



RESEARCH AND INNOVATION ROADMAP 2050

A Sustainable and Competitive Future
for European Raw Materials

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Why a raw materials research roadmap?

Demographic changes, such as population growth in developing countries and an ageing population in developed countries, coupled with increasing standards of living and urbanisation trends will foster a greater demand for products and applications linked to human well-being, health, hygiene and sustainability. As a consequence, the worldwide demand for raw materials is expected to increase while global resources and land become scarce.

To meet the challenges caused by an increased, continuous demand for sustainably sourced raw materials, waning natural resources and climate change, a shift towards a more resource-efficient, circular economy and sustainable development is becoming more crucial than ever. Meanwhile, trends such as the emerging “sharing economy” and changing raw material demands as new technologies develop, will reshape the world we live in and influence our need for raw materials. The opportunities enabled by emerging technologies, digitalisation, artificial intelligence (AI) and additive manufacturing applications will bring about unforeseeable breakthroughs in technologies and the organisation of human work.

Securing reliable and undistorted access to raw materials and developing domestic value chains are crucial to boosting growth, jobs and competitiveness in Europe. Currently, the EU is dependent on imports of many raw materials that are crucial for a strong European industrial base.

Europe is confronted with several challenges along the entire raw materials value chain composed of exploration and management, extraction and harvesting, processing and refining, manufacturing, use and recycling as well as substitution. Yet, innovation in raw materials value chains remains untapped despite the sector's great potential. A more coordinated approach towards raw materials management will help reduce external supply dependency and lead to an efficient use of resources.

To achieve these goals, a long-term vision and roadmap to 2050 aims to tap the full potential of raw materials supply and use in Europe and to boost the innovation capacity of the sector, turning it into a strong, sustainable pillar of the EU economy and an attractive industry, whilst addressing societal and environmental challenges and increasing benefits for society.

Raw materials in the 2050 society

The acceleration in digitalisation, evolution of consumer behaviour, such as increased connectivity, the sharing economy, mass-customisation and sustainability, are reshaping the future of both products and processes.

To achieve a global leadership in technological innovation, the industry in Europe is developing and improving smart technologies and applications that respond to consumer demands and global challenges that include the United Nations Sustainable Development Goals (SDGs) and the Paris Agreement on climate change.

At the same time, innovation in raw material value chains help the EU achieve the targets outlined by its roadmaps for a resource-efficient Europe¹, a competitive low-carbon economy by 2050² and a renewed EU Industrial Policy Strategy³.

In response to these future drivers, the EU raw materials sectors need to foster a sustainable supply and use of raw materials to feed existing and new value chains through research and innovation. At the same time, it needs to ensure base loads from EU resources, decreasing import dependencies and resilience of the EU industrial base through resource diversification.

1: Roadmap to a Resource Efficient Europe, the European Commission (COM2011) 571 final: <http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52011DC0571>

2: Roadmap for moving to a competitive low carbon economy in 2050, the European Commission (COM2011) 112 final: <https://eur-lex.europa.eu/legal-content/en/ALL/?uri=COM:2011:0112:FIN>

3: A renewed EU Industrial Policy Strategy, the European Commission (COM2017) 479 final: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2017%3A479%3AFIN>

Therefore, in the society of 2050:

- The raw materials sector is the backbone of a circular economy and main driver of a symbiotic industrial environment in Europe.
- European raw materials sustain the needs of people across the world. Minerals, metals and biotic raw materials are sourced sustainably through flexible, circular and knowledge-based systems that allow outstanding levels of customisation and transparency throughout the value chain.
- The EU raw materials sectors possess the know-how and technological capacity to adjust to the manifold innovations of upstream processes.
- It embraces digitalisation and manages technical and practical applications of digitisation in the sector. Traditional value chains will be revolutionised; current processes will change radically and become data-driven. New business models will develop.
- The raw material sectors develop and implement improved and better adapted measurable scientifically based values, indicators and standards associated with sustainability through the whole value chain where needs have been identified using newly developed data management systems.
- Thanks to the successful cross-sectoral collaboration, the EU raw materials producers compete with, complement and finds synergies with each other, which decreases import dependency and ensures the resilience of the EU industrial base through resource diversification.
- A long history of innovation leadership and entrepreneurial spirit attracts investments to Europe and secures the further development of the EU economy. The raw materials will strengthen the EU economy, develop and reinforce its position of EU sourced primary- and secondary obtained raw materials by decreasing import dependencies and ensuring base load supply through diversification of sources.

Minerals, metals and biotic raw materials

The 2050 roadmap for European raw materials covers relevant research and innovation activities of non-energy and non-agricultural raw materials used in industry. This includes minerals as well as wood and natural rubber and aggregates of these materials. These primary raw materials are directly derived from the natural environment and are being fed into the supply chain for the first time.

In addition, as part of the circular economy concept, secondary raw materials will become an increasing integral part of materials consumption, requiring targeted research and innovation efforts. The secondary raw materials can be obtained from end-of-life products and goods, that through (pre-)processing have been made available to be used as an input for industrial production, for example mining waste, industrial and household waste landfills, and end-of-life products. They also include non-energy, non-agricultural raw materials processing residues and side-streams, such as tailings, sludges, slags, dusts, scales and so on.

The roadmap distinguishes minerals, metals and the biotic raw material sectors. Together these encompass the entire value chain from primary raw material exploration and management, extraction and harvesting and their transformation through processing or refining, and the valorisation of waste and residues into secondary raw materials to closed loops material flows and the development of new products and applications to substitute fossil-based and/or critical raw materials, or where fossil-based raw materials cannot be used at all.⁴



The biotic value chain

The **European biotic raw material sector** is at the heart of the bioeconomy providing means to tackle global challenges by replacing fossil-based raw materials with sustainable, renewable raw materials sourced in Europe. Forests cover 42% of the EU's land area. The **forest-based sector** is a key enabler for a low-carbon, biobased society. The sector consists of different sub-sectors: woodworking; furniture; pulp and paper manufacturing and converting; wood-based biorefineries; and printing; as well as forest owners, managers and forestry. The value chains produce a wide range of products ranging from wood construction products, packaging, furniture, paper and pulp products, and hygiene articles to bioplastics, biocomposites, carbon fibres, textile fibres and biochemicals. Furthermore, forests provide biodiversity and many ecosystem services that are of importance for human well-being and health, including clean air and water and recreational activities. In addition, forest and forest products are a renewable resource, and therefore there is a need to include long-term sustainable measures in forest management. Forests are also fundamental to the mitigation of the effects of climate change.

Natural rubber is a strategic raw material, on which European industry has a complete import dependency. Natural rubber is mainly produced in Asia (93%). Hevea, however, a native tree from South America, is currently the only commercial source of natural rubber. Guayule (*Parthenium argatum*) is one of the alternative sources, growing on marginal lands in semi-arid regions of European Mediterranean countries.

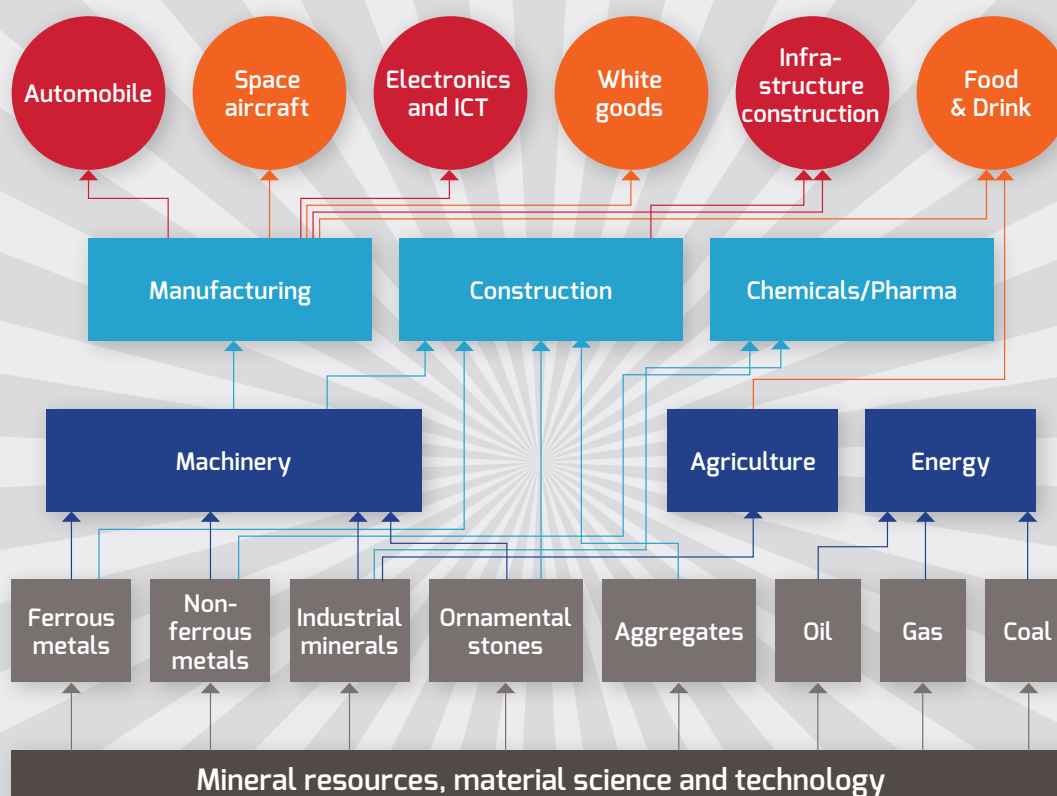
4: <http://ec.europa.eu/eurostat/web/environmental-data-centre-on-natural-resources/natural-resources/raw-materials>



Minerals, metals and aggregates

The **European mineral raw material sector** is facing critical challenges in terms of supporting the transition to a low-carbon, fossil-free sustainable Europe and the green economy. The metals mined are critical to build electric infrastructure as well as energy storage systems, renewable energy power plants and vehicles for both personal and commercial use. The sustainable supply of metals and minerals will also be critical to build a future sustainable society that will rely heavily on new transport infrastructure as well as new green buildings. The **mining sector** and the **mineral processing sector** are vital to securing the supply of metals extracted in a sustainable manner. The value chain spans from geological exploration, mining and processing to the recycling of metals. Embedded in the value chain is a strong environmental commitment both during operation, as well as for the reclamation of land used for mining. The **aggregate sector** is spread throughout Europe providing aggregates for the building and infrastructure industries. Over 26,000 active quarries in Europe are critical for the creation of new buildings and infrastructure. Local production is critical to minimise environmental impact from transport, but presents challenges related to local environmental impact in urban areas and fossil-free aggregate production.

Almost every industrial branch needs products from the minerals industry



The structure of the research roadmap

To secure the competitiveness and sustainability of the European raw material sector will require significant investment in research and innovation, as well as fostering synergies between and across the different value chains. Minerals, metals and the biotic raw material sectors have therefore identified four key priorities and nine research and innovation areas, including a number of activities with a view to addressing the key concerns of the raw materials community, as well as society and citizens at large. The concrete research and innovation activities cover specific needs within the supply and production of raw materials, creating closed loops, and developing new products and applications.

