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Advanced Materials for the Green and Digital Age

Harnessing Material Innovation for Europe's Economic Sovereignty

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Europe's simultaneous transformation to a climate-neutral and digital economy not only places new demands on production processes and energy carriers, but also on the properties of industrial materials. Unlike in the case of some important process technologies, the EU still possesses technological leadership in many important fields of material innovation. Thus, material development can play a key role in Europe's quest for economic sovereignty. To exploit its full potential, stakeholders must bundle their strengths. With its recent initiative on advanced materials, the Commission sketches a support strategy. This cepInput analyses potentials of a material-oriented innovation strategy and provides recommendations for its implementation.

- The establishment of stable cooperation networks along entire supply chains is key for maintaining Europe's strengths in material innovation. A priority should be the creation of a common digital knowledge pool that circulates information, promises scale economies and helps to cope with the trade-offs imposed by the material requirements of the twin transition.
- In managing these networks, central decision-making should be limited to the definition of main strategic technology fields, to ensure adaptability to future market developments. Any impetus to intensify EU-internal collaboration must be balanced against the need to maintain internal market competition and protect the interests of small- and medium-sized companies. This should involve targeted measures like vouchers or dedicated public-private venture capital funds to support the access of small players to large-scale innovation networks.
- The field of material innovation should become an integral part of the EU's strategic global outreach. The prospect of cooperation in material development and standardization represents a valuable asset in future negotiations of trade agreements and strategic partnerships with third countries.

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1 Background

The epochal challenge of switching to climate-neutral production processes is a central topic of current policy debates. However, the focus on new process technologies can tempt Europe to overlook the major importance of the role of production materials. Historically, the development of materials with superior functionalities has been the backbone of industrial innovation, giving rise to new products and markets and challenging established positions. This is also confirmed in the current transition phase. Technologies such as water electrolysis, electro mobility and carbon capture are defining new requirements for material properties like robustness or heat resistance. The trend towards mass customization through technologies like additive manufacturing requires tailor-made material solutions. On the demand side, increased awareness of sustainability issues has created new requirements on durability and recyclability of materials, reinforced by regulatory rules for product design. The time is ripe for a new focus on material innovation.

Recently, the European Commission outlined the main features of its future innovation strategy in the field of industrial materials in a Communication on "advanced materials for industrial leadership".[1] Advanced materials are materials whose innovative properties can turn them into a game changer for the central economic policy objectives of the EU, in particular the success of the green and digital transformation. Given their fundamental impact on the material and energy consumption of entire supply chains, they can contribute to overcoming existing trade-offs between sustainability goals. Due to the great importance of cooperation and knowledge exchange in material development, they can also provide an important impetus for progress in the implementation of new digital technologies in the European research landscape, in particular a targeted use of Artificial Intelligence (AI).

At the same time, Europe faces fierce global competition in the development of groundbreaking materials. In order to withstand competitors that partly rely on massive industry subsidies, Europe must pool its strengths and channel existing resources towards strategic priorities. In addition to the goal of long-term technological leadership, this is also vital for the competitiveness of whole supply chains. As EU locations are unlikely to be cost competitive with rivals from East Asia in the foreseeable future, the European business model must lie in constantly defining new market segments. Material innovation is a crucial lever for this.

This cepInput examines the potential and prerequisites for an EU innovation strategy in the field of advanced materials. It discusses the significance of advanced materials for overarching trends, existing challenges and the role of the current regulatory framework. As part of an own empirical analysis in the field of nanoscale materials, it identifies trends in global and European innovation activity and examines the role of R&D cooperation for research success. Finally, it defines key fields of action and makes recommendations for the implementation of a foresight-oriented innovation strategy.

[1] European Commission (2024a). Advanced materials for industrial leadership. Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions. COM(2024) 98 final.

2 Relevance of advanced materials

2.1 Categories

The OECD Working Party on Manufactured Nanomaterials has developed a proposal for a general definition. It defines advanced materials as "materials that are rationally designed to have new or enhanced properties and/or targeted or enhanced structural features with the objective to achieve specific or improved functional performance."[2] Hence, in contrast to natural raw materials, they are always human-made. They differ from materials already on the market in that they offer new usage-relevant properties or already available properties in a higher quality form. Technical innovation can take place at the product level (physical design) and/or at the molecular level (chemical design).[3] The user perspective is crucial. The set of user-relevant functions always depends on preferences and current technological conditions. The assignment of specific materials to this group is therefore necessarily fluid and subject to debate.

As part of a "Materials 2030 Roadmap", a broad-based European industry initiative has defined various fields of application for advanced materials that demonstrate the great need for material innovation across all sectors.[4] They distinguish between nine material innovation markets (see Table 1). Currently, each of these is characterized by a strong pressure for structural adjustments brought about by digitalization, climate policies and the gained importance of sustainability issues in general. The initiative gives examples how the development of advanced materials can help the supply side to meet the changing needs. Possible improvements to products are not only aimed at the sustainability of production, but also affect the stages of use (e.g. durability) and final disposal (repairability, recyclability). Concrete contributions to an improvement of the environmental balance can be made, for instance, by developing lighter materials (enhanced material and energy efficiency) or materials that promise a longer product life thanks to greater robustness. Materials with digital interfaces (sensors) that enable permanent monitoring of product properties are also being discussed in various areas of application (see Table 1). They can also serve various sustainability goals if the information obtained is used to optimize the efficiency of material use. Moreover, the development of new materials for additive layer manufacturing has been identified as an area of cross-sectoral importance.

Table 1: Overview on material innovation markets

Market	Application fields	Examples
Health and medical	Improved surfaces and coatings of medical devices; Additive manufacturing of medical devices; Monitoring and diagnostic instruments	Antibacterial surfaces; 3D printing of personalized implants; Wearable heart monitoring devices
Sustainable construction	Lightweight construction; Thermal insulation; Recyclable and renewable construction materials; Improved material protection	Lightweight composite foams; Heat reflecting materials; Bio-concrete; Green coatings

2 OECD (2023). Advanced materials working description. Series on the Safety of Manufactured Nanomaterials No. 104. Organization for Economic Co-operation and Development, Paris.
3 Wessel, J. K. (2004). The handbook of advanced materials: enabling new designs. John Wiley & Sons.
4 AMI (2022). Materials 2030 Roadmap – December 2022. Advanced Materials Initiative.

New Energy technologies	Renewable energy generation; Energy storage; Transformation of energy-intensive industrial production	Efficient coatings for solar absorbers; New cathode materials; Porous materials for carbon dioxide capture
Sustainable transport	Zero-emission vehicles; Lightweight vehicle components; Digital connectivity of vehicles	Cheaper materials for fuel cells; New metal-composites for chassis; Sensors
Home and personal care	Cleaning products; Cosmetics	Biobased cosmetics; Self-cleaning surfaces
Sustainable packaging	Renewable and recyclable materials; Monitoring of product quality; Substitution of harmful substances; Packaging design	Bio-based bags; Barrier coatings; Sensors
Sustainable agriculture	Monitoring of plant maturity; Monitoring of CO2 sequestration; Biodegradable agricultural material; Purification of water and air	Biodegradable mulch films; Coating of filters; Sensors
Sustainable textiles	Renewable fibers; Sustainable and resource efficient textile surfaces; Smart wearables	Biopolymer fibers; Textiles with integrated electronics
Electronic appliances	Semiconductors; 5G network infrastructure; Smart devices; Flexible/stretchable devices	Superconductors; Robust, low-loss materials for 5G Transmitters; Structural frames of sensors;

Source: AMI (2022); own representation.

2.2 Economic significance

As a technology field, advanced materials are considered to be an important driver of general innovation dynamics. They are classified by the EU as one of six Key Enabling Technologies (KETs) - alongside advanced manufacturing, life-science technologies, microelectronics, AI and security/connectivity.[5] These are technologies that are characterized by a particularly high knowledge intensity and short innovation cycles. They also possess a particularly high potential for follow-up innovations and thus act as a lever for establishing new production methods and markets. Their systemic importance results first from the diversity of knowledge requirements, favoring interdisciplinary approaches in research and development (R&D). Second, the resulting innovations can be used across many sectors. As a consequence, they not only contribute to innovation strength, but also to technological convergence between sectors.[6] This strengthens the absorption capacity for new technologies.

Advanced materials also perform a specific function as enablers of the twin transition. They can be an answer to new material requirements that the market penetration of digital and clean technologies brings with it. The ability to develop tailor-made materials can thus become a bottleneck for the implementation of process innovations. The protection of intellectual property in this area is therefore of strategic importance. Against this background, the Commission has included advanced materials as one of ten technology fields in the list of critical technologies published in a recent recommendation.[7] In the future, foreign investments in the EU in these areas shall be subject to increased screening with respect to the risk of knowledge outflows. The specific economic potential of advanced materials can be summarized in the following points.

5 European Commission (2012). A European strategy for Key Enabling Technologies – A bridge to growth and jobs. Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions. COM(2012) 341 final.

6 AMI (2023). Strategic materials agenda. Advanced Materials Initiative.

7 European Commission (2023a). Commission recommendation of 3.10.2023 on critical technology areas for the EU's economic security for further risk assessment with Member States. COM(2023) 6689 final.

1. **Creation of market rents through technological leapfrogging**: The use of advanced materials in production not only enables improvements in product quality, but also forms the basis for products with new functionalities. This enables suppliers to create new market segments in which they can hold a temporary monopoly, i.e. until new competitors enter the market. This monopoly position is all the more pronounced the less substitutable the innovative materials are in terms of their usage-relevant properties with existing solutions. In this way, the upfront costs of development can be compensated by skimming off the increased willingness of customers to pay for improved product properties. This creates incentives for market entry and typically leads to diminishing returns over time due to growing competition. In the search for new return prospects, companies find themselves in a continuous innovation competition for leading-edge materials that destroy existing business models. From a dynamic perspective, this mechanism of creative destruction represents an important incentive element for persistent innovation activity and thus for long-term productivity growth.[8] In view of the global competitive situation, constant leadership in the conquest of new market segments is of central importance, especially for EU companies. It is a prerequisite for compensating Europe's structural cost disadvantages in factors such as labor and energy. R&D in the field of advanced materials is particularly promising due to its high potential for follow-up innovations.

2. **Exploitation of economies of scope through multi-functionality**: The versatility of advanced materials also brings direct economic benefits. It enables the sharing of R&D costs across products and thus a lower cost burden per product manufactured. On the revenue side, this implies the prospect of monopoly rents in multiple markets (see Point 1). From a dynamic perspective, cross-sector innovation success also generates potential for follow-up innovations in several fields of applications, which can strengthen the general innovation dynamic. On the input side, the interdisciplinarity of R&D activities in advanced materials can strengthen the innovation system as a whole by contributing to the establishment of cross-discipline research networks with high potential for knowledge spillovers.

