Closing the loop: Energy-intensive industries and the circular economy

10 key technologies for Germany’s steel, cement and chemicals industries

IMPRESSUM

Publisher	WWF Germany (foundation under German civil law, represented by Board Member Meike Rothschädl), Reinhardtstraße 18, D-10117 Berlin, Germany
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1st edition

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Foreword by the WWF

Dear Reader,

If Europe is to remain competitive, we need to act now and invest in building and producing technologies that support climate action and the circular economy. Innovative technologies can contribute significantly to climate change mitigation and environmental protection. They offer solutions to the challenges currently facing us and help to safeguard our vital resources. Germany is a hub of engineering excellence which offers enormous potential for upscaling if applied to decarbonisation, particularly when combined with the circular economy. This would enable Germany to assert a leading role among its global competitors. **It calls for a European industry policy which recognises that the circular economy and climate neutrality are the cornerstones of competitiveness.**

Viviane Raddatz
Director of Climate and Energy Policy

Rebecca Tauer
Head of the Circular Economy Programme

This report showcases ten technologies that contribute to the circular economy and climate change mitigation. Lasers can be used to identify and eliminate copper residues from scrap steel to improve its quality. Modular construction methods help to minimise the use of concrete. Digital tracking can reduce the amount of packaging that ends up in landfill. Recycling raw materials also boosts efficiency and reduces our dependency on fossil energies by up to 20 percent. It makes our economy more resilient. The more raw materials we can avoid or reuse, the less we need to import. This translates into security and competitive advantages in an era of supply chain instability. The recent energy price crisis was a sharp reminder for the German economy of the consequences of gas dependency. **The technologies showcased in this report are market-ready.** Producers could already be using them in the energy-intensive steel, chemicals and cement industries which are under pressure to change, yet they are rarely applied. **WWF is determined to change this, and our report highlights the potential of these technologies for the climate, the circular economy and Germany's competitiveness.** It will explain that every technology has its own unique requirements, barriers and challenges, but if we want to progress, improve and upscale, merely adopting a policy of technological openness is no longer enough. Unless positive action is taken, Germany could miss its opportunity to become a pioneer in these sectors, leaving relevant technologies untapped.

Policymakers have long overlooked the potential contribution of the circular economy to the climate-neutral transformation of energy-intensive industries. Many benefits of the circular economy have been disregarded. A circular economy mitigates climate change and protects nature while also strengthening Europe's competitiveness. In developing green technologies in Europe, we are helping to safeguard our future, by achieving our climate goals, serving as role models for our counterparts in other continents, and maintaining our long-term competitiveness. We can build on this, provided we invest in genuinely green technologies, as elucidated by this report.

However much these and other technologies contribute to the decarbonisation of industry, **a truly comprehensive transformation calls for a systemic approach and societal change.** Technology cannot solve all the problems, but it is an important part of the solution. Industry can successfully follow new paths to net zero if technological innovations, government policy and social change are deployed as coherent elements of a comprehensive approach. A circular economy means moving away from linear business models in favour of circular approaches focussing on durability, repair and reuse.

Viviane Raddatz
Director of Climate and
Energy Policy

Rebecca Tauer
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WWF's recommendations

Recommendations to industry

- **Strategically apply circular economic principles to conserve resources and promote decarbonisation:** Industry should use systemic circular economy levers at every stage of the value chain to cut carbon emissions and minimise resource consumption. Durable design, material-efficient processes and circular business models can be more effective than technological measures alone, but they must also be scaled up simultaneously.
- **Use digital technologies such as digital twins and IoT (Internet of Things):** These technologies should be used to boost efficiency, improve design planning and facilitate the tracking of materials and products, leading to material savings, carbon reductions and extended product lifecycles.
- **Establish future-proof construction and design strategies:** In the construction sector, modular prefabrication and digital planning methods such as Building Information Modelling (BIM) should be applied to achieve material savings of up to 40 percent and a dramatic reduction in carbon emissions.
- **Encourage collaboration in multi-use and reuse systems:** Companies should join forces and invest in standardised, interoperable and digitally supported multi-use and reuse systems. These collaborative formats at every stage of the supply chain, including logistics, cleaning and deposit systems, can cut costs, create economies of scale and facilitate access for smaller players.
- **Scale up innovative recycling technologies:** Technologies such as chemical recycling should be used in cases where upstream optimisation opportunities have been exhausted and processing plastic waste is too costly or time-consuming for mechanical recycling (always assuming transparent life cycle analyses, clear legal definitions and allocation methods which reflect the actual material flows of the processes involved).

Recommendations to policymakers

- **Industrial policy today must incorporate the circular economy and climate neutrality as key pillars of competitiveness:** European and German industrial policy must coherently facilitate and incentivize the transformation of the basic materials industry. This should be underpinned by an integrated transformation strategy which identifies viable circular models within the context of realistic location factors, examines barriers and proposes clear solutions, including European and global partnerships. The circular economy must be anchored as an integral element of modern industrial policy. The German government should adopt a technology- and location-centric strategy for the steel, cement and chemicals industries which consciously invests in emission-reducing and resource-conserving circular economy solutions. This should include expanding national electric arc furnace (EAF) capacities, promoting digital and sorting technologies, and adopting a regulatory framework setting out minimum recycling quotas and design requirements. Only then will it be possible to build new value chains, allowing Germany to position itself as an exporter of circular technologies.

- **Carbon pricing must be a incentive for transformational innovations and investments:** Since the rollout of the European Emissions Trading System (ETS), industry has benefited from free allocation but fails to pay in full for the carbon it emits, and there is no application of the polluter-pays principle. Emissions from plants covered by the ETS have fallen only minimally since emissions trading began. Free allocation weakens carbon pricing, prevents it from developing the desired steering effect and fails to incentivize innovative investments. The 2023 reform of EU emissions trading ruled that free allocation would be phased out in 2034. As an absolute minimum, this level of ambition must be retained. Setting an earlier expiry date would have created incentives. To avoid further disincentives between now and 2034, free allocation should be linked to certain conditions, including a requirement for companies to set science-based climate and environmental targets and present medium- to long-term transformation plans. Moreover, investment funding should be tied to energy efficiency, climate-friendly processes and more extensive use of renewable energies.

- **Binding resource targets must be anchored in law:** Transformation to a climate-neutral, resource-responsible industry demands an ambitious political framework which systematically promotes resource conservation and the circular economy. Climate targets should be backed by binding resource targets, substantiated, implemented and effectively monitored by resource conservation legislation.

Direct financial support for investments is also needed, alongside measures to foster the demand for sustainable materials and products.

- **Adopt a financial and fiscal policy centred around conserving resources to promote the circular economy:** An effective circular economy needs targeted fiscal incentives. The German government should introduce environmental taxes on primary raw materials, grant tax concessions for circular services such as repair and sharing schemes, and phase out environmentally harmful subsidies. There is a particular need for subsidies such as "as-a-service" models among small and medium-sized enterprises (SMEs) to incentivize investments in innovative circular economy technologies such as LIBS systems, copper removal techniques and electric arc furnace (EAF)-based steel production.

- **Apply climate-friendly, circular principles to key markets:** In Germany alone, public procurement accounts for an investment volume of 500 billion euros. Although Section 13 (2) of the Climate Action Act (Klimaschutzgesetz) states that climate targets must be considered in all budget-related decisions at Federal Government level, particularly investments and procurements, contracts are still awarded primarily on the basis of cost-effectiveness and fail to consider the true climate and environmental costs.

- **Carbon Contracts for Difference (CCfD)** are a useful funding mechanism for supporting transformative investments. While carbon pricing remains below the required level and there is no incentive to switch to climate-friendly technologies and production processes, CCfDs can provide industry with the necessary planning and investment certainty. The scheme is expected to continue into the next legislative period. Subsidies should not be confined to climate action technologies but should also promote solutions for the circular economy.

- **Enforce strict framework conditions for the use of Carbon Capture and Utilization (CCU):** As the established circular strategies (reduce, reuse, recycle) alone are unlikely to achieve climate neutrality in the plastics industry, other approaches such as the production of plastics from CO_2 (CCU) and the use of biotic raw materials could also promote the circular economy in this sector. Strategies should be prioritised according to both energy use and land use. Furthermore, guarantees must be given that the carbon contained in the product will be bound for at least 200 years - otherwise, emission of the carbon stored in products will simply be delayed rather than permanently stored, and long-term climate change mitigation effects cannot be guaranteed.

- **Biomass** can also be used as a source of carbon in the chemicals industry, or as a fuel for rotary kilns in the cement industry. WWF is calling for strict regulations at every level, from local through to international, whereby the use biomass as energy should only be permitted if there are no other uses with **greater environmental benefits**. It is important to remember that biomass provides a habitat for fauna and flora species. Forests play a vital role as carbon sinks that absorb CO_2 over the course of their lifespan. As well as contributing to biodiversity, forests are an important leisure destination for human beings.

Core messages

A combination of decarbonisation and the circular economy could help German industry to assert itself in the face of global competition.

- Circular economy technologies can help reduce the cost of achieving climate neutrality by up to 45 percent, while also reducing energy dependency by up to 20 percent[1]. Efficiency gains associated with circular economy levers can help reduce the demand for costly green hydrogen and minimise the need for expensive Carbon Capture, Utilisation and Storage (CCUS).

- Material savings and substitutions can also make geopolitically unstable supply chains more resilient and reduce price volatility for raw materials. The construction sector is a prime example where the cost of material imports has risen sharply in recent years.

- With its reputation for engineering excellence, Germany is well-placed to showcase its skills in selected circular economy technologies and tap into new export markets, such as modular, digitally optimised buildings or material sorting systems for plastic waste.

While there is a need for systemic levers at every stage of the value chain (e.g. new business models to reduce packaging and better vehicle design for cleaner dismantling and materials recovery), **they must be facilitated and complemented by innovative technologies.**

- Circular economy technologies help to close substance cycles and prevent the excessive use of materials. They are also attractive export commodities for machine manufacturing, digital technology production and engineering services.

1 Shawkat, A. et al. (Agora Industrie u. Systemiq) [s. https://www.agora-industrie.de/publikationen/resilienter-klimaschutz-durch-eine-zirkulaere-wirtschaft)] (2023), online available here.

Many circular economy technologies for steel, cement and chemicals have already undergone field testing and offer significant economic potential and scope for reducing emissions (see Fig. 1).

- Germany is competitively positioned to tap into a range of new business segments, from deep tech innovations (such as digital twins in construction or battery optimisation) to circular technologies in downstream sectors (such as the circular production of green steel).
- Germany, with its engineering excellence, is well-placed to develop and export these technologies, often closely intertwined with services and (in some cases) machine manufacturing.
- However, more extensive analysis is needed to gauge the potential of selected technologies for Germany specifically, and Europe in general, against the backdrop of industrial and geopolitical developments such as energy prices and public investment.