PRIORITY AREA 1

Fostering a sustainable supply of raw materials to feed new and existing value chains

1.1

Primary supply of EU raw materials for sustainable value chains

1.2

Improved utilisation of raw materials from EU sources

PRIORITY AREA 2

Resource-efficient processing for raw materials

2.1

Development of resource-efficient, advanced processing for raw materials

2.2

Minimisation and valorisation of residues

PRIORITY AREA 3

Raw materials in new products and applications

3.1

Development of material applications and markets

3.2

Development of new biobased products

PRIORITY AREA 4

Closing material loops by maximising the recycling of products, buildings and infrastructure

4.1

Increasing material recovery by efficient detection, sorting and separation

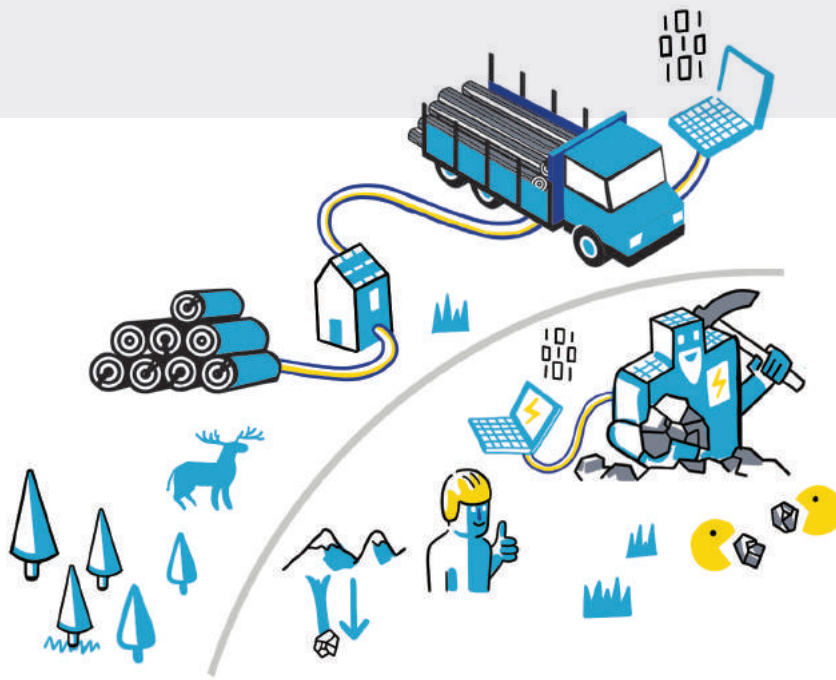
4.2

Reuse and recycling technologies adapted to complex, durable or miniaturised products

4.3

Developing and integrating methods for assessing and optimising cost and benefit in recycling





PRIORITY AREA 1

Fostering a sustainable supply of raw materials to feed new and existing value chains

The supply of primary raw materials through exploration, mining, quarrying and harvesting of biomass has been sustaining human civilisation since history began. And for the foreseeable future, the use of metals, minerals, stones, aggregates and biotic materials will be essential for supplying most manufacturing operations. However, the palette of raw materials seen today is evolving, as new consumer patterns arise, and technologies which allow for the substitution of non-renewable, critical or energy-intensive materials, or for climate-friendly processes, develop.

Technological innovation drives the deployment and integration of digitisation, efficiency, sustainability and safety aspects throughout raw material value chains. The ability to adopt and implement technological innovation represents a key asset for EU industries within

the raw material sector, allowing them to maintain and strengthen their competitiveness in the market.

The increased demand for raw materials along with economic and environmental requirements for sustainability and resource efficiency require new technologies, methods, processes, digital solutions and decision-making tools to support more efficient and sustainable sourcing and transportation of raw materials from mines and forests.

This priority area focuses on research and innovation activities to increase the resource base, resource efficiency, safety, as well as the utilisation of new and existing resources. It proposes activities that help improve framework conditions for primary raw materials that provide a stable and competitive supply from EU sources and facilitate their public acceptance.

Research and innovation areas

1.1 Primary supply of EU raw materials for sustainable value chains

1.2 Improved utilisation of raw materials from EU sources

1.1

Primary supply of EU raw materials for sustainable value chains



Rationale

Minerals and metals

The increased demand for metals and minerals is driven by the continuous global endeavour for improved living standards and environmentally friendly solutions. In order to increase the supply and to strengthen the competitiveness of the European mineral and metal sector, the focus should be on developing solutions for a sustainable supply of metals and minerals as well as enabling the sustainable extraction of Europe's mineral resources in existing and new mines.

Biotic sector

To maintain and strengthen the competitiveness of the European forest-based sector, it is crucial to secure an efficient, sustainable and high-quality wood raw material supply while following the principle of right wood to the right end use. The provision of raw materials in the context of sustainable forest management and the further development of efficient and environmentally friendly forest operations are core activities of the forest-based sector.

State of play

Minerals and metals

Today, at least 42 metals and minerals are extracted and processed in Europe. Over decades, annually, European exploration activities add more reserves than it extracts. Moreover, Europe is self-sufficient in aggregates and most industrial minerals, while it is import-dependent on other metals ranging between 60% to 100% depending on the specific metal. Europe's mineral potential is vast but underexplored both with regard to subsurface, particularly deeper than 150 metres and at sea in the EU Member States' exclusive economic zones. Some of Europe's mines and quarries are global leaders in productivity and safety, but are facing increased challenges due to greater depths, lower grades and strict environmental regulations. To increase the sustainable supply of raw materials from Europe, new equipment, methods and processes need to be developed. At the same time, increase in production in new and existing mines needs to be ensured, with the focus on sustainability, low environmental impact and high productivity.

Biotic sector

Europe's forest stock is increasing. In 2010, the annual increment of forest volume was 768 million m³, while the annual harvest was 484 million m³, equivalent to a 63% increase⁵. Though variation is considerable, harvest does not exceed increment in any EU country. Yet, countries rich in forests are net importers due to a limited availability of the required wood varieties and for economic reasons. Softwood is currently the main resource for automated wood processing while additional supply potential lies in hardwood, both from homogeneous and mixed stands. To increase the sustainable and economically viable supply of biomass from forests, there is a need to improve operational efficiency resulting in increased added-value, less waste, lower operational costs, reduced environmental impact, better direction of wood fibre to the most appropriate markets relative to its quality, and the supply of wood fibre from more diverse species, forest types and management regimes into the supply chain. There are forests that have potential to provide wood fibre to the value chain, but that are not doing so due to major knowledge gaps on the management, harvesting and use of both hardwoods and softwoods.

Expected achievements by 2030

By 2030, Europe has further strengthened its technological leadership aimed at economically viable and environmentally sound mining and mineral extraction and forest harvesting operations. Low-carbon and fossil-free solutions have been developed and implemented in mining and harvesting activities. New autonomous mining and harvesting systems have increased productivity and precision and improved the working environment for operators. Health and safety measures, as well as working conditions in the mines and at harvesting, have improved. Data generation and management, including life-cycle assessment (LCA), environmental footprint, and mass flow analysis, will be key to improving processing for operators as well as providing information to the general public and policymakers.

Minerals and metals

Newly developed exploration technologies for land- and sea-based mineral deposits have been up-scaled and piloted. Equipment and processes enabling high productivity and energy-efficient mining operations have been developed and implemented. Advances in digitalisation and ICT have enabled a real-time integrated process control for mining operations. Innovative methods for ground control and rock support have been implemented. Methods for recovery and use of geothermal energy from deep mines have been developed and implemented. The performance in the areas of sustainable management of water, energy emissions, environmental impact as well as health and safety conditions has evolved. The environmental footprint of mining has been minimised. Dedicated technologies for urban mining have been proposed and tested.

5: http://ec.europa.eu/eurostat/statistics-explained/index.php/Forests,_forestry_and_logging

Biotic sector

New, highly productive machine technologies, ICT and optimised harvesting systems, including semi- and full-automation harvesting, measurement and processing technology have made forest harvesting considerably more efficient and reduced its environmental impact. Improved technology is being adapted to various types of resources sensitive soils and forest ecoregions. New innovative uses and value chains based on hardwoods have emerged and gained sizeable market share, whilst low-quality assortments of wood have more chance of achieving market profitability. New supply chain standards, remote sensing technologies, integrated sensors and accessible GEO-data have made all forest machines closely interconnected and coordinated in real time with customers manufacturing processes. The monitoring systems embedded in the harvesting machines have also had a great impact on efficiency and the sustainability of all forest operations. Semi- and full-automation in terrain transport systems have improved efficiency and reduced environmental impact. Small-scale private forest and land owners have been provided with tested solutions and means to actively plan and manage forests for wood production and other new services with the support of ICT tools.

Expected achievements by 2050

Minerals and metals

By 2050, larger mines have reached deeper-seated operations, achieved low-emission, fossil-free production and the target of 'zero-impact' mining, as well as full automation and real-time control with driverless drill rigs and vehicles in surface and underground mines and quarries. Larger mines have introduced robots to conduct flexible tasks. The full exploitation process is automated from extraction to processing and is managed in real time and by one central hub, while smaller mines have achieved a certain degree of automation. There are no longer people in underground production areas or in quarries. The environmental footprint of mining is negligible. In marine mining, environmentally sound and sustainable extraction of identified sea deposits is a reality. The sector has achieved the target of 'zero-impact' mining and quarrying. In deep mining, mines and quarries across Europe have zero-impact on water and climate change. Dedicated technologies for facilitating space mining have been proposed and tested. The European self-supply of minerals and metals has increased substantially.

Biotic sector

By 2050, European forests are the foundation of a market-driven circular bioeconomy, as a source for biobased products and services, through added value and an efficient and environmentally friendly wood supply. To meet the requirements of the UN Sustainable Development Goals, the Paris Agreement on climate change, and EU regulations, together with an increased demand for biobased products, different approaches to forest management, harvesting and planning of forestry operations have been developed. Forest harvesting has been integrated and optimised along value chains at a regional supply and landscape level, which ensures the lowest impact, highest efficiency and long-term sustainability criteria adapted to forest management regimes and forest ecosystems. Digitisation of harvester fleets and equipment supported through the latest ICT have been widely adopted and implemented to ensure a constant data flow and feedback loop between forest management and processing for optimisation, monitoring and research purposes. Working conditions of foresters have been improved through the use of machinery, digital tools and robotics.

