026

Hinweise

Inhaltsverzeichnis

1 ORCHESTER Trend Report – Process Description

1.1 Purpose and Context

The ORCHESTER project aims to develop a digital ecosystem that supports a resilient and sustainable supply of functionally reliable materials. To anticipate future developments and guide strategic decisions, the project conducted a comprehensive trend analysis. This analysis identifies key drivers of change across technological, economic, social, environmental, and political dimensions, ensuring that demonstrator activities remain aligned with emerging opportunities and risks.

The resulting Trend Report provides a structured overview of trends with the highest relevance for ORCHESTER. It serves as a foundation for roadmap development, research prioritization, and stakeholder engagement.

1.2 Methodological Approach

The ORCHESTER trend work followed a semi-automated horizon scanning approach that combines AI-supported literature analysis with expert review. Content was structured using a STEEP frame to ensure coverage of Social, Technological, Economic, Environmental, and Political drivers relevant to "a digital ecosystem for resilient and sustainable provision of functionally reliable materials." The outcome is a prioritized set of trends (Game Changers, High Potential, Monitoring) with demonstrator-specific relevance and initial implications for action.

Step 1: Horizon Scanning and Longlist Creation

Goal: Build a robust longlist of trends as the starting point for expert validation.

Building on insights from ongoing and completed projects of Fraunhofer ISI, we compiled an initial set of signals and trends, which were then structured using the STEEP framework:

- **S – Social**: Society and labor market dynamics, skills and organizational change.
- **T – Technological**: Innovations and digital systems enabling monitoring, data spaces, and reliability by design.
- **E – Economic**: Market shifts, value creation models, cost/benefit of reliability, data-driven services.
- **E – Environmental**: Climate and resource constraints, circularity, lifecycle strategies.
- **P – Political**: Regulatory frameworks, standards, certification, and conformity assessment.

In addition, we began with a semi-automated literature and web analysis, leveraging natural language processing (NLP) and machine learning techniques (e.g., KeyBERT, YAKE!) to extract keywords and cluster emerging topics. This automated step was complemented by manual expert review, refining the results to ensure alignment with ORCHESTER's objectives. The outcome was a long list of 75 trends, serving as the foundation for subsequent validation and prioritization steps.

Iterative expert refinement

Step 2: Project Meeting (12 Oct 2024, Dresden)

Goal: Validate and qualify the longlist; collect initial relevance ratings for demonstrators.

The longlist was presented during an in-person workshop using a poster format. Participants assessed the relevance of each trend for ORCHESTER and its demonstrators through a dot-voting exercise, providing initial prioritization and qualitative insights.

Step 3: Online Demonstrator Survey using Miroboard

Goal: Broaden input and converge on a TOP 25.

To broaden participation, the same assessment was conducted online. Stakeholders rated trends for relevance and impact, contributing to the identification of the Top 25 trends for ORCHESTER. The focus was on the demonstrator's relevance, the strength of impact, and notes on current activities or gaps.

Step 4: Online Workshop (29 Apr 2025)

Goal: Translate prioritized trends into demonstrator-specific implications.

The prioritized trends were discussed in detail during an interactive workshop. Participants evaluated:

- Impact on demonstrator activities with short justifications and concrete implications.
- Trend classification: Game Changers (highly disruptive), High-Potential trends, and trends requiring monitoring.
- Existing activities within Fraunhofer: Participants documented ongoing activities that already address the trends (projects, pilots, standards work, testbeds, data spaces, etc.).

Step 5: Consolidation and Trend Description

Goal: Turn workshop insights into formal trend descriptions and a decision-ready report.

Finally, workshop results were synthesized using AI-assisted analysis to extract future assumptions and ensure consistency. Each trend was documented in a standardized format:

- Title and STEEP category
- Short description
- Facts and figures
- Relevance for ORCHESTER demonstrators
- Future assumptions (for Game Changers)

We selected ten game changers to initiate an automated search. We used qualitative data comprising descriptions of each game changer, which was essential to initiate the automated processing. This descriptive data was provided as input to FhGenie, a cloud-based AI chatbot created by the Fraunhofer-Gesellschaft. We designed a prompt to analyse each game changer's direct and indirect relevance to three demonstrators: Material Selection and Specification, Recycling, and Criticality. For each game changer, the model inferred future assumptions and generated corresponding scenarios. The analysis produced a structured output detailing demonstrator relevance and future assumptions for each game changer.

The report opens with **10 Game Changer trends**, followed by **10 High-Potential trends**, and **5 Monitoring trends**.

The full **75-trend long list** is included in the Annex, preserving transparency and enabling follow-up analysis.

2 25 Trends for a Digital Ecosystem

2.1 10 Game Changer Trends

2.1.1 Additive Manufacturing Technologies (Technological)

Short Description

These technologies enable precise material usage and reduce waste, thereby improving sustainability in production.

Additive manufacturing (AM), or 3D printing, is an innovative technology with significant potential for sustainable remanufacturing. It allows for the precise restoration of worn or damaged components, reducing the need for replacement parts and minimizing material waste (Oros Daraban et al. 2019; Tanuja et al. 2023). Life Cycle Assessment (LCA) studies show that additive manufacturing (AM) uses less material, minimizes handling, and shortens supply chains. It offers three key environmental benefits for reducing carbon footprints: (a) lower raw material requirements, reducing mining and refining; (b) decreased reliance on energy-intensive production methods like casting or CNC machining; and (c) improved product performance, such as hydraulic components with optimized fluid pathways. Ongoing research aims to implement AM technologies across various fields for diverse goods (Hegab et al. 2023).

In general, additive manufacturing (AM) produces less waste compared to traditional methods. However, waste can still arise, particularly from support structures or failed prints. The recycling of natural waste materials for AM is being explored, but challenges remain. First, the variability in recycled material properties can affect print quality and mechanical performance, necessitating standardized recycling processes. Issues like impurities and inconsistent particle sizes can lead to nozzle clogging and poor adhesion. Second, recycled composites often have lower mechanical properties than traditional materials. Advanced preprocessing techniques, such as thorough drying and impurity removal, can enhance their printability and performance.

It is essential to design specialized AM equipment to address these challenges, optimizing nozzle designs and print parameters. Additionally, comprehensive studies are needed to evaluate the long-term performance and environmental impact of 3D-printed biocomposites (Yousaf et al. 2024).

Facts and Figures

Statistics show that the AM market has undergone substantial growth. The global AM market was valued at $13.89 billion in 2021 and is projected to reach approximately $76.20 billion by 2030, with a compound annual growth rate (CAGR) of 20.9% during the forecast period from 2022 to 2030 (Additive Manufacturing industry Growth Prospects, Trends and Forecast up to 2030). This growth may be driven by several factors; industries are expanding their use of AM due to its design flexibility, resource efficiency, and cost-effectiveness in low-volume production. AM is well-suited to the fundamental principles of Industry 4.0, providing technical precision and lowering the work-intensive operations within the production facility (He et al. 2023; Dilberoglu et al. 2017; Kanishka and Acherjee 2023). Industry-specific examples include the healthcare sector, driven by the rising demand for personalized medicine, where 3D technologies are used to create custom tools and devices for patients; a strong recovery in the aerospace industry following the disruptions caused by COVID-19; and a growing demand for lighter components in the automotive sector. Additionally, the growing involvement of governments can significantly support the adoption of this technology through funding and initiatives that promote its advantages (3D Printing News 12.01.2023). In

Germany, the AM market is projected to be valued at $2.89 billion in 2025 and is expected to grow to $7.38 billion by 2030, reflecting a CAGR of 20.6% during the forecast period from 2025 to 2030 (Germany Additive Manufacturing Market Size & Share Analysis - Growth Trends & Forecast (2025-2030) 2024).

Relevance for Orchestra Demonstrator

Demonstrator I **Material Selection and Specification**	**Demonstrator II** **Recycling**	**Demonstrator III** **Criticality**
Direct: Accelerates material screening and development of alternative alloys. AM is used for material screening, offering cost savings during material development but not during production.	Direct: Relies on high-quality recycled feedstock; reduces waste by utilizing recycled materials. AM depends heavily on feedstock and powder properties, which are key to achieving the desired component performance given limited powder lifespan due to aging and contamination. Powder production is typically energy- and resource-intensive. We use AM for rapid material screening, though its overall footprint is not always advantageous.	Indirect: Optimizes designs to reduce reliance on critical materials.

Future Assumptions

Assumption a): Niche Adoption

Additive manufacturing remains a niche technology, primarily used for prototyping and low-volume production. High costs and technical challenges prevent widespread adoption, limiting its impact on sustainability (Zago et al. 2025; Gonçalves et al. 2023).

- **Key driver:** Economic and technological barriers.

Assumption b): Market-Driven Innovation

Industries adopt AM to reduce waste and improve production efficiency. Companies leverage AM as a marketing tool, emphasizing its sustainability benefits. However, adoption is limited to high-value sectors like aerospace and healthcare (Nyika and Dinka 2024; Getachew et al. 2023).

- **Key driver:** Corporate branding and sector-specific demand.

Assumption c): Technological Breakthrough

Advances in AM technology, such as improved material preprocessing and recycling methods, make it cost-effective and scalable. AM becomes a standard manufacturing process, significantly reducing waste and resource consumption (Sword et al. 2024; Bigliardi et al. 2024).

- **Key driver:** Technological innovation and cost reduction.

Assumption d): Circular Manufacturing Systems

AM is fully integrated into circular manufacturing systems, enabling the use of recycled materials and closed-loop production. Digital tools optimize designs for disassembly and material reuse, maximizing sustainability (Rojek et al. 2025; Mattos Nascimento et al. 2022).

- **Key driver:** Integration of AM with circular economy principles.

2.1.2 Secondary Raw Materials Markets (Economic)

Short Description

Production is adapted to variable material qualities through flexible facilities.

Secondary raw materials (SRM) markets are crucial for promoting the circulation of high-quality recycled materials in Europe, reducing the need for extracting natural resources. The success of these markets depends on their maturity, size, and the quality of available materials. However, several obstacles remain throughout the SRM value chain, including regulatory challenges, technological issues, quality concerns, economic factors, and competition from energy consumption. During the product design phase, there is a lack of motivation to prioritize recyclability. Moreover, inconsistent technical specifications and end-of-waste criteria across the EU hinder the effective operation of these markets.

Enhancing information sharing and standardization could lead to greater market efficiency. Currently, only three SRM markets – aluminum, paper, and glass – perform well, as they are well-established, international, and command a significant market share. In contrast, other markets, such as plastics and textiles, struggle due to their smaller scale, low demand, and inadequate specifications. Key components for a thriving SRM market include the size and growth of the market, the impact of policy drivers on supply and demand, the lack of competition from energy use, the participation of materials in closed-loop circular systems, and the availability of technical specifications and standardizations.

To improve SRM markets, possible actions include revising EU policies, broadening green public procurement, raising recycling targets, creating end-of-waste criteria, and expanding requirements for recycled content (Castell-Rudenhausen et al. 2022).

Facts and Figures

The EU's circular economy could be greatly enhanced by increasing the amount of secondary raw materials (SRMs) reintegrated into the economy. However, analyzing EU secondary markets is challenging due to the differing waste collection and management practices, as well as inconsistent definitions of waste operations across member states. Data from 2010 to 2020 reveal significant disparities in the volumes of secondary materials and recycling rates. For instance, in 2020, vegetable waste and paper and cardboard had the largest markets, marking 94% and 98% recycling waste, respectively. Glass and batteries also achieved full recycling, although their volumes were relatively low. Wood waste, with a lower recycling rate of 46%, still contributed significantly in terms of volume.

In 2023, recyclable ferrous metals like iron and steel exhibited the highest levels of intra-EU trade, with nearly 59 kg per capita traded within the EU, and the EU was also a net exporter of these metals outside its borders. Conversely, recyclable non-ferrous metals, such as aluminum, saw limited intra-EU trade and minimal exports. A decrease in the availability of raw materials can lower market prices, which in turn diminishes the demand for secondary materials. Additionally, poor product design can complicate and raise the costs of collection and sorting, further restricting the supply of recyclable materials. The absence of harmonized quality standards in waste management exacerbates these issues, while insufficient recycling capacity hampers the development of secondary markets for certain materials.

Several companies and regions are already advocating sustainable practices involving secondary raw materials. For example, Volkswagen's sustainability strategy incorporates both renewable and secondary raw materials, such as recycled plastics, in its vehicles. Xerox has established responsible business practices through its Green World Alliance, focusing on recycling printer supplies, including toner cartridges, plastics, and metals. Meanwhile, Norway has taken the lead in promoting circular production within battery manufacturing. Through the BAT-MAN project, initiated by the EYDE Cluster in 2019, Norway is investigating sustainable methods for managing the end-of-life of lithium-ion batteries, showcasing the potential for innovation in recycling and material reuse. These examples highlight the critical role of policy measures in overcoming obstacles and promoting the development of secondary material markets in the EU (Vergano 2024).

Relevance for Orchestra Demonstrator

Demonstrator I **Material Selection and Specification**	**Demonstrator II** **Recycling**	**Demonstrator III** **Criticality**
Direct: Promotes resilience by enabling flexible material specifications. Particularly relevant for sourcing critical materials such as Ni and Mn.	Direct: Addresses the availability and quality of recycled aluminum alloys, which strongly depend on market conditions. Emphasizes the need for flexible facilities and adaptable production processes to ensure supply security.	Direct: Contributes to developing secondary raw material (SRM) markets for rare earth elements, reducing dependency on imports. Supports industrial implementation of diverse recycling technologies.

Future Assumptions

Assumption a): Policy-Driven Expansion

Governments introduce policies such as mandatory recycled content quotas and harmonized end-of-waste criteria. These measures stimulate SRM markets, but the focus remains on compliance rather than innovation, limiting market growth (Pierri et al. 2024; OECD Environment Working Papers 2024).

- **Key driver:** Strong policy intervention.

Assumption b): Industry-Led Growth

Industries recognize the economic benefits of SRM markets and invest in flexible production systems to accommodate variable material qualities. Collaboration between industries and recyclers drives innovation, but market growth is uneven across sectors (Obaid et al. 2025; Flores Lara et al. 2025).

- **Key driver:** Economic incentives and industrial collaboration.

Assumption c): Fragmented Development

SRM markets remain fragmented due to inconsistent regulations, a lack of standardization, and limited demand. Only a few materials, such as aluminum and paper, achieve significant market penetration, while others, like plastics, lag behind (Wu et al. 2024; Hossain and Sahajwalla 2024).

- **Key driver:** Regulatory and market inconsistencies.

Assumption d): Circular Market Ecosystem

A fully integrated circular economy emerges, supported by standardized SRM quality criteria, digital product passports, and advanced lifecycle tracking. SRM markets thrive across all material types, reducing dependency on primary resources (Abedi et al. 2024).

- **Key driver:** Standardization and digital integration.

2.1.3 The Role of the CO_2 Price (Economic)

Short Description

A rising CO_2 price increases the demand for low-emission production methods and secondary raw materials.

Carbon pricing is one of the primary strategies of governments to promote firms’ investments in low emission technologies. Higher carbon prices provide an effective incentive for low carbon innovation (Cantone et al. 2023).

A Chinese study found that higher carbon prices significantly promote firms' substantive green innovation. However, they don't affect strategic green innovation. Carbon prices work through signalling and cost-saving mechanisms. They more strongly benefit regulated firms and those in liquid carbon markets. Rising carbon prices drive green innovation in nonstate-owned firms, particularly substantive innovation. Firms with limited cost pass-through ability show greater green innovation activity when facing a higher carbon price (Chen et al. 2024). In Germany, CO_2 pricing has a limited impact on industrial decarbonization and is supplemented by other measures and drivers. These include reduced production and an increased green product demand. ESG targets and company 'license to operate' requirements also drive change. Government strategies provide continuous renewable energy support and hydrogen production grants (Weale 2024).

There are some barriers that lead to market failure for material recycling, namely, the social cost of waste treatment remains external to consumers. Environmental costs aren't reflected in market prices, ignoring emission savings from recycling. Producers lack incentives for recyclable product design since additional costs aren't compensated. Carbon pricing policies shift emission costs to consumers, increasing recycled material use and reducing total consumption (Sun and Neuhoff 2024).

Facts and Figures

Research on the Spanish electricity market indicates that increasing CO_2 prices can enable low- or zero-emission technologies to be integrated into the energy mix, which leads to a cleaner energy supply in the market and a reduction in total emissions (Arcos-Vargas et al. 2023).