3. **Reduction of environmental footprint across the life cycle:** Thanks to their genuine properties, advanced materials offer a wide range of solutions for improving the environmental balance not only of supply chains, but also of the entire life cycle of products. First, this concerns the downstream processing step. Advanced materials can substitute raw materials obtained with high environmental risks in production. Second, they can contribute to improving the general material or energy efficiency of production and thus reduce the upstream environmental effects. There may also be additional advantages for the post-production stage. For example, material innovation can contribute to increasing the durability of products and thus reduce the need for material replacement within a certain time period. The recyclability of products can also be improved by new materials, which further reduces the need for resources. The potential contribution is both a reduction in global climate damage (reduction of CO_2 footprint) and a reduction in local pollution.[9] The latter point is particularly important with regard to the possibility of replacing so-called critical raw materials with advanced materials. For example, significant risks to local biodiversity and

8 Aghion, P., & Howitt, P. (1992). A Model of growth through creative destruction. Econometrica, 60(2), 323-351.
9 See AMI (2022).

human health have been identified for current mining practices for raw materials such as lithium[10] and rare earths.[11]

4. **Facilitated supply chain monitoring through traceability**: Materials research can create new opportunities to reduce existing information asymmetries on production routes. For instance, individual marking can already be ensured during the development phase through the use of digital verification technologies (e.g. blockchain).[12] This can not only improve information exchange between actors in supply chains on material properties and thus contribute to the optimization of production and recycling processes. It also creates an interface to pass on information about the locations and conditions of production in individual process steps. This allows to meet the increased consumer demand for transparency on the sustainability of supply chains.[13] In this way, the roll-out of tracking technologies could also relieve companies of the administrative costs of reporting obligations in the long term.

5. **Reduction of external raw material dependencies**: Forecasts predict a sharp increase in global demand for a few rare metals that are currently indispensable for the production of strategic future technologies such as wind power and e-mobility. Their extraction is concentrated in only a few countries which are geopolitical rivals of the EU, foremost China.[14] This creates one-sided dependencies that motivate economic blackmailing and entail considerable procurement risks for EU companies. European development initiatives in advanced materials can enable the substitution of such raw materials. In addition to avoiding environmental damage from raw material extraction (see Point 3), this would have the additional advantage of eliminating external dependencies. Materials research is therefore an important building block on the EU's path to strategic autonomy.

6. **Improved adaptability to changing consumer preferences and mass customization**: On the demand side, the continuing trend towards heterogeneous, group-specific consumer preferences and product customization places increased demands on the flexibility of industrial processes. Mass customization, the production of individually tailored products and associated services on a large scale, will continue to gain in importance as a business concept.[15] It allows to serve many market segments while at the same time exploiting economies of scale. Due to its versatility and speed, the use of additive manufacturing in the form of industrial-scale 3D printing can represent the appropriate technological solution once the current obstacles to scaling have been overcome.[16] The availability of a wide range of suitable materials (e.g. polymers, metal alloys, ceramic compounds)

[10] Kaunda, R. B. (2020). Potential environmental impacts of lithium mining. Journal of energy & natural resources law, 38(3), 237-244.

[11] Huang, X., Zhang, G., Pan, A., Chen, F., & Zheng, C. (2016). Protecting the environment and public health from rare earth mining. Earth's Future, 4(11), 532-535.

[12] Hastig, G. M., & Sodhi, M. S. (2020). Blockchain for supply chain traceability: Business requirements and critical success factors. Production and Operations Management, 29(4), 935-954.

[13] Sesini, G., Castiglioni, C., & Lozza, E. (2020). New trends and patterns in sustainable consumption: A systematic review and research agenda. Sustainability, 12(15), 5935.

[14] Wolf, A. (2022). Europe’s position on raw materials of the future. **cepInput** Nr.11/2022.

[15] Karnik, N., Bora, U., Bhadri, K., Kadambi, P., & Dhatrak, P. (2022). A comprehensive study on current and future trends towards the characteristics and enablers of industry 4.0. Journal of Industrial Information Integration, 27, 100294.

[16] Zhou, L. Y., Fu, J., & He, Y. (2020). A review of 3D printing technologies for soft polymer materials. Advanced Functional Materials, 30(28), 2000187.

is an important prerequisite for expanding the range of applications, improving printing quality and reducing the costs of necessary post-treatment processes.[17]

In summary, the development of new advanced materials functions as an important interface for the EU in its current phase of industrial transformation. It creates the conditions for technological advantages and thus contributes to securing competitiveness even in times of transformation-induced cost pressure. At the same time, it reduces undesirable side effects of the transformation by strengthening the potential for local sourcing. Due to their cross-sectoral nature, advanced materials also offer potential for synergy effects and strengthen general technological convergence. However, materials research is taking place in a very competitive global market environment.

2.3 Global position of the EU

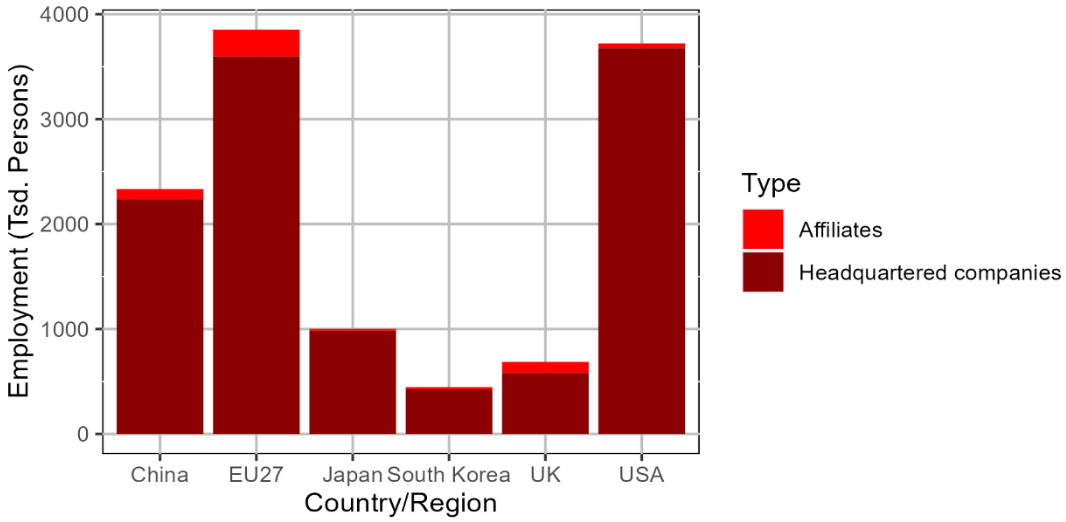
The nature of advanced materials as a broad cross-sectional segment makes it difficult to determine the market position of individual countries or regions. No public industry statistics can be utilized. An analysis of product-specific trade flows is also not very precise, as the share of advanced materials in individual product groups is fluid and can hardly be defined objectively. Alternatively, the analysis can start at the company level by analyzing the general market success of those companies whose business model is strongly based on the development of advanced materials. Van de Velde et al. (2024) took this approach in their most recent market analysis.[18] They identify a total of 56,355 companies active in this field worldwide. 29.3 % of these companies are based in the EU27. This is slightly less than the USA, the most important global location, where around one in three global companies are based.

Regional differences can also be observed in the ownership structure. Around 85 % of advanced material companies based in the EU are headquartered companies, i.e. companies with headquarters inside the EU. This proportion is significantly higher than in the USA (69 %) and UK (64 %). This indicates a comparatively strong role for independent, home-based companies in the EU compared to affiliates of multinational enterprises. Further indications are provided by the cumulative employment figures of the companies. According to data from Van de Velde et al. (2024), around 3.9 million people were employed in advanced materials companies in the EU in 2020, slightly more than in the US and significantly more than in China (see Figure 1). Headquartered companies accounted for 93 % of the EU workforce. In terms of employment figures, the headquartered companies are therefore larger on average than the affiliates.

[17] Singh, S., Ramakrishna, S., & Singh, R. (2017). Material issues in additive manufacturing: A review. Journal of Manufacturing Processes, 25, 185-200.

[18] Van de Velde, E., Braito, N., Van Roy, V., Stanciauskas, V., Girdzijauskaite, V., Cakic, M. (2024). Industrial R&D&I investments and market analysis in advanced materials. Summary report. Independent expert report for the European Commission.

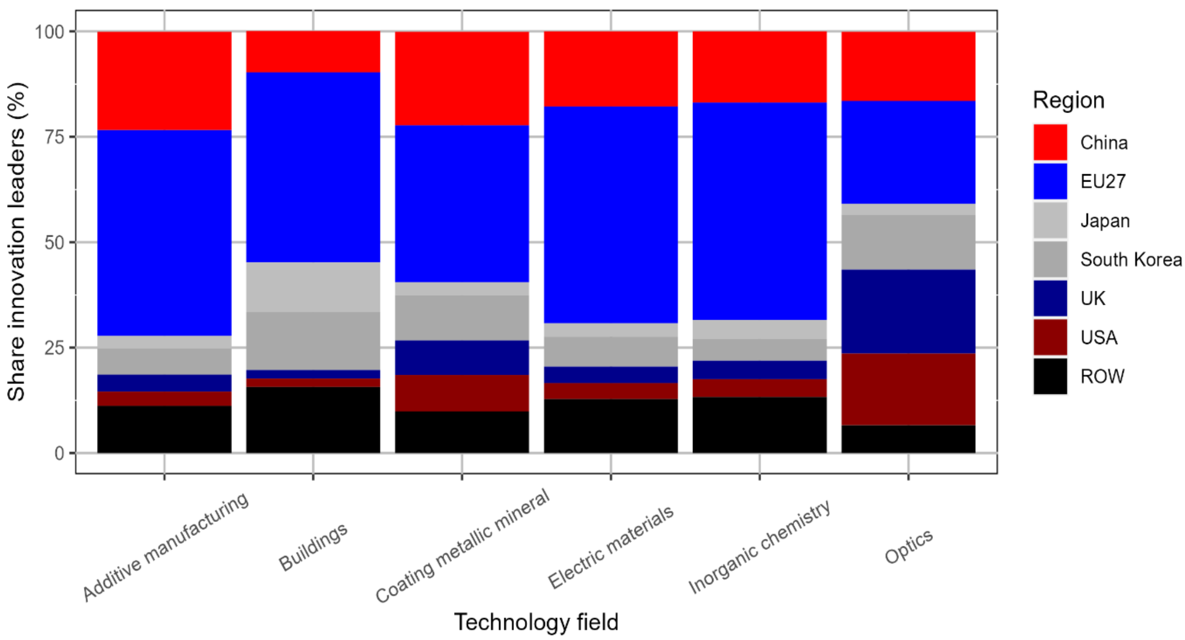
Figure 1: Total employment of advanced material producers in 2020 by country/region



Source: Van de Velde et al. (2024); own illustration.

In addition to economic size, innovative capacity is also an important indicator of market position. Van de Velde et al. (2024) used patent and bibliometric databases to identify so-called innovation leaders among companies. These are companies that have shown a high level of patent activity in the most recent period, specifically in the area of high-quality advanced materials patents. A total of 17.6 % of all globally active advanced materials companies were identified as innovation leaders on this basis. Figure 2 shows the geographical distribution of innovation leaders according to technology fields (CPC classes). The EU exhibits a larger number of companies than the USA and China in 18 of the 19 fields considered. The global share of EU companies across all technology fields is 42 %. In three technology fields, this share is even larger than 50 % (electric materials, inorganic chemistry, conveying and storing). The size of EU companies therefore hardly reflects their great innovative strength.