Required Research and Innovation Activities towards 2030-2050



Minerals and metals

- A.** Improve geochemical and geophysical exploration methods, micro analytical techniques and genetic models for major ore types, and prospecting techniques, such as integrated multi-disciplinary 3D/4D modelling, to improve cost-efficient, environmentally friendly exploration and to increase resource diversity in Europe
- B.** Improve systems to collect and predict ore-body and rock mass information, including seam and grade definition (resource characterisation), rock mechanical properties and seismicity
- C.** Study and improve the blasting process to optimise the use of explosives and to minimise environmental impact
- D.** Develop new and adapt conventional technologies and operations to increase automation in quarries and mines to reduce energy consumption on rock mass transportation and haulage and to advance fossil-free mine production
- E.** Develop methods and technologies for improved ore recovery and fragmentation
- F.** Develop methods and tools for improved ground control and rock support in deep mines to improve safety and productivity
- G.** Develop systems, technology and processes for integrated real-time process control, digitisation and automation in mines
- H.** Develop new technologies for environmental protection and for the reduction of emissions and waste from mining and quarrying activities
- I.** Develop new methods and technologies for utilisation of thermal heat and mine ventilation, for instance by optimising heat exchange and flow control
- J.** Develop new methods for monitoring, controlling and improving work environment for people in mines
- K.** Improve the access to mineral potential in the EU by using big data, including mineral deposits of public importance and land use planning
- L.** Develop technologies for extracting minerals from sea-bed deposits, deep-sea mining and mining under special conditions (2050)
- M.** Improve hard rock-cutting techniques and deploy continuous cutting machines for automated and efficient operations within small and large deposits, deep-sea mining and special conditions mining (2050)





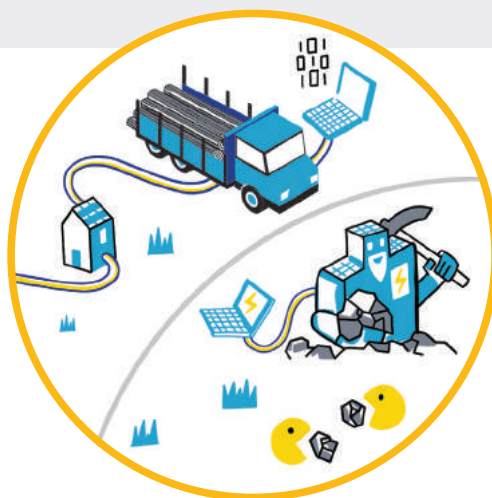
Biotic sector

- N.** Develop forest-based standardised information systems along the value chains for integrated communication from wood supply to products
- O.** Develop integrated ICT and big data solutions for human-machine-terrain interactions to increase automation in forestry operations and terrain transportation to roadside that improve working conditions, productivity, and safety
- P.** Develop real-time data management with big data solutions for the mapping and characterisation of forest resources and conducting site-specific forest management activities to enable precision forestry and integration with industrial processing systems
- Q.** Develop efficient ICT systems for precise quantification and characterisation of forest resources dedicated to hardwood and next generation trees
- R.** Develop efficient technology for low soil impact, to minimise rutting and increase accessibility to wood resources where soil-bearing capacity is limited
- S.** Develop methodologies for sustainable forest management for climate change adaptation and mitigation with the support of ICT tools that improve access to markets and enable forecasting trade-offs and synergies
- T.** Improve sustainable short-term rotation management schemes for woody biomass production
- U.** Develop methodologies for new business model development between small-scale private forest owners and enterprises, to actively manage forests for wood production and to mobilise and supply more raw material from private forests with the support of ICT tools
- V.** Develop new tree breeding strategies and assess the benefits and risks associated with the use of genetically-improved trees as well as accelerated traditional tree breeding through genomics, to increase sustainable produced biomass, and to improve wood quality and its resistance to stress⁶ (2050)
- W.** Develop human-robot collaboration for harvesting operations and for bringing logs to roadside to improve safety, productivity and working conditions (2050)
- X.** Improve the full integration of economically and environmentally efficient, smart harvesting, measuring, processing, sorting and logistics technology and systems, with evolving industrial processing technologies and systems to enable the valorisation of circular forest-based biomass in sustainable and continuously optimised products and value chains (2050)
- Y.** Develop new, cost-effective and feasible forest management measures to increase forest-based biomass production in a sustainable manner, including the use of fertilizers and intensive cultivation on suitable land and other production-enhancing measures, while safeguarding biodiversity and the resilience of forests in changing environments (2050)

⁶: Such as drought, pests and diseases, as well as at growth of most demanded wood species.

1.2

Improved utilisation of raw materials from EU sources



Rationale

Minerals and metals

Extraction and valorisation of European metal and mineral sources are vital to securing access to metals and minerals produced in a sustainable manner. Due to increasingly deeper mines, the haulage of ore is one of the main energy-consuming factors. At the same time, the transportation of the ore underground and in the pit, as well as transportation of the product leaving the mine on its way to the customer, produce emissions that are undesirable and costly. Furthermore, new transportation methods and better organisation are required to prevent empty loads. The environmental aspect is critical; with local raw material supply, controlled by European laws, it is essential to ensure that the desired social and environmental considerations are made, in all phases of the process, starting from extraction to the end user.

Biotic sector

The intelligent and efficient production and use of biotic raw materials and further development of climate-smart silviculture and precision forestry⁷ for efficient and environmentally friendly operations, transport systems and management models for biomass supply chains, are core activities of the biotic value chains. Improving technology for managing and utilising growing forest resources can be achieved through measurement and planning systems adding value with a minimum environmental load. These systems would also contribute to the development of highly productive harvesting and transport systems that are closely integrated with general and specific industry requirements. In addition, there are opportunities to improve resource use and value through segregation, sending wood fibre to the most appropriate markets, improving the use of wood fibre from undermanaged forests as well as the use of a wider range of species.

⁷: The concept of precision forestry takes advantage of best available knowledge and applied ICT. Standardised production records from Cut-To-Length (CTL) harvesters can be intensively utilised for planning of next harvesting operations and silviculture operations for next generation trees.

State of play

Minerals and metals

The mining industry is a critical source of wealth and employment in non-urban environments where co-existence with other parts of the local community, such as in tourism and regarding indigenous rights as well as national interests such as Natura 2000, need to be solved in a sustainable way. In addition, new ore bodies are more complex to reach and smaller and deeper mines require novel approaches to mining practices. For the aggregates industry, the challenges are also dual in nature. The material produced needs to have a low climate impact, but also meet local environmental expectations related to emissions, noise and dust. From a climate perspective, aggregates need to be locally produced. However, permitting processes for quarries in urban areas requires novel solutions for the entire production system. In the European mining industry most transportation is non-electric and developing and introducing electric vehicles is challenging.

Biotic sector

Ever more precise information systems to guide harvesting operations are under development, relying on technologies such as navigation systems and geographic information systems. Lack of societal acceptance among the public, politicians and environmental organisations is a significant barrier for the sector to grow and for the development of biobased solutions that meet the major challenges facing society. Meanwhile, wood mobilisation from European forests is, to a varying degree, affected by fragmentation of forest ownership. More knowledge is needed concerning the effects of forest operations on general biodiversity and different species, recreational preferences, trade-offs and synergies between different management regimes.

Expected achievements by 2030

Minerals and metals

By 2030, Europe has further developed a comprehensive intra-EU database of primary resources for minerals and metals and carried out an assessment of economic value for the resources identified. Innovative, energy-efficient and fossil-free transportation in mines and quarries has been implemented. One part of this is to secure methods to assess and prove the social and environmental impact, as well as the value created for society; this in turn ensures efficient permitting processes for new, large and small mining operations. Post-closure added-value at exhausted mines has resulted in the increase in biodiversity and improved possibilities for cultural heritage and other industries, such as reindeer keeping, tourism, outdoor recreation etc.

Biotic sector

A new generation of resource inventory and assessment systems, as well as flexible planning tools enabling precise information of quantity and quality at local, regional and global scales have evolved. The consequences of changing ownership structures for wood supply are better understood and this knowledge is used to advise on policy, reducing the negative impacts of these changes. New forest management and wood supply systems have improved the integration along value chains from forest to end-product, shortening lead times, reducing downgrade, increasing capital turnover, improving profitability of forest management and reducing environmental impacts. Enhanced harvesting systems assure reduced soil impacts, such as rutting and erosion, and assist forest operations regarding retention patching, concern for cultural heritage, preservation of the local economy and autochthonous species, water protection areas and other environmental concerns.

Expected achievements by 2050

Minerals and metals

The technological change in the raw materials supply for Europe from European, but also non-European, sources will have an impact on global market developments. The sourcing will be sustainable and more diversified from a wider range of sources. It will have reduced environmental footprint through its production and use phase and will be reintroduced in the circular economy after use. The complete change of the way in which raw materials are extracted and the way in which materials are managed throughout the economic cycle will result in an increased awareness and social acceptance by consumers and will foster a sustainable coexistence of material extraction and processing with local communities.

Biotic sector

Smart coordination of value chains guarantees the highest optimised harvesting of material and a secure, sustainable supply in the best interests of the regional forest-based sector, following the principle of right wood to the right end-use. Forest fibre is recognised as a 100% valuable biobased raw material choice for consumers. New multifunctional forest management solutions and payment models make it possible to meet the increased demand for forest-based materials, making appropriate trade-offs between these materials and numerous other important forest ecosystem services, while enhancing forest biodiversity. Processes are more adapted to societal values, and the requirements of forestry adaptation for resilience to climate change, pests and diseases. Waste in terms of value and energy is reduced through carrying out resource assessment at an earlier stage, and the improved transfer of information down the wood value chain. Forestry is operating across a wider range of forest types and species with better integration of other forest priorities, for example environmental, social and other economic uses of forests such as tourism.

Required Research and Innovation Actions towards 2030-2050



Minerals and metals



Biotic sector

- A. Develop new or adapt existing ICT solutions for sustainable supply chain management from local and regional to global scale, including new, smart and integrated transport and logistics systems
- B. Investigate opportunities to increase the capacity to transport loads, while reducing the number of modes in transit and minimising environmental impacts on the land, CO₂ emissions and energy consumption
- C. Develop concepts for long-term successive land-use planning for the whole life cycle of the extractive operation
- D. Compile a modern database and economic assessment of primary and secondary resources across the EU
- E. Develop knowledge on societal influence and social acceptance of different forest management systems, mining and exploration activities, e.g. research on areas of conflict regarding forestry and mining with regard to human health, ethics, gender, rural development and urban life, social and economic aspects, policy and governance, and new ways for planning and managing green infrastructure

- F.** Assess and develop scenarios for the market demand, availability and valorisation of different raw materials to optimise raw materials supply management in Europe in the global context under changing economic, social and climatic conditions

- G.** Apply ICT and automation to generate information of different raw material resources applicable for the processing and production on different products (2050)

- H.** Develop new land management integrating expertise from both sectors for the benefit of rehabilitation of closing European coal mining areas (2050)



Minerals and metals

- I.** Develop reduced use or recycling of chemicals used for flotation and other processing

- J.** Develop novel deep-sea processing without environmental impacts and integrated waste management (2050)

- K.** Develop in-situ bioleaching at large scale without environmental risks (2050)