Cantone et al. (2023) showed that a 1 USD increase in the expected future carbon price is associated with a 1.4% increase in the level of patenting in low carbon technologies, based on data for countries participating in the EU emissions trading system (ETS). The unit costs of several low emission technologies, e.g., photovoltaics, onshore and offshore wind, and EV batteries, have been falling continuously over recent years (Cantone et al. 2023).

Carbon pricing can encourage material recycling, as implementing a carbon price on production creates an economic advantage for recycled materials over their primary counterparts. Furthermore, extending the policy to waste disposal makes recycling more competitive against waste incineration. In the PET industry, for example, an estimation study showed that a carbon pricing policy on both PET production and incineration at the social cost of carbon of 100 euros leads to a 37% reduction in total emissions, contributed by a 23% reduction in total PET consumption and a 15% increase in PET recycling (Sun 2023).

Relevance for Orchestra Demonstrator

Demonstrator I **Material Selection and Specification**	**Demonstrator II** **Recycling**	**Demonstrator III** **Criticality**
Direct: CO_2 pricing integrates embodied carbon costs into material and process choices, favoring low-carbon alloys, recycled content, and energy-efficient routes. Drives adoption of Environmental Product Declarations (EPDs), recycled content specifications, and process innovations (e.g., near-net-shape manufacturing, additive	Direct: Improves the economics of recycled feedstock compared to primary materials and recycling versus incineration. Increases demand for high-quality recyclate and incentivizes low-emission recycling technologies and energy sources.	Indirect: Accelerates deployment of low-carbon technologies (e.g., EVs, wind turbines) that depend on critical materials such as NdFeB magnets. Heightens supply risk while strengthening the business case for recovery and closed-loop supply of critical materials.

Demonstrator I Material Selection and Specification	Demonstrator II Recycling	Demonstrator III Criticality
manufacturing where net emissions are lower).		

Future Assumptions

Assumption a): High, Predictable Carbon Price Alignment

- Sustained, rising, and predictable CO_2 prices across major markets (with CBAM-like measures) drive rapid material and process substitution, high recycled content, and widespread low-carbon manufacturing (Johnsen et al. 2024; Rokhmawati et al. 2024).
- **Key driver:** Strong, harmonized policy signals and price visibility.

Assumption b): Market-Led Adoption with Green Premiums

- Moderate CO_2 prices plus consumer/brand demand for low-carbon products lead firms to differentiate on embodied-carbon and recycled content; advanced buyers use EPDs and supplier carbon thresholds (Kundu 2025).
- **Key driver:** High customer awareness and corporate climate commitments.

Assumption c): Policy Fragmentation/Low CO_2 Price

- Stagnant or volatile carbon prices and uneven coverage limit change; firms prioritize least-cost compliance, offsets, and energy efficiency over deep materials transitions; recycling gains are modest (Evdokimova and Millischer 2026; Dhanda and Malik 2025).
- **Key driver:** Economic and political barriers; weak/fragmented carbon markets.

Assumption d): Integrated Carbon Markets with Digital MRV

- Interoperable carbon markets, border adjustments, and digital MRV (e.g., product-level footprints via IoT/blockchain) mainstream carbon-aware procurement; circular design and high-quality recycling become default (Heiss et al. 2024; Alfakihuddin et al. 2026).
- **Key driver:** Digitalization, MRV standardization, and cross-sector policy coordination.

2.1.4 Advanced Recovery Technologies (Ecological)

Short Description

Innovative technologies for recovering raw materials from complex composite materials or end-of-life products.

The conventional "take, make, dispose" model in manufacturing is no longer viable because of environmental issues, resource depletion, and waste production (Tanuja et al. 2023). The shift to a circular economy necessitates rethinking current products and processes, along with the creation and application of innovative technologies (van Gaalen and Slootweg 2025). Emerging technologies provide solutions to revolutionize recycling and remanufacturing processes. Advanced material separation techniques, like electrostatic and eddy current separation, enable efficient recycling by recovering valuable components and reducing contamination. Additive manufacturing (3D printing) allows for the precise restoration of damaged parts, thereby minimizing waste. Digital technologies, such as IoT, machine learning and blockchain boost efficiency by providing real-time data, optimizing processes, and ensuring transparency and traceability in the recycling supply chain. These innovations hold the potential to improve product quality, decrease waste, and lower energy consumption (Tanuja et al. 2023).

The primary goal of these technologies is to maximize recycling and reuse recovered fibers within the same process, thereby closing the material life cycle. They also aim to collaborate with other industries to repurpose high-performance materials across different sectors. Systems have been developed to recover carbon fibers from production waste and end-of-life components without significantly compromising their properties. However, it is challenging to reintegrate recycled fiber into the market. Current recycled products are available as compounds (ground and chopped fibers in powder or pellet form) and for layering (non-woven mats like dry fabrics, prepregs, and SMC materials), but their applications have been limited so far (La Rosa 2023).

Facts and Figures

It is essential for recycled materials to maintain consistency across recycling facilities and even among batches from the same facility, within an acceptable level of confidence. This is particularly important for industries such as aerostructures, where new materials must pass stringent certification processes. To achieve this, a testing campaign involving a sufficiently large sample of the secondary material is necessary, which can be resource-intensive in terms of both time and cost. Currently, there are no established standards for recycled fibers from End-of-Life (EoL) applications, which discourages suppliers and manufacturers from utilizing secondary raw materials. Decisions made in the early stages can affect the recyclability of components at EoL, such as opting for materials that are easier to recycle, like thermoplastic matrices, which can theoretically undergo multiple recycling cycles with minimal degradation of properties. Another strategy to enhance circularity involves developing innovative technologies for the energy-efficient recycling of thermosets. Both biodegradable and dynamic covalent systems are being researched, with some nearing market readiness (Emma Arussi et al.).

As part of the innovation drive of Industry 4.0, advanced production methods like additive manufacturing have been scaled up. These techniques can significantly lower scrap rates while also utilizing waste powder or cropped fibers from other processes. Consequently, integrating these processes within the same manufacturing facility offers substantial advantages. Additive manufacturing is increasingly favored for its design flexibility, automation, production speed, and reduced scrap rates (Emma Arussi et al.; Liu et al. 2021).

Digital tools are also showing promising results in recycling industries. For instance, digitally transmitted information can enhance the precision with which secondary raw materials are designed. An example of this is the use of digital watermarks for sorting packaging. These watermarks—codes that are invisible to the human eye—can be printed on labels, sleeves, films, bags, and bottles. Specialized scanners can then read these codes, providing information about the packaging's material and whether it previously contained food, cosmetics, or detergents. A notable example of this innovative approach is the Holy Grail project by Petcore Europe. According to Petcore Europe, existing sorting systems can be easily upgraded with such scanners. In the next steps, this new technology will be tested on a production line and at an industrial scale (IFAT Munich). These innovative approaches

Relevance for Orchestra Demonstrator

Demonstrator I Material Selection and Specification	Demonstrator II Recycling	Demonstrator III Criticality
Indirect: Supports material screening for alternative alloys, enabling more resilient and sustainable material choices.	Indirect: Improves recycling quality for aluminum alloys. Indirect Impact: Recovery processes influence the material quality of recyclate; sorting measures significantly affect subsequent production steps and functional properties.	Direct: Enables efficient recovery of rare earth elements from NdFeB magnets. NdFeB magnets are often complexly integrated, requiring the development of advanced recycling technologies.

Future Assumptions

Assumption a): Regulation-Driven Recycling

Governments enforce strict recycling mandates, requiring industries to adopt advanced recycling technologies. Compliance becomes the primary driver, with companies focusing on meeting minimum standards rather than innovating. Recycling rates improve, but the potential for circularity remains underutilized (Silva 2025).

- **Key driver:** Strong regulatory pressure, low voluntary innovation.

Assumption b): Market-Led Adoption

Consumer demand for sustainable products drives companies to adopt advanced recycling technologies as a competitive advantage. Brands market their use of recycled materials, leading to innovation in material separation and reuse. However, adoption is limited to high-value markets (Fischer and Burgstahler 2025; Polyportis et al. 2022).

- **Key driver:** High consumer awareness and corporate branding strategies.

Assumption c): Technological Stagnation

Despite initial interest, advanced recycling technologies fail to scale due to high costs, lack of standardization, and technological barriers. Companies prioritize other sustainability strategies, such as carbon offsetting, over recycling innovation (Castro-Amoedo et al.).

- **Key driver:** Economic and technological barriers.

Assumption d): Circular Economy Integration

Cross-sector collaboration and digital tools (e.g., IoT, blockchain) enable seamless integration of advanced recycling technologies into global supply chains. Material separation and reuse become standard practices, supported by interoperable platforms and circular business models (GACERE & UNIDO 2025).

- **Key driver:** Digitalization and circular ecosystem collaboration.

2.1.5 Design for Disassembly (Ecological)

Short Description

Materials are designed to be easily disassembled and reused.

Design for Disassembly (DfD) is a design methodology developed in the manufacturing sector to tackle challenges related to limited material and energy resources, as well as rising waste generation. DfD aims to prevent waste by design, aligning with the principles of a circular economy (CE). The recent standard ISO 20887:2020 defines DfD (originating from ISO 14021:2016) in the context of Architecture, Engineering, and Construction (AEC) as an approach *[that facilitates disassembly [...] at the end of its useful life, in such a way that enables components [...] and parts to be reused, recycled, recovered for energy or, in some other way, diverted from the waste stream.]* (Ostapska et al. 2024).

There are several methods and tools available to incorporate DfD into standard practices. These include Circularity Indicators (CI) at different levels, Life Cycle Assessment (LCA) with enhancements for DfD, disassembly evaluation and planning, and Industry 4.0 concepts like digital fabrication and material tracking systems. Additional methods, such as Material Flow Analysis and Service Life Design, are also relevant. DfD is a proactive approach often aimed at the long-term future, making it difficult to demonstrate its effectiveness without longitudinal studies. Integrating LCA into DfD is complex, as DfD allows multiple "lives" for a product, complicating the definitions of life and cycle. Typically, in LCA, the end of life (EoL) of a building marks the end of its cycle. To assess DfD benefits, it may be necessary to redefine the cycle or incorporate multiple cycles (multi-cycling). (Ostapska et al. 2024).

Neglecting a product's EoL status can lead to ineffective DfD recommendations for circularity. The EoL condition affects disassembly, as many DfD strategies assume products are in optimal condition, causing discrepancies in assessments. Design for Circular Disassembly (DfCD) addresses this by factoring in EoL status and circular potential. Defined as the process of (re)designing products for easier disassembly at EoL, DfCD enhances circular economy potential. It evaluates circularity based on the effort required for specific EoL scenarios and differs from traditional DfD by incorporating EoL status and insights on circular economy performance, focusing on both disassembly and circularity (Formentini and Ramanujan 2023).

Facts and Figures

The Netherlands as a country, and Europe as a continent, are leading in modern DfD construction, followed by the USA, Japan and China. The reason is the urgent need to reform the current wasteful construction practices in the global Western countries, the limits of landfill capacity, and the emerging law of extended producer responsibility (Ostapska et al. 2024).

Quantitative assessment of design for disassembly benefits through time-resolved prospective life cycle assessment reveals consistent environmental advantages across diverse future scenarios.

Buildings designed with high disassembly potential demonstrate embodied greenhouse gas emission reductions of 12-25% compared to conventional construction approaches when assessed across nine distinct development pathways, ranging from sustainable development to fossil-fueled growth scenarios. These benefits persist regardless of climate policy stringency, with emission reductions maintained under both aggressive decarbonization targets and less restrictive pathways.

Material recovery potential through enhanced disassembly design shows measurable benefits that vary according to future production scenarios. While absolute environmental advantages diminish in highly decarbonized futures due to cleaner background processes, buildings with minimal disassembly consideration consistently exhibit 8-11% higher emissions compared to standard designs across all projected pathways. The relative performance ranking between high, standard, and low disassembly potential designs remains stable regardless of technological or policy scenarios (Abu-Ghaida et al. 2025).

Relevance for Orchestra Demonstrator

Demonstrator I **Material Selection and Specification**	**Demonstrator II** **Recycling**	**Demonstrator III** **Criticality**
Indirect: Could support future material recovery strategies, especially for complex assemblies such as fuel cells and stainless steel components.	Direct: Facilitates separation of materials for efficient recycling. Dismantling enables better sorting, which significantly improves the quality of recyclate (e.g., aluminum scraps) and affects subsequent production steps and functional properties. Strong connection to engineering design for recyclability.	Direct: Availability of used magnets is tied to end-of-life products; dismantling and “Design for Recycling” are essential. This could be a game changer for secondary material markets.

Future Assumptions

Assumption a): Regulation-Driven Transformation

Governments introduce stringent regulations mandating DfD across industries. Companies comply to avoid penalties, but innovation is minimal and cost driven. Compliance, rather than circularity, becomes the norm (Abdelmeguid et al. 2024).

- **Key driver:** Strong regulatory pressure, low voluntary engagement.

Assumption b): Market-Led Innovation

Consumer demand and competitive advantage push companies to adopt DfD. Brands leverage it as a marketing and value proposition, leading to rapid innovation and niche market growth — but overall systemic impact remains limited (Assyiraq Ibrahim and Putri 2025).

- **Key driver:** High consumer awareness and corporate branding strategies.

Assumption c): Technological Plateau

Despite early interest, DfD remains niche. Technological limitations, high costs, and a lack of standardized methods prevent wide adoption. Companies focus on other sustainability strategies like carbon offsetting or recyclability instead (Järvelä et al. 2025; Kohl et al. 2025).

- **Key driver:** Technological and economic barriers; low prioritization.

Assumption d): Systems-Level Circularity

A systems approach emerges, driven by cross-sectoral collaboration, digital product passports, and advanced lifecycle tracking. DfD is embedded in global supply chains, supported by interoperable platforms and circular business models (Araújo et al. 2024; Di Stefano et al. 2025).

- **Key driver:** Integration of digital tools and circular ecosystem collaboration.

2.1.6 Decarbonization of the Global Economy (Ecological)

Short Description

The reduction of CO_2 emissions is crucial for a sustainable future, supported by innovative materials and technologies.

Global emissions are rising and expected to peak between 2025 and 2035 before declining, yet they will remain above the carbon budget for a 1.5°C trajectory. This continues despite various carbon-reducing policies and net-zero commitments since the Paris Agreement. A growing consensus on decarbonization exists, with countries representing over 90 percent of global GDP committing to net-zero goals. While effective policy implementation is challenging, government actions are crucial for the energy transition. Energy demand may increase by up to 18 percent by 2050 due to population growth, rising GDP per capita, and expanding manufacturing in emerging economies. Low-carbon energy sources are projected to account for 65 to 80 percent of global power generation by 2050, but this growth is insufficient for short-term targets. Technologies like solar and wind are likely to expand, while higher-cost options like hydrogen and carbon capture face challenges. The current global carbon price is too low for rapid decarbonization and does not align with a 1.5º pathway, and the market suffers from a lack of liquidity.

In Europe, energy demand has been flat or declining. High energy prices may hinder expected demand growth. Despite decarbonization efforts, energy prices remain significantly higher than historical averages, raising concerns about industrial competitiveness. By 2030, the adoption of sustainable fuels will mainly depend on proposed regulations and future technological advancements (McKinsey & Company 2024).

A holistic approach to corporate decarbonization recognizes the extensive organizational effort needed for long-term carbon reduction. It goes beyond viewing decarbonization as a project with a set start and end date, encompassing factories, suppliers, and corporate offices. Organizations must acknowledge the complexity of this challenge and its transformative potential. In a challenging economic climate, concerns arise about funding decarbonization efforts, especially with heightened focus on cost control and profitability. Shifting the perspective from initiative-led to whole-business transformation requires a new mindset regarding the business case for decarbonization funding. For instance, investing in an onsite renewable energy program across multiple facilities can yield environmental benefits through cleaner energy, economic advantages via reduced energy costs, and risk mitigation by diversifying energy supply sources (ENGIE Impact 2024).

Facts and Figures

As the world attempts to decarbonize different industries that lead to increased carbon waste, it is crucial to consider how energy can be regulated to prevent this. This involves evaluating current energy usage trends and scenarios that are likely to take place in the future (Hella Nyapom 2024).

Energy transition scenarios in discussion:

1.5° pathway: Under this scenario, a 1.5° pathway is adopted globally. International cooperation is mobilized to rapidly scale decarbonization technologies, release large-scale investments (including in emerging economies), and shift behavior. Limiting warming to 1.5°C is key to avoiding the worst impacts of climate change and doing so would require staying within a 570 gigaton (Gt) carbon budget, reducing CO_2 emissions by 50 percent by 2030 compared to current levels—and reaching net-zero emissions by 2050. Other greenhouse gases, especially methane and nitrous oxide, would also need to be steeply reduced. Achieving a 1.5° pathway requires a substantial departure from current trends and significant changes to the energy demand mix, pace of decarbonization, and investment into nascent technologies. However, it is still possible with rapid global action across all economic sectors.