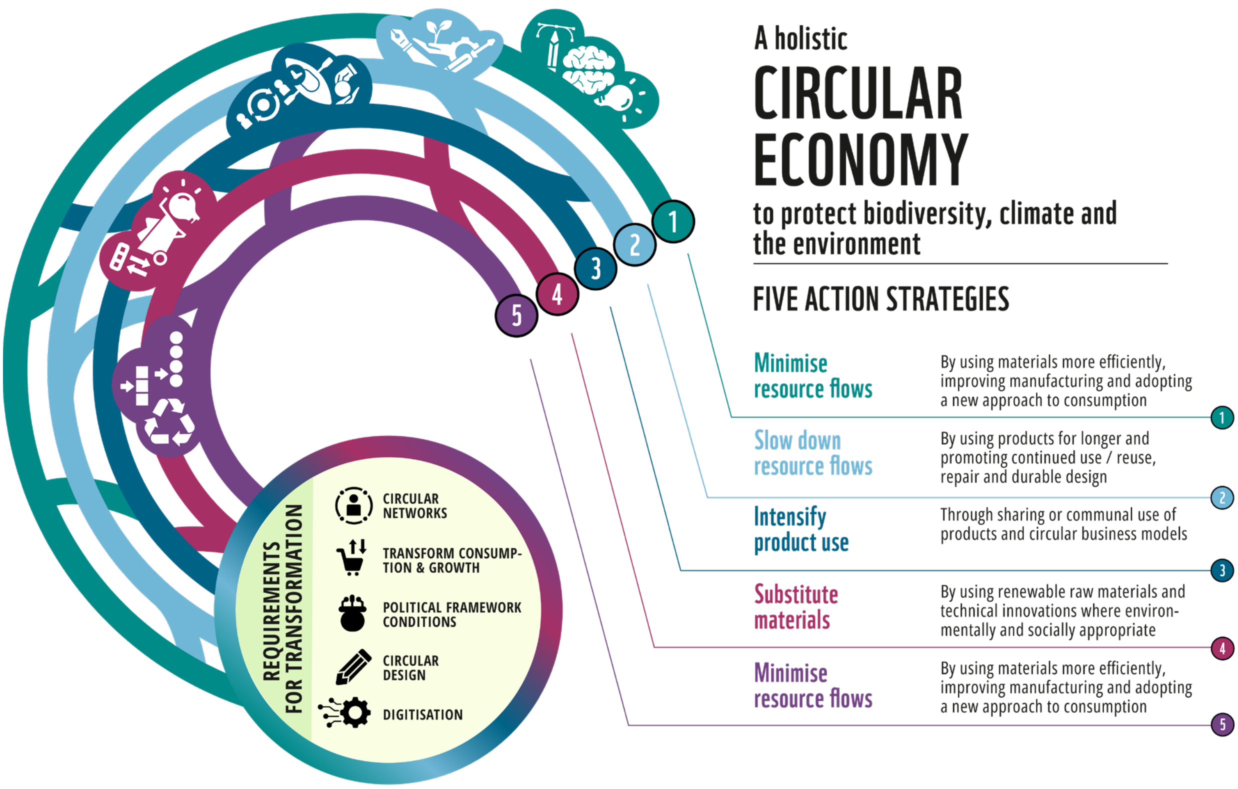


Figure 1: Own diagram; © epoqstudio.com

			Environmental potential		Economic potential		
Industry	**Technology**	**R-strategy**	**Potential emission reductions[2]**	**Potential primary material savings**	**Potential costs[3]**	**Import resilience[4]**	**Market potential[5]**
Steel	Laser-induced plasma spectroscopy (LIBS)	Recycle	▶	▶	▲	▲	Medium export potential with cross-sector applications but limited number of systems worldwide
	Copper separation technique	Recycle	▶	▲	▼	▲	Primarily domestic growth potential due to high volumes of scrap steel
	GrüGreen steel production via the EAF route	Reduce, Reuse	▲	▶	▼	▲	Growing market for green steel with export potential for equipment and expertise
Cement	Prefabricated parts	Reduce	▲	▶	▲	▼	Significant domestic potential
	Calcined clay	Reduce	▲	▼	▲	▶	Significant domestic potential
Chemicals	IoT-assisted packaging systems	Reuse	▶	▲	▶	▲	Growth potential for new reuse markets in DE and Europe
	Mechanical plastics recycling	Recycle	▲	▲	▶	▲	Regulation-dependent market growth in DE and Europe (e.g. EU Packaging and Packaging Waste Regulation, PPWR)
	Chemical plastics recycling	Recycle	▼	▲	▼	▲	Medium export potential for products and technologies due to limited use cases Low potential for domestic HVC[6] production
	Catalytic hydrogenation to methanol/ methanol-to-olefins (MTO)	Reduce, Recycle	▶	▲	▼	▶	Germany could develop the market for reprocessing imported methanol via MTO processes
Sector-agnostic	Digital twins	Reduce, Reuse, Recycle	▲	▲	▶	▼	High growth and export potential with strong German players

Figure 2: Circular economy technologies and their potential for Germany; © Systemiq

Technology potential versus current practice:

▲ High, ▶ Medium, ▼ Low

2 Cumulative potential savings in the sector, assuming the use of 100% renewable energies
3 Includes potential savings with energy costs, reduced process and production costs, plus potentially lower raw materials costs
4 Contribution to self-sufficiency; resilience to market fluctuations
5 Market potential for Germany and as an export commodity
6 High-value chemicals

Method

Having pragmatically assessed potential carbon and material savings, cost-effectiveness and scalability, we selected ten key circular economy technologies, focussing on the energy-intensive sectors of steel, cement and chemicals, where substantial emission reductions can be achieved through reduce, reuse and recycle strategies. We considered both low-tech and high-tech solutions, from prefabrication (modular construction) and LIBS (laser induced breakdown spectroscopy) through to digital and hardware-based approaches, including digital twins and chemical recycling.

We selected between two and four technologies for each industry based on their relevance, data availability and interconnectivity. This does not purport to be a comprehensive quantitative analysis; there are, of course, numerous other circular economy technologies, each of which has their own pros and cons.

Criteria for consideration in technology selection

- **Climate impact:** Focus on circular economy technologies with the highest cumulative emission reduction potential[7]. Here, the emission reduction potential refers to the circular economy lever, rather than the specific technology in question. The underlying data is drawn from existing analyses[8]. In the steel industry, for example, recycling offers the greatest potential for cutting carbon emissions. With this in mind, we examined technical solutions aimed at improving recycling rates, for example through better collection, sorting and processing. As the scope of this report was limited to a maximum of ten technologies, we selected three as being representative for the steel industry: LIBS, copper separation techniques and electric arc furnaces (EAF).
- **Market maturity:** We limited our selection to technologies with a Technology Readiness Level (TRL) of at least > 7, i.e. those that have reached demonstration phase or further. TRL and technology descriptions are based on the database of the International Energy Agency, where available[9].

7 Shawkat, A. et al. (Agora Industrie u. Systemiq) (2023).
8 Shawkat, A. et al. (Agora Industrie u. Systemiq) (2023).
9 IEA (2024). ETP Clean Energy Technology Guide. Database, available online here.

Technology analysis

We analysed the literature and selected expert interviews to qualitatively assess the technologies in terms of their cost and resilience benefits. To this end, we compiled the relevant literature and supplemented it with expert assessments.

1. **Key economic benefits:**

    - **Cost benefits:** We analysed the technology's potential cost benefits, ongoing operating costs, scalability and general cost-effectiveness (for example in terms of energy costs) versus existing alternatives.

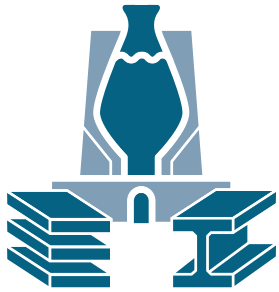
    - **Global competitive advantages:** We assessed the potential for safeguarding raw material supplies, import resilience and market potential in Germany and abroad (for example, suitability for export). We also considered whether the technology builds on Germany's existing strengths and contributes to Germany's positioning as an innovation leader in relevant sectors.

2. **We also considered environmental aspects**, focussing on the potential emission reductions and primary material savings, as well as water consumption and toxicity.

3. **Our analysis also included multiple illustrative sample projects …**

4. **…** together with **potential barriers** and **associated measures** at an overarching level. However, future studies will need to analyse specific technology-promoting measures in greater depth.

1. The circular economy and the steel industry: Principal levers, environmental potential and technologies



Circular technology segments and their potential

The German steel sector produces 54.7 million tonnes of Co_2e, corresponding to around seven percent of Germany's CO_2e emissions[10]. Iron manufacturing accounts for the bulk of emissions. To achieve climate neutrality, the steel industry would need to adopt climate-neutral production techniques[11] and, at the same time, use circular economy solutions to boost efficiency and scrap routes. Circular economy levers could accelerate decarbonisation, cut costs and reduce dependencies on iron ore and fossil fuels. In other words, they could limit the risk of interruptions to the global supply chain and enhance Europe's raw materials security in the pivotal economic sectors of machine production and vehicle manufacturing.

- The clean primary production of steel, primarily via electrification, could reduce emissions from this sector by between 65 and 75 percent by 2045 compared with 2020 levels. However, this would require vast quantities of renewable energy and green hydrogen. Without ancillary measures such as recycling, improved product design or reuse, we would need to produce significantly more new steel, making the transformation process time-consuming, cost-intensive, inefficient and generally too slow[12].

- Circular economy levers among downstream sectors of the steel industry could cut emissions by a further 20 to 30 percent. This includes the more efficient use of materials in client sectors such as construction and vehicles (potential savings totalling 10-15 percent of cumulative emissions), as well as improved recycling, including dismantling (a further 10-15 percent)[13].

The following **circular economy levers** are available:

- **Optimised product design** among downstream sectors of the steel industry, such as car manufacturing and the construction industry, would help to reduce steel consumption. An improved product design is the most effective path to higher scrap steel quality. However, this only applies to new products, and does not include the innumerable vehicles, machines and building parts already in circulation. During the transitional period, technologies should facilitate the more effective sorting

10 Oliver Wyman, IW Consult on behalf of the German Steel Association (Wirtschaftsvereinigung Stahl) (2024): Die Stahlindustrie am Scheidepunkt. Wegbereiter für Transformation und gesamtwirtschaftliche Resilienz, based on IEA, World Steel Association, IEFA calculation, available online here.

11 For example, water-based direct reduction, molten oxide electrolysis and electrowinning.

12 Oliver Wyman, IW Consult (2024).

13 More efficient use of materials includes effective modules, optimised design and efficient production & construction processes. Meanwhile, improved recycling incorporates collection, sorting and recycling solutions.

and separation of suboptimum products[14]. These levers account for around a third of the potential circular savings.

- **Using high-quality scrap steel** – Better recycling, in turn, generates more value from scrap steel. High-quality scrap steel is available in Germany[15] and potential client markets for cost-effective, carbon-reduced steel include machinery production, car manufacturing and civil engineering[16]. Germany already recycles 90 percent of its steel, but it is often used for lower-value products or the growing export market[17]. For example, large quantities of high-quality flat steel are exported in end-of-life (EoL) vehicle shells. As a result, these high-quality scrap volumes are lost to the domestic EAF scrap route[18].

- **Better collection and sorting technologies** are needed to boost the quality of recycled steel for use in higher-end applications. Over the coming years, many machines and buildings will be reaching the end of their service life, producing ever-greater quantities of scrap steel. The efficient use of this scrap as climate-friendly steel in steel-intensive sectors relies on high-quality processing.

- **Efforts to promote and more extensively research technological solutions for higher-quality steel recycling are therefore particularly crucial, from both an environmental and an economic perspective.** While political incentives may support a wide range of creative, sustainable innovations, market analysis indicates considerable potential for the following technologies:

  - Material identification technologies as the precursor to improved separation techniques, particularly laser-induced breakdown spectroscopy (LIBS)

  - Advanced copper separation techniques for superior scrap quality and better reuse of steel

  - More (H_2-DRI) electric steel capacity (EAF) for low-carbon processing of scrap steel into high-quality recycled steel

14 Shawkat, A. et al. (Agora Industrie u. Systemiq) (2023).

15 Wirtschaftsvereinigung Stahl (2024): Statistischer Bericht – Stahlschrott 2024.

16 (1) Modification of existing plant with blue or open blast furnaces that minimise external carbon input, together with AI-assisted control systems to optimise yield and energy efficiency; (2) New production methods such as hydrogen-based direct reduction (H -DRI), in which location-related factors such as the availability of renewable energies play a key role; (3) Innovative business models such as service packages for continuous process optimisation for long-term efficiency gains.

17 Wirtschaftsvereinigung Stahl (2024).

18 Shawkat, A. et al. (Agora Industrie u. Systemiq) (2023).

Key circular economy technologies in steel recycling

Identification technology for improved separation: Laser-induced plasma spectroscopy (LIBS)

LIBS enables fast, non-destructive inline (i.e. within existing sorting facilities) analysis of the chemical composition of materials, enabling the early identification and segregation of contaminants[19].

In Germany, LIBS offers significant market potential as its use extends far beyond the steel sector[20]. In Germany alone there are almost 950 sorting facilities. A market penetration of 30 percent in the steel sector (currently less than 10 percent) would create a potential of around 250 million euros[21]. Continuous advancements and integration with AI will further boost this potential over the coming years.

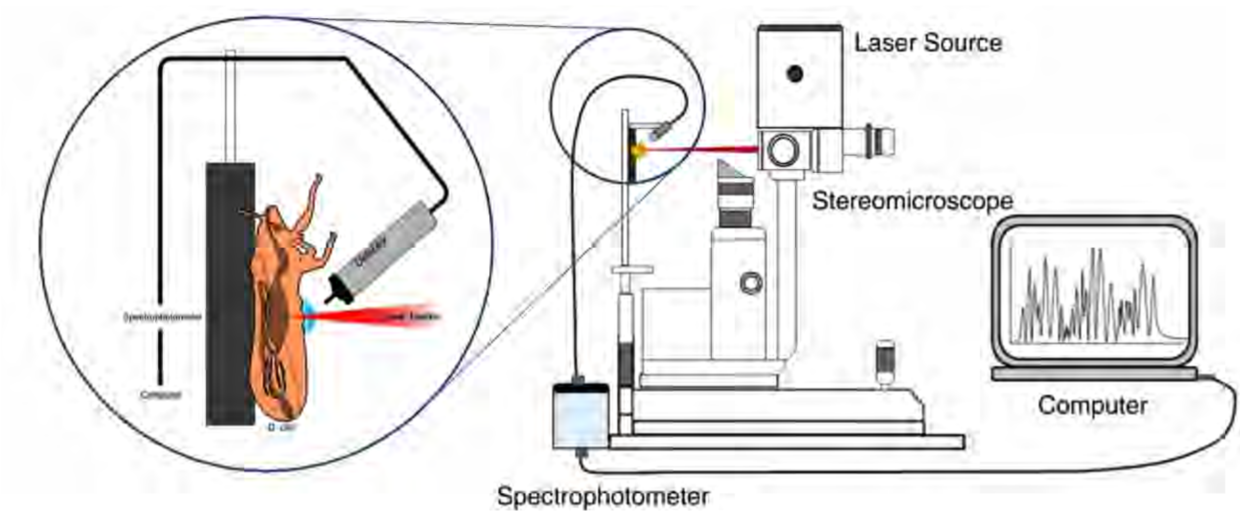


Figure 3: Diagram of laser-induced plasma spectroscopy[22];

19 For example, identification of manganese and other alloy components such as phosphorus, chromium, titanium.

20 Examples include aluminium and battery sorting and the recycling of polymer composites, together with the automotive industry (quality control), aerospace and aviation industries (materials testing), mining and raw materials analysis (ore sorting).