Biotic sector

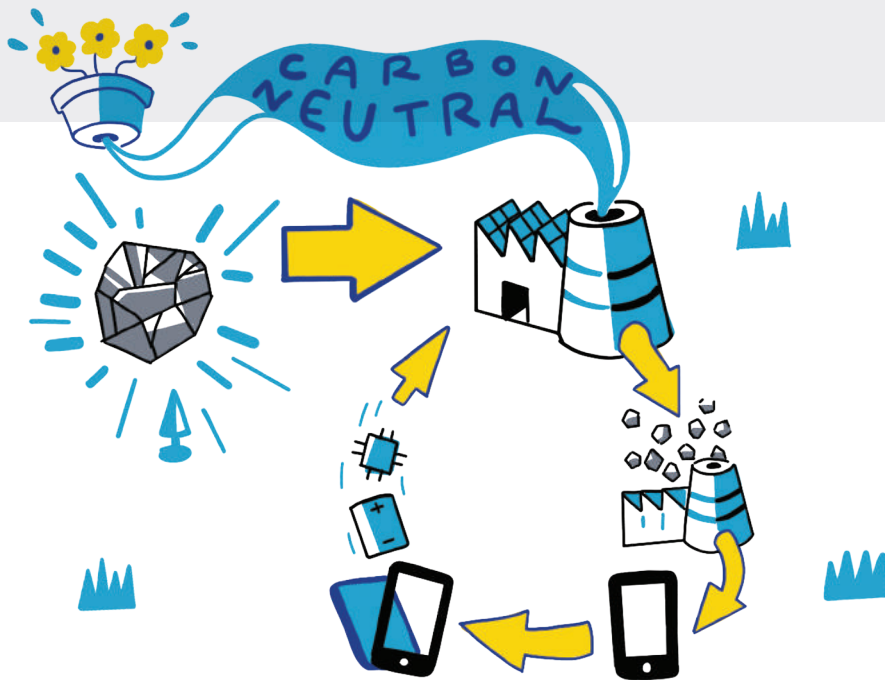
- L.** Explore new space-based, remote and onsite technologies to generate forest-related data, including high resolution space data, LIDAR-, IR- and radar data as well as detailed forest characterisation
- M.** Develop operations to improve wood product quality and utilisation, reduce waste, and increase profits, with reduced environmental impact
- N.** Improve fire resistance, forest management techniques, forest maintenance fire control and avoidance to preserve species and cultural heritage and avoid speculation of raw material
- O.** Apply ICT to develop precision forestry to enhance harvesting and silviculture operations for next generation trees and hard-to-reach stands (2050)
- P.** Develop big data solutions, for example through machine-learning processes, to monitor and suggest solutions for the preservation of biodiversity that cannot be observed by remote sensing or satellites, while performing forest harvesting (2050)

- Q.** Develop sophisticated and multifunctional approaches to forest management for different forest ecosystem services, such as wood fibre production, clean air and water, mitigation of CO₂, tourist industry and wildlife management, to meet the requirements of the UN SDGs and EU regulations (2050)

- R.** Develop coupled strategies for adaptation and mitigation of climate change to sustain and improve the long-term carbon sink strength of European forests, focusing on resilience to climate change and at the same time ensuring increased carbon sink strength through improved growth rates (2050)

- S.** Develop decision support tools for sustainable biomass mobilisation in a coherent way for different geographical (region, landscape, stand) and temporal scales for optimising forestry with different goals (nature conservation, providing ecosystem services, soil protection and water sequestration) (2050)

- T.** Develop regionally tailored forestry measures to reduce the impacts of natural disturbances and increase the resilience of forest ecosystems to climate change to maintain forests as long-term, effective carbon sinks (2050)



PRIORITY AREA 2

Resource-efficient processing for raw materials

Activities to foster resource efficiency in processing, refining and converting of primary and secondary raw materials have resulted in a continued reduction in energy and water use, as well as material input, per tonne of material produced in the European raw materials industries. However, the deployment of new technologies with built-in artificial intelligence and big data will not only contribute to a more resource-efficient production but allow raw materials input to be brought into a new era of customised manufacturing, imposed by environmentally-conscious customers and shifting market demands towards carbon neutral processes. Meanwhile, the circular economy will open new business models for production side-streams that become valuable raw materials for new products

and reuse, paving the way for integrated industrial symbiosis that benefits from old and new value chains.

The EU roadmaps for a resource-efficient Europe and for moving to a competitive low-carbon economy by 2050 outline visions of structural and technological changes that are required to move towards a decreased concentration of carbon dioxide and other greenhouse gases, and to create an economically viable, resource-efficient and climate-resilient economy by 2050. To achieve these goals, further technological innovation is required to reduce material input in production and optimise the use of raw materials allowing for consumer-driven flexibility, which will be enabled by automation and data-driven production sites.

Key research and innovation areas

2.1 Development of resource-efficient, advanced processing for raw materials

2.2 Minimisation and valorisation of residues

2.1

Development of resource-efficient, advanced processing for raw materials



Rationale

Being able to satisfy increasingly more demanding consumers requires a transition to agile manufacturing technologies and mass-customisation. This in turn requires more flexible, on-demand production and assembly processes. At the same time, automated processes and big data solutions, such as inline sensors, will help control and adjust material flows and steer processes towards a new phase of customisation, market driven production that is not only focusing on increased productivity and efficiency, but also on agility and responsiveness. The development of new innovative technologies fostering the use of economically viable and carbon neutral materials will continue to play a key role by offering many opportunities to improve the quality and functionalities of raw materials, while minimising waste and saving on energy and water in processing for raw materials. In this context, the enhanced processing for recovery of critical raw materials from primary and secondary resources will also develop further and result in higher material yields.

State of play

Thanks to the deployment of advanced technologies improving the purity of raw materials, today's mills and plants are increasingly resource-efficient, economically viable and environmentally friendly. Nevertheless, resource-efficient processes imply integrated production and processing chains that supply resources on an 'on-demand' basis.

In **mineral & metal ore processing**, the major difficulties encountered in supplying scarce, critical metals to the market are cost and energy-efficient pre-processing/beneficiation and metallurgical processing that enables refining of such elements and the cost of base metals. A great challenge is to enable carbon neutral metal production. Moreover, most of the unrecoverable losses that exist today on a macro-scale, will increase in the future, since primary ore body particle size will tend to shift towards smaller particles.

During **metallurgy and metal beneficiation steps**, securing the supply of raw materials requires an approach that tackles the complete value chain, particularly the relationship between a resource and a process. Because primary or secondary resources continue to become more complex and of a lower grade, while environmental regulations drastically change, the associated metallurgical processes will continue to raise more technical challenges.

In **wood processing**, the breakdown of logs and sawing are currently carried out with a rip saw, rounding saw or band saw. These technologies, however, limit the possibility for increasing log and lumber yield. New technologies, such as the use of 3D CT scanners in combination with laser cutting, allow the internal features of the log to be digitally reconstructed, enabling an assessment of the optimum cutting solution in real time. By optimising cutting solutions using such laser-cutting technology, the highest resale value of final products can be achieved.

Pulp and paper production is characterised by highly-efficient production facilities with high overhead costs. Breakthrough innovations in wood and wood-fibre-industry technologies, pulping, water recycling, energy recovery and process control may also require changes in preferred and sought-after wood and fibre materials. Processing of non-fibre primary wood raw materials, such as solid wood, chips, flakes and particles, is better optimised for softwood than for hardwood. This is particularly the case in construction-timber processing and larger-dimension solid wood assortments, while the optimisation of processing and the utilisation of by-products and side-streams are more advanced.

In the **construction sector**, the largest raw materials consumer globally, the increased amount of recycled materials in the production phase as well as the digitalisation of the entire process, from integrated design and new controls for material processing to advanced prefabrication, are expected to significantly reduce the required amount of raw materials.

Expected achievements by 2030

New resource-efficient production technologies have significantly helped achieve the targets set out in the EU's strategies for a resource efficient and competitive low carbon economy. More flexible production units, responding to future consumer needs and with a highly skilled workforce, have made a significant contribution to higher production efficiency. Deployment of technologies to reduce industry emissions have contributed to the reduction of energy and water demand and carbon footprint. The positive impact results in lighter, tailor-made products, lower demand for raw materials and additives, increased by-product valorisation and an overall reduction in waste. The biomining concept and its impact on the environment has been explored and tested. Considerations for more eco-design will result in a reduced impact on the environment.

Expected achievements by 2050

As part of the circular economy by 2050, customer-driven manufacturing, fully optimised production and material flows have been achieved thanks to the deployment of big data applications and on-demand customisation of materials and processes in production. Seamless data exchange along the value chains, from exploration and beneficiation, and from harvesting to the production of products designed and manufactured with reduced loss of materials throughout the process, contributes to more economically sound resource consumption, increased sustainability, smart logistics and supplying markets and suppliers with customised products. Solutions for carbon neutral raw materials production are available. In commercial mining operations, microbes play an important role and a full-scale application of biomining, with a reduced impact on the environment, has been achieved.

Required Research and Innovation Activities towards 2030-2050



Minerals and metals



Biotic sector

- A.** Develop flexible and adaptable production technologies of both primary and secondary raw materials resources that satisfy more demanding processors' and manufacturers' specifications to comply with changing standards and legislation
- B.** Develop Industry 4.0 solutions to improve process control for optimised primary and secondary processing of raw materials and design to fully control the material flows with regards to specific assortments as well as products, allowing for on-demand customisation
- C.** Develop sophisticated big data and ICT-based production technologies that allow for optimised energy efficiency and energy management throughout production
- D.** Develop closed systems for water cleansing and recirculation to reduce water consumption throughout production
- E.** Enhance the microbiological stability of industrial water systems
- F.** Develop innovative energy-efficient screening, classification and dewatering technologies
- G.** Develop advanced purification processes in hydrometallurgy and pyrometallurgy as well as for wood-based raw materials
- H.** Explore new technologies and synergies between the sectors that create closed loops to achieve carbon neutral processes
- I.** Optimise yields and energy efficiency of processes
- J.** Support the industrialisation of the construction sector by tailoring specific processing solutions that require a minimal amount of raw materials
- K.** Increase the monitoring of construction materials during their service life to optimise materials processing
- L.** Develop advanced ICT, including augmented and virtual reality, to meet highest process efficiency, improving material flow, resource efficiency, process stability, and machine productivity that allow for customer-driven, on-demand customisation (2050)
- M.** Develop sophisticated CO₂ valorisation techniques (2050)



Minerals and metals

- N.** Create innovative crushing, (selective) grinding and sorting technologies, the most energy-intensive parts of mineral processing, to reduce energy use
- O.** Develop dry separation technologies for fine particle processing
- P.** Develop more efficient and environmentally compatible flotation technologies
- Q.** Advance biomining
- R.** Develop commercially viable refining of critical raw materials in Europe
- S.** Develop advanced, more energy-efficient hoisting technology