Figure 2: Share of innovation leader companies between 2015 and 2020 by country/region



Source: Van de Velde et al. (2024); own illustration; Selected technology fields; ROW: Rest of the World.

However, recent analyses also point to dangers for maintaining technological leadership in advanced materials in the future. These include the EU's poorer performance in important related technology fields. The Advanced Technologies for Industry (ATI) project initiated by the European Commission identifies in its assessments of technology performance that the EU is lagging behind its strongest global competitor, the USA, in important application fields of advanced materials, particularly in industrial biotechnologies and nanotechnologies.[19] This is reflected, for instance, in a lower proportion of high-quality patents and lower investments in new production capacities. In the medium term, this relative weakness can also impair the innovation potential in advanced materials, as there are fewer knowledge spillovers from related areas.

In addition, Europe's general weakness in the dynamics of business formation also applies to start-ups in connection with advanced materials. The EU start-ups among the advanced material companies included in the data set of Van de Velde et al. (2024) amounted to a total of EUR 9.1 billion in capital raised over the period 2012-2022. This is only a 6.3 % share of the capital raised worldwide for advanced material start-ups. Around two thirds of the capital invested globally went to US start-ups. EU start-ups received more capital than their US competitors in only one of 19 technology fields examined (paper making). Even in areas where the EU is a particularly strong innovation leader, such as electric materials, the measured capital share of EU start-ups was less than 10 %.

This demonstrates that looking at research indicators such as R&D expenditure and patent applications alone is insufficient for the assessment of technology leadership potentials. Systemic obstacles to the commercialization of new material developments can hinder the transfer of knowledge into the conquest of new market segments and domestic production. In the worst case, public research funds subsidize the creation of jobs outside the EU if start-ups are relocated to regions with better framework conditions. If the needs of start-ups are neglected, there is also a risk of an increase in the concentration of R&D activities in the hands of a few established market players. This weakens intra-EU competition in materials research and threatens to further inhibit innovation potential in the long term. European policy should counter these dangers with a value chain-oriented strategy that identifies bottlenecks along all stages of the innovation process. The basis for this is firstly the identification of specific challenges in the generation, exchange and utilization of knowledge in materials development.

2.4 Specific challenges

The special significance of material innovation as a basis for economic transformation is also associated with characteristic challenges. In many cases, this is due to the high demand for diverse specialist knowledge. Combining complementary knowledge components forms the basis of material innovation. It requires an extensive exchange of information between people with different academic and often cultural backgrounds. For the transfer of individual knowledge to succeed under these circumstances, it must first be codified in a usable form.

As the necessary pool of knowledge is generally not fully available within individual institutions, it usually also involves an inter-institutional exchange: between companies, universities, research institutions and other players in the research landscape. In addition to a contractual basis for the joint use of generated knowledge, this kind of exchange always requires soft factors such as a willingness

[19] ATI (2021). Final report on technology trends and technology adoption. Advanced Technologies for Industry.

to engage in dialogue and trust between the individual actors. In order for this to take place efficiently, the exchange of knowledge must be institutionalized. This can include fixed organizational formats such as steering committees or research teams. The interface can also emerge from the institutions themselves, e.g. university start-ups to marketize the results of university research. Individual relations can also form an important interface. The literature on innovation economics, for instance, points to the key role of influential star scientists as a link between academia and industry and a starting point for entrepreneurial activity.[20]

Hence, from an economic perspective, material innovation can be viewed as the output of complex R&D networks. These are characterized by strong economies of scale (size of network) and scope (diversity of actors). The glue that holds these networks together and allows them to grow is the jointly generated and shared knowledge.

Difficulties in managing this interinstitutional, interdisciplinary exchange of knowledge represent a major obstacle to fully exploiting the innovation potential. This includes the general trend towards technological complexity. The cross-industry dissemination of digital technologies in production plays an important role. It requires a variety of information interfaces to established analog production technologies. This creates a high demand for innovative materials with very specific properties (e.g. materials for sensors). The pressure to switch to climate-friendly production methods is also accelerating process innovation, which is changing the requirements for materials. In the field of hydrogen production, for example, the introduction of high-temperature electrolysis technology is placing new demands on the heat resistance of materials.[21] As many of the technologies in question are still at an early stage of development, rapid changes in material requirements can also be expected in the future. This requires fast and flexible development processes in materials research.

Economy-wide sustainability trends also define development restrictions for material design. This affects the efficiency of the material in production as well as its long-term properties in the use phase of products. The requirements for the durability, repairability and recyclability of downstream products are increasing and are passed on as design requirements to the underlying materials. Longer testing periods are required to be able to better evaluate the long-term properties, including data at user level.[22]

The extensive and diverse information flows in material development also pose a technical challenge for data management. In order to efficiently optimize material properties, interfaces must be created between the various sources of information in the development cycle (data from material modelling, testing, processing, utilization, recycling). To this end, central data repositories must be created and hosted, which are used jointly by the stakeholders in the development process. This requires clear rules for data access and use as well as common interoperability standards to ensure the usability of external data sets.[23]

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[20] Zucker, L. G., & Darby, M. R. (1996). Star scientists and institutional transformation: Patterns of invention and innovation in the formation of the biotechnology industry. Proceedings of the National Academy of Sciences, 93(23), 12709-12716.

[21] Schmidt, O., Gambhir, A., Staffell, I., Hawkes, A., Nelson, J., & Few, S. (2017). Future cost and performance of water electrolysis: An expert elicitation study. International Journal of Hydrogen Energy, 42(52), 30470-30492.

[22] Ghobakhloo, M., Iranmanesh, M., Grybauskas, A., Vilkas, M., & Petraitė, M. (2021). Industry 4.0, innovation, and sustainable development: A systematic review and a roadmap to sustainable innovation. Business Strategy and the Environment, 30(8), 4237-4257.

[23] Batra, R., Song, L., & Ramprasad, R. (2021). Emerging materials intelligence ecosystems propelled by machine learning. Nature Reviews Materials, 6(8), 655-678.

Against this backdrop, the increased use of AI in material development promises great potential, but also additional challenges for data management. By establishing decision-making algorithms, entire development programs could run autonomously in the future. **The underlying vision is that of a self-driving lab**. Based on material requirements, algorithms could in the future decide autonomously on suitable model simulations and test series and use the results for decisions on the next development steps and follow-up tests.[24] Such loop structures could significantly reduce the necessary level of human intervention and thus free up additional human resources for more strategic decisions.

The prerequisite for training such algorithms is access to large and high-quality data sets. This requires harmonization of data categorization and documentation. The structure of data from different sources must be standardized as far as possible. The complexity and diversity of the information flowing into the process represents a particular hurdle. Existing data silos must be broken up and networked. Stakeholders who were previously less involved in the development processes, such as downstream producers and recycling companies, must also be activated as data sources.

A key policy implication of this strong coordination pressure is that state funding and regulation cannot function as a top-down approach. It needs to be embedded into a collaboration framework of mutual knowledge exchange. The complexity and short-lived nature of information needed for tailor-made regulation requires policy-makers to be provided with continuous data input. In this way, inter-institutional innovation networks with autonomous governance structures are formed. The challenge on the regulatory side is to ensure that these "regulatory satellites" are compatible with overarching objectives. From an EU perspective, this primarily concerns the objectives to maintain competition on internal markets and to protect the interests of small and medium-sized companies against influential industrial research conglomerates and their knowledge monopolies.

3 Advanced materials in EU policies

3.1 Overarching policy strategies

The presentation of the **European Green Deal** by Commission President von der Leyen on 11 December 2019 marked the beginning of a new era in EU climate policy.[25] The ambitious goal of a climate-neutral EU economy by 2050 was combined with an economic policy agenda focused on green growth, including just transition mechanisms for EU regions threatened by structural change. One core element of the implementation was the European Green Deal Investment Plan, which included new EU financing instruments for the green transformation (InvestEU, Just Transition Mechanism). A total of 1 trillion euros in sustainable investments are to be mobilized in the period 2021-2030, financed from private and public sources.[26] The second core element was a large number of new regulatory initiatives to accelerate the reduction of emissions and other societal goals (circularity, pollution, biodiversity), spreading across all sectors of the EU economy. This also defined new paradigms for material development.

[24] Abolhasani, M., & Kumacheva, E. (2023). The rise of self-driving labs in chemical and materials sciences. Nature Synthesis, 2(6), 483-492.

[25] European Commission (2019). The European Green Deal. Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions. COM(2019) 640 final.

[26] European Commission (2020a). Sustainable Europe Investment Plan – European Green Deal Investment Plan. Communication from the Commission to the European Parliament, the Council, the Eco-nomic and Social Committee and the Committee of the Regions. COM(2020) 21 final.

First, a major initiative relating to material circularity was provided by the update of the **Circular Economy Action Plan** published on 11 March 2020.[27] It announced numerous product- and sector-specific legislative proposals to strengthen circular supply chains. This led, among other things, to a proposal for a revision of the Packaging and Packaging Waste Regulation,[28] which raises ambitions on recycling targets and requires very lightweight plastic carrier bags to be compostable, and contains a proposal for the revision of the Waste Framework Directive, which sets additional targets for waste reduction in the food and textiles sectors[29]. Second, the EU Strategy for Plastics in the Circular Economy published on 16 January 2018 aimed specifically to curb plastic waste and improve the profitability of plastic recycling in the EU.[30] It has so far given rise to a Directive banning the use of certain types of single-use plastics[31] and rules restricting the use of microplastics in production[32].

On 10 March 2020, the Commission published the Communication "**A new Industrial Strategy for Europe**".[33] It defined priority areas for industrial policies to adapt to the goals of the Green Deal and the challenges of digitization. One of the mentioned priorities is the reinforcement of Europe's industrial and strategic autonomy through a reduction of external dependencies in core goods. This explicitly includes critical materials. The task is to boost competitiveness by developing own European markets for these materials through technological leadership., To this end, the document announces to further support the development of advanced materials as one of 12 Key Enabling Technologies (KETs). The 2021 update of the industrial strategy further supported this view, identifying enhanced autonomy in the material space as one of the key elements for a persistent economic recovery from the COVID-crisis.[34]

In 2022, the Commission summarized its efforts of supporting material research in a "**Strategic Research and Innovation Plan for safe and sustainable Chemicals and Materials**".[35] It identifies key areas for research and innovation and thereby attempts to provide guidance to future innovators. Moreover, it discusses how to improve the framework conditions for material innovation. One of the them is access to quality data. For this, the Commission aims to improve data sharing through open platforms and the use of big data tools. Further requirements are seen in the validation of material tests and the establishment of test guidelines, to facilitate the use of test results for regulatory

[27] European Commission (2020b). A new Circular Economy Action Plan - For a cleaner and more competitive Europe. Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions. COM(2020) 98 final.

[28] Schwind, S., Reichert, G. (2023). Packaging and packaging waste. cepPolicyBrief No.3/2023.

[29] European Commission (2023b). Proposal for a Directive of the European Parliament and of the Council amending Directive 2008/98/EC on waste. COM(2023) 420 final.

[30] European Commission (2018). A European Strategy for Plastics in a Circular Economy. Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions. COM(2018) 28 final.