21 Systemiq analysis based on Destatis (2022): Abfallentsorgungsanlagen, available online here.

22 Kiliny N. et al. (2019). Laser-induced breakdown spectroscopy (LIBS) as a novel technique for detecting bacterial infection in insects.

Technology		TRL	R-strategy
Laser-induced breakdown spectroscopy (LIBS)	LIBS uses lasers to generate a plasma cloud. The light emitted is then analysed to determine the material's elemental composition[23]. It can be applied to a broad range of other materials.	**11**	**Recycle**

Global competitive advantages

- The development and use of LIBS technologies reinforces Germany's position as an innovation leader in recycling technologies.
- Improved recycling processes help to secure the supply of raw materials and reduce dependency on imports, both for steel and beyond.
- Access to high purity, locally produced secondary raw materials is a competitive advantage for German industry[24].

Environmental considerations and precautions

- Overall, the environmental benefits such as material savings and reduced emissions outweigh other considerations. Nevertheless, the technology should be used responsibly with due regard for safety aspects (due to the use of laser).

Sample projects

- German company **cleansort GmbH** develops and delivers turnkey laser sorting systems for scrap metal. Since its foundation in 2018 it has installed ten systems, each of which saves around 290,000 megawatt hours of primary energy[25].
- **Fraunhofer Institute for Laser Technology ILT** is developing laser-induced breakdown spectroscopy (LIBS) to precisely identify reusable raw materials in waste streams. It also plans to integrate LIBS with **artificial intelligence (AI)** to optimise data analysis and further enhance the efficiency of recycling processes[26].

Barriers and possible measures

- Barriers to the more widespread use of LIBS technologies, particularly among SMEs, include the following:
  - Lack of personnel with industrial automation training
  - Low level of familiarity with the technology
- Possible measures to promote LIBS might include:
  - Practical project and prototype support to underscore and clearly communicate the potential of this technology for the circular economy
  - Specialist personnel training, for example by integrating innovative technologies more extensively into training programmes
  - Support for companies planning to offer "as a service" models, which could help reduce CAPEX costs and the complexity of installation and maintenance for smaller recycling companies.

23 Fraunhofer IPM (no date). Laser-induced breakdown spectroscopy LIBS, available online here.

24 Ciupek, Martin (2023): Hightech-Sortieranlage identifiziert Metall blitzschnell per Laser. VDI nachrichten (19.05.2023).

25 Cleansort GmbH (2024): Innovationen aus der Lasertechnik für die Industrie, Dr. Markus Kogel-Hollacher (press contact), available online here.

26 Fraunhofer ILT (2024) Lasertechnik und KI beflügeln die Kreislaufwirtschaft.

Separation techniques for copper removal

The ability to manufacture high-quality steel products from recycled material without copper reduces dependency on raw material imports and increases resource efficiency. If copper, as an undesirable by-element, could be separated using innovative methods, more than 70 percent of current steel demand could be met with recycled steel[27]. In Germany, the amount of copper in automotive scrap is constantly increasing (0.2 percent by mass), due to the growth in electromobility[28].

Although current techniques are theoretically capable of separating copper from recycled steel, in practice their potential for scaling is limited by the major technical and economic challenges this entails[29]. Some techniques (such as vacuum degassing and vacuum furnaces) are already used, for example, in high-purity steel sectors (such as aviation and aerospace engineering), but remain unprofitable for the mass market due to their high energy demand (300 to 2,000 kilowatt hours per tonne) and their impact is therefore moderate.

New approaches for better separation are therefore needed. Processes such as leaching in ambient temperature to remove copper impurities are still at an early stage of development, but are considered promising due to their low energy requirements (0 to 20 kilowatt hours per ton) and high efficiency (up to 80 percent).

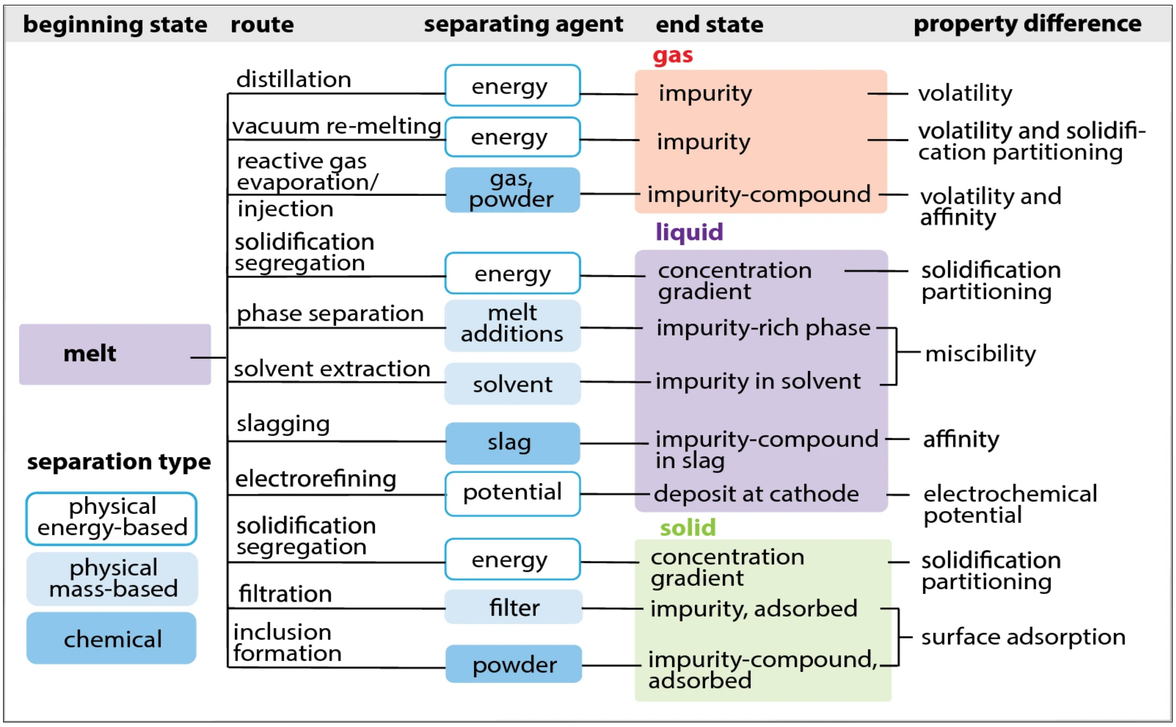


Figure 4: Approaches for removing contaminants from molten scrap steel

27 Shawkat, A. et al. (Agora Industrie u. Systemiq) (2023).

28 Dworak, S. et al. (2023): Stahlrecycling – Potenziale und Herausforderungen für innovatives und nachhaltiges Recycling. Österr. Wasser- und Abfallw. 75, 97–107. https://doi.org/10.1007/s00506-022-00903-3

29 Brahmer-Lohss M. et al. (2023): Nachhaltige Metallwirtschaft Hamburg. Erkenntnisse – Erfahrungen – praktische Erfolge.

Technologies		Effectiveness[30]	Energy demand	TRL
Vacuum degassing	Undesirable elements such as copper and other contaminants evaporate under significantly reduced pressure in a tempering bath.	0–25 % ▼	200–300 kWh/t ▶	**11**
Vacuum arc remelting (VAR) furnace	Metal is remelted in a vacuum, causing contaminants to evaporate or become oxidised.	25–50 % ▶	300–2.000 kWh/t ▼	**11**
Multiple vacuum arc remelting	Multiple remelting in a vacuum further improves the purity of the metal and removes low-volatility elements such as copper more effectively.	50–80 %	300–2.000 kWh/t	**11**
Leaching at ambient temperature	Copper is dissolved using chemical solutions without the need for a high energy input.	50–80 %	0–20 kWh/t	**4-5**

Cost benefits of the technology

- Using recycled scrap steel more effectively reduces the demand for primary raw materials, which in turn minimises energy consumption and carbon emissions, making production more sustainable.

Global competitive advantages

- The ability to manufacture higher-quality steel products from recycled materials reduces dependency on raw material imports and boosts resource efficiency.
- Copper separation techniques would enable steel producers to significantly reduce the copper content in recycled steel, for superior material quality, higher recycling rates and lower reject rates.
- Other environmental considerations and precautions

Environmental considerations and precautions

- Leaching uses chemical solvents which may pollute the environment.

Sample projects

- These copper separation technologies are either still at the research stage or are used in other industries (such as the aviation and aerospace engineering sectors) but not specifically for copper separation in the mass production of recycled steel.

30 Shawkat, A. et al. (Agora Industrie u. Systemiq) (2023).

Barriers and possible measures

- Barriers to the use of copper separation techniques include the following:
  - Energy-efficient methods are some way off technology maturity
  - There are uncertainties regarding the strategic handling of scrap steel at domestic and international level. Germany currently exports scrap steel for lower-quality use (e.g. in civil engineering) because it is difficult to sort. The economic and environmental benefits of using secondary steel more effectively in Germany must be backed up with data.
- Possible measures include:
  - Promoting pilot plants to optimise techniques and advance market maturitylangen
  - Incentivising circular design, i.e. less contamination of steel with copper and other substances, e.g. through extended manufacturer responsibility, for example by adopting a deposit system.

Key: ▲ Strong benefit, ▶ Medium benefit, ▼Minimal benefit or disadvantage

Manufacturing green steel with H_2-DRI-EAF

Figure 5: Electric arc furnace (EAF) (photos are for illustrative purposes only and are not indicative of support for specific companies or locations); © SMS group GmbH

Electric arc furnaces (EAF) enable almost zero-emission steel production (assuming the use of renewable electricity), from up to 100 percent scrap. When combined with hydrogen-based direct iron ore reduction (H_2-DRI), primary steel production can be almost carbon-free, for a climate-friendly alternative to the furnace route. The production processes reduce demand for water and fossil fuels, boost resource efficiency and reduce emissions by up to 94 percent versus the furnace route[31].

Existing EAFs in Germany have reached their capacity limits and further expansion is needed. Germany's scrap volumes are set to increase from 19 to 25 million tonnes by 2040. Using high-quality scrap would require a doubling of the existing EAF systems in Germany[32, 33]. Any capacity expansion will need to allow for location-related factors.

Technology		TRL	R-strategy
H_2-DRI	Iron ore is reduced to sponge iron (DRI) using green hydrogen (H_2) instead of carbon, which produces water instead of CO_2. The process is dependent on high-quality ore and the price of hydrogen.	**8**	**Reduce**[34]
EAF	Scrap steel and DRI are smelted using powerful light arcs to produce crude steel[35].	**11**	**Reduce/ Recycle**

Operating cost benefits of the technology

- As carbon prices rise, H_2-DRI-EAF could achieve OPEX parity with the furnace route by 2030.

Global competitive advantages

- A stronger domestic steel industry:
  - Although other EU countries manufacture steel (input) products[36], Germany's growing demand for low-emission steel makes domestic production advantageous, as well as creating local jobs[37].
  - A strong scrap economy helps to safeguard access to competitive, low-carbon steel for sectors such as the automotive industry, machine production and construction[38].
- Raw material security and flexibility:
  - EAF supports a flexible mixture of scrap, crude iron and DRI to respond dynamically to raw material prices and availabilities.

31 Oliver Wyman, IW Consult on behalf of the German Steel Association (Wirtschaftsvereinigung Stahl) (2024): Die Stahlindustrie am Scheidepunkt. Wegbereiter für Transformation und gesamtwirtschaftliche Resilienz, available online here.

32 Systemiq analysis based on the publication by the German Steel Association (Wirtschaftsvereinigung Stahl) (2024).

33 Piégsa, A. et al. (Wuppertal Institut and Prognos) (2022): Gutachten: Optionen für eine klimaneutrale und nachhaltige Grundstoffindustrie in Deutschland.

34 Only reduces emissions, not primary production.

35 Piégsa, A. et al. (Wuppertal Institut und Prognos) (2022)

36 In the green steel value chain, DRI may be compacted into hot briquetted iron (HBI) for easier transportation.

37 Verpoort et al. (2024): Report: Transformation der energieintensiven Industrie – Wettbewerbsfähigkeit durch strukturelle Anpassung und grüne Importe, available onliner here.

38 Wirtschaftsvereinigung Stahl (2024).

Environmental considerations and precautions

- The high energy demand must be met from renewable sources.
- Requires the efficient use of process waste (e.g. EAF dust produced from smelting steel scrap) (by contrast, the furnace route produces toxic gases)[39].