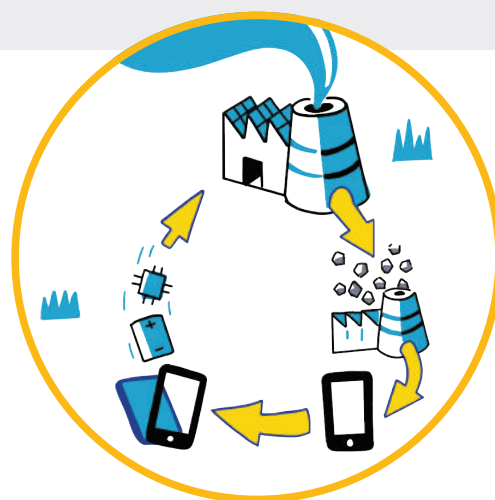
Biotic sector

- T.** Analyse the possibilities for primary-refining processes during forest harvesting to fully utilise the extreme variability of forest wood and fibre properties and to avoid waste and downgrading at merchant, secondary processor, or consumer stage
- U.** Develop and verify (complex) manufacturing lines allowing for increased wood and lumber yield, for example through 3D CT scanner use and laser cutting
- V.** Develop production technologies which optimise energy efficiency and energy management in defibration of wood, drying of sawn timber, production of panels, paper and board
- W.** Develop new processes and technologies for the modification of different wood assortments, such as solid wood, flakes, particles and fibres as well as for less robust species, to increase durability
- X.** Invent a functional surface treatment to enable bulk material reduction, enhance durability and final product properties, or to extend life cycle
- Y.** Enhance and improve processes and technologies for the modification of wood assortments, including lignocellulose (2050)



2.2

Minimisation and valorisation of residues



Rationale

A near-to-zero-waste concept aims to minimise waste and by-products throughout the production process. Turning residues into “feed” materials across industrial value chains helps create fully-integrated industrial symbiosis across the raw materials sectors. This results in novel business opportunities building on current and future value chains that enhance cross-sectoral cooperation in line with the principles of a circular economy. Such strategies for industrial symbiosis, in which by-products of one industrial process are re-inserted as a resource into another, contributes in turn to boosting the global competitiveness of European industries.

State of play

Already today, residues and side-streams are increasingly being treated as by-products, demonstrating how processing residues can be turned into added value materials with advanced functionalities to substitute fossil-based materials. During the processing, refining and converting of raw materials within **minerals and metals**, typically by-products, side-streams or wastes are produced simultaneously. There is huge potential to reduce waste or increase the value of current low-value side- and waste streams or by-products. Moreover, waste management in the context of mine closures will become a major challenge that needs to be addressed in terms of its economic and environmental impact.

In the **biotic value chain**, an increased use of residues from raw materials processing, for example bark, chips and sawdust, to make wood panels or pulp have significantly increased resource efficiency since 1990. Nevertheless, further progress is essential including improving the value from these by-products and creating new market possibilities for low-quality wood assortments, such as from thinning, and other forest management activities. Moreover, extraction, utilisation and profitability of forest-based materials such as branches, needles and stumps should also be considered. These biotic resources are partly needed for soil rutting protection and nutrient balance, but still a considerable amount of the entire stem volume (10-25% depending on region, species etc.) might be utilised as an additional raw material source from forestry.

Expected achievements by 2030

Innovative industrial symbiosis that integrates various value chains and creates new raw materials sources have been put into practice involving multiple stakeholders and emerging value chains. Innovative technologies for the processing of secondary sources have been developed to make waste a resource, residues an asset, including critical raw materials and lower-quality wood assortments. A wide range of bulk materials and added-value products resulting from the new and improved technologies have been demonstrated and provided in the market. At the same time, the standardisation development of material qualities has been followed up and adapted.

Minerals and metals

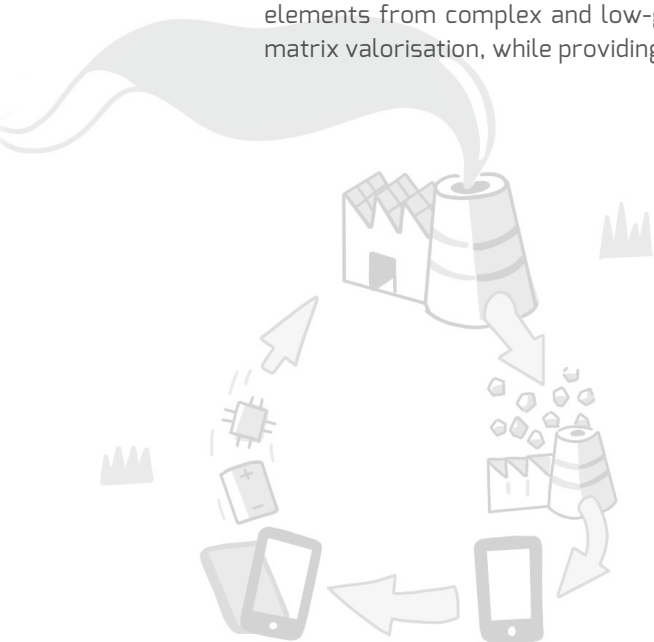
Raw materials and nutrients can be recovered from wastewater streams⁸, tailings or industrial side-streams, including the utilisation of the remaining residues⁹. The new and improved technologies are used for piloting the reprocessing of suitable old tailings and end-of-life material streams.

Biotic sector

Advances in processing and the introduction of wood modifications to improve its performance in outdoor conditions and increase its resistance prevent valuable raw materials from going to landfill in the short and medium term.

Expected achievements by 2050

A highly integrated, circular, flexible and modular concept of the factory, following the principles of ManuFuture¹⁰, will permit industrial symbiosis within and between minerals, metals and the biotic sectors. The generation of waste is minimised or valorised by the recovery of valuable elements from complex and low-grade feedstocks combined with technologies for residual matrix valorisation, while providing stable solutions for toxic remnants.



8: Such as phosphorus

9: For example, in the form of aluminosilicate-based products for another industry or consumer sector

10: <http://www.manufuture.org/>

Required Research and Innovation Activities towards 2030-2050



Minerals and metals



Biotic sector

- A.** Continue to develop knowledge of useful and harmful chemical compounds to develop innovations for the removal of chemicals, inks, additives etc.
- B.** Invent new, innovative concepts for the re-use of treated water as part of industrial symbiosis
- C.** Improve recovery of energy as well as valuable materials from slag, thereby turning residues into a resource
- D.** Develop methods and technologies for dust prevention
- E.** Develop and demonstrate alternative feedstocks from industrial side-streams including CO₂ valorisation
- F.** Develop and demonstrate options for industrial symbiosis dealing with industrial and urban waste
- G.** Develop value-added products from by-products, and extracted components from process water
- H.** Create databases for available by-products, residues, side-streams, including material quality standards, at industry, company and site level which ensures the circularity of resources within and across sectors
- I.** Develop new materials from extracted components and waste fractions (2050)



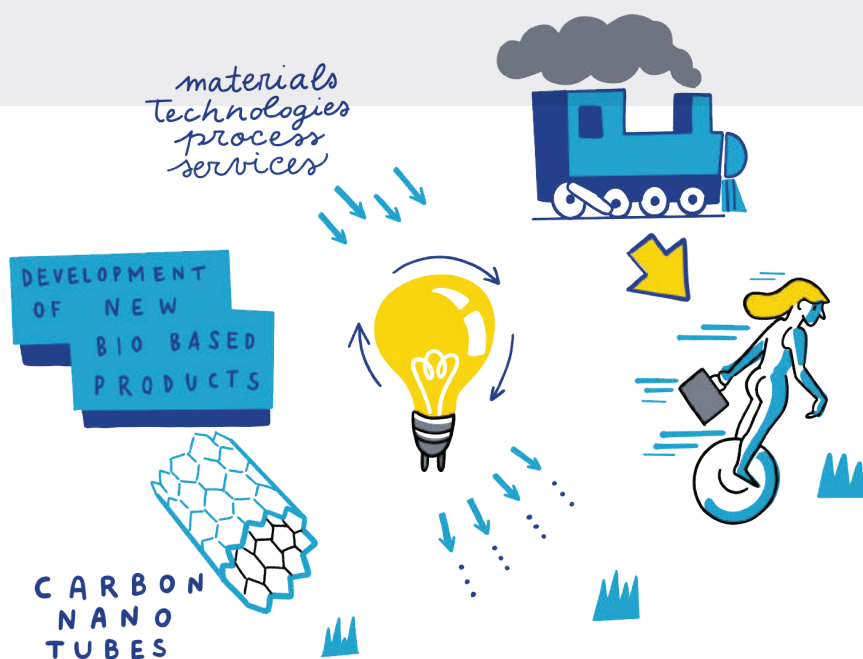
Minerals and metals

- J.** Develop metallurgical processes for low-grade and non-conventional ore deposits, such as complex polymetallic ores and secondary material streams
- K.** Enhance biometallurgical processes (extraction and concentration of metals)
- L.** Develop new processes, such as plasma technology, electron-beam technology, etc.
- M.** Develop new extraction technologies based on hydrometallurgy and/or pyrometallurgy or combination of the two
- N.** Develop innovative and smart metallurgical process routes for maximised resource efficiency with minimised environmental impact
- O.** Develop new methods and technologies for mine closure and remediation
- P.** Develop improved beneficiation technologies to increase yields from old mine waste disposal sites



Biotic sector

- Q.** Enhance the valorisation of medium-high added value products from side-streams with technologies that allow for full utilisation of processed biomass, such as lignin and other non-cellulosic components
- R.** Develop the use of by-products as fertilizer, found in waste water from wooden board gluing processes (water with high levels of nitrogen and urea) to reduce chemical fertilizer use
- S.** Enhance the valorisation of residues or natural extracts such as biocides
- T.** Develop new technologies for recycling fibre boards into new products and develop new binder formulations to valorise glue waste
- U.** Continue to develop close-to-market and market deployment of high-value products from side and waste streams with technologies that allow for a full utilisation of processed biomass, such as lignin and other non-cellulosic components, on an industrial production scale (2050)



PRIORITY AREA 3

Raw materials in new products and applications

By 2050, globally, there will be more competition for raw materials due to an increase in new advanced materials for specific applications including alloys, hybrid and composite materials, nanomaterials, and biobased materials. Market driven characterisation of new and advanced materials will deliver enhanced performance in new advanced products and applications, such as higher and multi-functionality, better safety and improved environmental performance all delivered with less raw materials, in response to consumer demands. Therefore, the industry needs to respond to the increased demand for raw materials and develop new, sophisticated materials with advanced and new functionalities.

The characterisation of existing materials, their qualities and performance abilities as well as their fate in the course of their use

phase will have to be studied in more detail. In addition, there will be a need for research on higher and multi-functionality of materials. Life-cycle assessment and environmental footprinting will remain key tools to understand and manage materials in the future. Basic economic and social research and monitoring are needed to identify economic, policy and market drivers to provide the industry with up to date information on whether certain commodities could become critical or experience bottlenecks in supply.

In future, more materials will compete for varied uses. Increased automation and artificial intelligence will drive demand for ore technologies and with it more materials. Potentially, this can lead to temporary or longer-term shortages which might need substitution strategies. The substitution of high-value materials can be achieved by

developing applications with an equivalent technology that does not rely on the same raw materials.