[31] European Union (2019). Directive (EU) 2019/904 of the European Parliament and of the Council of 5 June 2019 on the reduction of the impact of certain plastic products on the environment.

[32] European Union (2023a). Commission Regulation (EU) 2023/2055 of 25 September 2023 amending Annex XVII to Regulation (EC) No 1907/2006 of the European Parliament and of the Council concerning the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) as regards synthetic polymer microparticles.

[33] European Commission (2020c). A New Industrial Strategy for Europe. Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions. COM(2020) 102 final.

[34] European Commission (2021). Updating the 2020 New Industrial Strategy – Building a stronger single market for Europe's recovery. Communication from the Commission to the European Parliament, the Council, the Economic and Social Committee and the Committee of the Regions. COM(2021) 351 final.

[35] European Commission (2022a). Strategic research and innovation plan for safe and sustainable chemicals and materials. Staff document.

purposes. A specific bottleneck identified is the availability of skilled talent in research. The Commission suggests to answer this by adjusting academic curricula to a more interdisciplinary approach and intensifying collaboration between academia and industry. In addition, it sees the need for more innovation to achieve a consistent implementation of the "safe and sustainable by design" principle explained by the Commission in a separate Recommendation[36] in material research. This principle aims to minimize the use of potentially harmful substances in material development and strengthen the consideration of environmental and health effects across the lifecycle.

3.2 Recent regulation

Due to the wide range of materials classified as advanced materials, innovation activity in this field is confronted with a myriad of EU regulations and directives. At the same time, some recent legislative projects affect materials research in almost its entirety. To this belongs the **Ecodesign for Sustainable Products Regulation** proposed by the Commission on 30 March 2022.[37] A provisional trilogue agreement on the regulation has been reached on 5 December 2023.[38] Its purpose is to ensure that the reduction of negative environmental life cycle impacts becomes an integral part of product development, following the principle of ecodesign. In comparison to the preceding directive, it broadens the scope to more product groups and sustainability categories. Its approach is to provide a harmonized framework for defining performance and information requirements compatible with the sustainability goals of the Green Deal, such as durability, reusability, recyclability and improvements in material and energy efficiency. Within this framework, specific requirements for certain product groups will be defined later on through delegated acts by the Commission. Furthermore, as a general provision, mandatory digital product passports for products subject to the regulation are foreseen when being placed on EU markets. They are to inform consumers about relevant sustainability characteristics of the products and thus support them to make informed consumption decisions accounting for their sustainability preferences. The regulation thus has the potential to change future competitive conditions on product and material markets disruptively, both from the angle of supply and demand.

Given the ambition of material research to develop substitutes for scarce raw materials, the Critical Raw Materials Act proposed by the Commission on 16 March 2023 is likewise of high relevance.[39] A provisional trilogue agreement on the regulation has been reached on 5 December 2023[40] and officially approved on 18 March 2024.[41] The Critical Raw Materials Act defines ambitious targets for a list of critical raw materials for the development of domestic capacities in the area of raw material extraction, processing and recycling as well as for the diversification of EU raw material imports. The focus is on

[36] European Commission (2022b). Commission Recommendation (EU) 2022/2510 of 8 December 2022 establishing a European assessment framework for 'safe and sustainable by design' chemicals and materials.

[37] European Commission (2022c). Proposal for a Regulation of the European Parliament and of the Council establishing a framework for setting ecodesign requirements for sustainable products and repealing Directive 2009/125/EC. COM(2022) 82 final.

[38] European Council (2023a). Products fit for the green transition: Council and Parliament conclude a provisional agreement on the Ecodesign regulation. Press release.

[39] European Commission (2023c). Proposal for a Regulation of the European Parliament and of the Council establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) 168/2013, (EU) 2018/858, 2018/1724 and (EU) 2019/1020. COM(2023) 160 final.

[40] European Council (2023b). Council and Parliament strike provisional deal to reinforce the supply of critical raw materials. Press release.

[41] European Council (2024). Strategic autonomy: Council gives its final approval on the critical raw materials act. Press release.

prioritizing projects in connection with raw materials classified as "strategic". Approval procedures for such projects are to be shortened and special support is to be provided for access to financing sources. An important result of the trilogue negotiations is that not only projects aimed at strengthening the supply of these raw materials will be considered as candidates for strategic project status, but also those that could lead to the production of suitable substitutes. In this way, material development will also have access to the new instrument for prioritizing projects.

With regard to the importance of innovative process technologies as drivers and enablers of material innovation, the **Strategic Technologies for Europe Platform (STEP)** established through Regulation (EU) 2024/795 can provide additional impetus in the future.[42] STEP's task is to channel existing EU funding channels for investment support towards three target investment areas: digital technologies and deep-tech innovation, clean and resource-efficient technologies, biotechnologies. These technology classes are classified as critical. All three areas have diverse needs for advanced materials for their use (see Subsection 2.1). In addition, STEP is introducing a Seal of Sovereignty, a new label that will be awarded to high-quality projects funded by STEP. The first calls for project funding are expected to be published in Q2 2024.[43] If it is possible to increase the deployment of this group of critical technologies in the EU by streamlining public funding, this will also trigger a pull effect on material development and release additional private and public funds for this R&D segment.

3.3 Communication on advanced materials

With its Communication on "advanced materials for industrial leadership" published on February 17, 2023, the Commission aims to create general awareness of the strategic importance of advanced materials as a technology field and defines a catalog of measures for European technology leadership.[44] Its perspective on materials development processes is that of an ecosystem of cooperating stakeholders. According to the Commission's concept, this ecosystem should be "dynamic", "secure" and "inclusive".

The characteristic "dynamic" reflects the idea of creative destruction as a hallmark of industrial material markets. The development of innovative specialty materials enables the prospect of monopoly rents, but these are often only temporary. The market position is jeopardized on the one hand by the development of better materials by competitors, and on the other hand by technological and market developments on the application side, which can make the materials obsolete. Securing competitiveness therefore requires permanent investment in product development. The characteristic "secure" refers to the importance of advanced materials for the general economic security of the EU, both in terms of the need to secure access to special materials for European companies and the contribution of self-developed materials to overcoming external supply risks (see Subsection 2.2). In a broader sense, it also hints at the importance of advanced materials for the production of high-tech military goods. The characteristic "inclusive" refers to the great importance of research cooperation and knowledge exchange for the EU's innovative capacity in this field.

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42 European Union (2024). Regulation (EU) 2024/795 establishing the Strategic Technologies for Europe Platform (STEP), and amending Directive 2003/87/EC and Regulations (EU) 2021/1058, (EU) 2021/1056, (EU) 2021/1057, (EU) No 1303/2013, (EU) No 223/2014, (EU) 2021/1060, (EU) 2021/523, (EU) 2021/695, (EU) 2021/697 and (EU) 2021/241.

43 European Commission (2024b). Strategic Technologies for Europe Platform.

44 See European Commission (2024a).

To realize this vision, the Communication proposes measures structured into five pillars. The first pillar aims to **strengthen European research and innovation on advanced materials.** The Commission asks for a joint strategic approach to advanced materials research, to be developed together with Member States, associated countries and stakeholders from industry and research organizations. This is supposed to begin with the definition of a common set of objectives and thematic priority areas. A preliminary selection of strategic areas has already been made, involving energy, mobility, construction and electronics. Within these areas, a research focus on materials for specific product groups is envisaged, with materials that improve the performance and/or sustainability (e.g. energy efficiency, circularity) of products essential for the green transformation and digitization in the spotlight. The joint strategic approach is supposed to be developed by the end of 2024 and from then on regularly updated, taking into account the social and technological development. In addition, the Commission will undertake a substitution analysis for critical raw materials, identifying research and investment needs in the development of domestic advanced materials as substitutes. This again highlights the functional role of advanced materials for the Green Deal and the EU Industrial Strategy. Strategic specialization in the materials field has to occur under the restriction of safeguarding the technological transformation of the industrial base, by contributing to its goals and limiting its unwanted side effects (increased cost pressure, new external resource dependencies).

The second pillar ("from lab to fab") aims to improve the **transfer of material development to industrial production**. It is one element in the attempt to minimize the gap between research success and commercialization. The main instrument to achieve this is the establishment of a common digital data space, termed the "material commons". It is planned to create a controlled environment for innovators in materials sciences. By improving fast and uncomplicated access to modelling and experimental data, it is supposed to speed up the process of developing and testing new materials. This shall involve the targeted use of AI to bring forward tailor-made solutions for material problems (e.g. by transforming data from heterogeneous sources into new testable hypotheses for material advancement).[45] The type of data exchanged is not restricted to relevant material properties, but shall also involve information on methodological practices, to ensure reproducibility of material tests. To guarantee the responsible use of such sensible data and avoid unintended competition distortions, a rigorous governance structure is needed. The Commission proposes the FAIR (Findable, Accessible, Interoperable and Reusable) principles as guidelines for governance. This requires the data space to be accessible across sectors, to be interoperable with other data platforms and to provide data in a standardized format that allows for their reusability by other participants. Existing EU regulation, in particular the rules for data sharing and use defined by the Data Governance Act[46] and the Data Act[47], provide the necessary framework for this.

This digital infrastructure is supposed to be complemented by a joint physical testing infrastructure. For this, the concept of Open Innovation Test Beds (OITBs) is key. These are clusters of laboratories, testing facilities and providers of innovation services, which cooperate based on a Single Point of Entry. They are envisaged to offer an accessible all-in-one solution for testing newly invented material and developing it further to industrial products. Technically, the aim is to advance from laboratory

45 See AMI (2022).

46 European Union (2022). Regulation (EU) 2022/868 of the European Parliament and of the Council of 30 May 2022 on European data governance and amending Regulation (EU) 2018/1724 (Data Governance Act).

47 European Union (2023b). Regulation (EU) 2023/2854 of the European Parliament and of the Council of 13 December 2023 on harmonized rules on fair access to and use of data and amending Regulation (EU) 2017/2394 and Directive (EU) 2020/1828 (Data Act).

validation (Technological Readiness Level (TRL) 4) to industrial prototypes (TRL 7). They are required to be open at fair prices to any institution, including public and private organizations, industry and research. Transparent agreements on data exchange and handling of intellectual property are important preconditions. Besides the provision of infrastructures services, OTIBs are also actively shaping the research landscape through own calls for project proposals matching the thematic field of the OITB.[48]

From a macroeconomic perspective, well-managed OITBs thus provide at least three kinds of welfare-increasing services. First, they allow for the exploitation of industry-wide scale economies in the joint use of testing infrastructure. Second, they reduce transaction costs by matching innovators and industrial applicants in the innovation process of advanced materials. Since this matching specifically reduces information barriers for small- and medium-sized companies, it can also have pro-competitive effects. Third, the work of OITBs signals current research priorities and thus supports the steering of industrial and public R&D efforts towards areas with favorable economic outlook and general strategic importance. Currently, EU-wide OITBs are already active in areas such as construction and pharmaceuticals, partly emerging from Horizon project funding.[49] Based on previous experience, the Commission announces the launch of a single-entry catalogue. It shall provide guidance on services of and access to technology infrastructures like OITBs, to overcome observed regional discrepancies in infrastructure access.[50]

The third pillar summarizes measures to **raise overall capital investments in the development and deployment of advanced materials**, thus addressing the funding bottleneck (see Subsection 2.3). To unlock private capital, the Commission aims to employ a mixture of existing and new public funding channels. First, at EU level, it refers to the new Public-Private-Partnership (PPP) “Innovative Materials for EU” announced under the Horizon Europe framework. It will co-fund projects in materials innovation worth of a total of 500 million EUR in the time period 2025-27, with half of the contribution coming from the participating private companies. Moreover, it builds hopes on the new Strategic Technologies for Europe Platform (STEP).[51] It is planned to channel existing funding sources like InvestEU or the cohesion policy funds to the financing of domestic development and manufacturing of critical technologies. These also involve various forms of advanced materials (see Subsection 2.1). Further mentioned EU funding channels with some focus on material applications are the Innovation Fund supporting the decarbonization of the European industry (i.e. manufacturing of advanced materials for reducing the carbon footprint) and the funds of the Global Gateway Initiative (cooperation with third countries in advanced materials deployment).[52] In addition, the Commission announces to explore the opportunity for enhanced Member State cooperation through a dedicated new Important Project of Common Europe Interest (IPCEI)[53] for first industrial deployment of innovative advanced materials.