Illustrative sample projects

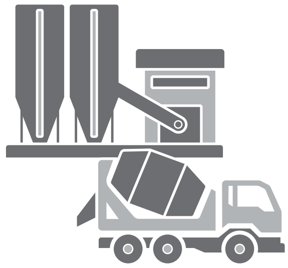
- **Stahl-Holding-Saar (SHS):** As part of the Power4Steel initiative, SHS plans to build one of the world's most powerful electric arc furnaces on a dedicated brownfield site with a connected load of 300 MVA[40] by 2028. It will process a flexible mixture of up to 100 percent scrap or 80 percent cold sponge iron/hot briquetted iron and 20 percent scrap[41,42].
- **SMS group:** The SMS group specialises in technologies for the efficient, grid-friendly operation of EAFs. The new 190-tonne EAF from SSAB should allow the SMS group to stabilise high demand for electricity, prevent grid anomalies and achieve optimum control of energy consumption[43]
- **Salzgitter:** SALCOS® steel is produced via two routes: the new DRI-EAF route (from 2026) and the established EAF route at Peiner Träger, which uses 100 percent high-quality recycled scrap steel and green electricity. Even though it is derived from 100 percent scrap, the steel meets the required level of purity for use in the automotive industry.

Barriers and possible measures

- The principal barriers to the expansion of EAF capacity in Germany or the EU are:
  - The future of steel production in Germany – or even Europe – due to energy prices[44] is also unclear in Germany due to the lack of a resilient industry strategy. The advantages of a domestic, sustainable steel industry are important for resilience. The demand for steel cannot be answered definitely.
  - As exporting high-quality scrap is financially attractive (25 percent from Germany[45]), this is currently impacting domestic availability.
  - Domestic demand for high-quality recycled steel remains limited, partly due to a lack of clarity over the minimum steel quality required for vehicle manufacturing and machinery production.
- Key measures include:
  - A targeted German and European analysis of the prospective strategic/economic benefits of domestic scrap processing (it is currently more expensive to process scrap than it is to purchase new raw materials) versus export[46]
  - Based on this, a location-specific strategy for expanding EAF.
  - Political (regulatory and market-based) incentives to increase the use of scrap (in-depth analysis will be needed to gauge the effect of combined instruments):
    - Imposing limits on embodied carbon content
    - Regulation of scrap exports[47]
    - Minimum recycling rate requirements.

39 Deutsche Rohstoffagentur (2024): Factsheet Eisen, available online here.
40 MVA = Megavolt-ampere.
41 Stahleisen.de (14.10.2024): Leistungsstarker Elektrolichtbogenofen für die Stahl-Holding Saar, available online here.
42 The production of DRI in Germany and in other (European) countries is conceivable, depending on renewable energy costs.
43 SMS group (26.11.2024): SMS group und SSAB treiben gemeinsam grüne Stahlrevolution an, available online here.
44 Verpoort, P. C. et al. (2024): Transformation der energieintensiven Industrie – Wettbewerbsfähigkeit durch strukturelle Anpassung und grüne Importe, available online here.
45 Shawkat, A. et al. (Agora Industrie u. Systemiq) (2023).
46 Leitner, M. (24.9.2024): Stahlrecycling: Herausforderungen und Lösungen. Wissenschaftsforum Circular Economy, available online here.
47 Wirtschaftsvereinigung Stahl (2024): Stellungnahme zum Clean Industrial Deal, available online here.

2. The circular economy and the cement industry: Principal levers, environmental potential and technologies



Circular technology segments and their potential

The cement and concrete sectors produce some 20 million tonnes of Co_2e, equivalent to 2.5 percent of total national emissions[48], around two-thirds of which originate from raw material-related processes, and the remaining one-third from fuel emissions associated with the high heat demand. 88 percent of concrete emissions are from clinker and can be reduced by CCU/S and substitute materials[49]. Cement production remains anchored in Germany due to its local orientation and minimal trade flows. Efforts to reduce emissions should therefore target the domestic level.

Levers for a circular economy can and should be utilised at every stage of the value chain, parallel to electrification and CCU/S. While electric rotary furnaces can reduce fuel emissions, they do so only very slowly, and do not eliminate the process-related emissions from limestone neutralisation. Overall, circular economy levers have the potential to eliminate more than 65 percent of cement emissions (equivalent to around 13 million tonnes of Co_2e) by 2045 compared with business-as-usual (BAU), while electrification and carbon capture, use and storage (CCUS) would only reduce them by around 30 percent. Principal levers here include the optimised, alternative use of materials plus increased material efficiency.

- Material efficiency gains with concrete use include modular construction methods, intelligent design and smart construction processes, with a maximum emission reduction potential of 35 percent[50].

- Optimised, alternative materials can be used in construction and in concrete manufacturing itself, in the form of alternative binding agents (supplementary cementitious materials (SCMs)), recycled cement, concrete additives or new recipes. This lever has the potential to cut emissions by up to 30 percent[51].

It is therefore particularly important, both from an environmental perspective and for financial reasons, to promote and research technologies targeting material efficiency in construction and substitution in concrete production. Market analysis suggests that the following technologies offer extensive potential for cost-effective use and emission reduction in Germany:

- Material efficiency using lean prefabricated construction parts, combined with digital efficiency optimisation.

- The use of calcined clay[52] as an alternative material to reduce the use of cement clinker and cut emissions.

48 Verein Deutscher Zementwerke e.V. (2023): Klimaschutz, available online here.

49 Mission Possible Partnership (2023): MAKING NET-ZERO CONCRETE AND CEMENT POSSIBLE. An industry-backed, 1.5°C-aligned transition strategy, available online here.

50 Shawkat, A. et al. (Agora Industrie u. Systemiq) (2023).

51 Shawkat, A. et al. (Agora Industrie u. Systemiq) (2023).

52 A combination of calcined clay and limestone fines may also be used .

Combining prefabricated parts / prefabrication / prefabricated units with digital measures to optimise efficiency

Figure 6: Hybrid, efficient, digitally optimised construction using prefabricated parts[53]; © GROPYUS AG

Material-efficient design and prefabricated modules could reduce material use in the European construction sector by 250 million tonnes, leading to a significant reduction in carbon emissions[54]. Prefabricated construction is not automatically more material-efficient than traditional construction methods, but more reliable optimisation is achievable with digital planning, in particular.

Using precast elements facilitates greater standardisation, speeds up the construction process, and reduces costs by up to 20 percent[55].

A combination of prefabricated parts and digital solutions such as "building information modelling" could help Germany to reach its annual target of 400,000 new homes, despite a limited workforce.

53 O. V. (2024): GROPYUS secures €100M (AU$167M) for sustainable modular housing development. BUILT OFFSITE (11.10.2024), available online here.

54 Ellen MacArthur Foundation (2024): Building prosperity, available online here.

55 Ibid.

While modular construction in Germany has previously been confined to smaller buildings, such as detached houses and offices, there is a growing potential for larger-scale apartment blocks. Modular construction currently accounts for around five percent of the market, but under the right framework conditions it offers major potential. In Sweden, for example, it accounts for 60 percent[56].

Technology		TRL	R-strategy
Prefabrication	Prefabrication is the assembly of structural elements (from minerals or timber) in a controlled off-site environment e.g. using 3D printing or robotics. The preassembled structure is then transported to the construction site and completed on-site, reducing local dust and noise pollution[57]. As an additional benefit, depending on the concept, selected modules may be removed and reused at some point in the future. Modular construction systems are a sub-category of prefabrication.	**9**	**Reduce**
BIM	Building Information Modelling (BIM) is a digital technique for the planning, construction and administration of buildings and infrastructures. It assists with industrial prefabrication.	**9**	**Reduce**

Cost benefits of the technology

- Reduces material procurement and installation costs by up to 50 percent compared with traditional building methods. The cost of construction materials such as steel reinforcing bars has risen by 42 percent over the last three years, and material-saving methods are therefore financially advantageous[58].
- Significantly shorter construction times
- Prefabricated parts are designed to fit perfectly together and are therefore more precise than on-site construction with its dependency on the weather.

Other economic benefits

- Germany's wealth is being impacted by the housing crisis. The demand for new builds across Germany is estimated at a minimum of 330,000 units per annum between now and 2030, and progress is slow. Efficient construction could offer a faster solution to the housing shortage.
- The cost of construction materials has risen by around 90 percent since 2000[59]. More efficient construction methods are crucial for economic resilience and productivity.

56 Deutscher Bundestag (2023): Sachstand Serielles und modulares Bauen im Gebäudesektor, available online here.

57 IEA (2024): ETP Clean Energy Technology Guide, available online here.

58 Bauindustrie (no date): Bauwirtschaft im Zahlenbild, available online here.

59 Trading Economics (2024): Germany - construction cost index, available online here. Statista (2025): Construction price index in Germany from 2015 to 2024, by type, available online here.

Environmental considerations and precautions

- Prefabrication is not always more sustainable or efficient. Manufacturers must be carefully selected.
- Building Information Modelling (BIM), like any sophisticated, AI-assisted digital technology, consumes vast quantities of electricity which must be sourced from renewables; using this much energy is only worthwhile if the potential savings are significant (otherwise, efficient low-tech construction methods are considered preferable).
- With sustainable production and usage volumes as a part of regenerative forest management, the more extensive use of timber can offer major benefits. At the same time, unregulated procurement can also harm ecosystems. Further studies are needed to determine the maximum availability of regenerative timber in Germany and Europe.

Sample projects

- **Bau-Fritz:** This Bavarian company delivers prefabricated timber construction systems made from local spruce. Its target is to achieve net carbon savings of around 21,000 tonnes per annum through its projects. The company's founder was awarded the German Environmental Award (Deutscher Umweltpreis) in 2023[60].
- **Polycare:** SEMBLA® is a modular construction system based on cement-free geopolymer concrete (GPC). The standardised hollow blocks fit together without mortar, making them reusable, flexibly modifiable and fast to assemble. By eliminating cement, the system reduces carbon emissions by up to 70 percent and supports the circular economy in the construction sector[61].
- **CREE:** This Austrian start-up has developed an innovative timber hybrid prefabrication system for flexible construction which reduces grey emissions[62] by up to 50 percent and boosts material efficiency through standardisation. Its showcase projects include the "EDGE Sued-kreuz" office building in Berlin (29 metres, eight storeys) and "LCT ONE" in Dornbirn (27 metres, eight storeys).

60 Deutsche Bundesregierung (2023): Auszeichnung für Klimaforscherin und Holzbau-Pionierin, available online here.

61 Padalkina, D. et al. (DENA) (2023): Kreislaufwirtschaft im Bauwesen, available online here.

62 Grey emissions are the carbon emissions produced throughout a construction material's or building's lifecycle but which do not originate directly from operation of the building.

Barriers & possible measures

- The main barriers to the more widespread use of copper separation techniques are:
  - Smaller and individual developers tend to be influenced by outdated models and are hampered by misconceptions that prefabrication is inflexible and not aesthetically pleasing.
  - Larger investors are reluctant to become dependent on a limited number of suppliers due to concerns about pricing and delivery bottlenecks.
  - Investors are also put off by the prefabrication timeline, mistakenly believing they must commit to a particular model early in the construction phase, with minimal scope for modifications. Many of these ideas are outdated.
  - Prefabrication requires large-scale industrial production plant and stable capacity utilisation, which can prove difficult in the highly cyclical real estate development market.
- Possible measures include:
  - Embodied carbon limits could be used to encourage climate-friendly prefabrication.
  - A targeted national and European-wide study focussing on new industry and competitive strategies should address misconceptions about flexibility and risks.
  - Public procurement should stimulate demand and encourage more stable capacity utilisation for industrial manufacturing plant by adopting a pioneering role and showcasing the options available to private industry.

Manufacture and use of calcined clay

Figure 7: Inauguration of the flash calciner plant in Weimar; © IAB Weimar gGmbH

Supplementary cementitious materials (SCMs) help to cut emissions and reduce demand for primary raw materials. As 96 percent of SCMs in Germany originate from and are returned to the furnace route, new alternatives are needed. Calcined clay is a clinker substitute and can significantly reduce carbon emissions by up to 65 percent compared with clinker[63] because the process occurs at significantly lower temperatures and the raw materials contain no or significantly less CO_2. Calcined clay is plentifully available in selected regions of Germany and therefore minimises dependency on raw materials compared with the alternatives, while also supporting more sustainable cement production.

Under optimum market conditions, up to 50 percent (around ten million tonnes) of Germany's annual clinker production of around 20 million tonnes[64] could be replaced with calcined clay as a clinker substitute. However, this is heavily dependent on the regulatory framework conditions, investment levels and the future transformation of the cement industry.

Technology		TRL	R-strategy
Calcined clay	Calcined clay is produced by heating clay minerals such as kaolinite to around 700-900°C. This process, known as calcination, transforms the structure of the clay to give it pozzolanic properties, enabling it to be used as a substitute for cement clinker in certain types of concrete manufacturing.	**9**	**Reduce**
Cost benefits of the technology ▶ The raw materials for calcined clay (costing between five and 20 dollars per tonne) are cheaper than other additives (slack is around 40 to 55 dollars per tonne, fly ash between 15 and 30 dollars per tonne)[65].			
Internationale Wettbewerbsvorteile ▶ Global availability of calcined clay is around 6,000 metric tonnes per annum, compared with less than 1,000 metric tonnes per annum for fly ash and slag. Germany (which is potentially facing limited availability in future) could reduce its dependency on exports by using local products and thereby make itself more resilient to market fluctuations[66]. ▶ By acting swiftly and forging strategic partnerships for calcined clay, Germany could strengthen its raw material security, benefit from existing trade relationships and position itself in a growing market for clinker substitutes. ▶ The growing use of clinker substitutes is more labour-intensive than conventional cement and could partially compensate for the job losses associated with carbon capture (resulting from cement's transition path) and falling production volumes[67].			