New advanced products include emerging biobased solutions and applications that will be key enablers with equal or better performance in the move from fossil fuels towards a sustainable low-carbon society. These advanced products will also have a competitive advantage with regard to performance/cost ratio compared to earlier

products. The current trend highlights the development of new material properties for new products and greater flexibility in manufacturing and production, contributing to a more judicious use of raw materials through product design. Through increasing use of information technology and digitisation along the value chain, future products will be traceable and optimised, from raw materials to final products, regarding environmental impact and raw material utilisation.

Key research and innovation areas

3.1 Development of material applications and markets

3.2 Development of new biobased products

3.1

Development of material applications and markets

Rationale

Product manufacturing has evolved from mass production, when a small scale of standard products was designed, to the current job-shop manufacturing structure, where customers can select customised products for their needs from within a wide range of options. High performance, high quality and competitive cost are the key aspects, together with as short as possible product development time. Moreover, the life-cycle energetic cost of the product, its durability and the possibility of recycling, play an ever more crucial role.



To satisfy the needs of consumers the use of sophisticated optimisation techniques is rapidly growing, including the development of nano-structured and nano-functionalised materials, composites and hybrids. At the same time, the development of new manufacturing processes, such as additive manufacturing, responds to the requirements of different materials. Hybrid materials are composites including two or more materials mixed in different scales, for example on a microscopic scale, to create more homogenous or new material properties. Composites could include both mineral, metal and biotic material sheets in a wide range of applications from transportation to construction, ranging from metal composites and reinforced plastics, such as fibre-reinforced polymers applied in aeronautics and automotive parts, to concrete and mortar panels used in building and infrastructure.

The major drivers for down-stream markets have been identified as follows:

- Staying a competitive economy and having competitive enterprises on a world or EU market depending on supply and demand situations
- Maintaining current standard of living for the EU population and enabling other parts of the world population to achieve similar standards
- Increasing health and safety
- Reducing environmental footprint
- Reducing energy consumption and emissions of climate change gases

In **transportation**, the main driver is energy efficiency, related to the issues of weight reduction and electrification. Weight reduction can be achieved by replacing traditional raw materials with composites and alloys, i.e. multi-materials. This encompasses road vehicles as well as trains and aeroplanes where carbon fibres may play a major role. Electrification of cars pushes the market to develop new battery storage systems and/or more durable hydrogen fuel cells, and to allow higher density electric motors to be used.

Electronics and consumer goods are becoming smarter and more complex, most of them include more than 50 raw materials to provide all their functionalities. The technology lifetime of these appliances is substantially shorter than the lifetime of their raw materials. Product replacement is mostly triggered by next generation products, providing higher performance with the same or lower cost. Use of critical and expensive raw materials in these products is continuously reduced by down-gauging, ICT, and new production technologies, for example circuit board printing and thin films using less raw material quantity for the same or better functional performance.

The **energy sector** is seeking continuous growth in the volume of advanced materials used, permitting it to generate, convert and transport energy at maximum efficiency with minimum energy losses. This has a particular emphasis when dealing with renewables, as is the case of photovoltaic energy. Higher efficiency demanded by the process industry is related to the intensive use of catalysts, optimising the use of raw materials and intermediates, limiting the use of polluting or noxious chemicals, and increasing yield in a sustainable way.

In the **construction sector**, there is an increased demand for advanced materials with new (multi-) functionalities, e.g. (self-) monitoring, self-healing and the ability to improve durability, strength, energy efficiency, and the health and comfort of people and the environment. A combination of strength and insulation with surface treatment for colour, hardness, humidity control or fire safety can also be obtained with recycled products and new biobased solutions.

State of play

There are challenges to meet the demands for the drivers identified above.

In terms of quantities of **bulk materials required**, there is an increase in global demand driven by population growth and the need to raise standards of living worldwide. Infrastructure and housing are key drivers, but also development of energy infrastructure can have an impact.

Enhanced functionality as well as substitution in applications are driven by availability, price, functionality and sustainability.

As of 2017, the list of **critical raw materials (CRM)** comprises 20 materials¹¹. It is understood that there will always be critical materials needed by the industry for their technological functions. The list of such materials will evolve with time and with industrial priorities. Critical raw materials are not only driven by politics and supply issues, but also because their processing is in some cases considered environmentally difficult. Public acceptance will be lacking if this challenge is not resolved. Therefore, there is a need to understand both the market drivers of CRM, but also why these materials are not being processed.

The fabrication of **composite structures and products** is evolving from being manually labour-intensive, to automated manufacturing methods, including the use of intelligent feedback monitoring systems and robotic technology. Developments in automated integration of pre-form fabrication and moulding already make available technologies more desirable from the point of view of economics and productivity.

Substitution efforts will concentrate on ensuring access to the relevant function, enabled by critical materials, overcoming the risk of supply shortages. Currently, substitution projects are lacking the momentum to cross the “valley of death” (i.e. bringing the results to market) due to political interference in global markets. The strategic relevance and the long-term vision of such projects usually clash with difficulties in terms of entrepreneurship for sponsoring long-term investments, as well as the inherent risk in substituting something that risks becoming obsolete through the natural product cycle.

Expected achievements by 2030

There is an increased demand for producing more with less raw materials to satisfy the needs of society and a growing global population. Base-load demand must maintain the standard of living, drives excellence and leadership, secure sustainability, functionality and security of supply.

Composites are widely employed in building materials and consumer goods, giving rise to a revolution in product design. New types of composite concepts can be derived from hybrid construction systems combining the best properties of minerals, metals and biotic materials in high performance, prefabricated and fully-finished modular elements and structures for housing.

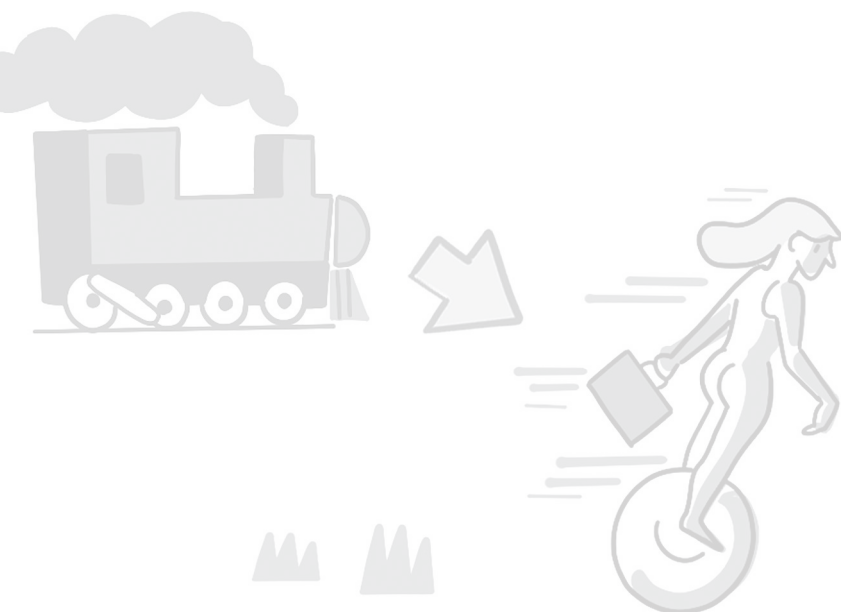
¹¹: The methodology for assessing criticality was defined in 2010, and since 2011 the list is updated every three years, on the basis of the technical and market demand of materials, as well as the socio-economic conditions worldwide.

Miniaturisation and nanotechnology are key enablers for advanced (neuro)bionics, for which biocompatibility and the impact of new materials on human well-being and health is much more of an issue than their design for recycling. Moreover, harmonised data exchange along the supply chain and between stakeholders has increased the performance of the industry. Business models are based on consumer and end-user perceptions. Interactive communication has an important role to play.

Expected achievements by 2050

Substitution projects for critical raw materials are implemented with success, leading to a re-thinking of the global process of consumer products – if not a significant revolution. The way energy is produced, transformed, stored and transported is also involved, generating a common understanding of the problem and recognition of the issues by consumers. An innovative generation of products has encompassed the current concepts and a holistic process, starting from the conception phase, drives the manufacturing and consumption phases. Aspects of awareness, training and education are fundamental to ensuring the penetration of substitution efforts, in particular whenever the substitute is not in an optimal cost-performance position.

Technology adaptations such as additive manufacturing, biomimicry of materials and self-healing materials have substituted many linear economic solutions. Wide circulation of nano/micro-structured and nano/micro-functionalised materials has been achieved. The positive effects of materials improving the living environment (housing, work, automotive/transportation) and human well-being and health are fully understood and adopted in the design of new products.



Required Research and Innovation Activities towards 2030-2050, but not limited to:



Minerals and metals

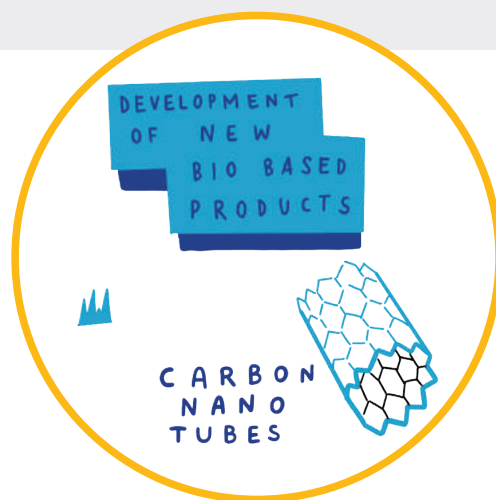


Biotic sector

- A. Explore new materials, such as ceramics, composites, independent of the super-alloying elements of critical raw materials that provide advantages in terms of density, thermal resistance, toughness and mechanical performance
- B. Develop new materials for new products and design
- C. Create smart solutions and new business models associated with a materials revolution leading to independence from critical raw materials in the EU
- D. Develop novel materials and integrate in designs for substituting critical materials
- E. Continue monitoring process environments, components and materials to prevent damage and maximise the lifetime of components and materials
- F. Demonstrate energy conversion, for example, in wind turbines and electric motors, by exploiting permanent magnets with reduced content of critical raw materials
- G. Demonstrate the use of photovoltaic materials with reduced content of critical raw materials but retaining current performance standards
- H. Create energy storage which is enabled through a low content of critical raw materials, with respect to current state-of-the-art batteries, and with improved energy density
- I. Develop biocompatibility, miniaturisation and nanotechnology for applications in advanced (neuro)bionics
- J. Develop cost-effective integrated prefabricated building systems including hybrid and composite materials, timber and other biobased construction materials
- K. Develop economical, more durable and resistant composites, alloys and multilayer materials that enable the extension of the life of a product
- L. Develop construction products that can be dismantled and modularised considering also reversibility of manufacturing, to recover raw materials during maintenance or product end-of-life without (or with minor) further chemical/physical/mechanical operations
- M. Explore new building materials installation and fixation systems focusing on the development of new industrialised construction methodologies
- N. Develop applications that allow the use of secondary materials with higher concentrations of impurities or degraded molecules, thus offering new market opportunities for recycles
- O. Increase the durability of construction materials
- P. Conduct market and/or social-economic research on economic, policy and/or market drivers for products and markets in the light of the current state of the art ICT and automation
- Q. Monitor new developments in new areas that have impact on new products and markets
- R. Conduct social science and/or market trends research on the drivers for consumption in light of sustainability, new markets and population growth, for example
- S. Conduct social, economic and/or market research on the impact of public policy on material sciences, raw materials and material design
- T. Demonstrate and fully integrate restorative environmental and ergonomic design (REED) strategies into the construction, interior design, transportation, and other sub-sectors of the circular bioeconomy, including the preparation of business models and broad strategies for the uptake of the knowledge created in this field up to 2030 (2050)

3.2

Development of new biobased products



Rationale

Building a circular bioeconomy in Europe requires significant investment in the development and innovation of new and sustainable alternatives to current fossil-based and non-renewable materials.