The fourth pillar seeks to **foster production and use of advanced materials**. It thus involves support in the post-development stage, in particular the task of upscaling innovative solutions and establishing

48 European Commission/European Health and Digital Executive Agency (2023). Open innovation test beds – Improving access to knowledge to accelerate European innovation. Publications Office of the European Union, 2023.

49 European Commission (2023d). Open innovation test beds for advanced materials. Publications Office of the European Union, 2023.

50 European Commission (2019). Technology infrastructures. Commission Staff Working Document.

51 See European Union (2024).

52 Wolf, A., Poli, E. (2024). A Global Gateway to secure supply chains? cepStudy No. 3/2024.

53 European Commission (2024c). Important Projects of Common European Interest (IPCEI).

stable market positions. To improve the EU's performance in this respect, the Commission proposes to focus on three essential instruments: standards, skill upgrading and public procurement. Industry standards are technical standards used by stakeholders in an industry based on voluntarily agreements. This can involve areas such as the design of products and processes and the application of measurement and test procedures.[54] In general, standardization practices involve several economic benefits such as cost savings through facilitated technology uptake for firms, guaranteed safety and improved interoperability of devices for consumers and the support of international trade and open markets.[55] In the Communication, the Commission particularly stresses the roles of interoperability standards and harmonized testing methods as a means to reduce frictions and improve the external information flow. To promote standardization activities, the Commission has already issued a Recommendation asking educational institutions and research organizations to develop a dedicated standardization policy, including increased cooperation with standardization bodies, internal training activities and indicator-based monitoring of standardization activities.[56] Furthermore, it announces increased cooperation with international standardization bodies to identify existing gaps in industry standards related to advanced materials.

To address the issue of skill shortages as a bottleneck in material innovation, the Commission refers to its pact for skills.[57] This is a network of private and public organizations aiming at enhancing upskilling and reskilling of European adults, with a particular focus on individuals from deprived groups. Moreover, it announces a call for the establishment of an Advanced Materials Platform. Its purpose is to develop fitting curricula for study and training programs focused on material sciences. In this way, it resembles the role of the Net Zero Academies launched as part of the Net Zero Industry Act (NZIA) in teaching the skills necessary for strategic net zero technologies. As a demand-side measure to promote domestic manufacturing, the Communication envisages a strategic role for public procurement. It refers to the extended awarding criteria for public tenders, mentioning the energy efficiency requirements set by the Renewable Energy Directive as an example.[58] They could exert a positively discriminating effect on demand for the most innovative materials, to the extent that these materials exhibit superior properties in the relevant aspects. In addition, also the new sustainability and resilience criteria defined by the NZIA for public procurement related to net zero technologies could be mentioned, as they favor domestic sustainable solutions in the material field.[59] The Commission announces to complement these existing incentives by a targeted "Big Buyer" initiative, aiming to achieve strategic market power by pooling public procurers and steering their demand towards innovative and sustainable material solutions.

Finally, the fifth pillar consists of **the establishment of a governance structure**. It serves to coordinate and monitor the implementation of the single measures announced in the Communication. This will involve the creation of a Technology Council for Advanced Materials, with representatives from the

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[54] ISO (2024). Standards. International Organization for Standardization.

[55] Swann, G. P. (2010). International standards and trade: A review of the empirical literature. OECD Trade Policy Papers, (97).

[56] European Commission (2023e). Commission Recommendation (EU) 2023/498 of 1 March 2023 on a Code of Practice on standardization in the European Research Area.

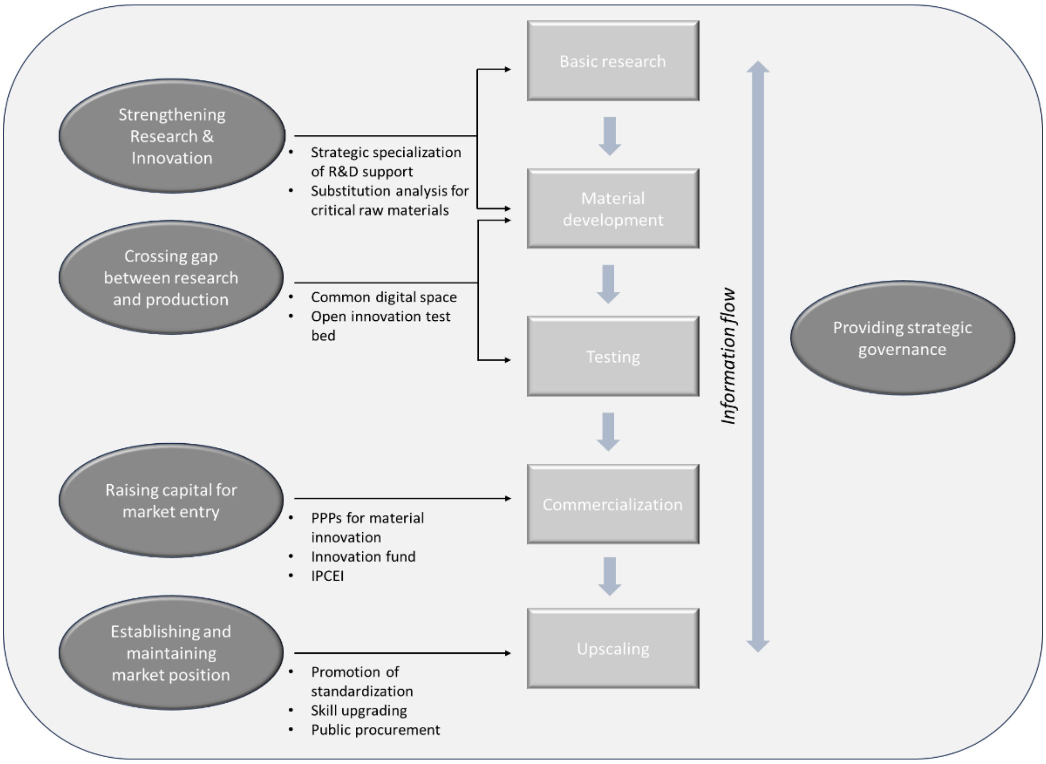
[57] European Commission (2024). Pact for skills.

[58] European Union (2023c). Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652.

[59] European Commission (2023f). Proposal for a Regulation of the European Parliament and of the Council on establishing a framework of measures for strengthening Europe's net-zero technology products manufacturing ecosystem (Net Zero Industry Act) (COM(2023) 161 final).

Commission, EU Member States as well as research and industry stakeholders as members. Besides coordination and monitoring, its task is also to reach out to existing regional innovation valleys and to third countries, to create synergies and develop common innovation strategies. It is thus very similar in its functions to other coordination boards recently approved in the context of EU regulation, e.g. the NZIA and the Critical Raw Materials Act.[60]

Figure 3: Structure of the EU advanced materials strategy



Source: own illustration

In sum, **the overall structure of pillars closely follows a value chain logic of innovation**. It starts with measures to promote research and development, continues with tools to transfer newly created knowledge to the industry and to provide the necessary capital basis and finishes with instruments to facilitate market entry and upscaling for new material solutions. At the same time, the concept envisages a mix of different types of support instruments (financial, institutional (coordination), strategic) applied in a cross-sectional manner on all value chain stages. Figure 3 illustrates the structure.

4 Dynamics and drivers of innovation: the case of nanomaterials

4.1 Definition and application fields

The field of nanotechnology encompasses the development and application of structures that involve the use of nanomaterials. Nanomaterials are materials whose single units (particles) do not exceed a size of 100 nanometers (nanoscale) in at least one of their three spatial dimensions.[61] If the particles

[60] See European Commission (2023c).

[61] European Commission (2022d). Commission Recommendation of 10 June 2022 on the definition of nanomaterial (2022/C 229/01).

are at nanoscale level in all three dimensions, they are referred to as nanoparticles. Nanomaterials occur both in nature and in synthesized form. Synthetic production can take place both bottom-up and top-down. In bottom-up processes, nanomaterials are obtained by means of chemical manipulation at an even smaller level (single atoms, molecules). In top-down processes such as mechanical milling and electrospinning, bulk materials are broken down into nanostructures.[62]

A common property of all nanomaterials is a high surface-to-volume ratio. The advantage of nanomaterials lies in their significantly different mechanical and chemical properties compared to bulk materials. The magnetizability and electrical conductivity of elements and compounds can be higher in nanostructures than in macro-scale materials. The exact properties can vary significantly depending on the size and shape of the particles. This enables a high degree of adjustability of desired properties and thus a high potential for tailor-made material solutions. Recently, nanocomposites have been attributed particularly promising properties. They consist of several materials in different phases, at least one of which is present on a nanoscale.[63]

The range of applications for nanomaterials is as diverse as their composition. A generally important area is the use of nanoscale materials as additives to improve the properties of products. This includes, for example, additives to increase the efficiency of catalysts in chemical processes, to improve the properties of polymer-based materials (e.g. more durable, less heavy) in sectors such as the automotive industry and to increase the effectiveness of cosmetics. The functional properties of biochemical compounds such as enzymes can also be modified by combining them with nanoparticles, creating new production methods for bio-based products and fuels. The medical sector also offers promising potential applications for the future. For example, nanoparticles can be used as carriers for medicine, e.g. to better reach diseased cells directly in chemotherapy or to replace the use of needles in administering vaccines. Nanotechnologies can also be used to develop more efficient diagnostic tools. Another important area of application is the electronics industry. In the future, nanoparticles could also be increasingly used to clean up environmental damage, e.g. to purify groundwater from industrial pollution. Nanomaterials and their related technologies can therefore contribute to the goals of the EU Green Deal in a variety of ways.[64]

4.2 Trends in nanotech patents

Any attempt to compare innovation success in nanomaterials is confronted with measurement difficulties. This is partly due to the ambiguity of the term “innovation”. In the general sense of the word, innovation can refer to a new idea, its concretization in the form of a design or product or the process of developing new ideas, designs or products. In the economic context, innovation is usually understood as the market launch of new products or processes that differ from existing ones in relevant characteristics. It is therefore based on prior research and development. Overall, innovation is therefore best described as a multi-stage process of cumulative discovery: researchers discover new mechanisms through basic research, which are taken up by product development, tested, piloted and finally commercialized on markets. Innovation success thus depends on a whole range of actors with interests that are not always homogeneous. Technology Readiness Levels (TRLs) are a common way of characterizing the stages of innovation processes. The official TRL scale was developed by NASA and

[62] Roduner, E. (2006). Size matters: why nanomaterials are different. Chemical society reviews, 35(7), 583-592.