Sustainable Transformation: This scenario charts a pathway to decarbonization based on current global economic conditions and technology maturity and viability. Here, nations intensify their commitment to sustainability, with increasing global coordination to alleviate bottlenecks, unlock investment pledges for low-carbon technologies, and improve energy efficiency above recent historical levels. Global cooperation to decarbonize is underscored by the creation of cross-regional financing, with nations adopting cost-efficient policies to reduce emissions. However, despite this momentum, practical constraints impose certain limits on the pace of clean technology adoption. For this scenario to materialize, several economic and technological issues would need to be resolved, and interim targets might not be met if not plausible under these assumptions.

Continued Momentum: In this scenario, nations' focus on sustainability is balanced by other factors, including affordability and security of energy supply, with some emerging economies mostly prioritizing affordability and security of supply over sustainability. Technology and efficiency improvements largely follow current trends, driven by economics, where practical constraints persist in the widespread adoption of low-carbon technologies. This scenario largely mirrors current trends and assumes they will continue, resulting in uneven deployment of low-carbon technologies across different technologies and regions.

Slow Evolution: This scenario sees local decision making focused on (domestic) energy affordability and supply security, relegating sustainability to a secondary priority. This fragmented response to decarbonization leads to a decrease in prior low-carbon investments, resulting in reduced investments in low-carbon technology and lower CO_2 prices, which, in turn, leads to significant environmental, economic, and social impacts. Stark geographic differences emerge in this scenario, with some countries and regions making good progress toward decarbonization targets, while others lag behind significantly (McKinsey & Company 2024).

Relevance for Orchestra Demonstrator

Demonstrator I **Material Selection and Specification**	**Demonstrator II** **Recycling**	**Demonstrator III** **Criticality**
Direct: Drives selection of low embodied carbon materials and processes (e.g., green steel, low-carbon aluminum, high recycled content). Promotes electrified and efficient production routes and the use of EPDs/PCFs in specifications.	Direct: Positions circularity as a key decarbonization lever. Increases demand for high-quality recyclate, prioritizes low-carbon energy in recycling operations, and emphasizes design for disassembly.	Indirect: Electrification and renewable technologies scale up demand for critical materials (e.g., NdFeB magnets, battery metals), heightening supply risk. Strengthens the business case for recovery and closed-loop supply of critical materials.

Future Assumptions

Assumption a): 1.5°C Pathway Acceleration

- Rapid policy alignment, high investment, and global cooperation scale low-carbon power, green materials, and electrified processes; strict embodied-carbon thresholds and recycled-content requirements become standard (Nie et al. 2022).
- **Key driver:** Strong, coordinated policy and finance.

Assumption b): Sustainable Transformation

- Coordinated but pragmatic decarbonization; efficiency gains and targeted support unlock progress with some constraints (infrastructure, costs). Recycling and green materials grow steadily; interim targets sometimes slip (Kuttimarks et al. 2024; Belaïd 2025).
- **Key driver:** Cross-regional financing, cost-effective policies, and technology maturity.

Assumption c): Continued Momentum

- Mixed priorities (cost, security) keep progress uneven; firms pursue cost-effective decarbonization first (efficiency, partial fuel switching). Recycling expands where economics allow; green material premiums persist (Hechelmann et al. 2023; Egeland 2023)
- **Key driver:** Market economics and incremental tech improvement.

Assumption d): Slow Evolution

- Fragmented policies, lower CO_2 prices, and security/affordability focus slow investment; low-carbon materials remain niche; recycling growth stalls; criticality risks intensify with uneven electrification (Lin et al. 2025; Wilson et al. 2025)
- **Key driver:** Policy fragmentation, high capital costs, and energy price volatility.

2.1.7 Autocracies on the Rise (Political)

Short Description

The influence of autocratic governments on markets and supply chains challenges companies to adapt to changing political frameworks.

Democracy continues losing ground worldwide. Since 2009, more people have been living in countries that are becoming more autocratic than in countries that are becoming more democratic. Fewer states are governed democratically than at any point in the past 20 years. Countries increasingly restrict political participation rights, including free elections, assembly, and expression. Almost all democracy components are worsening in more countries than improving compared to ten years ago, demonstrating a clear wave of autocratization (Nord et al. 2024; Hartmann and Donner 2024).

Corporate boardrooms increasingly balance risk management with operational performance as supply-chain risks proliferate. Geopolitical tensions, Covid-19 disruptions, and supply chain reshaping to reduce China dependency create new challenges. Threats now include regulatory changes, labor shortages, and cyberattacks beyond traditional geopolitical risks. Geopolitical conflicts disrupt logistics, while protectionism introduces trade barriers affecting costs and market access. High inflation and interest rates strain operations and increase supplier risks. Protectionist policies significantly impact global trade and supply chains. Key challenges include uncertainty about government actions and policy timeframes. Businesses must invest in process modifications and new technologies to meet regulatory requirements, but lack certainty about investment returns (Ferguson et al. 2024).

Facts and Figures

71% of the world's population – 5.7 billion people – live in autocracies – an increase from 48% ten years ago. Autocratization is ongoing in 42 countries, home to 2.8 billion people, or 35% of the world's population (Nord et al. 2024).

In 2024, 63% of executives flagged macroeconomic uncertainty and geopolitics as major supply-chain disruptors, consistent with the 2023 figure. This was a sharp rise from 2022, when only 29% expressed concern over these issues. Across all risks, 55% of executives anticipate significant supply-chain disruptions in 2024. (Economist Impact, 2024)

As an impactful example: Recently, the 2022 Russian invasion of Ukraine caused oil and gas prices to skyrocket and cutt off a major artery of trade. This has led to a widespread energy crisis within Europe. In 2021, supplies from Russia covered approximately 40% of the EU-27's natural gas consumption; with Germany – the EU's largest economy – receiving 65% of i gas supply from Russia. The implementation of sanctions impacted the security of continuous operations and the competitiveness of Europe's most gas-reliant industries, such as chemicals, steel, cement, glass, refining and coking, and paper and printing production. In response to gas price hikes, European governments introduced price caps to protect private households. Some countries, such as Germany, went even further and extended price protection measures towards industry at a cost of €200bn. Indeed, the compounding disruptions caused by geopolitical disputes like this have prompted many firms to reconsider the design of their global supply chains entirely (Bednarski et al. 2023).

EU exports to Russia have fallen by at least 70%, indicating that sanctions have had a significant effect. In contrast, EU exports to selected countries, including Azerbaijan, Georgia, Kazakhstan, Kyrgyzstan, Turkmenistan, Uzbekistan, and Tajikistan, have increased by more than 40% compared to the rest of the world, reflecting abnormal growth in shipments. Additionally, the increase in the value of EU exports to these selected countries accounted for more than 20% of the drop in value to Russia, suggesting a degree of diversion in trade patterns (S&P Global 2024).

Relevance for Orchestra Demonstrator

Demonstrator I **Material Selection and Specification**	**Demonstrator II** **Recycling**	**Demonstrator III** **Criticality**
Direct: Political risk and trade barriers influence material availability and price volatility, driving specifications toward substitute alloys, multi-sourcing strategies, and reduced dependence on single-country supplies. May require adjusting tolerances to enable alternative elements and production routes.	Direct: Geopolitical fragmentation and import constraints strengthen the case for local recycling and closed-loop systems to reduce exposure (e.g., for Mg alloys and other China-dependent streams). Logistics and energy price volatility push process redesign for resilience and stable local supply.	Direct: Governance risks (sanctions, export controls, conflict) alter access and concentration for critical materials (e.g., rare earths, strategic metals), increasing criticality scores. Prioritizes recovery, substitution, and diversification; some impacts remain uncertain and require further analysis.

Future Assumptions

Assumption a): Bloc Fragmentation and Sanctions Escalation

- Trade blocs harden; export controls/sanctions widen for strategic materials; firms regionalize supply, build local recycling, and redesign alloys for substitutes; costs and volatility rise (Zeng und Peterson 2025).
- **Key driver:** Heightened geopolitical conflict and protectionist policy.

Assumption b): Managed Interdependence

- Governments maintain selective engagement with guardrails; companies implement dual-sourcing, inventory buffers, and digital risk monitoring; disruptions occur but are contained (Hamdan et al. 2025).
- **Key driver:** Risk-aware policy coordination and corporate resilience investments.

Assumption c): Shock Escalation and Energy/Commodity Stress

- Acute crises (conflict/cyber/energy) cause severe price spikes and supply interruptions; emergency policies reshape flows; rapid substitution, rationing, and onshoring accelerate (Krzywnicka und Barner 2025).
- **Key driver:** Systemic shocks and critical infrastructure vulnerabilities.

Assumption d): Partial Stabilization with Persistent Risk Premium

- Diplomatic de-escalation reduces acute barriers; some trade corridors reopen; firms keep resilience measures (regionalization, recycling, diversification) due to lingering uncertainty (Fosu 2025; Peng et al. 2025).
- **Key driver:** Pragmatic diplomacy and enduring governance risk awareness.

2.1.8 CO_2 Pricing Mechanisms (Political)

Short Description

Governments promote climate-friendly materials through the pricing of CO_2 emissions.

'Greenhouse gases are responsible for global warming and all its consequences. To keep climate damage as low as possible, carbon dioxide (CO_2) and CO_2 equivalents (CO_2eq) are assigned a monetary value' (Deutscher Bundestag 2024).

In fact, CO_2 pricing can be one of the most powerful tools available to policymakers to promote emission reductions as part of an integrated package of measures. A decade ago, carbon pricing policies covered only 7% of global emissions. Today, nearly a quarter is covered by these instruments. CO_2 pricing and carbon markets continue to evolve and grow, with new systems and instruments being introduced, leading to record revenues of $104 billion in 2023. Encouragingly, most of the revenue generated was directed toward climate and nature-related programs. The total number of instruments in use has also increased: there are now 75 CO_2 pricing instruments in operation, with recent efforts in Australia, Hungary, Slovenia, and Mexico (World Bank 2024).

A recent concrete example from Germany: At the turn of the year 2023/2024, the federal government raised the national CO_2 price from €30 to €45 per ton. Current forecasts suggest that the CO_2 price will reach €200 by 2027 (Behringer et al.).

Despite the positive trends indicated by several sources, higher prices and broader coverage will be crucial to fully unlocking the potential of CO_2 pricing. This will require political commitments, stronger global frameworks, and initiatives to share best practices that can help scale up efforts (World Bank 2024).

Facts and Figures

There are two fundamentally different approaches to pricing:

- Price: A market-determined price, e.g., to acquire a certificate that allows for a limited amount of CO_2 emissions in the EU (emission trading). The starting point for the price is the limited amount of CO_2 resulting from international agreements, among other factors. Simply put, the price is derived from supply and demand.
- Cost: The starting point is the projected external costs of CO_2 emissions (simply put, the costs of 'climate damage'). These costs are, for example, considered in Germany when deciding on certain infrastructure projects (Federal Transport Infrastructure Plan). A monetary value is assigned to the expected CO_2 impact of the new road (€/ton).

Looking at the numbers and facts, it can be observed in hindsight that CO_2 pricing has faced limiting factors in recent years, but a positive trend is particularly evident in middle-income countries.

- Worldwide, there are 75 types of CO_2 taxes and emissions trading systems in operation.
- In the last 12 months, there has been a net increase of two carbon pricing instruments.
- Middle-income countries, including Brazil, India, and Turkey, have made the most progress in implementing CO_2 pricing.
- Implementation has also made progress at the subnational level, despite some setbacks.
- Progress has also been observed in sector-specific, multilateral initiatives for international aviation and shipping.

- The European Union Carbon Border Adjustment Mechanism has been introduced, which requires importers of certain products to report hidden emissions as well. (World Bank, 2024)

Overall, revenue from CO_2 pricing has reached a new high.

- Revenue from CO_2 pricing, driven by high prices in the EU and a shift in certain ETS revenues (European Union Emission Trading System) in Germany, surpassed the $100 billion mark for the first time in 2023.
- ETSs continued to account for the majority of revenues from CO_2 pricing.
- More than half of the collected funds were used to finance climate and nature-related programs.

Despite record highs in CO_2 pricing revenues, their contribution to the national budgets of countries remains low (Umwelt Bundesamt 01/2025; World Bank 2024).

Relevance for Orchestra Demonstrator

Demonstrator I **Material Selection and Specification**	**Demonstrator II** **Recycling**	**Demonstrator III** **Criticality**
Direct: CO_2 pricing internalizes embodied carbon costs, steering material and process selection toward low-carbon options (e.g., green steel, recycled content). Encourages EPD/PCF-based specifications and supplier thresholds.	Direct: Higher CO_2 prices improve the economics of recyclate versus primary production and incineration. Increases demand for high-quality recycling and prioritizes low-carbon energy in recycling operations.	Indirect: Pricing asymmetries and CBAM shift trade flows and cost competitiveness, potentially altering supply concentration and import reliance for critical materials. Strengthens the business case for domestic recovery and diversification, though impacts remain context dependent.

Future Assumptions

Assumption a): High, Harmonized Pricing with CBAM Expansion

- Broad, predictable CO_2 pricing across major economies and sectors, reinforced by CBAM-like measures; strong procurement standards (EPD/PCF) accelerate low-carbon materials and recycling (White et al. 2025; Yan et al. 2025).
- **Key driver:** Policy alignment, high price levels, and market liquidity.

Assumption b): Sectoral/Partial Expansion at Moderate Prices

- Growth in sector-specific systems (aviation, shipping, industry) and subnational schemes; firms respond via green procurement and recycled content where economics allow (Barbosa 2023; Galimova et al. 2025).
- **Key driver:** Incremental policy rollout and corporate demand.

Assumption c): Fragmented/Low Pricing

- Uneven coverage and low prices yield limited decarbonization; carbon leakage persists; companies favor efficiency and compliance-minimum approaches; recycling gains modest (Habibi 2025; Chen et al. 2023)
- **Key driver:** Political resistance, budget constraints, and market volatility.

Assumption d): Digital MRV and Linked Carbon Markets

- Product-level digital MRV (PCF, IoT/blockchain) enables precise carbon-aware procurement; linked ETSs improve liquidity and price signals; circularity and low-carbon materials become standard (Gallopp Ramirez und Issa 2025; Heiss et al. 2024)
- **Key driver:** Standardized MRV, interoperability, and cross-border coordination.

2.1.9 International Raw Material Agreements (Political)

Short Description

Cooperations secure access to critical raw materials and promote their sustainable use.

Access to raw materials is essential for the EU economy and the functioning of the internal market. The International Energy Agency projects that mineral demand for clean energy technologies will quadruple by 2040 compared to 2020, highlighting the urgent need for primary raw materials, most of which are sourced outside of Europe. This scenario underscores the critical importance of cooperation with partner countries to facilitate a successful energy and mobility transition in Germany and the EU (Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ GmbH) 2024). Many non-EU countries impose export taxes and import duties that disrupt free markets. The EU addresses this through dialogues and its raw materials strategy (2008 Raw Materials Initiative, revised 2011) aimed at transparency in international raw materials markets. Key bilateral agreements with Korea, Singapore, and Vietnam prohibit export duties on raw materials. Multilateral agreements with Central America and Colombia/Peru also ban such taxes with minor exceptions, while Tajikistan committed to prohibiting export duties on most raw materials during its WTO accession (Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs).

Certain non-energy, non-agricultural raw materials are deemed critical due to economic importance and supply risks from concentrated sources. Demand is surging for green and digital transitions and defence applications. Geopolitical tensions heighten supply disruption risks, while these materials are typically sourced, processed, and recycled across different locations. Land use conflicts barrier projects, but effective spatial planning can mitigate conflicts and promote sustainable development (Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs 2024). As an example, in February 2024, the EU and Rwanda signed a key agreement to develop sustainable and resilient value chains for critical raw materials. This cooperation aims for responsible production and enhancement of these materials, focusing on improved due diligence, traceability, combating illegal trafficking, and aligning with international Environmental, Social, and Governance (ESG) standards (2024).

The EC allocated €500 million from Horizon Europe for critical raw materials R&I projects. New initiatives will boost innovation through the European Innovation Council and the European Institute for Innovation and Technology, including coordinated action plans on advanced materials and substitution (European Commission 2023).