63 Padalkina, D. et al. (DENA) (2023).

64 Verband Deutscher Zementindustrie. Klinkereffiziente Zemente – ein wichtiger Baustein auf dem Weg zur Dekarbonisierung von Zement und Beton: Schritte zur weiteren Reduzierung des Klinker/Zement-Faktors, available online here.

65 ChemAnalyst (Q3 2024); GGBFS Price Trend and Forecast, available online here. ChemAnalyst (Q3 2024): Fly Ash Price Trend and Forecast, available online here. GCCA (2024); Global Blast Furnace Tracker (2024); IEA (2024); Scrivener (2019); UNEP (2016).

66 Maier M. and Univ.-Prof. Dr.-Ing. K.-Ch. Thienel (no date): Calcinierte Tone als Zementersatzstoff (SCM) im Mastermodul "Vertiefte Kapitel Anorganische Bindemittel und Betontechnologie", available online here.

67 Wuppertal Institut (2022): Studie "Dekarbonisierung der industriellen Produktion (DekarbInd) – Teilbericht 3: Bewertung von Dekar-bonisierungsmaßnahmen und Erarbeitung von Eckpunkten einer Roadmap für die Zementindustrie", available online here.

Environmental considerations and precautions

- Compared with other SCMs, calcined clay has a higher water requirement (between 40 and 70 percent) than fly ash (24 percent)[68].

Sample projects

- In 2024, the **Weimar Institute of Applied Construction Research (*Institut für Angewandte Bauforschung Weimer*, IAB)** launched the world's first pilot project for efficient clay calcination in a low-oxygen atmosphere, known as the flash calciner. One key feature of this technology is its colour control which prevents the typical red colouring, making it more suitable for use in concrete[69].
- **Thyssenkrupp** has developed the "polysius® activated clay" technology, which allows up to 30 percent of cement clinker to be replaced with calcined clay, cutting process-related carbon emissions by up to 40 percent. The Cameroon plant of CIMPOR Global Holdings, which has cut carbon emissions by more than 120,000 tonnes per annum[70], is one example where this technology has been applied.
- Berlin start-up **alcemy** develops AI software to precisely control the quality of calcined clay as a cement substitute, enabling carbon reductions of up to 65 percent. A low-carbon cement with a reduced clinker proportion has already been commercially produced in collaboration with alcemy[71].

Barriers & possible measures

- The principal barriers to the more widespread use of calcined clay as a clinker substitute are:
  - A lack of experience in industry and in the construction sector with new cement mixtures
  - High building licence standards and regulations (the admissible ratio of clinker in cement must not exceed 44 percent). Other key regulatory hurdles include existing standards such as DIN EN 1971 and the Construction Products Ordinance (BauPVO), which are traditionally based around the composition of Portland cement.
  - Conservative interpretations of construction standards (such as Eurocode 2)
  - Lack of long-term data and lengthy approval procedures
- Various measures are conceivable:
  - Industry alliances to promote knowledge-sharing between suppliers, construction companies and ready-mix companies
  - Digital quality assurance systems to alleviate doubts about new cement mixtures, either private (e.g. operated by industry associations) or government-run
  - Modification of standards to increase the proportion of SCMs, nationally, regionally and at European level
  - The introduction of Embodied Carbon Limits

68 Ibid.
69 Institut für Angewandte Bauforschung Weimar gGmbH (no date), available online here.
70 ThyssenKrupp (no date): Zementproduktion: Kalzinierter Ton senkt CO_2-Fußabdruck deutlich, available online here.
71 Alcemy GmbH (no date): Company website

3. The circular economy and the chemicals industry: Principal levers, environmental potential and technologies

Circular technology segments and their potential

The chemicals industry has an extremely high energy demand. In 2021 it accounted for around four percent of Germany's carbon emissions[72], and its final energy consumption equates to around one-quarter of industry's total energy demand, making it the most energy-intensive sector in Germany[73].

The sector faces economic pressure from rising energy prices, carbon reduction targets under the German Climate Action Act (*Klimaschutzgesetz*)[74] and other legislation, as well as its dependency on fossil-based raw materials. At the same time, the growing demand for sustainable chemical products worldwide offers attractive growth potential which could be seen as an opportunity for change.

A climate-neutral chemicals industry by 2045, as called for in the Federal Climate Action Act, requires both the electrification of energy consumption (particularly in the heating supply segment) and circular economy technologies. The more efficient use of materials, better-quality plastics recycling and the use of renewable carbon sources could make the industry less dependent on fossil raw materials[75].

Around 20 percent of the energy and raw materials consumed by the chemicals sector is attributable to plastic packaging production alone, making this the largest demand segment after basic chemicals. Measures to reduce, increase durability, reuse and recycle are therefore particularly urgently needed[76]. Reusable and returnable packaging models could therefore be the most effective lever for reducing demand[77].

- The circular economy in this sector needs systemic measures, especially in consumer sectors such as food retail, e.g. in the form of bulk products or reusable packaging. At the same time, however, technology must be deployed more effectively, because even a scenario with reduced packaging volumes will still produce significant quantities of plastic waste. A well-functioning sorting and recycling technology is therefore crucial.

72 UBA (2024): Strukturdaten: Chemikalien und chemisch-pharmazeutische Industrie, available online here.

73 Ibid.

74 Sector target for German industry: Reduce Co$_2$e to a max. of 118 million tonnes by 2030; the overarching target is GHG neutrality by 2045

75 BDI (2024): Transformationspfade für das Industrieland Deutschland, available online here.

76 BUND (Federal Government) (2023): Deutsche Chemieindustrie größter fossiler Rohstoffverbraucher und Treiber der Plastikkrise, available online here here.

77 Systemiq analysis on behalf of the Energy Transitions Commission (2025): Publication pending.

- Within the plastic value chains for packaging, buildings and vehicles, circular economy technologies could reduce emissions by between 40 and 60 percent by 2045 compared with 2020 levels[78]. Among these technologies, plastic recycling offers exceptional decarbonisation potential, since the bulk of carbon emissions are emitted during the incineration of plastics at the end of their useful life.

As not all chemical value chains can achieve efficiency and climate-friendliness through reduce and reuse strategies, additional renewable and circular sources of carbon will need to replace the remaining fossil raw materials in the chemicals industry[79, 80], particularly for essential basic chemicals such as high-value chemicals (HVC)[81]. Three core challenges will need to be addressed:

- Availability of sustainable raw materials: Biogenic carbon sources are limited and should only be used under strict sustainability criteria to minimise environmental impacts and competition for land.

- Technological feasibility: Carbon Capture and Utilization (CCU) enables the use of carbon and (unlike other raw material uses) may be considered a circular technology. However, the technology is highly energy-intensive and not yet economically scalable. It should only be used very selectively in situations where other solutions will not work.

- Political and economic framework conditions: Despite the extensive emission reduction potential, we lack the regulatory guidelines to allow reliable upscaling of these technologies for the most relevant and justified applications.

There is a need for research, targeted investments and political measures to make central technologies economically viable, enable the sustainable transformation of the chemicals industry and preserve one of Germany's major employers and key value creation sectors.

78 Shawkat, A. et al. (Agora Industrie & Systemiq) (2023); cumulatively, reducing additives, minimising new polymer types, improving product separability and achieving maximum separation and sorting could potentially increase mechanical plastic recycling levels within the value chains for buildings, vehicles and packaging to around 42%. This equates to a twelve percent reduction in greenhouse gas emissions by 2045.

79 Shawkat, A. et al. (Agora Industrie u. Systemiq) (2023).

80 Alternative sources of carbon for chemicals manufacturing include biogenic CO (long-term limitations), direct air capture (DAC) technologies for separation from the air (costly) and separation from industrial waste gases (long-term limitations). These offer potential for the chemicals, shipping and aviation sectors.

81 The green methanol route, the green naphtha route and electrochemical processes are all worth considering for the sustainable production of HVCs (aromatics and olefins), although the latter have low TRLs.

Four specific technologies have the potential to drive key circular economy levers and boost competitiveness for a climate-friendly German chemicals industry:

1. Internet-of-Things (IoT)-assisted systems to optimise reusable packaging
2. Smart sorting processes to improve mechanical plastic recycling and supply non-fossil secondary raw materials
3. Chemical plastic recycling to complement mechanical recycling and supply non-fossil secondary raw materials where there is no alternative material flow available
4. Reprocessing of methanol from catalytic hydrogenation processes as a starting material for platform chemicals

Key circular economy technologies

Reuse systems: IoT-assisted packaging systems

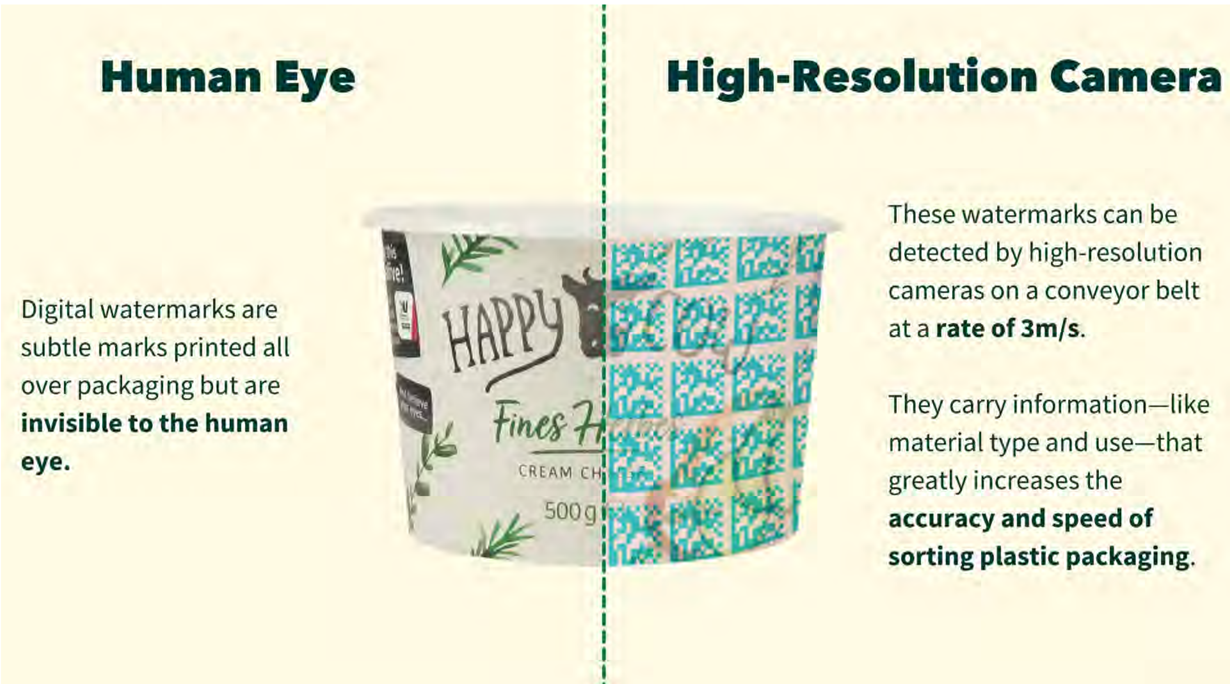


Figure 8: Digital watermark for smart packaging[82]; © AIM, European Brands Association, and Alliance to End Plastic Waste

82 IQPAK® is an innovative packaging system developed in collaboration with Fraunhofer LBF which adopts a minimal-material approach combining single-use and reusable components and incorporates the digital product passport. Picture credits: Fraunhofer LBF.

Reuse models have the potential to reduce global demand for chemicals among key plastic value chains – particularly packaging, but also textiles and automotive – by between 12 and 20% by 2050[83].

Digital technologies like the Internet of Things (IoT)[84] can aid the upscaling of reuse systems with real-time tracking (reduced losses, optimised return), status monitoring (sensor data for quality assurance), process automation (e.g. cleaning, return via digital tools) and user incentives (digital deposit systems, apps for returns).

Across all industries and applications, the future global market for IoT technologies is valued at an estimated 0.8 billion euros by 2030[85].

Technology		TRL	R-strategy
IoT-assisted packaging systems	▸ Data for real-time tracking, use and status monitoring of reusable packaging systems is collated using technologies such as RFID, GPS, Near Field Communication (NFC), digital water-marks[86], QR codes and sensors ▸ Data supply and (AI-assisted) analysis on IoT data platforms and/or apps	**9–11[87]**	**Reuse**

Cost benefits of the technology

- Reduces the cost of reuse systems by digitising and streamlining processes (e.g. logistics and deposit management, cleaning, returns) and by extending the service life of products within the system. If upscaled, it has the potential to be cheaper than single-use packaging[88].
- Potentially reduces EPR (Extended Producer Responsibility) costs[89] for companies, because reuse solutions are EPR-exempt. For example, by converting 20 percent of its packaging to reusable, assuming an average EPR cost of €0.50 per kilogram, a company that places around 1,000 tonnes of single-use plastic packaging on the German market each year could save €100,000 per annum in EPR charges (we still need to analyse the extent to which these savings outweigh the cost of using the IoT).