[63] Baig, N., Kammakakam, I., & Falath, W. (2021). Nanomaterials: A review of synthesis methods, properties, recent progress, and challenges. Materials Advances, 2(6), 1821-1871.

[64] NNI (2024). Applications of nanotechnology. US National Nanotechnology Initiative.

adopted by the EU for the Horizon 2020 framework program. It consists of nine levels - from concept development to commercial readiness.[65]

From an economic point of view, it makes sense to start measuring innovation at the point where the prospect of commercialization of inventions becomes evident through the registration of property rights. Patent data is therefore often the basis for output-based innovation indicators. Their limitations are well known.[66] They do not provide information about the actual subsequent market success of patented inventions and their general societal impact. They are also not a perfect measure of innovation at the development stage, as many types of inventions are not patentable for technical or legal reasons. Nevertheless, main advantages are the high degree of international harmonization and the high level of technological detail in patent statistics. The International Patent Classification (IPC) system enables an extremely fine-grained subdivision according to fields of technology.[67] In addition, information on innovation networks via cross-referencing (citations) and supra-regional cooperation between institutions and inventors is available.

For the international comparison of innovation activities in the field of nanotechnology, we use data from PATSTAT, the worldwide patent statistical database of the European Patent Office (EPO).[68] It is one of the world's most comprehensive patent databases and a popular choice for innovation analyses. For the definition of nanotechnologies, we apply the corresponding subclass “Nanotechnology” (B82) of the IPC classification. It comprises all types of innovation associated with nanotechnologies. Besides the development of new nanostructures, this includes specific technologies for production, information processing and measurement. For this class, data on all registered patents over the period 2000 to 2022 was retrieved via search queries in PATSTAT. The data collected for each patent includes affiliation to a specific technology class, membership in a patent family and institution type(s) of the applicant(s) (see below). The dataset generated contains a total of 861,918 observations. In the next step, it was merged with data from the OECD REGPAT database.[69] This contains additional information on the names and residential addresses of the inventors registered in the patents, thus enabling a detailed spatial allocation. Compared to using the addresses of the applicants, which in the case of multinational enterprises can be a parent company or an affiliate located far away from R&D activities, this results in a more precise spatial picture of innovation.

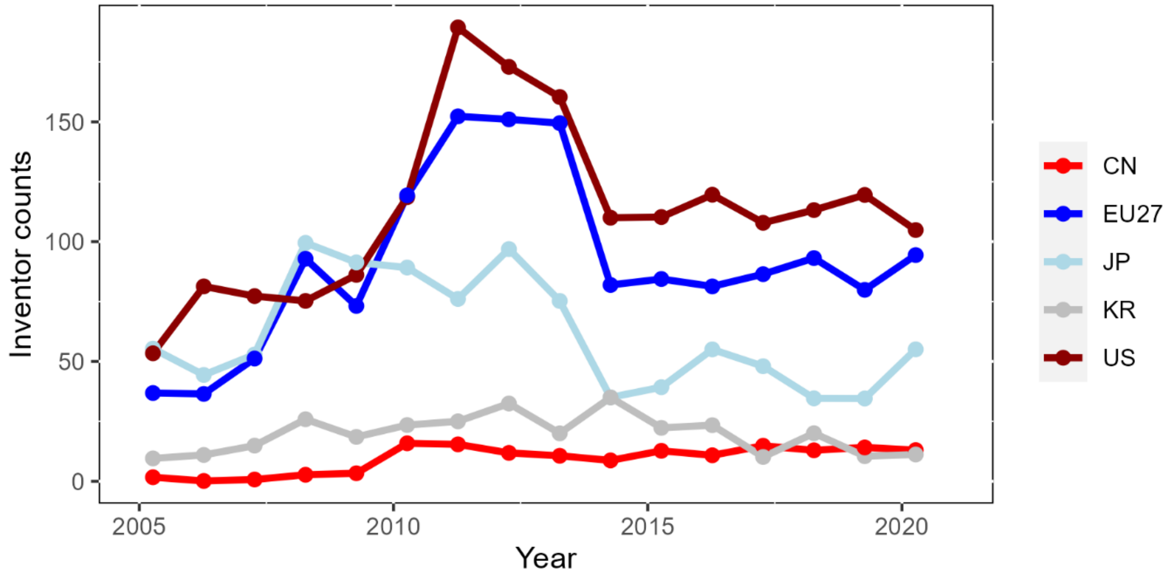
The number of patent applications is a common indicator for quantifying patent activity. For a country comparison, we must consider that often several people are registered as the inventors of a patent, who may be located in different countries. As is common in the literature, we account for this by applying an equal share for each inventor as a weighting factor. For instance, in the case of a patent with eight registered inventors, each inventor is assigned a share of 0.125. Then, we calculate the total nanotech innovation activity of a country as the sum of the shares of inventors residing in the respective country ("inventor counts").

Figure 4 first shows the development of these inventor counts for the EU27 as a whole in comparison to the most active third countries. It reflects the dominant roles of the USA and the EU as global drivers

65 NASA (2024). Technology Readiness Levels. The National Aeronautics and Space Administration.
66 Wydra, S. (2020). Measuring innovation in the bioeconomy–Conceptual discussion and empirical experiences. Technology in Society, 61, 101242.
67 WIPO (2024): International Patent Classification (IPC). World Intellectual Property Organization.
68 EPO (2024). PATSTAT – Backbone dataset for statistical analysis. European Patent Office.
69 OECD (2024). Intellectual property (IP) statistics and analysis. Organization for Economic Co-operation and Development, Paris.

of nanotech innovation. In recent years, both innovation champions have been able to build up a clear lead over Japan, which was one of the world's strongest innovators in the early 2000s. However, the pace of innovation has slowed for almost all major forces over the last decade. China is an exception, although its level of innovation is still far below that of the USA and the EU.

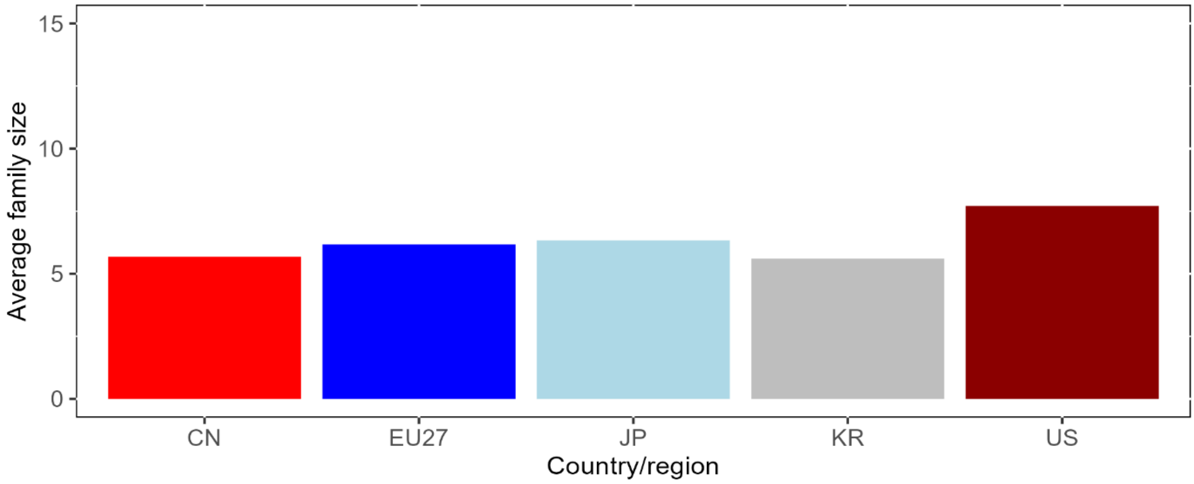
Figure 4: Evolution of nanotech patenting activities in major inventor countries worldwide



Sources: EPO (2024); OECD (2024); own calculations.

A look at the quality of patent applications offers an important complementary perspective. A variety of measures for recording patent quality are discussed in the literature. The patent family size indicator contained in PATSTAT allows to measure quality on the basis of the degree of dissemination. All patent applications that have the same or very similar technical content are grouped together to form a patent family. Such a family can arise, for example, when an original application is extended to additional countries (and patent offices). The family size thus approximates the expected global market potential of innovations. Below, we use the average family size of all nanotech patents involving domestic investors as an indicator for national patent quality. Figure 5 depicts the average family sizes over the period 2005 to 2020. In this respect, the USA clearly outperformed the EU and the major competitors from Eastern Asia. The EU ranks above China and South Korea and close to the level of Japan.

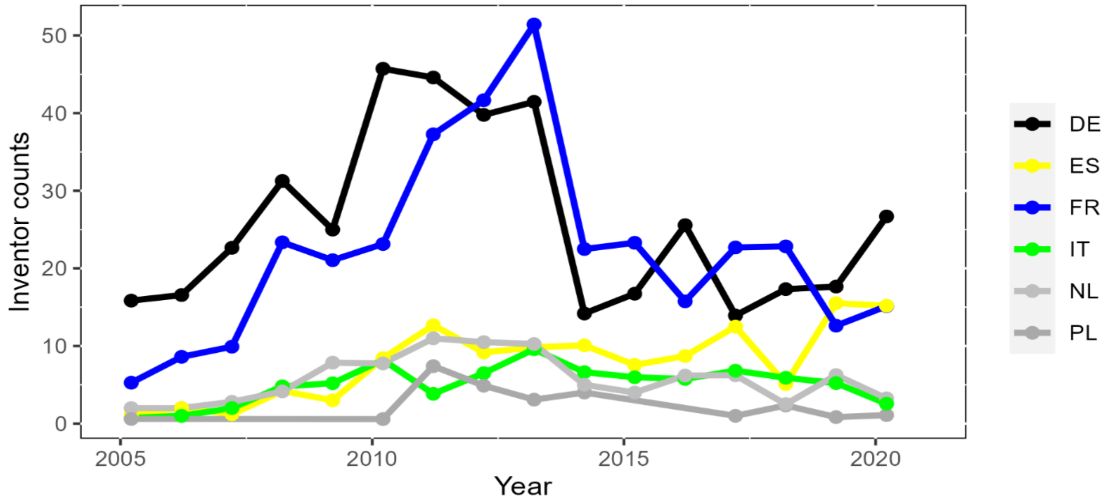
Figure 5: Average nanotech patent family sizes by country 2005-2020



Sources: EPO (2024); OECD (2024); own calculations.

In a comparison of the largest EU economies, Germany and France exhibited the highest level of patent activity in recent years in absolute terms (see Figure 6). However, the decline in innovation activity during the last decade was in both countries particularly pronounced. In 2020, Spain could catch up to the level of France. In per capita terms, France's innovation activity was regularly higher than that of Germany. Italy and Poland continuously exhibited comparatively low inventor counts per capita.