Facts and Figures

Germany does not have abundant resources and is forging global partnerships to sustainably secure raw materials. These partnerships are key to its raw materials strategy, which focuses on domestic resources, imports, and recycling. During a January 2023 visit to Chile, Chancellor Olaf Scholz highlighted the goal of enhancing Germany's partnership with Chile, vital for its lithium resources, which are integral elements of electric mobility. Since 2011, Germany has partnered with Mongolia, and in February 2024, they established a broader strategic partnership that emphasizes the raw materials sector. Additionally, Germany and Australia initiated cooperation in 2017 on energy and raw materials, with a focus on climate action. They are planning a joint project to explore the value of critical raw materials for clean energy technology, including the "Australia-Germany Critical Minerals Supply Chains Study" (deutschland.de 18.09.2024).

GIZ is running a support plan for partner countries that are expanding mining sectors, in establishing socially and environmentally just frameworks for raw material extraction and processing. This involves developing strategies for sustainability along the raw materials supply chain. Sustainable development in the extractive sector requires coherent and constructive policies that balance the development needs of resource-rich countries with local supply security, corporate responsibility, and traceable supply chains for responsibly mined materials. GIZ's initiative focuses on fostering regional multi-stakeholder exchanges and political dialogues among diverse stakeholders in resource-rich countries and Europe. It operates through two main fields of action: "Partner Perspective" and "Sustainability along Raw Materials Supply Chains." The first field involves developing sustainable solutions through exchanges and dialogues in Africa, Asia, and Latin America, while the second emphasizes scientific research and the establishment of universal standards for traceable supply chains. The overarching goal of GIZ's Raw Materials Initiative is to create a responsible, resilient system for raw material extraction, processing, and recycling, ensuring that supply chains are transparent and accountable. This initiative supports sustainable development in resource-rich nations, promotes circular economy practices, and addresses the challenges of decarbonization, ultimately securing livelihoods for future generations (Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ GmbH) 2024).

Relevance for Orchester Demonstrator

Demonstrator I **Material Selection and Specification**	**Demonstrator II** **Recycling**	**Demonstrator III** **Criticality**
Indirect: International agreements shape material availability, price stability, and ESG/due-diligence requirements, steering specifications toward traceability, responsible sourcing, and recycled content. Support substitution through R&I programs and funding access.	Indirect: Agreements enable cross-border flows of secondary raw materials, harmonize standards (traceability, recycled content), and unlock funding. Without such agreements, Europe’s recycling supply chains remain constrained; project-level influence is limited, but compliance and alignment are essential.	Direct: Diversifies supply and reduces dependence on single producers through enforceable commitments and cooperative governance. Improves resilience via long-term contracts, though durability under shifting geopolitical realities remains uncertain.

Future Assumptions

Assumption a): Fragmented Geopolitics

- Description: Resource nationalism and trade barriers limit agreement scope; supply risks and price volatility persist; recycling flows remain constrained (Xu et al. 2024; Dou et al. 2024).
- **Key driver:** Geopolitical tension, protectionism, and weak enforcement.

Assumption b): ESG-Focused Bilateral Expansion

- Description: Select bilateral agreements emphasize due diligence, traceability, and responsible sourcing; benefits concentrated in a few partner countries and high-value sectors (Gervais et al. 2023; Goyal et al. 2025).
- **Key driver:** Corporate branding, EU ESG requirements, and sector-specific demand.

Assumption c): Multilateral Breakthrough

- Description: Enforceable multilateral frameworks (incl. critical raw materials, secondary flows) standardize rules, reduce supply risk, and lower transaction costs (Sesini et al. 2025; Gómez et al. 2024).
- **Key driver:** Institutional innovation, monitoring/traceability technologies, and cost reduction through coordinated policy.

Assumption d): Circular Value-Chain Integration

- Description: Agreements embed circular economy principles (digital product passports, recycled-content targets, joint recycling investments, substitution R&I), enabling closed-loop cross-border material flows (Krüger et al. 2025; Khorshidvand et al. 2023).
- **Key driver:** Policy alignment on circular economy, harmonized standards, and digital infrastructure for traceability.

2.1.10 National Strategies of the USA and China (Political)

Short Description

The strategies of the USA and China to secure economic dominance and technological leadership influence global value chains.

The tech rivalry between the U.S. and China is a key geopolitical matter of the 21st century, rooted in the Cold War but evolving with AI and digital dominance. This competition may shape global power dynamics, shifting from military to technological superiority (Mark Craddock 2025). The industrial policy has become a vital tool for both nations. The US implements export controls and investment restrictions on semiconductors and advanced technologies, while China emphasizes self-reliance through programs like "Made in China 2025." Since 1978, China has transformed from a technology importer to a global player, with GDP increasing 44-fold versus the US's threefold growth (1979-2023). By 2024, China holds the world's second-largest high-tech sector, leading in nuclear power and electric vehicles, installing more industrial robots than the rest of the world combined in 2023. China's chemical R&D spending reached 16.8% (nearly matching the US at 18.6%) and accounts for 62% of global EV production. Both countries are moving toward technological decoupling in semiconductors, 5G, and AI, potentially reshaping global supply chains.

This competition affects global technology standards and geopolitics, with East Asian countries like Japan, South Korea, and Taiwan navigating pressures to align with either power through techno-economic statecraft (Zhang 2024). In 2021, China accounted for significant export shares of East Asian countries: 25.3% for South Korea, 21.6% for Japan, and 28.2% for Taiwan, highlighting their economic dependence on China. This interdependence complicates their strategies, as these countries must balance cooperation with the US against maintaining their economic ties with China. The dynamics of techno-economic statecraft differ among East Asian countries. For instance, South Korea adopts a gradual diversification strategy while maintaining ties with China, reflecting its cautious approach to US alliances. In contrast, Taiwan is more proactive in aligning with U.S. policies, particularly in semiconductor production, indicating a divergence in strategies and priorities among these countries (Lee 2024).

Facts and Figures

The technological competition has been central to US-China relations since the 2010s, with the US policies transitioning from non-proliferation to a strategic tool aimed at limiting China's access to advanced technologies. The perception of China's technological advancements as a threat to U.S. leadership has prompted significant changes in export control policy, particularly under the Trump and Biden administrations. Historically, U.S. export controls were primarily focused on non-proliferation and military concerns. However, since the late 2010s, export controls have increasingly been viewed through the lens of national security, intertwining economic and security interests. It is notable that the number of Chinese entities on the U.S. Entity List quadrupled between 2018 and 2022, with 29% of the list comprising Chinese organizations by 2022. This underscores the expanded use of export controls as a strategic tool to curb Chinese technological growth, particularly in sectors such as semiconductors and telecommunications. A paradigm shift began with the Trump administration, which broadened the definition of national security to include economic aspects, coining the phrase "economic security is national security." The Export Control Reform Act of 2018 (ECRA) marked a significant legislative change, enabling the identification of "emerging and foundational technologies" critical to U.S. national security. Although ECRA did not explicitly mention China, it was designed in response to China's strategies to acquire advanced U.S. technologies.

Under the Biden administration, there has been a continuation and expansion of these policies, with a focus on maintaining a technological lead over China. The introduction of new export controls in October 2022 explicitly targeted China and included advanced semiconductors and manufacturing equipment, marking a significant shift from previous policies that primarily addressed military-related technologies. The Biden administration has also reinforced extraterritorial controls, significantly increasing the capacity to limit China's access to critical technologies through diplomatic efforts, successfully engaging allies like Japan and the Netherlands to restrict technology exports to China (Velliet 2025).

Relevance for Orchester Demonstrator

Demonstrator I **Material Selection and Specification**	**Demonstrator II** **Recycling**	**Demonstrator III** **Criticality**
Indirect: Export controls, standards competition, and price volatility for Mg, REEs, graphite, gallium/germanium, and battery precursors drive substitutions, dual-sourcing strategies, and updated specifications (origin, traceability, ESG compliance).	Direct: US–China strategies push domestic supply security and may restrict cross-border scrap and secondary flows. Elevates recycling as a strategic supply source but can limit access to equipment, technology, and certain inputs (e.g., magnesium, graphite). Project Actions: Design for recycling, secure compliant feedstock, and align with evolving trade rules.	Direct: Heightens supply risk and geopolitical leverage over resource-rich states, necessitating diversification, friendly-shoring, stockpiles, and transparent supply-chain governance.

Future Assumptions

Assumption a): Hard Decoupling

- Description: Rival blocs expand export controls and investment restrictions; supply chains bifurcate; volatility and shortages persist (Li 2025; Attinasi et al. 2025).
- **Key driver:** National security framing, protectionist industrial policy, extraterritorial enforcement.

Assumption b): Managed Competition

- Description: Guardrails limit worst-case escalation; selective cooperation in climate and standards; targeted controls continue but with carve-outs (Franchino and Mariotto 2025).
- **Key driver:** Economic pragmatism, cost pressures, allied coordination.

Assumption c): Substitution and Domestic Capacity

- Description: Accelerated R&I delivers substitutes, recycling/processing tech, and regional capacity, reducing exposure to restricted inputs (Yuan et al. 2024)
- **Key driver:** Technological innovation and large-scale funding (IRA, EU CRM Act, Made in China 2025).

Assumption d): Bloc-Centric Circular Integration

- Description: Allied regions embed circular-economy rules (digital product passports, recycled-content targets) and enable secure secondary-material trade within blocs (Rahnama et al. 2024; Pal und Sen 2025)

- **Key driver:** Policy alignment on circular standards, harmonized ESG requirements, digital traceability infrastructure.

2.2 High Potential Trends

2.2.1 Societal Acceptance of Secondary Materials (Social)

Short Description

Secondary materials must be accepted as equivalent to primary materials.

Social factors and norms play a significant role in sustainable consumer behavior. Therefore, if selecting products made from recycled materials were to become a social norm, people would be more inclined to view it as the right choice and prefer them over products made from virgin material (Polyportis et al. 2023). Customers assign a personal value to a product or service, known as Customer Perceived Value (CPV). The social value aspect, particularly perceived quality, can be a significant barrier to implementing a Circular Economy. This is especially true if lower prices for secondary products are associated with lower quality. Changing customer perceptions to overcome these biases may take time and require educating consumers, while also being influenced by cultural attitudes (Bayram et al. 2024).

Through the continuous activities and incentives happening in recent decades, consumers have gained a positive attitude towards products made from recycled materials; however, they are also concerned about the perceived product risks (Polyportis et al. 2022). This risk may be more associated with certain products, such as products made from recycled disposable facemasks (Widiastuti et al. 2025) or recycled food packaging, due to contamination perceptions. Although the presence of a temporal appeal, emphasizing that the sustainable action has already been performed, reduces contamination inferences and mitigates negative quality perceptions (D'Aniello and Donato 2025).

Facts and Figures

A significant gap exists between consumer attitudes towards sustainability and their actual purchasing behaviours. While there is an increasing awareness of the circular economy and a positive sentiment toward sustainable products, research indicates that consumers often perceive recycled products as inferior and are less willing to pay for them compared to products made from new materials. This perception poses a barrier to the social acceptance of secondary materials. Demographic factors such as age, education level, and income influence consumers' willingness to engage with recycled products. Specifically, younger consumers with higher education levels tend to show more favourable attitudes towards sustainability, yet this does not always translate into purchasing behaviour. Furthermore, consumers' willingness to pay for eco-certified refurbished products is significantly impacted by their environmental attitudes and knowledge (SZILAGYI and BACALI 2023).

A study on the acceptance of recycled plastic products within an academic community revealed generally positive perceptions towards these materials. The findings implied that concerns regarding the inferior quality of recycled products may not apply universally, especially with effective product design. Stakeholders are encouraged to implement awareness campaigns that emphasize the safety and functionality of recycled products to bridge the gap between environmental consciousness and purchasing behaviour (Widiastuti et al. 2025).

Relevance for Orchestra Demonstrator

Demonstrator I Material Selection and Specification	Demonstrator II Recycling	Demonstrator III Criticality
Indirect: If recycled materials become a social norm, acceptance rises; CPV and perceived quality influence material choices and willingness to pay.	Direct: Acceptance of recycled technical aluminum hinges on perceived quality and risk; social norms can raise demand for high-quality recyclate. Higher acceptance of technical aluminum products requires standardization of properties for secondary materials; current chemical composition standards are a barrier.	Direct: Transparency expectations grow: “Where do critical raw materials come from?”; disclosure affects acceptance and license to operate. Obligation for disclosure of origin and critical raw materials; complexity of products makes resource choices opaque, requiring clear reporting.

2.2.2 Awareness for Circular Economy (Social)

Short Description

Consumers and companies increasingly value recycling and sustainability.

Global waste production is rising, with the EU alone generating over 2 billion tons annually (4.8 tons per capita), mainly from construction, mining, and industry. Europeans also produce half a ton of household waste per person yearly, with less than half recycled. This waste harms the environment, biodiversity, and health while incurring significant costs and demonstrating inefficient use of Earth's finite resources (Europäische Investitionsbank 2024; Dr.-Ing. Ulrike Lange 2022).

Beyond household waste, consumers face challenges in sustainable consumption. A 2022 Federal Environment Agency study shows many consumers want to contribute to sustainability but encounter obstacles such as uncertainty about environmental claims, high costs, and limited availability of sustainable alternatives. To address these barriers, political measures should be consumer-oriented and include social compensation mechanisms for low-income households (Münsch et al. 2024).

This trend is also confirmed by non-governmental organizations and companies. For example, Deloitte writes in a market-oriented study from 2024 under the heading "Customer insights on sustainability" that the topic of sustainability has entered societal consciousness and will therefore be a central aspect of market-oriented product development and marketing in the future. Consequently, a steadily increasing demand for products and services that align with the acknowledgment of ecological and social responsibility has been identified. The final results of the study show that many German consumers consider themselves well-informed about socio-ecological issues. This is another indication of the growing awareness of recycling and sustainability (Deloitte 2024).

Facts and Figures

Based on the results of the main survey of the Environmental Awareness Study 2022, it can be concluded that a large majority of the surveyed consumers are willing to make their consumption more environmentally friendly. Additionally, a majority finds it important to increasingly recycle materials in the sense of a circular economy, promote long product use, and counteract a throwaway mentality (Münsch et al. 2024).

In the in-depth study of the Environmental Awareness Study 2022, it was also examined how topics of the circular economy and sustainability are reflected in the attitudes and engagement of consumers, as well as how they assess concrete policy measures. This in-depth study is methodologically based on two representative online surveys conducted in December 2022 and April/May 2023. Overall, the results of the two surveys show that essential principles of the circular economy were important to many people in Germany. Most respondents also indicated that they regularly inform themselves about environmental aspects and know about measures that can reduce their individual carbon footprint. However, these attitudes and knowledge were only partially reflected in people's behaviors. While the use of sharing services has increased in some areas in recent years, practices such as repairing broken items and using reusable packaging have declined or are not widely practiced. When evaluating environmental policy instruments, there was strong support for measures that promote easy repair options, for stronger regulation and control of product-related environmental claims, and for a reform of value-added tax based on the environmental friendliness of products. Based on the study results, impulses for environmental policy were derived (Münsch et al. 2024).

Relevance for Orchester Demonstrator

Demonstrator I **Material Selection and Specification**	**Demonstrator II** **Recycling**	**Demonstrator III** **Criticality**
Indirect: Drives demand for sustainable products and influences material choices; supports higher recycling rates and eco-friendly specifications.	Direct: Increased demand for ecological products must lead to higher aluminum recycling rates due to the high footprint of primary aluminum.	Direct: EU/German legislation on recycling rates for rare earth magnets will become mandatory, shaping recovery strategies and compliance requirements.

2.2.3 Digitalization of the Supply Chain (Technological)

Short Description

Real-time data from the supply chain improves resource utilization and material efficiency.

In the digital transformation era, supply chains are becoming increasingly interconnected and autonomous, requiring minimal human input. Companies need flexible structures and digitally skilled workforces to succeed. Key components of successful digital supply chains include dynamic segmentation, intelligent logistics, sustainability, transparency, integrated planning, and closed-loop manufacturing. These investments reduce operational costs while increasing revenue and customer satisfaction (Geimer et al. 2025). Digital technologies enhance resource management, improve information sharing, and support better decision-making. They allow companies to monitor emissions, trace carbon footprints, and optimize waste management, fostering more sustainable practices. To boost supply chain performance and competitiveness, companies must align their sustainability objectives with digital technologies (Androod et al. 2024).