The complex chemical composition and physical structure of biotic raw materials offer a solid starting point to be exploited and incorporated in future biobased products. New and improved products from cellulose, lignin, hemicellulose, bark and resins (including natural rubber) are valuable resources in a world that craves more sustainable raw materials.

In addition, the positive effects of wood on indoor climate and human well-being need to be further investigated and established as this may play a vital role for human health issues.

State of play

Today, cellulose pulp and sawn wood are the primary products of the forest-based industries. These are further refined into a spectrum of products, ranging from commodity products to consumer and building products. Many new applications are under development for mass deployment and commercialisation. In particular, the housing sector needs more advanced and reliable solutions that can be used in industrialised and sustainable construction systems. Clear trends are visible, as seen in the development of new non-wood fibre sources, biocomposites, printed electronics, micro-fibrillated cellulose, new packaging concepts, new paper qualities, insulation materials, clothing and food products.

Rubber-based products are essential for the automotive industry and speciality products. However, research is needed to determine optimal or “good enough” purity levels in materials that offer solutions with higher strength, lower resistance, lighter weight, increased control of the light spectrum, and greater chemical reactivity, among other benefits, for new applications.

Expected achievements by 2030

Many new biobased products and applications have been commercialised and are widely used as substitutes for materials from non-renewable sources. Applications ranging from textiles to building structures have been developed creating green growth and jobs. Additive manufacturing has substantially improved production processes through the integration of enhanced material properties, such as connectivity and water-repellence. The durability of wood has been upgraded using specific additives, modifications, material selection and conditioning processes. Advanced biocomposites are used, for instance, in automotive parts, while bioplastics bring novel solutions to the packaging sector. Meanwhile new wood-based products with self-healing properties have significantly reduced maintenance needs.

Expected achievements by 2050

Biobased products provide the highest possible value added from primary and secondary raw materials. Renewable and recyclable products satisfy the demands of the 2050 consumer society. Wood-based construction materials have helped the sector achieve an 80% reduction in CO₂ emissions compared to 2020. Packaging plays an even greater role in society, offering advanced and smart solutions for smaller- and larger-sized packaging, based on advanced design and nanotechnology while producing less waste. Investment in research, development and innovation has led to the full deployment of new biorefinery processes to produce textiles, chemicals and new materials, including composites and also pharmaceutical, dietary and healthy food products for customised market needs.

Required Research and Innovation Activities towards 2030-2050



Biotic sector

- A.** Develop value-added applications for extracted wood polymers, nanofibrils, lignin, hemicellulose, pulp fibres and paper, for example, for carbon fibres or ultra-lightweight composites
- B.** Adapt biomimetic design approaches and integrate recycling-oriented product design criteria into the development processes of new biobased products
- C.** Improve existing, long-lasting adhesive systems for flakeboard, medium density fibre board (MDF), oriented strand board (OSB) and plywood board as well as for glued laminated timber
- D.** Develop new weatherproof and fire-resistant wood-based panels, fibre-based insulation materials and wood-polymer composites suitable for exterior use
- E.** Research and develop structured and nano-structured surfaces of all kinds, for any use, and using new techniques to avoid microbial and bacterial activity with the aim of improving the performance of wood- or fibre-based packaging materials
- F.** Develop smart and intelligent features for applications based on printed electronics or printed biosensors, functional inks and tags, for example, in packaging
- G.** Develop enhanced lightweight and hi-tech products that are moulded, extruded or assembled from wood components
- H.** Improve the basis for efficient, sustainable and competitive use of wood in wood-based buildings by developing better documentation, better database systems and enhanced calculation methods for construction
- I.** Develop indoor system solutions including multi-material concepts and multi-functionality for wood and wood-based products in interior fittings, furniture, and everyday products that promote human health and well-being, that respond to changing needs of inhabitants (ageing inhabitants, changing family structures, growing children etc.)
- J.** Develop additive manufacturing in production, for example 3D printing, injection moulding, including new business and warranty models



PRIORITY AREA 4

Closing material loops by maximising the recycling of products, buildings and infrastructure

The shift towards increased material efficiency in manufacturing will highlight the demand for more complex and diverse material compositions in various applications, from consumer products to buildings and infrastructure. The move towards circular economy policies will provide significant momentum for the optimisation and redesign of the whole product life-cycle. This includes product design, manufacturing, use and end-of-life (EOL). Actions are needed to increase knowledge and develop tools that enable maximum recovery of useful materials and work towards closing material loops. From the very outset of the product design phase, innovations need to address both the recycling and extended lifespan of products made from minerals, metals and biotic raw materials. Success will require creating new

relationships between stakeholders within and across multiple supply chains.

This roadmap priority area specifies three key research and innovation areas for a successful future; the first is to increase the efficiency of recovery processes, the second is to have a more successful reuse and recycling of complex products, the third and final is to strike a better balance between costs and benefits in the recycling loop.

A common enabler for these priority areas is the replacement of the current material-centric perspective and its corresponding waste hierarchy principles with a product-centric perspective. In such a product-centric approach, product life-cycles are conceived and designed to enable a maximum recovery of useful materials.

Key research and innovation areas

- 4.1 Increasing material recovery by efficient detection, sorting and separation
- 4.2 Reuse and recycling technologies adapted to complex, durable and miniaturised products
- 4.3 Developing and integrating methods for assessing and optimising cost and benefit in recycling

4.1

Increasing material recovery by efficient detection, sorting and separation



Rationale

Recycling is an option to obtain materials from processed goods and a means to enhance resource efficiency that, in turn, relieves the pressure of extracting and harvesting resources from nature, while preventing the need to dispose of materials in the environment. However, complete recycling of products, parts and components, with a view to recovering pure raw materials with their original performance and value, is environmentally, economically and technically neither achievable nor feasible. Often, today, the original functionalities and material value cannot be recovered in the recycling process, particularly when the material concentration is low, different materials are being mixed, or the material is susceptible to degradation. Innovative solutions are essential to improve the value and the market opportunities for recycled materials.

State of play

The EU has already become the global leader in recycling end-of-life products, metals, paper, packaging and several industrial wastes despite the existence of heterogeneous practices, standards and regulations across the Union. The European **wood processing industries and pulp and paper sector** have a well-known tradition of using residues as a secondary raw material or as a bioenergy source for their industrial processes, with products being up to 100% manufactured from recovered fibres and wood. A good example, and one that is still evolving, is the paper fibre loop: the sector attained a recycling rate of 71.5% in 2015¹² and maintains efforts to raise this level through progress in paper collection, sorting, and in recycling and de-inking technologies. Particle board manufacture also has a good track record in combining recycled wood with virgin fibre, and there is potential for further development for engineered wood products and composite materials. It is necessary to increase the reuse ratio of bulk materials, including wood-based materials and foams, to reduce bulk waste going to landfill.

12: http://ec.europa.eu/environment/waste/construction_demolition.htm

Construction and demolition waste (C&DW) is one of the heaviest and most voluminous waste flows generated in the EU, accounting for around 25% to 30% of all wastes. It includes concrete, bricks, gypsum, wood, glass, metals, plastic, solvents, asbestos and excavated soil. Moreover, in Europe there are several seismic areas, where recent earthquakes have further increased the volume of C&DW. The potential to raise levels of C&DW recycling and material recovery is estimated to range between less than 10% to over 90%, with an average value of 54%¹³. A market for secondary aggregates derived from C&DW is in place while the technology for separation and recovery is accessible mainly for down-cycling low-grade C&DW applications. Yet, there are challenges to increase the value of C&DW used in more high-end applications. It is of great importance to improve C&DW recycling in those Member States where the rate is low. Moreover, several types of waste still have limited application and reuse and require a high-value recovery.

Similar goals need to be achieved for the recycling of **critical raw materials (CRM)**, where significant deficits still exist, with low collection from consumer products and low recycling rates for most technology metals (in some cases below 5%). Recent studies on recycling of EOL products with respect to CRM shows that, during the next decade, recycling is unlikely to substantially contribute to the global rare earth element (REE) supply. In general, efficient metallurgical separation and refining projects remain the main challenges and significant research and innovation efforts are needed to bring about more efficient recycling practices.

Expected achievements by 2030

By 2030, a product-centric approach to waste management, starting from material composition and product design, has allowed for a coherent and consistent integration of recycling in a circular economy. Substantial increases have been obtained both in recycling rates, quality and applicability of recycled materials. End-of-life management is fully integrated into the product's value chain. Mining, harvesting and industrial processing have minimised residues and increased waste feeding into other added-value uses. Innovative and comprehensive solutions have contributed to raising the rates of recycling and recovery of C&DW to well above 70% in the EU¹⁴. In addition, a shift in relation to the ownership of products, in which product manufacturers retain ownership of equipment and devices with economically valuable raw material content, could provide opportunities for achieving higher collection efficiencies and dramatically change product design and longevity.

Expected achievements by 2050

Optimised C&DW reutilisation, significant improvements in recycling rates of critical and technology metals and composite materials, as well as enhanced extraction from secondary sources in all Member States have expanded the overall availability of resources for the European economy. This makes a crucial contribution to maintaining the EU's independence from external supplies of raw materials. Multilateral, international cooperation through dedicated networks and logistical platforms have been operating and maintaining the viability of collection, recovery, recycling and transport of waste and materials. A vital industrial symbiosis has emerged underpinning EU-based businesses. Recycled paper and board material is used as a major packaging material, fulfilling the safety demands of logistics and consumers.