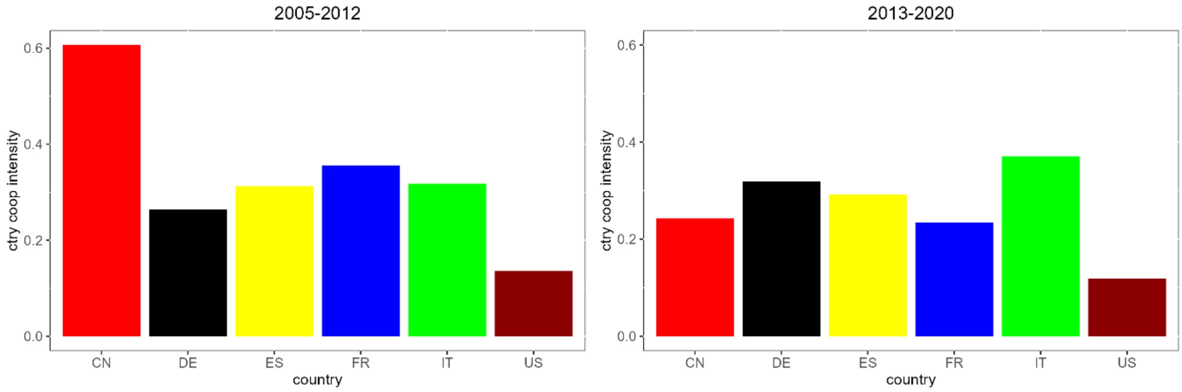
Figure 6: Evolution of nanotech patenting activities in selected Member States



Sources: EPO (2024); OECD (2024); own calculations.

In addition, our data set allows us to make country comparisons on the extent of international cooperation in innovation activities by comparing the addresses of the inventors registered in the patent applications. Figure 7 presents the intensity of cross-country cooperation in nanotech patents for a selection of countries. The intensity of cooperation is measured as the proportion of nanotech patents with inventors from the respective country in which inventors from other countries were involved. There are clear differences among EU Members as well as in comparison to China and the USA. In the period 2005-12, the intensity of international cooperation was particularly high in China. Within Europe, French inventors (around 35 %) showed the biggest share of involvement in international patent networks. In the subsequent period 2013-2020, the patterns looked slightly different. Nevertheless, the consistently higher international cooperation intensity of the depicted EU Members compared to the US is striking. In parts, this reflects the high domestic innovation potential of the US. Moreover, when comparing the two periods, the significant decline in China's international cooperation intensity is striking. This may to some extent be the outcome of a policy-induced cutting of ties to international research, but could also document a reduced need for external knowledge inflow.

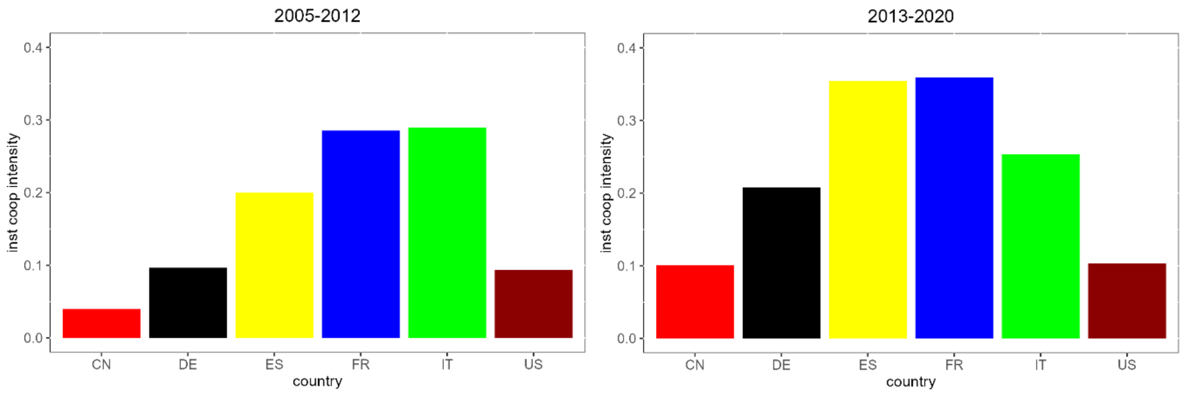
Figure 7: Intensity of cross-country cooperation in nanotech patents by country



Sources: EPO (2024); OECD (2024); own calculations.

Finally, we can also illustrate the intensity of research cooperation across different kinds of institutions. The PATSTAT database does not only offer names and addresses of the inventors, but also at least a broad delineation of the types of institutions the patent applicants can be assigned to. Precisely, it distinguishes types such as “Company”, “Government”, “University” and “Non-Profit Organization”. As the innovation economics literature suggests that cooperation between companies and research institutions can play a vital role in exploiting innovation potential, we will consider this information as well. In the following, we speak of interinstitutional cooperation in relation to a patent application if applicants from different types of institutions are reported. Figure 8 shows a country comparison of the resulting cooperation intensities. In both periods, the EU members exhibited far higher values for this indicator than China and the USA. France in particular stands out with a high degree of interinstitutional cooperation in both periods.

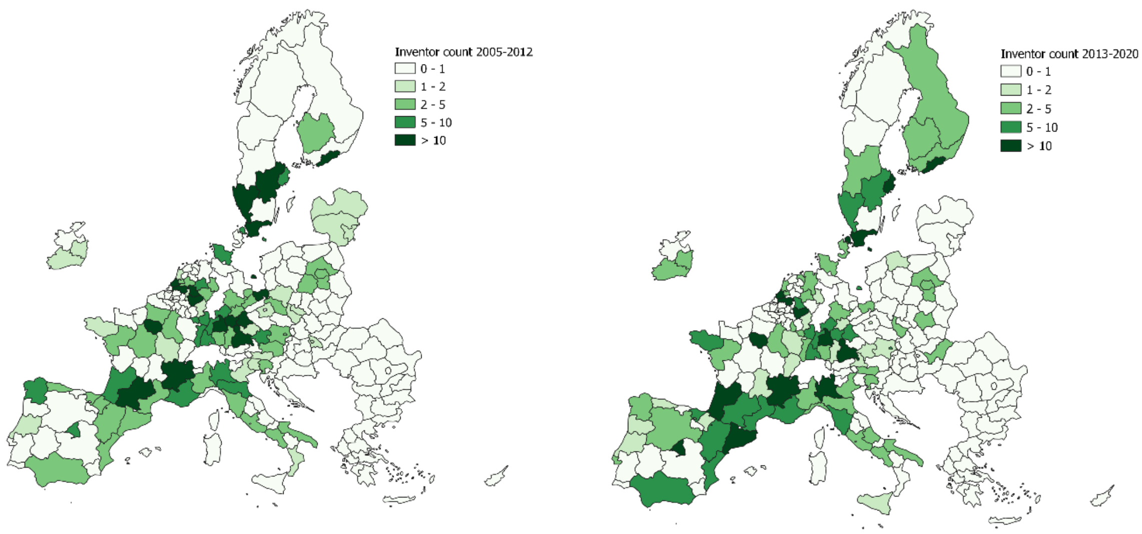
Figure 8: Intensity of interinstitutional cooperation in nanotech patents by country



Sources: EPO (2024); OECD (2024); own calculations.

Our database enables an even stronger spatial breakdown of patent activity in the field of nanotechnologies within the EU. REGPAT also contains indicators for the allocation of inventors' addresses of residence to NUTS regions. In the following, we choose the NUTS-2 level for the spatial comparison. Figure 9 depicts the average annual level of our *inventor count* measure, broken down by the periods 2005-12 and 2013-20. In general, a clear east-west divide is evident. Within the western Member States, markable spatial centres of innovation activity can be identified. The NUTS 2 region with the by far strongest patent activity in both periods was *Rhône-Alpes* (FRK2). In the latest period 2013-20, it was followed by *Île-de-France* (FR10) and *Upper Bavaria* (DE21). All three regions are characterized by a generally high degree of industrial agglomeration, which points to the importance of cross-industrial external scale economies. Macro-regional clusters of great importance in both periods were the south of France (plus Catalonia) and the south/south-west of Germany. In addition to this continuity, a comparison of the two periods also shows signs of a gradual shift in innovation activity. For example, Finland and some regions in Spain were able to gain ground in the more recent period.

Figure 9: Distribution of nanotech patent applications by NUTS-2 region (inventor count measure)



Sources: EPO (2024); OECD (2024); own calculations.

4.3 Drivers of EU nanotech innovation

We now examine the factors behind the pattern of nanotech innovations in the EU NUTS-2 regions. We measure the annual level of nanotech innovation in a region by the number of different patent families for which inventors from the region have filed patent applications (*fam_count*). Multiple applications within the same patent family are thus only counted once. This aims to ensure that we only count technically different inventions (see previous Subsection).

Our particular focus is on the impact of cross-regional and inter-institutional research cooperation. The promotion of strong supra-regional innovation networks has always been an objective of EU R&D support, both in general and specifically for focal areas such as nanotechnologies. So far, however, there is still a lack of evidence for the actual significance of this maxim for research success in nanotechnologies, especially with regard to the quality of the resulting patents. Similarly, the role of cooperation across institutions is still underexplored.

To arrive at testable relationships, influences on innovation activities that are related to time and place must also be considered. Our regional patent dataset, which is extensive in terms of both time and space, provides an ideal basis for this. In the following, we use it for our own econometric analysis. Following a procedure commonly referred to in the literature, we merge the patent dataset with a set of EU regional indicators from Eurostat.[70] One limitation in choosing regional control variables is that no sector-specific regional characteristics are available, as nanotechnologies are of a cross-cutting nature (see Subsection 4.1). Due to the coarser granularity of sectoral economic accounting measures such as value added at the regional level, these cannot be constructed from existing data for NUTS-2 regions. However, we can draw on aggregated indicators for high-tech manufacturing and research sectors, which are generally collected on a regular basis. Another limitation is the need for a sufficiently long time series for a dynamic analysis. Therefore, some interesting regional indicators (e.g. from the EU Regional Competitiveness Index) that have only been collected very recently cannot be incorporated.

We approximate the extent of direct regional R&D input using Eurostat data on human resources in sciences and technology, specifically the number of scientists and engineers working in the region (*HRST*). Potential effects of the degree of regional economic agglomeration on research success (e.g. through industry-external economies of scale) are considered by using regional GDP per capita as a control variable (*GDP_pc*). We approximate the general level of local cognitive capital (a possible influencing factor on the adoption of created knowledge and its implementation in future innovation)[71] based on the share of 25–64-year-olds with tertiary education (*tert_ed*). In addition to the intensity of interregional cooperation (*reg_coopins*), we consider the intensity of interinstitutional cooperation (see previous subsection) as a measure of cooperation (*inst_coopins*). It tests for the importance of cross-institutional knowledge networks, e.g. universities regularly sharing the latest findings from academic research with private companies and producers sharing production experience with academia.