Supply chain digitalization enhances efficiency and reduces information asymmetry between enterprises, improving resilience and performance. However, effective information-sharing mechanisms are essential for synergistic effects. A Chinese study found digitalization's impact is strongest among state-owned enterprises (SOEs), companies with robust internal controls, and those with dispersed supply chains. This occurs because SOEs have greater resource redundancy that digitalization can optimize, companies with better controls implement more effective processes, and dispersed supply chain participants face coordination challenges that digital technology can address (Yu et al. 2024b). The results of another study in China showed that supply chain digitalization significantly reduces carbon emissions, with pilot companies experiencing a 5.4% decrease compared to non-pilot companies. The mechanisms of this impact are facilitating advancements in green technologies, improving resource efficiency and reducing emissions, as well as reducing information asymmetry, which enables better decision-making and resource allocation (Meng and Lin 2025).

Facts and Figures

Supply chain managers and leaders in digital transformation can leverage Industry 4.0 tools to enhance the KPIs related to sustainability in supply chain performance. The use of near real-time data collection (IoT) and big data analytics can optimize supply chains, leading to improved resource efficiency. Technologies like additive manufacturing and AR/VR (augmented and virtual reality) can accelerate time to market, resulting in more effective product lifecycles. Additionally, AI and machine learning can facilitate better decision-making, promoting more sustainable methods for addressing supply chain complexities. Solutions such as cyber-physical systems, digital twins, and automated vehicles can provide complete traceability to ensure ethical sourcing practices. The digitization of the supply chain aligns well with sustainability goals. Managers can take an integrated approach to create a sustainable and digital supply chain based on these findings. Furthermore, this paper introduces a framework that identifies suitable Industry 4.0 technologies across different stages of the supply chain. Diligent implementation of this framework will lead to performance improvements in various aspects of a sustainable supply chain (Govardhan et al. 2025).

The study by Wang et al. (2025) explored the relationship between supply chain digitization, energy efficiency, and sustainable development across 146 economies from 1990 to 2023. Their findings indicated that supply chain digitization positively impacts social measures of sustainability but negatively affects economic and environmental aspects, particularly by decreasing the utilization of produced capital and emissions footprint. Furthermore, energy efficiency is found to play a constructive role in fostering all facets of sustainable development, suggesting that improving energy efficiency can reduce carbon emissions and enhance sustainable practices. There is a need for policies supporting sustainable supply chain practices, such as renewable energy targets and carbon pricing, while advocating for investments in digitization and energy efficiency to promote global cooperation and standardized sustainable operations (Wang et al. 2025a; Wang et al. 2025b). Another study revealed that digitalization in supply chain processes in metal industries significantly impacts decarbonization efforts. Digital technologies enhance resource efficiency, improve energy management, and enable the adoption of cleaner production methods. Supply chain mapping can act as a critical mediator in the relationship between digitalization and decarbonization. By providing visibility into the supply chain, mapping allows organizations to identify carbon hotspots and areas for improvement, thereby enhancing the effectiveness of digital solutions in achieving sustainability goals (Jiang et al. 2024).

Relevance for Orchester Demonstrator

Demonstrator I **Material Selection and Specification**	**Demonstrator II** **Recycling**	**Demonstrator III** **Criticality**
Direct: Enables faster and optimized material selection based on current supply chain conditions and resource availability.	Direct: Real-time supply chain data influences subsequent recycling steps; improves coordination and efficiency in closed-loop systems.	Direct: Enhances visibility of critical materials and enables more accurate, up-to-date criticality screening; supports flexible control during supply chain disruptions.

2.2.4 Robotics for Material Sorting (Technological)

Short Description

High-precision robots identify and sort materials for optimized recycling

The global waste management crisis, exacerbated by increasing consumption and urbanization, necessitates innovative solutions to enhance recycling efficiency. Traditional waste sorting methods, which rely heavily on manual labour, are often inefficient, costly, and prone to errors. In response, the integration of Artificial Intelligence (AI) and robotics in waste sorting processes has emerged as a promising solution to these challenges. These technologies offer the potential to transform the recycling industry by improving the accuracy and speed of waste sorting, thereby increasing material recovery rates and reducing the environmental impact of waste disposal (Olawade et al. 2024; Mesta 2024).

AI-powered robotic arms equipped with sensors and cameras facilitate waste sorting by rapidly picking and placing waste items. These robots mimic human dexterity, handling materials from cardboard boxes to bottle caps. Benefits include continuous operation without fatigue, the ability to work in hazardous environments, reducing injury risks and labor costs, and easy scalability into existing infrastructures. The combination of AI and robotics significantly enhances recycling efficiency by automating sorting, reducing operational costs, increasing processing speed, and minimizing contamination. This technology enables more precise material sorting, producing higher-purity recycled products with increased market value, making them more attractive to manufacturers and supporting circular economy development (Mesta 2024; Fang et al. 2023).

Facts and Figures

Sorting garbage is crucial because it can increase the amount of waste that is later recycled, lowering the pollution of the environment and landfills. The dynamic rise in garbage production and the despicable dumping of waste are becoming matters of concern. Automated garbage segregation plays a crucial part in preventing this situation and making recycling easier. The automated sorting process can be divided into two parts: The first part involves classifiying or differentiating the waste into certain categories or classes. The second part involves mechanically sorting the waste according to material.

India generates approximately 42.0 million tons of solid waste annually, according to research. Also, waste management in India depends only on landfills and informal sectors, which is not sufficient to overcome its waste generation. According to the Planning Commission Report, by 2031, the urban cities in India will generate 165 million tons of waste per year. This value could reach 436 million tons of waste by 2050. To relieve public and environmental concerns, effective waste management measures for segregation, collection, treatment, and disposal must be implemented. Unpleasant greenhouse gases are produced in lowlands when mixed dry and moist garbage decomposes. It is possible to properly use and recycle the trash owing to waste management and efficient sorting. There are various types of plastics where most of which are recyclable. Around 12% of the spent plastic is recycled globally, around 25% is incinerated, but approximately 60% ends up polluting the environment. Glass can be recycled repeatedly and never loses its quality after being recycled. 70% less energy is used when new paper is made from recycled paper stock than when using virgin pulp. Manual waste sorting can cause serious health issues for the workers due to various disease-causing agents present in the garbage. Various technologies used to sort waste are present, such as Eddy current based sorting, Metallic sorting, X-ray based sorting, Optical based sorting, Spectral imaging-based sorting, Laser induced breakdown spectroscopy, etc. With the current wave of innovation and robotics penetrating almost all sectors, it is noteworthy that the use of robots in waste sorting proves to be a great advantage to our society. In this paper, the focus was on studying existing systems that use artificial intelligence, machine learning and deep learning technologies to automate waste detection tasks and sort and segregate waste using robots. This work reviewed recent studies on the contribution of robotics and AI to efficient waste sorting for recycling, its advantages and challenges, and exploring the future scope of robotics in waste sorting (Satav et al. 2023; Fang et al. 2023).

Relevance for Orchester Demonstrator

Demonstrator I **Material Selection and Specification**	**Demonstrator II** **Recycling**	**Demonstrator III** **Criticality**
Indirect: Sorting of scrap (e.g., stainless vs. construction steel) is critical for material recovery; robotics could support future specification accuracy but is challenging to implement.	Direct: Improves quality of recycled aluminum scrap, which significantly influences subsequent production steps and functional properties; automation is essential for efficiency and purity.	Indirect: Support criticality management by enabling higher recovery rates of critical materials (e.g., rare earths in complex assemblies) and reducing losses during dismantling. This strengthens closed-loop supply and resilience.

2.2.5 Resource Efficiency and Availability (Economic)

Short Description

Companies must increasingly manage resources more efficiently to remain competitive and promote sustainable practices.

The entire world is currently in the midst of unprecedented environmental challenges. Three global crises stand in the way of reaching the Sustainable Development Goals: climate change, biodiversity losses, and contamination. These crises are directly related to the prevailing unsustainable patterns of consumption and production. Any strategy designed to mitigate climate change, protect biodiversity, and reduce contamination must therefore imply changing these patterns (Landauer et al. 2024).

Referring this to business, unmitigated material consumption on a planet with finite resources is a medium-term risk. Resource use links to climate, nature, and pollution hazards directly, making climate and nature risks business and investment risks. GRO's analysis shows global value chains face physical risks (extreme weather) and transition risks (declining demand, regulatory requirements). Investors increasingly scrutinize sustainability exposure while customers embrace it as a buying factor. Growing competition for natural resources pressures volatile supply chains across sectors, making them less reliable due to climate change and geopolitical disruptions. Resource decoupling must become central to business growth strategies, enabling growth while minimizing environmental footprint and enhancing competitiveness. It's possible to reduce resource use while growing the economy, reducing inequality, and improving wellbeing. GRO24's Sustainability Transition Scenario shows a path toward sustainable resource use, though global consumption would still increase as some regions need more resources to meet human needs (World Business Council for Sustainable Development 2024; Schandl et al. 2024).

Therefore, circular economy approaches in manufacturing improve resource utilization and promote sustainable development. The concept offers environmental benefits and economic improvement through resource recovery, product lifecycle management, and waste minimization, making it appealing to businesses. New technologies such as digital twin systems, recycling technologies, and eco-design facilitate sustainable solutions. Multi-stakeholder commitment from policymakers, manufacturers, and consumers ensures effective strategies for closing resource loops. These approaches address resource scarcity and environmental decline while creating robust supply systems and sustainable future industries that maintain ecological balance (RAO et al. 2024).

Facts and Figures

What does Resource Efficiency mean? The term covers de-materialisation (material and energy reduction and savings) and re-materialisation (reuse, repurposing, and recycling) strategies with a systemic focus on the circular economy. Resource Efficiency has been identified Introduction in three of the Sustainable Development Goals (SDG). Additionally, SDG6 emphasizes the efficient use of water, while SDG7 pertains to energy efficiency. Goal 8 aims to promote sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all. Goal 11 focuses on making cities and human settlements inclusive, safe, resilient, and sustainable. Lastly, Goal 12 seeks to ensure sustainable consumption and production patterns.

Resource efficiency in the production sector focuses on meeting a predetermined production target (output) with the minimum input. The concept involves searching for technical strategies, business models, consumer preferences, and political instruments that lead to a substantial reduction in the high-volume materials produced and the energy consumption required to ensure human well-being (Allwood, Ashby, & Gutowski, 2013). These materials include biomass, fossil fuels, metals, and non-metallic minerals (Landauer et al. 2024).

Apple is a prominent example of a business that has taken action. Apple has set itself some very ambitious goals regarding its resource strategy. These include using only recycled and renewable materials in products and packaging, enhancing material recovery, eliminating plastics in their packaging by 2025, reducing the water impact in the manufacturing of products, and finally eliminating waste sent to landfills from corporate facilities and suppliers. Their 2022 Environmental Progress

Report states that 20% of the material in their products came from recycled or renewable sources. The company is working hard to transition to 100% recycled cobalt, tin, gold, and rare earth elements in select components by 2025. Furthermore, their product packaging contains only 4% plastic, down from 21% in 2015. Apple's Prineville, Reno, and Mesa data centers and 17 supplier facilities have been certified to the Alliance for Water Stewardship standard for leading water management practices. Finally, Apple's corporate facilities' waste diversion rate increased to 71%, mainly due to progress achieved at data centers (World Business Council for Sustainable Development 2024).

Relevance for Orchester Demonstrator

Demonstrator I **Material Selection and Specification**	**Demonstrator II** **Recycling**	**Demonstrator III** **Criticality**
Direct: Drives replacement of conventional materials with sustainable alternatives Central theme for Demonstrator I.	Direct: Circular solutions must be value-creating and cost-competitive to ensure adoption and scalability.	Direct: Replacement of common materials with available, sustainable options reduces dependency and criticality risk. Optimal balance between resilience, efficiency, and material availability is needed.

2.2.6 Material Databases (Economic)

Short Description

Creation of digital platforms for the identification and storage of recyclable materials from products.

Material banks are platforms that concentrate on end-of-life procedures and require access to a range of datasets (Keles et al. 2025). Digitizing the materials makes them accessible to potential users, leading to a quicker turnover of the stored materials (Coluccia und Petitjean 2023). Digitalization should be based on the information needs of identified key stakeholders and market drivers. This approach facilitates the closing of the material loop between the decommissioning phase and the reuse phase through information exchanges among stakeholders using semantic technology (Akbarieh et al. 2022).

In recent years, the idea of a material passport has been discussed in relation to products and buildings. These are usually presented as digital datasets that document precisely which materials, products, and components are used in a structure. This makes it significantly easier to recover valuable items at the end of the building's life, helping to prevent these materials from being discarded or incinerated during demolition or renovation (Block et al.). However, there are several challenges to the widespread adoption of these technologies, such as the absence of a unified approach, the need to keep all details current, and concerns regarding the privacy and security of the platforms.

Facts and Figures

In the urban mining concept, buildings are envisioned as material banks. Within Circular Economy models, end-of-life building materials should be reused, and their components dismantled to serve as material banks for new constructions, thereby maintaining materials in a closed-loop system. A notable example is the case study of the Materials Bank in Porto, Portugal, which seeks to recover and preserve the tile heritage of the municipality's historic buildings. This material bank is intended for the storage, conservation, restoration, and return of tile items during the renovation of historic façades. It results from collaborative efforts between local governance and public policies. This example demonstrates the need for effective legislation and public policies that support the reuse and recycling of construction materials and components. Joint actions by stakeholders and the government can further facilitate the development of the Materials Bank, strengthening the oversight and execution of the secondary materials market (*Edited by* Bragança et al.).

Examples of digital platforms and projects in Europe include DuSpot [https://www.duspot.nl] in the Netherlands, which serves as a digital matching tool connecting supply and demand in the infrastructure, construction, and green materials sectors, thereby fostering sustainability and a circular economy. To date, it has documented over 56,000 items and facilitated more than 178,000 matches. Another notable platform is the EME [https://hollandcircularhotspot.nl/case/excess-materials-exchange-the-digital-platform/] digital marketplace, also based in the Netherlands and operating across the EU. Established in 2017, EME enables organizations to trade various types of excess materials or products across different industries, allowing them to securely register sensitive material or waste information and track it throughout the supply chain, thus automatically connecting these streams to valuable subsequent uses.

In Austria, SECONDTRADE [https://secontrade.com/start-en] operates as a digital marketplace for secondary raw materials, including ferrous and nonferrous metals, plastics, glass, construction waste, wood waste, and biogenic residues, offering a B2B trading platform across Europe. Additionally, SUM4Re [https://sum4re.eu/], funded by the European Commission and launched in June 2024, aims to develop a comprehensive strategy for establishing materials banks from the built environment, combining urban mining with technologies for automated on-site data collection and identification of building materials and asset components.

Finally, the BAMB (Buildings as Material Banks) [https://www.bamb2020.eu/] project, also funded by the EU, provides circular solutions for the building sector. Its goal is to outline a vision and desired system in a blueprint for a dynamic and circular built environment, with a strong emphasis on reversible building design and materials passports.

Relevance for Orchestra Demonstrator

Demonstrator I **Material Selection and Specification**	**Demonstrator II** **Recycling**	**Demonstrator III** **Criticality**
Direct: Enables identification of existing materials and their criticality, supporting search for alternatives and optimized specifications.	Direct: Material databases can link to ORCHESTRA's digital tools, guiding recycling decisions and improving closed-loop efficiency.	Direct: Provides data on availability of critical materials at EoL, improving recovery planning and resilience strategies.

2.2.7 Intelligent Materials (Ecological)

Short Description

Materials that can adapt their properties to external conditions increase efficiency and durability.

Smart materials have been recognized as the 4th generation of functional materials, following synthetic polymers, natural materials, and engineering materials. They possess the ability to respond to external stimuli, such as light, temperature, magnetic field and pH alterations. Hence, smart materials could be categorized in different types according to different stimulus (Nie et al. 2025). They can be single-stimulus or multi-stimulus responsive, which are still in early development stages (Goh et al. 2025).

These materials reduce waste and energy consumption while enhancing product lifespans. Innovations like self-healing, self-cleaning, recyclability, and degradation control help manage material breakdown for extended use and reduced waste, ultimately lowering operational costs. In recent years, these materials have become practical for applications in manufacturing, biomedical sciences, and environmental fields. Despite growing interest, the integration of polymer-based smart materials into manufacturing processes for sustainability is still underexplored, particularly concerning net-zero emissions (Goh et al. 2025).

Facts and Figures

The intersection of smart materials and sustainable manufacturing (SM) is gaining increasing attention, especially considering the ongoing digital transformation characterized by Industry 4.0. Advanced technologies like the ''Internet of Things'' (IoT), ''additive manufacturing'' (AM), and artificial intelligence (AI) synergize with smart materials to create more efficient, flexible, and environmentally conscious manufacturing systems. Adopting green chemistry and sustainable engineering can significantly enhance the development and application of smart materials, ensuring they contribute to more eco-friendly and responsible innovations. Lifecycle assessments (LCA) can be done on smart materials to evaluate their environmental impact from production to disposal. Cradle-to-grave approaches can assess factors such as greenhouse gas emissions, energy use, and resource depletion (Qureshi et al. 2025).