83 Systemiq analysis on behalf of the Energy Transition Commission (publication pending).
84 Networking and digitalisation of objects for data exchange and analysis..
85 BDI (2024): Transformationspfade für das Industrieland Deutschland, available online here.
86 Digital watermarks are machine-readable codes embedded in packaging materials that are identified by optical scanners or cameras and enable greater sorting accuracy in the recycling process or improved product tracking.
87 While GPS, RFID and NFC are already in broad commercial use, parallel to this, cloud-based IoT platforms are still in the process of standardisation across downstream value chains.
88 Systemiq analysis on behalf of the Energy Transition Commission (publication pending).
89 EPR (Extended Producer Responsibility) is the obligation for manufacturers and distributors of packaging to bear the cost of collecting, sorting and recycling their products.

Global competitive advantages

- Supports the upscaling of reuse systems and associated infrastructure (including cleaning, logistics), which creates jobs at every stage of the reuse/value chain and aids the establishment of a future reuse market in Germany and Europe.
- Reusable systems make us less dependent on fossil raw materials (such as naphtha).

Environmental considerations and precautions

- Usage efficiency: The environmental benefits of reusable containers do not kick in until there are large numbers of them in circulation.
- Transport emissions: The environmental benefits are limited by long transport routes and low return rates. Optimised logistics are essential.
- Energy consumption: Digitalisation and cleaning systems must run on renewable energy.
- Design and operation: Standardised pool containers, minimal single-use elements, efficient cleaning, short transport routes and high levels of recyclability are all crucial.

Sample projects

- **VYTAL** tracks its food takeout boxes with QR codes and RFID chips and is testing smart technologies for their cleaning and return. The start-up operates with thousands of restaurants and canteens in more than 17 countries. In July 2024, it was awarded six million euros of funding to expand its digital solutions[90].
- **Algramo** provides refillable containers with RFID or NFC chips for household products in Chile and the USA. An app allows users to track refills and the amount of packaging waste saved. The company collaborates with Unilever and others.
- **HolyGrail 2.0** is a European initiative to improve the sorting of packaging waste by using digital watermarks. Some 160 companies and organisations are on board, including TOMRA, Procter & Gamble, Nestlé, Unilever, Henkel, Greiner Packaging, Mondi, Tetra Pak and BASF.

Barriers & possible measures

- Two major barriers to the widespread use of digitally assisted packaging systems are:
  - The lack of clarity regarding the cost of reuse systems, because they have yet to be deployed on a large scale.
  - Single-use plastic is often cheaper. However, higher recycling fees, carbon taxes or statutory requirements could balance out the price difference.
- Possible measures:
  - Companies could collaborate more extensively to introduce reusable systems across the board and make them cheaper.
  - A carbon tax would make single-use packaging more expensive and incentivise investments in reusable systems.

90 Packaging Europe (2024): Vytal directs €6 million in funding into data-driven reusables at events venues, available online here.

Smart sorting techniques to improve mechanical recycling

Figure 9: Example of a modern sorting system combining colour and hyperspectral near-infrared sensors (HSI-NIR) [91]; © REMONDIS

Mechanical recycling is significantly more energy-, material- and cost-efficient than chemical recycling and virtually emission-free. Maximising the use of mechanical recycling should therefore be clearly prioritised over chemical recycling to boost plastic recycling rates. Other environmental regulations and carbon taxes would help make it more competitive than fossil-based plastics[92].

Mechanical recycling has the second-greatest potential to reduce primary carbon demand, after CCU technologies. Higher sorting rates are crucial for boosting the recycling yield and further enhancing the overall potential of mechanical recycling[93].

The expansion of mechanical recycling relies on improved sorting technologies. With its well-established waste collection and sorting systems, Germany has excellent access to high-quality raw materials, and more advanced material identification and sorting techniques could boost the recycling potential by a further 25 percent[94].

91 Picture credits: F&S Journal (2023), available online here.
92 Shawkat, A. et al. (Agora Industrie u. Systemiq) (2023).
93 Systemiq-Analyse für die Energy Transition Commission (Publikation fortfolgend).
94 Ibid.

Technology variant		TRL	R-strategy
Electrostatic separation	Applies a selective charge to plastics depending on their composition and separates them using electric fields.	**8–10**	**Recycle**
Near-infrared (NIR) sorting systems	Identify different plastic types according to their unique spectral signature.	**9**	**Recycle (identification)**
AI-based and robot-assisted sorting systems	Use machine learning, cameras/sensors and visual detection and sorting of plastics based on their colour, shape and polymer type.	**8–9**	**Recycle (identification & separation)**
Sink-float sorting systems	Separate plastics in water or salt solutions according to their density - for example, PET sinks while PE and PP float.	**11**	**Recycle (identification & separation)**

Cost benefits of the technology

- Reduces dependency on fossil primary resources and could therefore potentially help keep recycled plastic prices stable.
- Mechanical systems are significantly cheaper than chemical recycling systems, partly due to simpler processes and lower energy intensity.

Global competitive advantages

- Digital sorting technologies enable a more cost-efficient, scalable recycling infrastructure and can also create new jobs at every stage of the recycling value chain.
- Germany and Europe are global market leaders for mechanical recycling solutions and machines. Better sorting technology could further enhance the export potential of this expertise.

Environmental considerations and precautions

- Because mechanical recycling shortens the polymer structure and allows contaminants to accumulate, the number of reuses and circular potential are limited[95].
- Reduced material properties may limit the functionality of recycled plastics, making them less suitable for high-quality applications and potentially leading to an increased use of resources due to additional material mixtures or new production.
- Mechanical recycling systems may produce microplastics during recycling operations such as the shredding, grinding and granulating of plastics[96].
- On the other hand, digitalised sorting systems have a negligible energy demand compared with their potential greenhouse gas savings.

95 Uekert et al. (2023): Technical, Economic, and Environmental Comparison of Closed-Loop Recycling Technologies for Common Plastics. ACS Sustainable Chemistry & Engineering, 11: 965-978.

96 Suzuki, G. et al. (2024): 2024: Global Discharge of Microplastics from Mechanical Recycling of Plastic Waste. Environmental Pollution, 348

Sample projects

- **Interzero** uses near-infrared (NIR) sorting with AI and sensor technology to boost sorting accuracy in five plants processing more than 800,000 cubic meters of lightweight packaging per annum – equivalent to around one-third of Germany's waste in this category.
- **Greyparrot** incorporates AI-based real-time waste analysis into sorting systems to improve recycling efficiency. It boasts more than 4,000 installations worldwide, including a partnership with Bolle-graaf. Operations are centred around Europe plus its first branch in North America.
- **AMP Robotics** uses AI-based real-time waste analysis with robot-assisted sorting to boost the efficiency of recycling plants. With more than 300 installations worldwide, the focus is on North America, but EU expansion is forging ahead via a partnership with REP-TEC and its own teams.

Barriers & measures

- Several barriers inhibit the upscaling of sorting technologies:
  - At present, the output from mechanical recycling is not competitively priced compared with new fossil-based plastic.
  - Investments in new sorting technologies are limited, hampering advancements in upscaling and price reduction.
- Possible measures to foster competitiveness and stimulate investments include the following:
  - Increase the carbon tax
  - Impose more ambitious recycling quotas
  - CAPEX incentives – possibly within the framework of the EU Clean Industrial Deal or industry loans e.g. from the KfW Development Bank or European Investment Bank (EIB)[97].

97 Given the high technological maturity of waste identification and sorting technologies, existing optimisation potential is likely to be leveraged within the context of greater investment (e.g. increasing the number of identified materials and improved speed and accuracy of identification).

Chemical recycling:
A niche solution for specific use cases

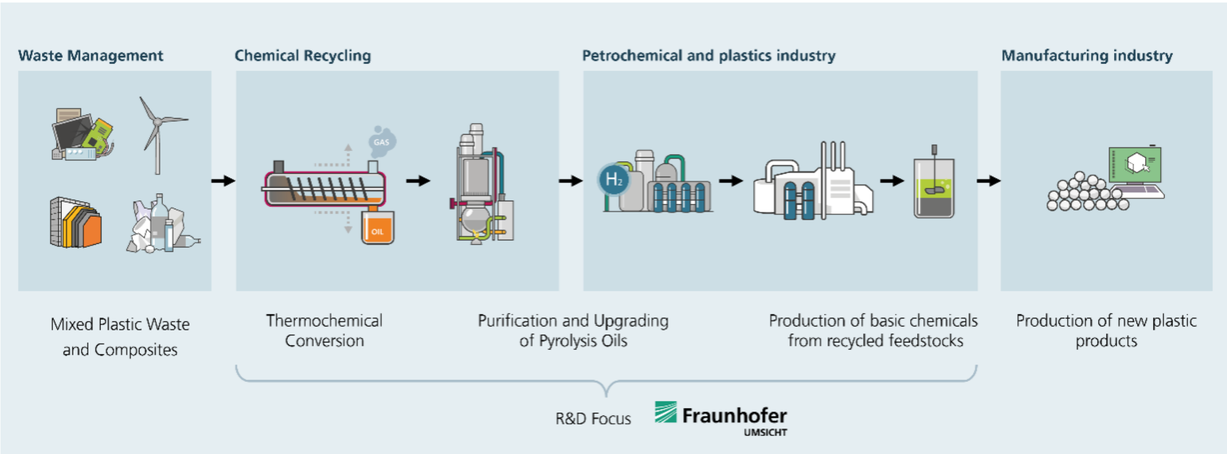


Figure 10: Chemical recycling[98]; *© Fraunhofer Institute for Environmental Safety and Energy Technology UMSICHT*

Chemical recycling decomposes plastics into monomers or basic chemicals and facilitates the reuse of heterogeneous or contaminated waste (such as textiles)4[99, 100].

The application areas, efficiency levels and environmental influences vary considerably depending on the process. Differences in reusable plastics, raw material requirements, emissions and energy input necessitate an in-depth analysis of the environmental impacts[101].

High costs, energy consumption and mass losses limit the use of chemical recycling to plastic waste streams that are either difficult to recycle, multi-material or very small, primarily in the textiles, construction, automotive and electronics sectors[102].

The chemicals industry and other sectors under significant pressure to adopt decarbonisation strategies could benefit from chemical recycling, provided a comprehensive environmental assessment justifies their use.

98 Picture credits: Fraunhofer UMSICHT (no date), available online here.

99 As well as plastic-to-plastic recycling processes, there are also chemical recycling processes that produce fuel. However, most regulatory and industry standards (such as EU Directive 2008/98/EC or ISO 18604:2013) do not class this as recycling and it is therefore not included when calculating recycling rates, because plastics do not remain in the materials cycle.

100 Following initial variations in the underlying legislation in the Member States, the EU allowed the output from chemical recycling to be used in contact with food, provided the same basic chemical substances are admissible in the food sector for new products. Unlike mechanical recycling, this applies independently of the raw material used to produce the output.

101 For example, pyrolysis and gasification can operate with less pure material flows, but their efficiency drops off significantly, which in turn increases costs.

102 Shawkat, A. et al. (Agora Industrie u. Systemiq) (2023).

Technology	Details	Raw material tolerance & application area	Energy consumption versus new products	TRL	R-strategy
Solvent-based recycling	Solvent-based cleaning process whereby plastics are separated into **polymers**, additives and contaminants[103]	**Medium raw material tolerance: Suitable for condensation polymers (PET, PUR, PC, PA, PLA), but not for olefins.**	**Comparably good energy footprint** because there are few downstream processing stages	**8**	**Recycle**
Depolymerisation	Polymers are split into **monomers or shorter fragments**[104] using various combinations of chemicals, solvents and heat.	**Limited raw material tolerance:** Only suitable for PET/polyester, polyurethanes, polyamides and polystyrene[105]	**Comparable to lower** (processing temperatures of 150-250°C for PET, few downstream processing stages)	**5–8**	**Recycle**
Pyrolysis	Mixed plastics are heated in an oxygen-free environment, whereby polymers etc. are converted into **liquid pyrolysis oil**[106,107]	**Medium raw material tolerance[108]:** Only suitable for polyolefins (primarily PP, PE[109])	**Higher** (processing temperatures from 400-800°C, energy is consumed during downstream processing stages)	**6–8[110]**	**Recycle**
Gasification[111]	Mixed plastics are heated in a limited-oxygen environment and converted into synthetic gas which may, in turn, be converted into polymers or other organic chemicals.	**Maximum material tolerance:** Wide range of plastics.	**Significantly higher** (processing temperatures often >800°C, energy is consumed for downstream processing stages)	**7–8**	**Recycle**

103 Solvent-based chemical recycling is sometimes referred to as mechanical recycling because the composition of the polymer remains intact throughout the entire process.

104 However, PET is the only plastic which makes sense, because the quantities of PA, PUR and PS are minimal.

105 Most applications to date have been for mono-material packaging waste streams and, to a limited extent, pre-sorted streams of flexible plastics from industrial applications; use with polystyrene has been very limited to date; raw material tolerance is higher than with mechanical recycling.