13: http://ec.europa.eu/environment/waste/construction_demolition.htm

14: Target laid by the EU Waste Framework Directive for 2020: http://ec.europa.eu/environment/waste/target_review.htm

Required Research and Innovation Activities towards 2030-2050



Minerals and metals



Biotic sector

- A.** Create European cooperation through dedicated networks and logistics platforms to improve and increase the viability of transport and recovery of materials in Europe, including C&DW
- B.** Develop new product-centric process technologies for separation, fractionation or extraction with improved selectivity for various components in recycling stock which enables utilisation in value-added applications inside and outside the production value chain
- C.** Develop flexible disassembly, sorting and separation technologies that can deal in a cost-effective manner with increasing levels of impurities within recovered materials as well as various processing incompatibilities
- D.** Develop technologies to extend the use of residual products and waste as feedstock in building- materials production (pre-treatments of wastes, quality control of waste and final products manufactured with waste) with the support of public procurement
- E.** Improve treatment technology for C&DW comprising pre-treatments and/or characterisation of waste, quality control of waste and final products containing waste
- F.** Explore waste and recycling technologies that provide effective sinks for (eco-)toxic substances and materials to avoid reuse in a circular economy
- G.** Develop innovative technologies for the value-added use of separated and extracted components from waste water treatment
- H.** Develop integrated processes and systems to recover and reuse mineral resources utilised in pulp and paper making, e.g. fillers and pigments in a cross-sectoral symbiotic approach
- I.** Develop new certification and traceability methods for construction materials to enable better control of C&DW
- J.** Develop new education and awareness tools to increase collection rates among citizens
- K.** Enhance multilateral, international cooperation through dedicated networks and logistical platforms to increase or maintain the viability of transport and recovery of materials in Europe (2050)
- L.** Develop effective solutions for the recovery of useful elements within toxic waste (2050)



Minerals and metals

- M.** Investigate methods and technologies that enable recycling of critical metals (e.g. germanium, tungsten and REE), technology metals (e.g. lithium and tellurium), and toxic metals (e.g. mercury and arsenic)
- N.** Recover critical metals from industrial residues, such as gases and ashes, on an economic scale
- O.** Recover critical raw materials, for example indium from gases and ash from the concentration of base metal ore, and the future recycling of display applications on an economic scale, to increase yield



Biotic sector

- P.** Develop systems for converting recovered, solid wood products into fibres and other high-value products
- Q.** Improve paper collection systems and sorting technologies for enhanced paper quality for recycling of the different paper grades
- R.** Develop agile sorting systems using new sensors for detection and robotic technologies for paper, wood waste and forest residues to separate according to different types of fibres, inks and fillers, contaminants and soil residues and resulting in higher sorting accuracy and velocity
- S.** Improve separation and cleaning technologies, by using physical chemistry and/or industrial biotechnology, for a further closure of water cycles and to reduce the amount of discharged effluent
- T.** Research the treatment and pre-treatment of recycling stock, including biotechnology processes for pulp and paper, for recycling and other wood-based products
- U.** Develop non-destructive wood property measurement techniques and systems that allow for traceability of individual wood objects, for optimised resource utilisation
- V.** Enhance separation, detection and cleaning techniques for turning recycled, solid wood and/or fibre-based products into highest-possible-value products (e.g. specialty, high-purity chemicals, food additives, pharmaceuticals, etc.) (2050)



4.2

Reuse and recycling technologies adapted to complex, durable or miniaturised products



Rationale

Over the next decades, an increased demand for purer raw material qualities to manufacture goods is expected, while their recycling will be far more complex. This is especially the case with regard to the concepts of miniaturisation, the merging of multiple functionalities into a single device, and nanotechnology applications, to name a few, that represent the trends in product development.

In product design and development, the recent trend of product miniaturisation demands excellent separation technologies and intensive efforts to recover low volumes from high added-value consumer goods. The shortening of both technology and product life-cycles and the introduction of disruptive technologies, particularly in photovoltaics, packaging, ICT, batteries, consumer and professional electronics, makes it difficult for the recycling industry to keep pace. In addition, there is a need to determine an appropriate flow of secondary raw materials and develop strategies to make, for instance, paper fibres more resistant to degradation during recycling loops.

State of play

In the EU, as in most developed regions of the world, the mass of electronic devices placed on the market has been decreasing over the past years¹⁵. In the final products, minerals, metals and biotic raw materials can be mixed in complex structures that are not able to be dismantled or disintegrated, for example, in metallic-ceramic-bio composites. Increasingly, new technologies and innovative products are brought to the market before viable and suitable recycling technologies are in place. At the same time, existing recycling technologies and facilities might become obsolete before achieving targeted return on investment. The private investment in such technologies, and thus official collection rates, remain particularly low.

15: http://ec.europa.eu/eurostat/statistics-explained/index.php/Waste_statistics_-_electrical_and_electronic_equipment

Expected achievements by 2030

Digitalisation and block-chain technologies have enabled sufficient information flows on the traceability of materials. All recycling business should be certified to ensure citizens' trust in terms of product safety, and administrative control.

Expected achievements by 2050

By 2050, retailers, industries, raw materials suppliers and research institutions in the internal market are interwoven, minimising fragmentation. They jointly possess all the technological leadership and know-how required to operate in a symbiotic industrial environment in the EU. The collaborative efforts of various institutions and public authorities in Member States have resulted in adjustments of the legal and social framework for the uptake of innovative recycling technologies.

Required Research and Innovation Activities towards 2030-2050



Minerals and metals



Biotic sector

- A. Develop treatment technologies capable of handling-specific input combinations that allow high yields and purities from complex products to be obtained, e.g. alloys and composites with low concentrations of various valuable materials
- B. Deploy technical means for tracking and tracing of material flows, e.g. by tagging relevant products and components such as mobile phones, circuit boards, batteries etc. with radio-frequency identification (RFID) chips or other types of tags
- C. Devise recommendations on technical design for disassembly, recycling and detection, including the obligation for clear identification or labelling
- D. Develop demonstration projects to evaluate reusability and recyclability of specific resource streams on different scales and across different geographical dimensions, including local, city, regional and rural areas
- E. Integrate digital systems to optimise circular design and circularity of raw materials and critical raw materials with a view to increasing the levels of, or realise smart substitution of, recycled, secondary and waste material in product materials
- F. Expand systematic research on materials and their properties, modelling routes for tailored material performance throughout their lifespan and within a particular value chain, mainly for bulk applications or critical raw materials
- G. Investigate additive manufacturing technologies to improve durability and functionality of products as well as streamlining design for easy maintenance, easy upgradability and modularity, including new business models and warranty aspects
- H. Develop incentives for new added-value technology solutions and business concept models that allow for expanding the use of recycled and recovered raw materials

- I. Develop tools and systems that enable information exchange on product design, architecture and composition along the value chain, for increased integration of end-of-life management of the product's value chain, and for enhanced impact and efficiency of recycling processes
- J. Develop technologies and analytical processes for improving and examining recycling quality and reducing contamination without referring to the origin of a material, also adaptable for use on a small scale
- K. Develop small-scale and mobile technologies to adapt to decreasing volumes of consumer goods and of the concentrations of critical and valuable materials they contain
- L. Develop viable and suitable recycling technologies to anticipate the spreading of potentially disruptive technologies and innovative products in advanced applications
- M. Develop design concepts for ensuring recyclability of hybrid products and technologies for the separation and reuse of used material components
- N. Develop prototypes of new materials containing construction waste for use in other applications with similar characterisation
- O. Develop new business models and markets for recycled/recovered products
- P. Devise services and tools that support the implementation of new design methodologies
- Q. Develop new technologies for complex EOL products to expand their end-of-life properties and areas of use
- R. Develop solutions for advanced construction products design fit for the circular economy to minimise C&DW



Minerals and metals

- S. Develop mechanical and chemical processing of complex end-of-life products without dissipation of technology metals
- T. Create efficient sorting, pre-treatment and metallurgical processing of complex multi-metallic and material EOL products, including functional surfaces, e.g. liquid crystal displays (LCDs), photovoltaic, etc. and interface optimisation, addressing interdependencies of the steps by using a systems approach



Biotic sector

- U. Develop models and simulation tools for new product design approaches and associated new production technologies to obtain greater functionality from less material and energy input, e.g. lightweight wood construction or reduced paper grammage
- V. Develop and establish design criteria to ensure the full recyclability of packaging materials, in particular barrier layers and embedded electronics
- W. Develop product design approaches for the reusability of packaging or easy-to-dismantle building components to facilitate optimal sorting and recycling
- X. Develop technologies and processes to restore the length and strength of lignocellulosic fibres (enzymatic re-processing following recycling), possibly following cleaning/separation procedures (e.g. de-inking) (2050)

4.3

Developing and integrating methods for assessing and optimising cost and benefit in recycling



Rationale

Currently, the assessment of the best product recycling solution must consider economic, environmental, health and safety, social and functionality constraints. The optimal well-informed and balanced solution always represents a compromise among all these variables. The extent of the technological, environmental and socio-economic advantages or disadvantages of recovering materials from increasingly complex products must be carefully assessed.

State of play

Despite being a good alternative for sourcing valuable secondary raw materials, today's recycling processes are not always the safest and most environmentally friendly, let alone economically viable options. The logistical efforts to collect post-consumption materials in geographically challenging regions, associated with an increment in the emissions of greenhouse gases and transport costs, makes the decision on recycling very complex – with a need to balance costs and benefits at system level.

End-of-life (EOL) materials derived from consumer products, in particular electronics or products containing electronic parts, are currently the centre of attention given the high value of the different components. The concept of “urban mining” offers opportunities both for dedicated business models and for recovering materials from alternative sources.

Expected achievements by 2030

Thanks to the successful development, testing and implementation of appropriate assessment methodologies and comprehensive decision-making support tools, knowledge on how to balance the economic and environmental costs, and the benefits of collecting and recycling processes have progressed. The recycling targets of whole-product EOL using economic, social and environmental indicators have replaced weight-based material recycling targets.

Expected achievements by 2050

AI decision-making systems are helping recycling managers and businesses to optimise the recycling processes in a dynamic environment, both at local and global scale. The EU recycling system is part of an efficient global recycling framework.

Required Research and Innovation Activities towards 2030-2050



Minerals and metals



Biotic sector

- A.** Research the consequences of disruptive technologies and their impact on products' EOL phase
- B.** Develop digital solutions to improve the current monitoring and calculations of the optimisation of repair, reuse, recycling, and energy utilisation of minerals, metals and biotic materials
- C.** Examine the role of fiscal incentives to increase circularity
- D.** Promote business models for "servitisation" based on product-service systems (PSS) oriented to the circular economy and centred on end users
- E.** Develop new applications for extended producer responsibility, in design of product and also in business models, before considering the product as waste, to allow for closed loops in repairing and re-use activities
- F.** Develop new and cost-efficient chain of custody technologies, for example block-chain technologies
- G.** Develop, test and implement assessment methodologies and indicator sets that include parameters such as criticality and circularity of materials
- H.** Develop assessment tools and monitoring systems for international production and trade flows including storage and CO₂ sequestration in forest-based raw materials and wood-based products
- I.** Improve the flow and logistics of secondary raw materials across and within value chains by empowering local and regional clusters in Europe through mutual transfer of knowledge and cooperation
- J.** Continue the development of the Raw Material Information System (RMIS)¹⁶
- K.** Develop methods to integrate different sustainability methodologies (LCA, LCC, SLCA)



16: <http://rmis.jrc.ec.europa.eu/>

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