An example of an environmental benefit is the combination of additive manufacturing with smart materials, which minimizes material waste by building products layer by layer. This approach not only reduces the amount of raw material required but also decreases the energy needed for manufacturing. Additionally, using biodegradable smart materials in packaging can help reduce plastic waste and its associated environmental issues by incorporating materials that respond to environmental stimuli and degrade naturally (Prasad et al. 2024).

Challenges associated with the adoption of smart materials for sustainable manufacturing include the need to balance mechanical performance with environmental sustainability. Many smart materials, while functional, may necessitate trade-offs in terms of strength, durability, or adaptability when derived from bio-based materials. Furthermore, scaling up the production of smart materials using sustainable manufacturing techniques presents a significant barrier, particularly for industries aiming for cost-effective, high-volume solutions (Qureshi et al. 2025).

Relevance for Orchestra Demonstrator

Demonstrator I **Material Selection and Specification**	**Demonstrator II** **Recycling**	**Demonstrator III** **Criticality**
Direct: Enables specifications for materials that extend product life, reduce waste, and improve durability; supports sustainability goals.	Direct: Smart materials designed for controlled breakdown or recyclability can simplify end-of-life processing and improve recovery efficiency.	Indirect: Intelligent materials may substitute or reduce the need for certain critical elements by enhancing performance and lifespan, lowering supply risk.

2.2.8 Life Cycle Management in After Sales (Ecological)

Short Description

Strategies for monitoring and optimizing the entire lifecycle of a product after sale help maximize resource use and minimize waste.

Managing the life cycle of a product after sales would push forward the lifespan of the product, enhancing resource use efficiency and reducing waste generation. Supporting consumers for better performance, take-back programs and recycling strategies are sustainable approaches in the after-sales life cycle management. Take-back programs are good examples of extended producer responsibility for the end-of-life phase of their products. Customers send used products through the initiative, often receiving points or discounts from the manufacturer. The producer either processes these products internally or sends them to a partner (Doshi 2025).

Integrating IoT and AI in the after-sales sector offers real-time insights and enhances process efficiency. It ensures the seamless availability of spare parts and enables proactive maintenance. By building a network that connects suppliers, warehouses, and logistics providers, supply chain transparency is significantly improved. These networks also drive continuous service quality improvements and act as catalysts for innovation. They provide the infrastructure needed to implement new technologies quickly, facilitating seamless data exchange and system integration. Consequently, they help companies adapt their business models and respond flexibly to market changes (Hoffmann 2025).

Facts and Figures

Market evolution trends indicate fundamental shifts toward sustainability and circular economy principles within after-sales operations. The transition from throwaway consumption patterns toward maintenance and repair emphasis necessitates increased after-sales sector investment. Simultaneously, qualified technician availability represents a central challenge for industry expansion, while last-mile logistics optimization presents significant efficiency enhancement opportunities through enhanced connectivity and technological integration (Hoffmann 2025).

Relevance for Orchestra Demonstrator

Demonstrator I **Material Selection and Specification**	**Demonstrator II** **Recycling**	**Demonstrator III** **Criticality**
Direct: Facilitates production of same or similar alloys; requires material knowledge during recycling for accurate specifications.	Indirect: After-sales lifecycle data can feed Orchestra's digital tools, improving traceability and enabling better recycling decisions.	Indirect: Improves recovery of critical materials through structured EoL strategies and transparent supply chain management.

2.2.9 Resource-Efficient Construction Methods (Ecological)

Short Description

New construction methods with reduced material usage, e.g., through lightweight design and innovative structures.

The use of natural resources in building construction generates greenhouse gas (GHG) emissions through fossil fuel consumption in transportation and construction activities, while construction waste contributes significantly to CO_2 emissions. Resource-efficient construction conserves natural resources and protects the environment. Constructing in existing contexts conserves more resources than new buildings by requiring fewer raw materials, reducing transport trips, and enhancing the energy efficiency of existing buildings. Sourcing materials from regional suppliers with resource-conserving practices is advisable. Primary material choice significantly affects overall resource efficiency throughout the building's life cycle, from raw material extraction to deconstruction. Water and local environment conservation are essential for resource conservation (Wiest 2024).

Repurposing waste materials from demolition or other industries, such as mining waste, into construction promotes eco-friendly practices (Yu et al. 2024a). Recycled and upcycled materials are gaining recognition in modern construction. They contribute to energy efficiency, resource conservation, and environmental sustainability (Milad 2025). It is necessary to assess their performance and durability, as well as economic feasibility, for a successful application in the construction sector.

Building Information Modelling (BIM) can help manage data throughout a structure's life cycle and optimize workflow during construction. Consistent use of BIM in implementation planning can enhance resource efficiency (Wiest 2024). A potential approach to enhance resource efficiency in concrete construction is using structural optimization software tools. These tools optimize the size, shape, or topology of a structure, guiding the design of mass-reduced concrete girders (Pressmair und Kromoser 2023).

The suppliers and/or production companies also play a role in maximizing resource efficiency by taking back unused or recyclable materials and packaging, and by fabricating project-specifically to minimize waste. Just-in-time delivery (delivering smaller quantities when needed) reduces construction waste by preventing product damage from transport and on-site storage (Wiest 2024).

Facts and Figures

The greatest opportunities to increase resource efficiency can be leveraged in the planning phase, as this is when fundamental decisions are made, affecting the entire lifetime of the building. Asking a set of basic questions, such as "How long will the building be used for?", "Is it possible to increase the usage density?", etc, would help identify the usage requirements. A status analysis can reveal the resource efficiency potential of the existing building and its surroundings: "Is it possible to continue using an existing building?", "If a building in the vicinity is to be dismantled, are there any building materials that can be re-used/recycled?", etc. (Pichlmeier 2023).

The implementation of an energy management system, such as according to ISO 50001, is suitable for structured recording and reduction of energy consumption on the construction site. The Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB, German Sustainable Building Council) also offers certification specifically designed for sustainable construction sites that can be used to markedly reduce resource consumption. This certification system is universally applicable for national and international building and civil engineering projects and in specialist foundation engineering works. The system is organized into criteria and indicators, which may be mandatory as minimum requirements or optional. The use of energy-efficient construction machinery and equipment is, for instance, a mandatory criterion within resource conservation. Successful certification requires at least 65 % of the defined criteria to be met (Wiest 2024).

A number of sources and tools are available for advanced knowledge in resource efficiency in construction: VDI Zentrum Ressourceneffizienz GmbH [https://www.ressource-deutschland.de/], dena – Deutsche Energieagentur GmbH Information on energy efficiency and energy transition [https://www.dena.de/], eLCA free lifecycle assessment tool, Ökobaudat database, Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR) [https://www.bauteileditor.de/projects/], CAALA energy pre-dimensioning and lifecycle assessment software [https://www.caala.de/], Ökobaudat standardised database for lifecycle assessment, German Federal Ministry of the Interior and Community (BMI) [https://www.oekobaudat.de/], Informationen zur Flächeneffizienz Redevelopment – Leitfaden für den Umgang mit vorgenutzten Grundstücken und Gebäuden (Redevelopment – Guidelines for dealing with previosly used land and buildings), gif Gesellschaft für Immobilienwirtschaftliche Forschung e. V. [https://gif-ev.com/produkt/redevelopment-leitfaden-fuer-den-umgang-mit-vorgenutzten-grundstuecken-und-gebaeuden/] (Pichlmeier 2023). An example initiative in Germany: BauCycle [https://www.baucycle.de/en.html]:

Relevance for Orchestra Demonstrator

Demonstrator I **Material Selection and Specification**	**Demonstrator II** **Recycling**	**Demonstrator III** **Criticality**
Direct: Reducing sheet thickness and optimizing structures, while considering processing properties.	Indirect: Design choices (e.g., additive manufacturing) can influence recyclability and material recovery efficiency.	Indirect: Reduced material consumption decreases dependency on critical raw materials and mitigates supply risk.

2.2.10 Standards for Secondary Materials (Political)

Short Description

Uniform standards define quality and application areas for recycled materials.

The lack of EU-wide quality standards for secondary raw materials, especially plastics, is a major barrier to their widespread use in the circular economy (CE) and creating closed-loop supply chains. This absence creates challenges not only in the trading of these materials but also in ensuring their safety due to potential chemical contaminants (European Parliament 2016). CE standards, especially from the scrap level, will force companies to measure waste and trace its origins. This can add value to their operations. Reliable quality certification would reduce consumers' perceived risks and ensure certain quality levels for the treatment of waste streams used as secondary resources (Bayram et al. 2024). Several factors are key to improving recycling quality. These include consumer behavior, collection efficiency, and the technical properties of secondary materials (recyclates) from mixed waste. Technical properties refer to the characteristics that enable materials to perform specific functions (Roosen et al. 2023).

The need for a Government Fund Policy (GFP) and green certifications, like the Global Recycled Standard (GRS) and Recycled Claim Standard (RCS), is significant in industries such as textiles. These certifications require proof of recycled material content and compliance with social, environmental, and chemical regulations. Most criteria demand effective management from raw materials to finished products. Some require proof of the percentage of recycled materials used. Due to challenges in implementation, companies can initially provide qualitative explanations or certificates as standard. They can also set conditions for future compliance. If they later adopt quantitative life cycle assessment methods as conformity certificates, they will earn more points in compliance (Zhang et al. 2023); (Lin and Ma 2023).

Facts and Figures

In terms of functionality, secondary materials need to fulfill the same requirements as virgin materials, and this quality is a critical aspect of material substitution. Studies have shown that low-quality recycled materials, such as those subject to downcycling, present a significant barrier to the CE (Bayram et al. 2024). In response to the issue of "recycled materials," many international brands have required their upstream suppliers to obtain related green certifications. These green certifications may also include social, environmental, and chemical requirements. According to ISO standards, green certification can be divided into three categories: the first category is "environmental labeling" (ISO 14024), which sets a clear standard for each product, and applicants need to find suitable product category criteria to apply for labeling. The second category is the "self-declared environmental claims" (ISO 14021) of a product or service, meaning there are no standard criteria. The third category is "environmental declarations" (ISO 14025), which uses the life cycle method for quantitative evaluation and declaration. In addition, there is another category called "other green labels," which provide criteria for particular products, industries, or environmental demands. Among the four categories, the second category of self-declared environmental claims does not require third-party certification, while the other categories must be certified by a third party to prove compliance with the criteria or standards. The successful implementation of green certification is related to promoters (government units or NGOs, among others), users (for example, industries or enterprises), consumers, and other stakeholders. Therefore, it is necessary to comprehensively consider how to set the standard content and audit mechanism so that promoters can easily advocate the green certification system, users are willing to apply, and consumers can agree and adopt it (Lin and Ma 2023).

In the plastic sector, for example, mechanical recycling is hindered by legislation that demands high-quality standards for food packaging and a single indicator for representing the secondary material's quality seems insufficient (Volk et al. 2022). As an example, frameworks like GreenBlue's Recycled Material Standard (RMS) demonstrate the potential of market-based systems for certifying recycled content and promoting transparency (RMS Framework, 2021) . As another example, two individual Danish companies have introduced national standards for product certification to foster demand for secondary products (Bayram et al. 2024). Some additional examples of quality standards for secondary materials include the Council Regulation (EU) No 333/2011, which provides end-of-waste (EoW) criteria for aluminum scrap, setting quality standards for when recycled aluminum can be regarded as a secondary raw material ready for production. The European standardization body CEN/TC 261/SC 4/WG 3 focuses on material recovery, ensuring that secondary materials meet specific quality standards before being reintroduced into the market. Additionally, the British Standards Institution's Publicly Available Specification (BSI PAS) 102 outlines requirements for processed glass intended for selected secondary end markets, establishing standards for the quality and handling of recycled glass. Furthermore, European standards such as EN 15342, EN 15345, EN 15346, EN 15347, EN 15348, and EN 15344 concentrate on the characterization of various plastic recyclates, including polystyrene (PS), polypropylene (PP), polyvinyl chloride (PVC), polyethylene terephthalate (PET), and polyethylene (PE). These standards provide guidelines for assessing the quality and suitability of these materials for recycling and reuse (Castell-Rudenhausen et al. 2022).

Relevance for Orchestra Demonstrator

Demonstrator I **Material Selection and Specification**	**Demonstrator II** **Recycling**	**Demonstrator III** **Criticality**
Direct: Standards define quality and application areas, enabling reliable specifications and reducing perceived risk for secondary materials.	Direct: Better standards improve material quality and functionality, ensuring recyclates meet performance requirements and support closed-loop processes.	Indirect: Standards help manage variability in compositions (e.g., NdFeB magnets), supporting recovery strategies and reducing uncertainty in critical material supply.

2.3 Monitoring Trends

2.3.1 Energy-Efficient Material Production (Ecological)

Short Description

Processes for material production are optimized for energy efficiency

Improving energy efficiency is a practical, low-cost method for reducing GHG emissions, often requiring no major changes to industrial processes and yielding immediate results. In the EU, industrial energy consumption is projected to decrease by 25% by 2050 compared to 2015 levels, primarily driven by waste heat recovery applications. Energy efficiency improvements are expected to cut energy-related CO_2 emissions by 22% in the iron and steel sectors, 22% in chemicals, 35% in non-metallic minerals (like cement), 15% in non-ferrous metals, and 32% in refineries by 2050.

In the US, nearly three-quarters of industrial GHG emissions come from manufacturers, mainly in iron and steel, chemicals, food and beverage, petroleum refining, pulp and paper, and cement. Most emission reductions by 2030 will stem from existing energy efficiency technologies. Overall, 66% of the manufacturing sector's CO_2 emissions arise from process energy use, primarily due to process heating, steam, and motor-driven systems (Kamath et al. 2023). Energy efficiency improvement approaches include using alternative and renewable fuels like biomass, wind, solar, or hydrogen; implementing low-temperature and energy-conserving production methods such as low-temperature ceramic sintering and cold working; and adopting green chemistry with environmentally friendly chemicals and bio-based materials.

Setting energy efficiency targets in manufacturing is essential yet complex, as it involves trade-offs among various factors. This complexity highlights the importance of innovative technologies that aid decision-making regarding energy efficiency. For instance, frameworks utilizing advanced digital twin tools can support energy-efficient manufacturing by addressing specific decision-making questions. These digital twins can represent different types of energy consumption in manufacturing systems, along with components such as machines, raw materials, produced products, energy sources, manufacturing processes, HVAC systems, transportation systems, and building climate (Mohamed und Al-Jaroodi 2024).

Facts and Figures

The manufacturing of materials accounts for approximately 21% of global energy demand, with metal production contributing around 8% of total global energy consumption. Recycling offers significant energy savings compared to primary production; however, the choice of recycling methods must be tailored to the specific properties of different materials. For example, conventional recycling methods for aluminium alloys typically involve re-melting, which is not energy-efficient and can lead to permanent material losses (Ingarao et al. 2021).

In the Net Zero Emissions (NZE) by 2050 Scenario, annual growth in industrial energy demand is less than 0.5%, driven by deployment of more efficient technologies and processes, material efficiencies, recycling and electrification. China continues to drive industrial energy demand growth along with India, which in the STEPS, sees the largest growth of any country to 2030, at 4% per year. Global industrial energy intensity was static in 2023, with an improvement of 0.6%. However, with hard-to-abate sectors accounting for almost three-quarters of energy use in the sector in 2023, progress on energy efficiency can be challenging, due to the long lifetime of assets, high investment volumes of new plants and the limited availability of low-emissions technologies or processes to reduce the emissions intensity of production in these sectors. The energy use of less intensive industrial sectors at a global level has seen the fuel mix changing, with the share of fossil fuels contracting. While total energy consumption in these sectors is up by almost 13% from 2010 to 2022, the share of fossil fuel use declined from 45% to 36% in the same time frame.

In 2024, various industry stakeholders expressed their commitment to collaborating with policymakers to enhance energy efficiency. During the IEA's 9th Global Conference on Energy Efficiency, business leaders participated in a roundtable discussion aimed at promoting increased investment and stronger private sector action in partnership with government initiatives, culminating in the Nairobi Business Leaders' Action Plan (Callioni et al. 2024).