106 Non-condensing gases and solid residues are also produced.

107 As well as being used in the production of new monomers and polymers (plastic to plastic), pyrolysis oil may also be used to produce fuels such as diesel, petrol or synthetic crude oil (plastic to fuel).

108 Tolerance to mixed and uncontaminated plastics (e.g. textiles) and organic residues, but simultaneous intolerance to non-plastics (including organic substances, metals, glass) and certain plastics (PET, PVC - produces harmful by-products).

109 Used primarily for flexible packaging and, in limited quantities (to date), for used tyres.

110 Many pilot and demonstration projects are at TRL 7-8, including those from Plastic Energy and Agilyx. Full commercialisation to TRL9 or above is associated with various challenges such as ensuring adequate raw material purity on a large scale.

111 Process also used for the gasification of carbon and biomass (with higher TRLs).

Cost benefits of the technology

- Chemical recycling reduces dependency on fossil-based primary resources and, in the long term, may contribute to the price stability of recycled plastics.
- Once scaled up, it could be less expensive than waste incineration, because ever more stringent requirements, e.g. on the use of CCU, are driving the cost of incineration up.

Global competitive advantages

- Theoretically, chemical recycling can help to recycle materials which would otherwise be difficult to recycle, such as composite packaging and mixed/synthetic fibre textiles[112, 113].
- This could help Germany to build on its leading role in recycling technologies and secure a competitive advantage.
- It strengthens Germany's position as an innovation leader for recycling technologies and gives it a competitive edge.
- Upscaling the technology will create jobs, drawing on the comprehensive expertise of the Germany chemicals industry and its existing infrastructure, such as chemical industrial parks and steam cracker plants for pyrolysis and gasification.

Environmental considerations and precautions

- As scientific evidence regarding the environmental impacts of chemical recycling remains limited, there is an inadequate understanding of various aspects including mass losses, the deployment of chemicals and the wider environmental footprint[114].
- The high energy consumption of some processes limits their emission benefits compared with new fossil-based products. Chemical recycling should only be used if it has a better carbon balance[115] than new fossil-based products.
- There are concerns that wider investment in chemical recycling will reduce investment in the mechanical recycling infrastructure, and less emphasis will be placed on upstream solutions such as reduce and reuse, which could encourage a lock-in effect[116].
- Despite the limited data situation, for PET and PP plastics, we can assume that chemical recycling is not generally competitive with mechanical recycling in cost terms[117]. However, costs vary considerably depending on the process and plastics used, as well as regional energy and raw materials prices[118].
- The potential to reduce demand for primary or fossil-based carbon primary resources is minimal compared with other recycling processes[119].

Sample projects

- **Reju** operates a plant near Frankfurt which uses chemical depolymerisation to break polyester down into its basic materials and then processes it into high-quality recycled polyester[120].
- **BASF** is developing a technique known as ChemCycling® to convert plastic waste into pyrolysis oil to be used as a raw material in plastics with new-product quality[121].

112 Statista (2025): Aufkommen an Bekleidungs- und Textilabfällen in Deutschland in den Jahren 2004 bis 2023, available online here.

113 EU requirements governing the separate collection of textile waste which came into force in 01/2025 could increase the availability of raw materials and, in turn, reduce costs.

114 Hann, S. and Connock, T. (Eunomia) (2020): Chemical Recycling: State of Play, available online here.

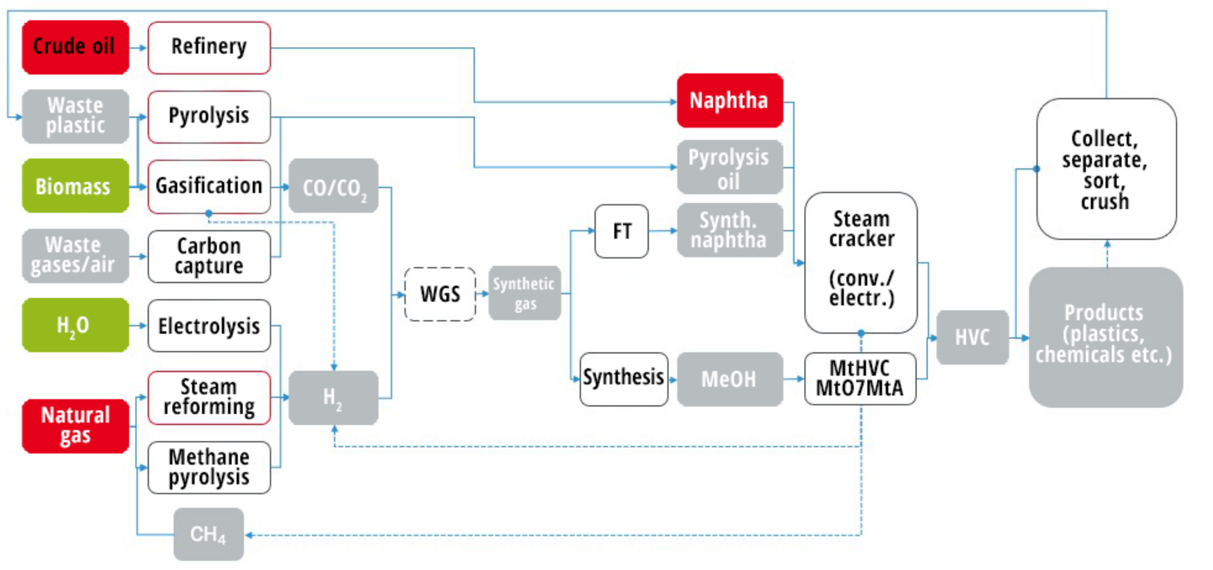
115 Calculating the carbon footprint of chemical recycling and other processes is currently the subject of much debate. At EU level, efforts are underway to devise a uniform framework, the principal focus of which is to ensure fair comparability with other technologies and an accurate representation of carbon emissions

Barriers & measures

- The main barriers to the use of chemical recycling are:
  - A lack of regulatory framework conditions for this technology in Germany.
  - Waste sorting limitations restrict the availability of relevant pre-sorted raw material.
  - Processes have a low level of technical maturity in terms of material efficiency, greenhouse gas intensity and process outputs, which limit their usability in industry[122].
  - The technology's cost-effectiveness and emission reduction potential are limited by high energy prices.
- Measures to develop the technology and its market maturity within the context of appropriate use include:
  - Clear definition and standardisation of the mass balance approach for calculating recycling rates. This would allow chemical recycling to be recognised as recycling in Germany and facilitate coherent regulation
  - More efficient and transparent licensing processes would allow recycling plants to become operational faster
  - Investments in modern sorting and processing technologies to improve the purity of plastic streams. These are also essential for upscaling mechanical recycling, necessitating an overarching German and European investment strategy for mechanical and chemical recycling
  - Beyond mechanical and chemical recycling, targeted political incentives such as tax breaks, subsidies or minimum quotas for recycled content in new products are also needed.

115 WWF (2022): WWF Position: Chemical Recycling Implementation Principles, available online here.
116 Uekert et al. (2023).
117 Depending on the process, costs also depend on scalability as well as pretreatment and investment costs.
118 Systemiq analysis on behalf of Energy Transition Commission (publication pending).
119 Wicker, Alden (2025): The World Is in a Polyester Crisis. One Company Is Trying to Recycle a Way Out. WIRED (21.02.2025).
120 BASF website
122 Shawkat, A. et al. (Agora Industrie u. Systemiq) (2023).

MTX processes and the circular use of methanol from catalytic hydrogenation



WGS = Water-gas shift / FT = Fischer-Tropsch process / MeOH = Methanol / HVC = High-value chemicals / MTHVC/MTO/MTA = Methanol-to-HVC/olefins/aromatics / Process stages are depicted with a black border, while (intermediate) products are depicted in colour (green = renewable, red = fossil-based, grey = mixed)

Figure 11: HVC production routes showing process stages and intermediate production. Current and potential routes (for Germany); © Prognos AG, Wuppertal Institut, Optionen für eine klimaneutrale und nachhaltige Grundstoffindustrie, commissioned by the Deutscher Bundestag (German Parliament), 2022

MTX processes enable the (virtually) climate-neutral production of high-value chemicals (HVC) from green methanol by substituting fossil raw materials such as naphtha and dramatically reducing carbon emissions[123, 124].

Green methanol can be produced via the catalytic hydrogenation of captured carbon and used as a substitute for fossil-based carbon in the production of methanol and hence HVCs. However, the high energy demand of this process is a barrier to the large-scale manufacture of green methanol in Germany[125]. As an alternative, methanol could be produced elsewhere (in Europe) and imported.

The methanol could then be converted into HVCs (either olefins (MTO) or aromatics (MTA)) in Germany using MTX processes. These are core elements of the chemicals industry.

123 Climate-neutral HVC production can be achieved either via chemical recycling, electrically powered steam crackers (traditional naphtha route) or, alternatively, via the green methanol route. Under the right market conditions, each variant can contribute to decarbonisation.

124 Systemiq analysis on behalf of the Energy Transitions Commission.

125 Piégsa, A. et al. (Wuppertal Institut and Prognos) (2022): Gutachten: Optionen für eine klimaneutrale und nachhaltige Grundstoffindustrie in Deutschland. Entwicklungspfade ausgewählter Wirtschaftszweige.

In the long term, MTO/MTA could replace conventional steam crackers, producing just 3-11% of the carbon emissions released by the naphtha route, with a comparatively high energy efficiency compared with other production routes, as shown in Figure 11[126].

The existing chemical infrastructure, coastal locations and nearby CO_2 sources create favourable conditions for the industrial upscaling of MTX processes[127].

In the long term, Germany's entire demand for ethylene and propylene could be met from (imported or domestic) green methanol and MTO processes, subject to an assessment of its financial feasibility compared with other processes[128].

Since carbon from tested and sustainable sources is always associated with high environmental and/or energy costs, WWF would argue that this process should only be used to meet the remaining demand after having implemented far-reaching, systemic circular economy levers in client sectors (for example, reducing aromatics in end products).

Technology		TRL	R-strategy
Catalytic hydrogenation	CO_2 acaptured from point sources[129] reacts with hydrogen at high temperatures and high pressure in the presence of a catalyst (typically copper-based due to its high selectivity and low cost) to form methanol and water[130].	**7–8[131]**	**Reduce/ Recycle**
Methanol-to-X (MTX) processes	In a downstream process, MTO technology converts methanol via dimethyl ether (DME) into olefins (e.g. ethylene, propylene), while MTA technology converts methanol into aromatics (such as benzene, toluene and xylene).	**11[132]**	**Reduce**

126 UBA (2024): Note: Fuel-related emissions from the steam cracker + naphtha as fossil-based feedstock are substituted.

127 Rosental, M. et al. (UBA) (2024): Prozessintegrierte Maßnahmen und alternative Produktionsverfahren für eine umweltschonendere Herstellung von Chemikalien.

128 Verpoort et al. (2024): Report: Transformation der energieintensiven Industrie – Wettbewerbsfähigkeit durch strukturelle Anpassung und grüne Importe, available online here.

129 For example, from unavoidable CO_2 sources associated with cement production.

130 IEA (no date): CCUS Technology Innovation, available online here.

131 The first commercial systems are expected towards the end of the 2020s.

132 Large-scale plants already exist in China.

Cost benefits of the technology

- **Energy costs:** Although energy costs associated with the MTO process could potentially be reduced after 2030, the high investment and green methanol costs currently make it less competitive in Germany than conventional naphtha-powered steam crackers[133].
- **Raw materials efficiency:** The current generation of MTO systems requires less methanol per tonne of ethylene and propylene than its predecessors, making them more efficient than conventional steam crackers that use naphtha as a raw material[134].

Global competitive advantages

- **Industrial scalability:** Germany's existing chemical infrastructure offers good potential for implementing innovations, even though high investment and methanol costs currently pose a challenge. China already operates large-scale MTO plants with capacities on a par with steam crackers, albeit using methanol from fossil sources[135].
- **Optimum infrastructure:** Coastal locations in Germany, with their proximity to import ports, sources of CO_2 and chemical plants, provide the ideal infrastructure for methanol production, import and reprocessing.
    - **Value & job creation:** Domestic methanol reprocessing (MTO) offers a substitute for fossil imports as well as creating jobs[136].
    - **Reliable supply:** Importing e-methanol via Rotterdam and other import ports helps to safeguard supply chains for subsequent MTX reprocessing in Germany.

Environmental considerations

- The environmental impacts of raw material supply from MTO are primarily associated with methanol production. The origin of the CO_2 is decisive, because this determines the carbon intensity of the methanol production and hence of the HVC. There are various carbon capture routes available. The UBA report defines sustainable sources of carbon as those which do not enlarge the CO_2 cycle, such as biogenic sources or CO_2 from the air (direct air capture, DAC). However, cement capture is also considered necessary for the permanent storage of carbon emissions, so in this instance, CCS remains indispensable[137].
- CCU requires very large quantities of electricity, and climate neutrality is therefore highly dependent on the origin of the electricity. Without 100 percent renewable electricity there can be no CCU and hence catalytic hydrogenation to methanol should not be an option[138, 139].