Relevance for Orchestra Demonstrator

Demonstrator I Material Selection and Specification	Demonstrator II Recycling	Demonstrator III Criticality
Direct: Rising energy costs make energy efficiency a key criterion for material and process selection; supports low-carbon specifications.	Direct: Optimizing recycling processes to reduce energy consumption and emissions, improving economic viability.	Indirect: Energy costs influence raw material prices; improving efficiency reduces dependency on volatile energy markets and strengthens supply resilience.

2.3.2 Decentralized Recycling Centers (Political)

Short Description

Establishment of small, regional recycling centers that simplify the recovery and reuse of materials.

In countries without a recycling infrastructure, the current practices involve disposing of waste in landfills, incinerating it, or exporting it to purchasing countries. In nations with established recycling systems, waste is usually processed in large, centralized facilities, necessitating long-distance transportation. Additionally, new products made from recycled materials often require further transportation and distribution to different markets. Both approaches face their own challenges (Gerbier and Buscher 2024). They frequently face high operational costs, environmental challenges from extensive transportation and landfilling, and scalability issues in densely populated urban areas. Additionally, a significant barrier for centralized systems is the lack of community engagement. This often results in low compliance rates for source waste segregation, illegal dumping, and a general unawareness of the importance of waste management (Kumar Dwivedi and Kumar 2024).

Decentralized Waste Management (DWM) is a localized solution designed to address these challenges, where waste is collected, processed, and treated at or near its source. It encompasses practices such as community composting, small-scale recycling facilities, and localized waste-to-energy systems. The benefits of DWM include lower transportation costs and emissions, increased community engagement, enhanced ownership and accountability, scalability and flexibility, as well as environmental advantages. However, DWM also faces challenges such as financial and technological resource limitations, the need for ongoing awareness and education initiatives, and the necessity for robust policy and regulatory support. Understanding how to effectively engage communities in DWM is vital to unlocking the potential benefits of this approach (Kumar Dwivedi and Kumar 2024).

Facts and Figures

Mobile and modular recycling facilities can enhance both the capacity for recycling and the decentralization of waste treatment. Owing to the miniaturization of these recycling units and their placement in standard containers, they can be quickly relocated from one site to another, enabling a more responsive approach to spatial and temporal waste generation. Planning such a network requires the integration of location, production, and transportation decisions. It is essential to account for the anticipated large volumes of waste expected in the coming years. For instance, photovoltaic (PV) panels, which have been increasingly installed in recent years, have an approximate lifespan of 30 years and will need to be replaced and recycled in the near future (Gerbier und Buscher 2024).

Decentralized recycling can be incorporated into urban water and resource management systems. Stormwater management and water conservation in urban settings can be easily decentralized, as the components of these systems are often spread throughout the urban landscape (Varma et al. 2024). Moreover, implementing decentralized greywater treatment systems can serve as an effective long-term solution to address water scarcity by meeting at least non-potable water demands. This approach also helps eliminate the need for long-distance water transportation in remote regions, such as rural and isolated areas (Khajvand et al. 2022). Furthermore, integrating centralized treatment systems with decentralized and nature-based solutions could lead to wastewater management strategies that are more resilient and sustainable (Varma et al. 2024).

In plastic waste management, there are various opportunities to leverage a diverse array of technologies to enhance the operations of decentralized waste management enterprises. For instance, mobile apps, artificial intelligence (AI), cloud servers, and the Internet of Things (IoT) can assist with collection and processing procedures (Okoya et al.). The incorporation of AI-driven cloud platforms can enhance decentralized plastic recycling processes by enabling smart resource allocation, real-time monitoring, and data-informed decision-making. This progress in decentralized recycling is essential, considering the shortcomings of traditional waste management systems in tackling the escalating plastic waste issue (Vadisetty 2023).

Relevance for Orchestra Demonstrator

Demonstrator I **Material Selection and Specification**	**Demonstrator II** **Recycling**	**Demonstrator III** **Criticality**
Indirect: Localized recycling centers can influence material availability and specifications by ensuring consistent supply of secondary materials.	Direct: Decentralized centers can connect to Orchestra's digital solutions for data exchange, improving recycling efficiency and enabling closed-loop systems.	Indirect: Regional recycling reduces dependency on global supply chains and mitigates risks from geopolitical disruptions, enhancing critical material security.

2.3.3 Sustainable Design Guidelines (Political)

Short Description

Introduction of mandatory design guidelines for products to facilitate recycling and reuse.

Design for recycling (D4R) offers insight into the compatibility of different elements of a product, such as packaging, including caps, labels or adhesives, with given recycling streams. D4R Guidelines therefore support the industry on how to improve overall recyclability of products. Guidelines are living documents, as they are continuously updated based on new laboratory findings, including technology approvals. For features of a product that are not yet covered by the D4R Guidelines, testing is recommended via the Recyclability Evaluation Protocols (Löw et al. 2021). In a wider sense, D4R can be regarded as a material efficiency perspective on Eco-design. The implementation of D4R takes place on two playing fields: a technical development of criteria and the embedding of this design principle in a legal framework or policy initiative (European Union 2024b).

The European Green Deal highlights the need for investment in a competitive and sustainable Europe, with products playing a crucial role in the green transition. To promote a circular economy, the Commission launched the Circular Economy Action Plan (CEAP) on March 11, 2020, to establish a sustainability regulatory framework. However, there are currently no comprehensive requirements to ensure that all products in the EU market are increasingly sustainable and support circularity. Product design often does not encourage sustainability throughout the life cycle, leading to frequent replacements that waste energy and resources. Additionally, businesses and consumers struggle to make sustainable choices due to a lack of relevant information and affordable options, which hinders sustainability, reduces demand for secondary materials, and obstructs circular business models.

In its resolution on the New Circular Economy Action Plan dated February 10, 2021, the European Parliament emphasized that sustainable, circular, safe, and non-toxic products should be the norm in the EU market, making them the default choice for consumers. It called for binding targets to significantly reduce material and consumption footprints across the Union. The Parliament believes that transitioning to a circular economy can help tackle current environmental challenges and the economic crisis caused by the COVID-19 pandemic. The Council also supported the Commission's plan to propose legislation for a sustainable product policy framework that promotes climate neutrality, resource efficiency, public health, biodiversity, and consumer protection (European Union 2024b).

Facts and Figures

The Eco-design for Sustainable Products Regulation (ESPR), which entered into force on 18 July 2024, is the cornerstone of the EC’s approach to more environmentally sustainable and circular products. In this regulation, the Commission should, when preparing eco-design requirements, consider their impact on SMEs, in particular on microenterprises, active in the relevant product sector. The Member States should, in their respective areas of responsibility, provide adequate information, including guidance, provide targeted and specialized training, and provide specific assistance and support, including financial support, to SMEs active in the manufacturing of products for which eco-design requirements are set. Those actions are particularly important for product groups where the presence of SMEs is relevant. The Commission should, where appropriate, support the calculation of the product environmental footprint by providing digital tools, such as tools for life cycle assessment calculation, and support the implementation of the digital product passport. This Regulation will therefore play a significant role towards achieving several targets established under the Sustainable Development Goals of the United Nations 2030 Agenda for Sustainable Development, both inside and outside the Union, in particular targets under Sustainable Development Goal 12 (Responsible consumption and production’).

Information on the presence of substances of concern in products is a key element in identifying and promoting sustainable products. The chemical composition of products largely determines their functionalities and impacts, as well as the possibility for their reuse or for recovery once they become waste. The Commission’s communication of 14 October 2020, ‘Chemicals Strategy for Sustainability Towards a Toxic-Free Environment’ calls for the presence of substances of concern in products to be minimized, and the availability of information on chemical content and safe use to be ensured, by introducing information requirements and tracking the presence of substances of concern throughout the life cycle of materials and products. Regulation (EC) No 1272/2008 and other existing chemicals law, such as Regulation (EC) No 1223/2009, already ensure communication on hazards to health or the environment posed by certain substances of concern on their own or in a mixture (European Union 2024b).

Relevance for Orchestra Demonstrator

Demonstrator I Material Selection and Specification	Demonstrator II Recycling	Demonstrator III Criticality
Indirect: Design guidelines influence specifications for components (e.g., bipolar plates, heat exchangers), requiring recyclability considerations in material choices.	Direct: Improved design for disassembly enhances purity of recyclates, positively impacting subsequent recycling processes and functionality.	Direct: Mandatory design for reuse and recycling phases increases availability of critical resources and supports compliance with EU sustainability frameworks.

2.3.4 Criticality Assessment as Law (Political)

Short Description

Companies must assess and disclose the criticality of their materials.

Criticality can generally be understood as a combined assessment of economic significance and supply risk. The definitions of criticality and the lists of critical materials vary by jurisdiction and over time: In 2011, the EU identified 14 individual materials in its 'list of critical raw materials,' while in 2023, it specified 34 materials, including two new 'strategic materials' that do not meet the criticality thresholds but are considered strategically important (Jacob Mardell 2024).

The EU Commission has recently approved a list of 47 strategic projects for the first time to strengthen the strategic raw material capacities of the EU. These projects aim to enhance the European value chain for raw materials and diversify supply sources. In Germany, projects are being initiated for the extraction and processing of lithium and graphite (Europäische Kommission 25.03.2025). The focus is on the Critical Raw Materials Act (EU) 2024/1252 of the European Union, dated April 11, 2024.

The regulation reduces supply disruption risks for critical raw materials by supporting strategic projects, diversifying imports, and promoting technological advancement (European Union, 2024). It requires large companies to assess supply chain risks and coordinate strategic stockpiles among member states (Europäische Kommission 13.11.2023)

The new industrial strategy for Europe strengthens strategic autonomy. It warns that climate transition could shift dependence from fossil fuels to foreign raw materials under global competition. Therefore, the EU needs diversified access to global raw material markets (Europäische Kommission 03.09.2020)

Facts and Figures

In this section, we can gain an exemplary insight into selected articles of the Critical Raw Materials Act (EU) 2024/1252 of the European Union, dated April 11, 2024.

- Article 5 of the regulation, for example, contains benchmarks to strengthen the value chain in the EU, ensuring that by 2030, no more than 65% of the annual consumption of a raw material must be imported from any third country (such as China).
- Also illustrative is Article 24, which initially addresses the EU member states and then directly targets companies:
- *(1) By May 24, 2025, and within 12 months of each update of the list of strategic raw materials in accordance with Article 3(3), member states shall identify the large companies operating within their territory that use strategic raw materials for the production of batteries for energy storage and electromobility, equipment for the generation and use of hydrogen, equipment for the generation of energy from renewable sources, aircraft, propulsion engines, heat pumps, equipment for data transmission and storage, mobile electronic devices, equipment for additive manufacturing, equipment for robotics, drones, rocket launchers, satellites, or advanced chips.*
- *(2) The large companies referred to in paragraph 1 [more than 500 employees and a global net turnover of more than 150 million euros] shall conduct a risk assessment of their supply chain for strategic raw materials at least every three years, to the extent that the necessary information is available to them, which shall include: (…)* (European Union 2024a).
- Additionally, the EU created forecasts for critical raw materials needed for strategic technologies and sectors in 2020, highlighting the necessity for legislative regulation. The scenarios developed by the EU prior to COVID-19 aimed at achieving climate neutrality by 2050 were translated into estimated demand for raw materials and addressed supply risks across various levels of the supply chains. In particular, for electric vehicle batteries and energy storage, the EU would require up to 18 times more lithium and five times more cobalt by 2030 compared to the current supply for the entire EU economy. By 2050, this demand could escalate to almost 60 times more lithium and 15 times more cobalt, raising concerns about potential supply issues if no action is taken. Furthermore, the demand for rare earths, which are essential for permanent magnets used in applications such as electric vehicles, digital technologies, and wind generators, could increase tenfold by 2050 (Europäische Kommission 03.09.2020).

Relevance for Orchester Demonstrator

Demonstrator I **Material Selection and Specification**	**Demonstrator II** **Recycling**	**Demonstrator III** **Criticality**
Indirect: External pressure motivates companies to reduce the use of critical materials and integrate criticality considerations into specifications.	Indirect: Mandatory criticality assessments increase demand for recycling solutions that recover critical materials efficiently.	Direct: Legal requirements for disclosure and risk assessment strengthen the case for ORCHESTER solutions, promoting recovery, diversification, and resilience.

2.3.5 Sustainable Funding Policy (Political)

Short Description

Governments create incentives and subsidies for sustainable material innovations. Subsidies and support for sustainable actions have a significant impact on prices, competition, and market structure. The term "subsidy" in this discussion encompasses a variety of measures that can differ depending on their effects, sector, and intended use (Deutscher Bundestag 2023a).

New materials form the basis for technological progress, creating opportunities for science, growth, prosperity, competitiveness, and societal value. Research and development (R&D) are the starting points for innovative products and services. Small and medium-sized enterprises (SMEs) play a crucial role as innovation drivers and interfaces for transferring research results to industry. R&D investments secure future jobs and living standards. The Federal Government sets thematic priorities through the "Future Strategy for Research and Innovation," focusing on the digital economy, sustainable practices, and workplace innovations. The funding measure targets SMEs seeking market establishment and competitiveness (Federal Ministry of Education and Research 2024; Federal Government 2024).

The transition to circular business models plays a central role but requires high initial investments for new technologies and processes. A conflict arises between cost reduction and sustainability, particularly during the transition phase. Companies must weigh when investments will pay off and when efficiency gains will achieve desired cost reductions.

The shift to a circular economy requires targeted political support and legal framework conditions. This includes incentives, regulations, and cost adjustments. Early-acting companies should receive promotional advantages, while other actors need targeted incentives to introduce circular business models. Clear regulations should then ensure all market participants engage in the desired transformation. This creates an effective mix of incentives and long-term guidelines anchoring the circular economy throughout the economic system (Hartmann and Donner 2024).

Facts and Figures

There are already examples of successful incentive instruments that could be utilized, such as tax breaks, grants, low-interest loans for sustainable innovations, or raw material funds. Additionally, the B2B sector could be further supported through incentives: Companies that offer products with a high recycled content could be incentivized through premiums to save customers the transition costs and thus strengthen innovation and research. It would be particularly beneficial to start with materials that have a high international dependency, as addressed in the Critical Minerals Act (Hartmann und Donner 2024; Bundesministerium des Innern und für Heimat 2024).

Financial incentives can offset higher initial costs that arise from adjustments, securing the competitiveness of companies. This mechanism has been successfully used in the past, for example, through feed-in tariffs for the installation of solar PV systems in the 1990s, which led to a boom in this area (Hartmann and Donner 2024)

The incentive systems should be adequately communicated (through multipliers such as chambers of commerce or associations) and designed to be unbureaucratic (Hartmann and Donner 2024).

An example from practice: According to a study by the European Commission, Germany supports the generation of energy from renewable sources such as wind, solar, water, and biogas more strongly than other EU member states, with a financial volume of 33.5 billion euros (which corresponds to about 1 percent of GDP). According to the study, the EU average for renewable energy funding as a percentage of GDP is about half (0.57%) (Deutscher Bundestag 2023b).

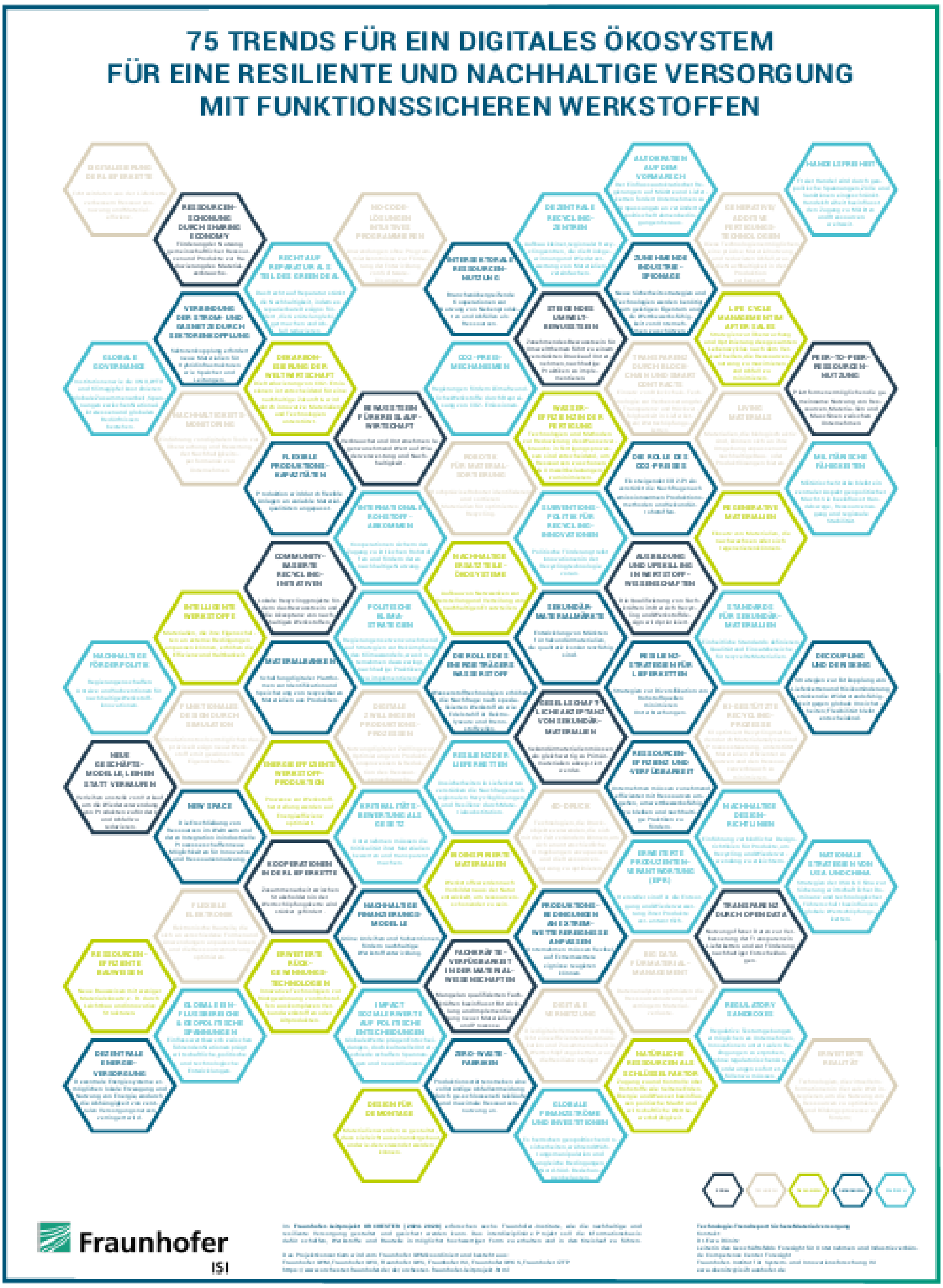
Relevance for Orchester Demonstrator

Demonstrator I **Material Selection and Specification**	**Demonstrator II** **Recycling**	**Demonstrator III** **Criticality**
Direct: Funding and subsidies accelerate R&D and adoption of low-carbon or circular materials; supports substitution and eco-design.	Direct: Incentives make recycling economically viable, enabling investment in advanced sorting and closed-loop systems; reduces transition cost barriers.	Indirect: Funding programs and legal frameworks promote recovery and diversification strategies, reducing dependency and criticality risk over time.

3 Annex

3.1 Poster Trends in the ORCHESTER Project

75 Trends für ein digitales Ökosystem für eine resiliente und nachhaltige Versorgung mit funktionssicheren Werkstoffen



3.2 Trend Long List

Sozial (S): Gesellschaft und Arbeitsmarkt

Titel	Kurzbeschreibung
Ausbildung und Upskilling in Werkstoffwissenschaften	Die Qualifizierung von Fachkräften im Bereich Recycling und Werkstoffdesign wird priorisiert.
Bewusstsein für Kreislaufwirtschaft	Verbraucher und Unternehmen legen zunehmend Wert auf Wiederverwertung und Nachhaltigkeit.
Community-basierte Recyclinginitiativen	Lokale Recyclingprojekte fördern das Bewusstsein und die Akzeptanz von nachhaltigen Werkstoffen.
Fachkräfteverfügbarkeit im Bereich Materialwissenschaften	Der Mangel an qualifizierten Fachkräften beeinflusst die Entwicklung und Implementierung neuer Materialien und Prozesse.
Gesellschaftliche Akzeptanz von Sekundärmaterialien	Sekundärmaterialien müssen als gleichwertig zu Primärmaterialien akzeptiert werden.
Kooperationen in der Lieferkette	Zusammenarbeit zwischen Stakeholdern in der Wertschöpfungskette wird stärker gefördert.
Neue Geschäftsmodelle, Leihen statt Verkaufen	Neue Geschäftsmodelle, die auf das Verleihen anstelle des Verkaufs setzen, fördern die Wiederverwendung von Produkten und reduzieren Abfall.
Peer-to-Peer-Ressourcennutzung	Plattformen ermöglichen die gemeinsame Nutzung von Ressourcen, Materialien und Maschinen zwischen Unternehmen.
Ressourcenschonung durch Sharing Economy	Förderung der Nutzung gemeinschaftlicher Ressourcen und Produkte zur Reduzierung des Materialverbrauchs.
Steigendes Umweltbewusstsein	Zunehmendes Bewusstsein für Umweltthemen führt zu einem verstärkten Druck auf Unternehmen, nachhaltige Praktiken zu implementieren.
Transparenz durch Open Data	Nutzung offener Daten zur Verbesserung der Transparenz in Lieferketten und zur Förderung nachhaltiger Entscheidungen.

Technologisch (T): Innovation und digitale Systeme

Titel	**Kurzbeschreibung**
4D-Druck	Technologien, die Druckobjekte verwenden, die sich mit der Zeit verändern können, um sich an unterschiedliche Umgebungen anzupassen und die Ressourcennutzung zu optimieren.
Big Data für Materialmanagement	Datenanalysen optimieren die Ressourcennutzung und verringern Materialverluste.
Digitale Vernetzung	Die digitale Vernetzung ermöglicht eine effizientere Kommunikation und Zusammenarbeit in Wertschöpfungsketten, was die Resilienz steigert.
Digitale Zwillinge in den Produktionsprozessen	Nutzung digitaler Zwillinge zur Optimierung von Produktionsprozessen und zur Reduzierung des Ressourcenverbrauchs.
Digitalisierung der Lieferkette	Echtzeitdaten aus der Lieferkette verbessern Ressourcennutzung und Materialeffizienz.
Erweiterte Realität	Technologien, die virtuelle Informationen in die reale Welt integrieren, um die Nutzung von Ressourcen zu optimieren und Bildungsprozesse zu fördern.
Flexible Elektronik	Elektronische Bauteile, die sich an verschiedene Formen und Anwendungen anpassen lassen und die Ressourcennutzung optimieren.
Funktionales Design durch Simulation	Simulationstools ermöglichen das präzise Design neuer Werkstoffe mit gewünschten Eigenschaften.
Generative/additive Fertigungstechnologien	Diese Technologien ermöglichen eine präzise Materialnutzung und reduzieren Abfall, was die Nachhaltigkeit in der Produktion verbessert.
KI-gestützte Recyclingprozesse	KI optimiert Recyclingmethoden durch Materialanalysen und Prozesssteuerung, unterstützt Materialien effizienter zu nutzen und den Ressourcenverbrauch zu minimieren.
Living Materials	Materialien, die biologisch aktiv sind, können sich an ihre Umgebung anpassen und nachhaltige Bau- oder Produktlösungen bieten.
Nachhaltigkeits-Monitoring	Einführung von digitalen Tools zur Überwachung und Bewertung der Nachhaltigkeitsperformance von Unternehmen.
No-Code-Lösungen - intuitives Programmieren	Erstellung von Anwendungen ohne Programmierkenntnisse zur Förderung der Entwicklung von Softwarelösungen.
Robotik für Materialsortierung	Hochpräzise Roboter identifizieren und sortieren Materialien für optimiertes Recycling.

Titel	Kurzbeschreibung
Transparenz durch Blockchain und Smart Contracts	Einsatz von Blockchain-Technologie zur Verbesserung der Transparenz und Rückverfolgbarkeit in Lieferketten / Wertschöpfungsketten.

Ökologisch (E): Klima und Ressourcen

Titel	Kurzbeschreibung
Bioinspirierte Materialien	Werkstoffe werden nach Vorbildern aus der Natur entwickelt, um ressourcenschonender zu sein.
Dekarbonisierung der Weltwirtschaft	Die Reduzierung von CO2-Emissionen ist entscheidend für eine nachhaltige Zukunft, was durch innovative Materialien und Technologien unterstützt wird.
Design für Demontage	Materialien werden so gestaltet, dass sie leicht auseinandergebaut und wiederverwendet werden können.
Energieeffiziente Werkstoffproduktion	Prozesse zur Werkstoffherstellung werden auf Energieeffizienz optimiert.
Erweiterte Rückgewinnungstechnologien	Innovative Technologien zur Rückgewinnung von Rohstoffen aus komplexen Verbundwerkstoffen oder Altprodukten.
Intelligente Werkstoffe	Materialien, die ihre Eigenschaften an externe Bedingungen anpassen können, erhöhen die Effizienz und Haltbarkeit.
Life Cycle Management im After Sales	Strategien zur Überwachung und Optimierung des gesamten Lebenszyklus eines Produkts nach dem Verkauf helfen, die Ressourcennutzung zu maximieren und Abfall zu minimieren.
Nachhaltige Ersatzteile-Ökosysteme	Aufbau von Netzwerken zur Herstellung und Verteilung von nachhaltigen Ersatzteilen.
Natürliche Ressourcen als Schlüsselfaktor	Der Zugang zu und die Kontrolle über Rohstoffe wie Seltene Erden, Energie und Wasser beeinflussen politische Macht und wirtschaftliche Wettbewerbsfähigkeit.
Regenerative Materialien	Einsatz von Materialien, die nachwachsen oder sich regenerieren können.
Ressourceneffiziente Bauweisen	Neue Bauweisen mit weniger Materialeinsatz, z. B. durch Leichtbau und innovative Strukturen.
Wassereffizienz in der Fertigung	Technologien und Methoden zur Reduzierung des Wasserverbrauchs in Fertigungsprozessen sind entscheidend, um Ressourcen zu schonen und die Umweltbelastung zu minimieren. Effiziente Wassernutzung fördert nachhaltige Produktionspraktiken.

Ökonomisch (E): Markt und Wertschöpfung

Titel	Kurzbeschreibung
Anpassung der Produktionsbedingungen an Extremwetterereignisse	Unternehmen müssen flexibel auf häufigere und intensivere Extremwetterereignisse reagieren können, um Resilienz der Produktionssysteme zu erhöhen und ihre Betriebsabläufe aufrechtzuerhalten.
Dezentrale Energieversorgung	Dezentrale Energiesysteme ermöglichen die lokale Erzeugung und Nutzung von Energie, wodurch die Abhängigkeit von zentralen Versorgungsnetzen verringert wird.
Die Rolle des CO2-Preises	Ein steigender CO2-Preis verstärkt die Nachfrage nach emissionsarmen Produktionsmethoden und Sekundärrohstoffen.
Die Rolle des Energieträgers Wasserstoff	Wasserstofftechnologien erhöhen die Nachfrage nach spezialisierten Werkstoffen wie Edelstahl für Elektrolyseure und Brennstoffzellen.
Flexible Produktionskapazitäten	Produktion wird durch flexible Anlagen an variable Materialqualitäten angepasst.
Internationaler Handel: Decoupling und Derisking	Strategien zur Entkopplung von Lieferketten und Risikominderung stärken die Widerstandsfähigkeit gegen globale Unsicherheiten; Flexibilität bleibt entscheidend.
Intersektorale Ressourcennutzung	Branchenübergreifende Kooperationen zur Nutzung von Nebenprodukten und Abfällen als Ressourcen.
Materialbanken	Schaffung digitaler Plattformen zur Identifikation und Speicherung von recycelbaren Materialien aus Produkten.
Nachhaltige Finanzierungsmodelle	Grüne Anleihen und Subventionen fördern nachhaltige Werkstoffentwicklung.
New Space	Die Erschließung von Ressourcen im Weltraum und deren Integration in industrielle Prozesse schaffen neue Möglichkeiten für Innovation und Ressourcennutzung.
Resilienzstrategien für Lieferketten	Strategien zur Diversifikation von Rohstoffquellen minimieren Unterbrechungen.
Ressourceneffizienz und -verfügbarkeit	Unternehmen müssen zunehmend effizienter mit Ressourcen umgehen, um wettbewerbsfähig zu bleiben und nachhaltige Praktiken zu fördern.
Sekundärmaterialmärkte	Produktion wird durch flexible Anlagen an variable Materialqualitäten angepasst.
Verbindung der Strom- und Gasnetze durch Sektorenkopplung	Sektorenkopplung erfordert neue Materialien für Hybridinfrastrukturen wie Speicher und Leitungen.

Titel	Kurzbeschreibung
Zero-Waste-Fabriken	Produktionsstätten streben eine vollständige Abfallvermeidung durch geschlossene Kreisläufe und maximale Ressourcennutzung an.
Zunehmende Industriespionage	Neue Sicherheitsstrategien und Technologien werden benötigt, um geistiges Eigentum und die Wettbewerbsfähigkeit von Unternehmen zu schützen.

Politisch (P): Poltische Lage, Regulierungen und Standards

Titel	Kurzbeschreibung
Autokratien auf dem Vormarsch	Der Einfluss autokratischer Regierungen auf Märkte und Lieferketten fordert Unternehmen zu Anpassungen an veränderte politische Rahmenbedingungen heraus.
CO_2-Preismechanismen	Regierungen fördern klimafreundliche Werkstoffe durch Bepreisung von CO_2-Emissionen.
Dezentrale Recyclingzentren	Aufbau kleiner, regionaler Recyclingzentren, die die Rückgewinnung und Wiederverwertung von Materialien vereinfachen.
Erweiterte Produzentenverantwortung (EPR)	Hersteller sind für die Entsorgung und Wiederverwertung ihrer Produkte verantwortlich.
Globale Einflussbereiche und geopolitische Spannungen	Der Einflusswettbewerb zwischen führenden Nationen wie den USA, China und der EU prägt wirtschaftliche, politische und technologische Entwicklungen.
Globale Finanzströme und Investitionen	Es herrschen geopolitischen Unsicherheiten, während Währungsmanipulation und ungleiche Bedingungen Nord-Süd-Beziehungen belasten.
Globale Governance	Institutionen wie die UNO, WTO und Klimagipfel koordinieren globale Zusammenarbeit, Spannungen zwischen Nationalinteressen und globalen Bedürfnissen bestehen.
Handelsfreiheit	Freier Handel wird durch geopolitische Spannungen, Zölle und Sanktionen eingeschränkt. Handelsfreiheit beeinflusst den Zugang zu Märkten und Ressourcen weltweit.
Impact sozialer Werte auf politische Entscheidungen	Globale Werte wie Nachhaltigkeit, Inklusion und Menschenrechte prägen Entscheidungen, doch kulturelle Unterschiede schaffen Spannungen und neue Allianzen.
Internationale Rohstoffabkommen	Kooperationen sichern den Zugang zu kritischen Rohstoffen und fördern deren nachhaltige Nutzung.
Kritikalitätsbewertung als Gesetz	Unternehmen müssen die Kritikalität ihrer Materialien bewerten und transparent machen.

Titel	Kurzbeschreibung
Militärische Fähigkeiten	Militärische Stärke bleibt ein zentraler Aspekt geopolitischer Macht. Sie beeinflusst Handelswege, Ressourcenzugang und regionale Stabilität.
Nachhaltige Designrichtlinien	Einführung verbindlicher Designrichtlinien für Produkte, um Recycling und Wiederverwendung zu erleichtern.
Nachhaltige Förderpolitik	Regierungen schaffen Anreize und Subventionen für nachhaltige Werkstoffinnovationen.
Nationale Strategien von USA und China	Die Strategien der USA und Chinas zur Sicherung von wirtschaftlicher Dominanz und technologischer Führerschaft beeinflussen globale Wertschöpfungsketten.
Politische Klimastrategien	Regierungen setzen zunehmend auf Strategien zur Bekämpfung des Klimawandels, was Unternehmen dazu zwingt, nachhaltige Praktiken zu implementieren.
Recht auf Reparatur als Teil des Green Deal	Das Recht auf Reparatur stärkt die Nachhaltigkeit, indem es reparierbare Designs fördert, die Geräte langlebiger machen und Abfall reduzieren.
Regulatory Sandboxes	Regulative Testumgebungen ermöglichen es Unternehmen, Innovationen unter realen Bedingungen zu erproben, ohne regulatorischen Anforderungen sofort erfüllen zu müssen.
Resilienz der Lieferketten	Unsicherheiten in Lieferketten verstärken die Nachfrage nach regionalen Recyclinglösungen und Resilienz durch Materialsubstitution.
Standards für Sekundärmaterialien	Einheitliche Standards definieren Qualität und Einsatzbereiche für recycelte Materialien.
Subventionspolitik für Recycling-Innovationen	Politische Förderung treibt Innovationen in der Recyclingtechnologie voran.

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