133 Piégsa, A. et al. (Wuppertal Institut and Prognos) (2022).

134 UBA (2024): Prozessintegrierte Maßnahmen und alternative Produktionsverfahren für eine umweltschonendere Herstellung von Chemikalien, available online here.

135 Ibid.

136 Piégsa, A. et al. (Wuppertal Institut and Prognos) (2022).

137 Ausfelder, F. et al. (UBA) (2024): Umweltauswirkungen der stofflichen Nutzung von CO_2, available online here.

138 WWF (2022): Position paper on CCU/S, available online here.

139 The potential savings mentioned here (pursuant to Piégsa, A. et al. [Wuppertal Institut and Prognos] 2022) assume 100% green methanol production.

Sample projects

- **UOP (Feluy, Belgium):** A methanol to olefins (MTO) plant with an annual capacity of 200,000 tonnes operates on site. Commercial trials (TRL 9) have already been completed. The plant helps boost the efficiency of petrochemical processes[140].
- **La Robla Nueva Energía (Spain):** Reolum chose e-methanol technology from Johnson Matthey for this project; the plant is due to commence operation by the end of 2027 and will produce up to 140,000 tonnes of e-methanol annually[141].

Barriers & possible measures

- The main barriers to upscaling are:
  - Lack of clarity over demand, given that costs are currently higher (particularly due to energy-intensive green methanol production) than for conventional naphtha cracking
  - The additional transport and infrastructure costs associated with a sustainable supply of CO_2, because sources (such cement production facilities with CCUS) are only sporadically available
  - Uncertainties regarding technical alternatives and the long-term viability of potential future innovations are a particular barrier to large, capex-intensive conversions because the investment cycles are long. The scope for experimental testing with such large facilities is very limited.
- Possible measures include:
  - high carbon pricing (or stable carbon pricing with predictable increases)
  - Targeted support programmes to improve the cost-effectiveness of low-carbon raw materials, such as CO_2 from CCUS
  - More intensive analysis and testing of synergies at integrated sites (those which combine sustainable raw materials with production potential, e.g. in the vicinity of cement production plants) to optimise further cost-cutting potential.

140 UBA (2024): Prozessintegrierte Maßnahmen und alternative Produktionsverfahren für eine umweltschonendere Herstellung von Chemikalien, available online here.

141 Johnson Matthey (2025): Johnson Matthey technology selected for one of the largest planned e-methanol plants in Europe. Press release (21.01.2025).

4. Digital twins as an example of a trans-sectoral technology for a more circular economy

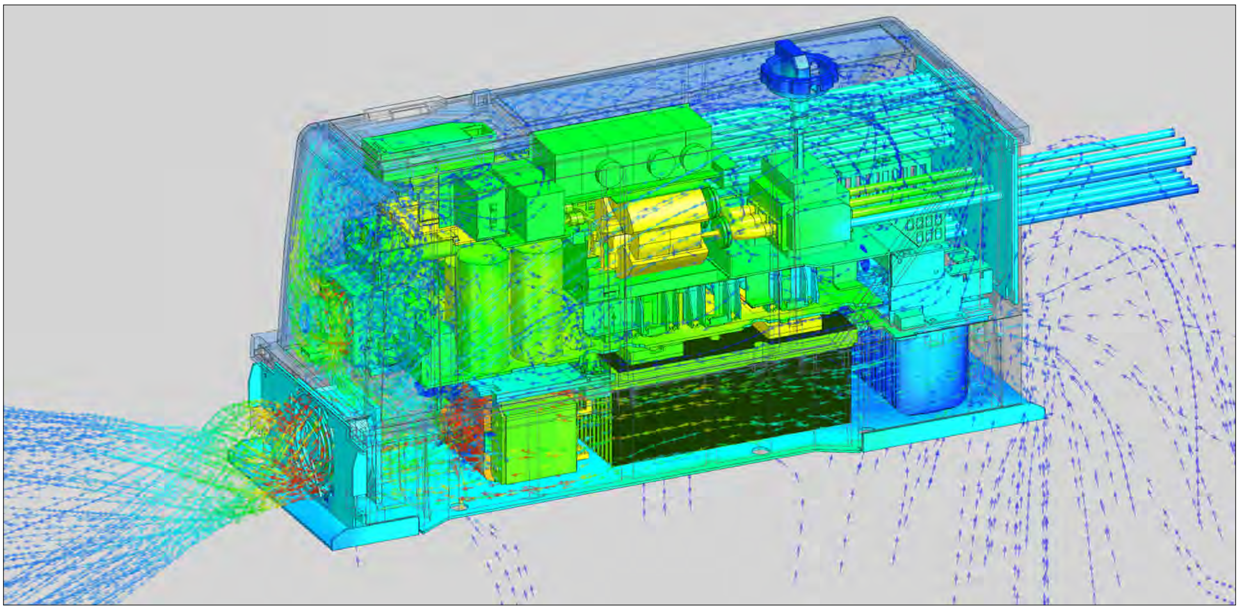


Figure 12: Digital twin of a building – "Autodesk Tandem"[142]; © Siemens AG

Digital twins are a digital simulation of a product, created using artificial intelligence. They may be used to optimise the product design and processes from production through to the end of life, thereby reducing material and operating costs e.g. via preventive maintenance. They also provide CO_2 transparency at every stage of the supply chain. From 2027, a simpler form of the digital twin known as the "product passport" will become mandatory[143] for batteries.

Digital twins facilitate energy and material savings of at least 20 percent at every production stage, by allowing greater precision with production planning and monitoring[144].

Demand for digital twin technologies is rapidly rising, particularly in the execution & planning software segment, with an anticipated annual growth rate (CAGR) of 14 percent between now and 2030[145].

These technologies make an important contribution to sustainable industrial value creation in Germany by severing the link between productivity and resource consumption.

142 Picture credits: Siemens AG: "Autodesk Tandem".

143 As of February 2027, all new traction batteries, bicycle batteries and industrial batteries with a capacity of more than 2 kWh entering the market will need a digital battery passport, with the aim of ensuring transparency and sustainability in the battery value chain: https://www.dke.de/de/arbeitsfelder/components-technologies/batteriepass

144 Wuppertal Institut (2022): Circular Economy digitale Zwillinge, available online here.

145 Systemiq analysis (2024): based on LEK Statzon, WH-Automation.

Use cases for digital twins in the circular economy

Building sector: Building Information Modelling (BIM) has been in use since the early 2000s but is becoming ever more precise and now allows buildings to be rendered in detail with all their components. This supports the optimisation of designs in terms of material efficiency and dismantling for circular use, enabling material savings of up to 40 percent.

Batteries: Detailed lifecycle information in the battery passport facilitate the reuse, reprocessing and efficient recycling of valuable raw materials. This in turn helps to extend the service life of the battery and boost recycling rates[146].

Production & manufacturing: Predictive maintenance and automation reduce material consumption and extend the service life of machines (e.g. computer-assisted manufacturing, CAD).

Technology		TRL	R-strategy
Digital twins	Digital twins are virtual renderings of physical objects and processes, incorporating real-time data for monitoring, analysis and optimisation.	**10**	**Reduce, Reuse, Recycle**

Cost benefits of the technology

- Faster market launches: Virtual testing helps to speed up development and time-to-market.
- Cost savings: Optimisation potential reduces material wastage and maintenance costs.
- Predictive maintenance, virtual commissioning and flexible production are facilitated, which in turn boosts material efficiency.

Global competitive advantages

- Productivity boost: Improved planning and automated processes
- Business model development: New monetarisation options for R-strategies (such as battery refurbishment)
- Germany is a pioneer of Industry 4.0 and digitised supply chains. Its solid industry expertise combined with the wide range of potential use cases enable an economically viable circular economy.
- More competitive: The technology speeds up innovation cycles (by allowing simulation-assisted testing of new production methods or product designs), thereby reinforcing Germany's competitiveness.

Environmental considerations and precautions

- **The Jevons Paradox:** Increased efficiency may lead to a rise in overall consumption if there is additional consumption or reinvestment in other, more resource-intensive processes.
- **Data infrastructure and energy consumption:** The storage and processing of digital twins demands energy-efficient data centres and sustainable digitalisation strategies.

146 Fraunhofer IPK (no date): Nachhaltigkeit mithilfe von Digital Twins, available online here.

Sample projects

- **Madaster** generates digital twins of buildings, collates material data and assesses reusability. In this way, the platform supports sustainable building management and a circular construction sector economy.
- **Circulor** tracks materials in supply chains using blockchain and digital twins.
- **Siemens:** With SiGREEN and Catena-X, Siemens enables precise calculation of carbon footprints at every stage in the supply chain

Barriers & possible measures

- The principal barriers to upscaling digital twins are:
  - The technical capability to collate, integrate and manage large volumes of data from multiple sources at every stage in the value chain, the complexity of which may vary depending on the product
  - Lack of unity between European players on data exchange and product data standards
  - Willingness to use in downstream sectors, such as the construction sector and SMEs in particular.
- Measures to facilitate upscaling include:
  - Uniform EU data standards, as has been successfully achieved with the EU regulations on digital product passports for batteries
  - Targeted support to help SMEs to use digital twins, especially in areas where it is not a regulatory requirement (e.g. in the construction sector)

International Energy Agency (IEA) Technology Readiness Scale

The IEA scale describes a technology's development stages from the initial idea (concept phase) to prototypes and demonstration through to commercial maturity and large-scale integration[147].

TRL-level	Scale	Description
Concept	**1**	Initial idea – Basic principles have been defined.
Concept	**2**	Application formulated – The solution's concept and use have been formulated.
Concept	**3**	Concept needs validation – Solution needs to be prototyped and applied.
Small prototype	**4**	Early prototype - Prototype proven in test conditions
Large prototype	**5**	Large prototype – Components proven in real-life conditions
Large prototype	**6**	Full prototype at scale – Prototype proven at scale in real-life conditions
Demonstration	**7**	Pre-commercial demonstration – Solution working in expected conditions.
Demonstration	**8**	First of a kind commercial application – Commercial demonstration, full scale deployment in final form
Early adoption	**9**	Commercial operation in relevant environment – Solution is commercially available but needs evolutionary improvements to stay competitive.
Early adoption	**10**	Integration needed at scale – Solution is commercial and competitive but needs further integration efforts.
Mature	**11**	Proof of stability reached – Predictable growth

147 IEA (no date): Innovation Needs in the Sustainable Development Scenario, available online here.

Glossar

Term	Abbreviation	Definition
CO_2 equivalent	**CO_2e**	CO_2e is a unit of measure for converting the climate impact of various greenhouse gases based on their **Global Warming Potential (GWP)** into CO_2 equivalent to enable a comparison of overall impact.
Renewable energies	**-**	Energy sources that regenerate naturally, and unlike fossil fuels, are available in unlimited quantities. These include solar energy, wind power, hydropower, biomass and geothermal energy.
Embodied Carbon Limits	**-**	Statutory or voluntary limits for the carbon emissions contained in construction materials and products that are released at every lifecycle phase, from raw material extraction, to production, through to disposal. The aim is to improve the climate footprint of the construction and industry sectors.
Direct reduction – electric arc furnace	**DRI-EAF**	DRI: Low-carbon method for reducing iron ore to sponge iron in an electric arc furnace, which is subsequently reprocessed into raw steel EAF: Process for obtaining secondary steel from scrap steel or primary steel via direct reduction (DRI)
Hydrogen-based direct reduction	**H_2-DRI**	Hydrogen-based direct reduction is a process for manufacturing iron using hydrogen instead of carbon to reduce iron ore. Provided the hydrogen is sourced from renewable energies, this produces significantly lower carbon emissions.
High-value chemicals	**HVC**	High-value chemicals are organic basic chemicals used as precursors for numerous value chains and secondary products. They include: Olefins with 2–4 carbon atoms, particularly ethylene, propylene, butene (butene isomers) and 1,3-butadiene. Aromatics with 6–8 carbon atoms, including benzene, toluene and xylene (xylene isomers), known collectively as BTX.
Circular economy technologies	**-**	Circular economy technologies are technological solutions that support circular economy principles (R-strategies) and facilitate the transformation to a circular economy. According to the OECD, the term “technology” comprises a knowledge of how products are manufactured, services are delivered, or processes are executed, as well as the physical and organisational systems that facilitate them.

Term	Abbreviation	Definition
Pozzolanic properties	**-**	The ability of certain additives (such as calcined clay, fly ash or volcanic ash) to create additional cement-forming compounds in the presence of water and calcium hydroxide, which improves the strength and durability of cement.
Supplementary Cementitious Materials	**SCM**	Alternative binding agents, used in selected concrete construction applications as a substitute for clinker to reduce carbon emissions. Examples include fly ash, slag sand, calcined clay (e.g. metakaolin) and natural pozzolans. They improve the concrete's performance and support sustainable construction.
Technology Readiness Level	**TRL**	An established international system for assessing the degree of technological maturity. The scale ranges from basic research (TRL 1) through to full commercial use (TRL 9 or above).

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To stop the degradation of the planet’s natural environment and to build a future in which humans live in harmony with nature.

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