Moreover, we use the lag in the inventor counts indicator as a further explanatory factor from the patent statistics *(inv_count*). It measures the potential importance of past regional engagement in patent activities for the quantity and quality of future innovations. It thus reflects path dependencies in innovation processes, i.e. the utilization of generated knowledge for subsequent innovations. To reduce endogeneity problems and account for the time lag in the creation of innovation, all explanatory factors are included in the model in lagged form (one year lag), following a recommendation in the literature.[72] Finally, to control for the influence of time-dependent effects, we include year dummies in the model.

When selecting the estimation method, the significant number of zero values for the dependent variables in the initial dataset must be handled with care. By far not all NUTS-2 regions possessed R&D capacities in the nanotech segment. Some regions did not generate any nanotech patents over the entire period of the sample. These were omitted from the estimation, as it is unlikely that any serious efforts were made to conduct commercial nanotech research. Another group of regions did generate nanotech patents within the sample period, but not in every year. Since we cannot assume that these

[70] Eurostat (2024). Regional statistics by NUTS classification. Eurostat Database.

[71] Caragliu, A., & Nijkamp, P. (2012). The impact of regional absorptive capacity on spatial knowledge spillovers: the Cohen and Levinthal model revisited. Applied Economics, 44(11), 1363-1374.

[72] Kekezi, O., Dall'erba, S., & Kang, D. (2022). The role of interregional and inter-sectoral knowledge spillovers on regional knowledge creation across US metropolitan counties. Spatial Economic Analysis, 17(3), 291-310.

patterns are random, we should not simply eliminate these zero values. Instead, we draw on the classic selection model approach established by James Heckman.[73] The mechanism underlying the observations is split into two processes. A process that determines the existence of positive values (i.e. the existence of patent activity) and a process that determines the level of positive values (i.e. the extent of patent activity). To apply the method, one variable must be defined as an exclusion restriction and appears only in the selection equation. For this, we choose the education variable, theorizing that a minimum amount of human capital in the region is needed to bring about any innovation in such an upfront field. The Heckman model with time fixed effects was estimated on the basis of a total of 1,933 observations. For the practical estimation, we used the statistical package *sampleSelection* implemented in the software *R*. Table A1 in the Appendix shows the resulting coefficient estimates.

The considered variables show heterogenous effects on existence and extent of nanotech patenting activity in EU regions. The lagged innovation count and the HRST variable exhibit in both steps highly significant and positive coefficients. As to be expected, this points to prominent roles of regional researcher pools and path dependencies for innovation activity. The roles of the two cooperation variables are less easy to pin down. The positive coefficient of the intensity of cross-regional cooperation is mildly significant in the selection equation and highly significant in the outcome equation. Since we check for GDP per capita and past regional inventor activity, this is not simply an expression of a stronger spatial outreach of research-focused agglomeration regions. For a given level of current inventor activity, a higher proportion of cross-regional cooperation in patenting is associated with more research success in the future.

The second cooperation variable, the measure of interinstitutional cooperation, is mildly significant in the selection equation and insignificant in the outcome equation. This suggests that the degree of interinstitutional cooperation primarily shapes the chances of a region to remain a nanotech innovator in the future. In view of the difficulties of delineating institution types in PATSTAT, however, it does not necessarily indicate a complete lack of importance for the extent of future nanotech innovation. Moreover, an unobserved form of value added could consist of boosting patenting activities in technology groups outside our delineation of nanotechnologies. This motivates the inclusion of additional data sources (e.g. at company level) to reflect more closely the sectoral background of the registered inventors. In general, given the lack of measures to check for differences in regional infrastructure, great caution must be exercised in inferring on causality.

[73] Heckman, J. J. (1979). Sample selection bias as a specification error. Econometrica: Journal of the econometric society, 153-161.

5 Policy implications

5.1 Fields of action

The Commission's strategy of securing the EU's industrial competitiveness through a pioneering role in advanced materials requires the consistent pooling of all resources. The main goal must be to increase the speed and effectiveness of development processes. This requires a profound degree of strategic alignment between regulators and private stakeholders in the EU. The envisaged definition of priority areas with a focus on green transformation and digitization is the right approach. However, the contribution of individual research areas to the transformation goals must not be too narrowly defined. The systemic perspective is crucial. Even materials that themselves do not possess superior environmental properties or are required for digital technologies should have strategic priority if they accelerate the transformation of supply chains as a whole. This applies, for example, to materials that can replace previously indispensable and scarce critical raw materials and thus support the implementation of emission-neutral or digital supply chains. The basis for the identification and updating of priority areas for material research should therefore be an indicator-based monitoring system. It should apply environmental and economic life cycle analysis methods to identify and continuously update requirements from a value chain perspective.

In addition to strategic monitoring, the establishment and management of an open collaboration infrastructure for material development should become a priority. The complexity and diversity of knowledge requirements ask for increased cooperation across at least four dimensions: along value chains, across economic sectors, across institutions (companies, research, regulators) and across research disciplines. Our empirical analysis of the factors influencing nanotech innovation also points to the importance of supra-regional R&D networks (see Subsection 4.3). Only if Europe succeeds in channeling and maximizing the internal flow of knowledge it can compensate for structural disadvantages such as the limited availability of venture capital. The infrastructure required for this has digital and analog components. At the digital level, interfaces must be created via a common data space to create a shared data pool. The regulators' task is to ensure that the FAIR principles (see Subsection 3.3) are enforced to prevent inefficiencies and the emergence of new information monopolies. At the analog level, the development of joint open test infrastructures for new materials should be promoted more strongly. In doing so, close institutional cooperation with venture capital investors should be sought. Material developers with smaller capital budgets can thus benefit equally from testing opportunities for their prototypes and the establishment of contacts for subsequent commercialization.

Finally, the EU should integrate the field of advanced materials as a strategic component in its external economic policies, in particular its trade and resource policies. In the negotiation of new free trade agreements or strategic partnerships with third countries, the prospect of knowledge exchange and access to EU research infrastructures can be an important asset in the negotiation process. Offers of long-term cooperation in the area of material development, protection of intellectual property and the definition of common standards for material properties and information processing could strengthen Europe's geo-economic weight.

5.2 Recommendations

1. **Reviewing product regulation with respect to innovation friendliness:** The regulatory framework relevant for material development in the EU (see Subsection 3.2) and in Member States should be examined with a view to incentives for innovation. In view of the prospect of sharply rising CO_2 prices and increasing demand pressure for greater sustainability, the need for detailed regulatory requirements such as those defined by the EU ecodesign regulation should be critically examined. The high regulatory complexity not only increases the information and monitoring costs of innovation processes. It could also hinder the development of materials that are superior from a supply chain perspective. One example would be the development of groundbreaking materials that do not offer any immediate sustainability benefits, but which consequently provoke the establishment of completely new domestic supply chains and thus the substitution of environmentally harmful production in third countries. Potential environmental trade-offs in material development should therefore be decided upon by the actors in the innovation processes, within the framework defined by the general EU environmental and climate legislation. Instead, regulation should focus on supporting the further development of voluntary certification and labeling systems that render the environmental footprint of products using advanced materials transparent to consumers. Finally, the concept of regulatory sandboxes, which has already been tried and tested in other technology fields (e.g. renewable hydrogen), should be applied to the trial phase of innovative materials as well.

2. **Streamlining of funding schemes for development and deployment of innovative materials:** Existing funding channels at EU and Member State level should be streamlined by establishing joint strategic funding priorities. These should not be limited to support of laboratory-level development and testing, but should include early stages of commercialization. Funding programs should be coordinated with the financing of downstream technologies by the STEP platform (see Subsection 3.2). The transversal role of digital technologies (e.g. dissemination of development data, product monitoring, consumer information) should be acknowledged through dedicated financing of digital innovation. In funding research initiatives, a focus should be set on consortia that feature a high degree of value chain integration and an outreach to stakeholders from different kinds of institutions (e.g. private companies, universities, research centres).

3. **Strengthening the knowledge base:** Shortages in the supply of young talent and experienced professionals for material research and manufacturing must be overcome in a targeted manner. An important step is the expansion of university study programs that are closely tailored to the needs of an industry that is strongly research based. Specialized master’s degree programs that involve an intensive exchange with local manufacturing companies can lay the foundation for regional "talent factories", overcoming the problems of finding the right matches on local labour markets, and providing companies with a reliable flow of highly qualified workers. Moreover, knowledge flows along supply chains should be strengthened by supporting technologies of digital material tracking. This can improve consumer sovereignty (e.g. digital product passports), facilitate design improvements (e.g. digital twins) and enable co-creation. Special promotion should be devoted to the integration of AI in research infrastructure, with the idea of self-driving labs as a central vision.

4. **Prevailing the contestability of internal material markets:** In order to maintain Europe's competitiveness on global material markets, it makes sense to bundle decentralized R&D resources

into large cross-sectoral consortia. At the same time, care must be taken to ensure that this does not result in closed clubs that jeopardize internal competition on European markets in the medium term. In particular, barriers for young firms as well as small and medium-sized companies (SMEs) in general in accessing competitive R&D networks must be removed. In addition to ensuring a rule-based openness of research infrastructures (see Point 2), this also requires dedicated support for SMEs. To strengthen knowledge spillovers, the awarding of R&D vouchers is a more effective way than funding through isolated research grants.[74] Large companies that enter into R&D partnerships with SMEs can redeem these vouchers and receive a payment. This increases the attractiveness of SMEs as partners for established R&D networks without direct state interference in private research programs. Public-private venture capital funds could also be a suitable means of promoting the commercialization of start-up innovations. Investments by the European Investment Bank (EIB) in privately managed venture capital funds supported by experienced industry players are a suitable means of ensuring the targeted use of funds. In addition, Member States should examine options for targeted tax policy incentives for venture capital (e.g. treatment of loss carryforwards in the event of a change of shareholders) within their national tax systems. Finally, all instruments targeting advanced materials should undergo a regular check of SME friendliness.

5. **Harnessing material innovations for the goal of open strategic autonomy:** With the paradigm of "open strategic autonomy", elaborated in its trade policy review 2021,[75] the EU aims to align the idea of a rule-based and open world trade with the creation of more leeway for own unilateral trade policy actions and a reduction of external dependencies. To enhance its geostrategic weight and gain new partnerships for the diversification of trade routes, the EU must bring all its strengths to bear. This currently includes, in particular, its outstanding capacity for groundbreaking material innovation in various industry segments (see Subsection 2.3). The offer of cooperation in material development should become an integral part of the EU’s global outreach, involving negotiations on future trade agreements, strategic resource partnerships as well as the Global Gateway initiative.

6 Conclusion

The competition for global technology leadership has been completely recalibrated by the advance of climate-neutral and digital technologies. Instead of incremental productivity improvements, it consists of designing, implementing and securing entire new supply chains. In this race, Europe has fallen behind as a production location due to a hesitant attitude towards the promotion of many new key technologies such as PV and battery production. In the present situation, instead of entering into a ruinous subsidy competition to regain lost capacities, Europe should focus on better utilizing its own strengths.

These lie primarily in the area of materials research. The EU's innovation potential in materials with properties crucial for the implementation of future technologies remains very high, both in terms of the breadth of application fields and the diversity of participating companies and research institutions. This is a considerable strategic advantage. The group of advanced materials can become a silver bullet for the twin transition by increasing the efficiency of future technologies and resolving existing

[74] Sala, A., Landoni, P., & Verganti, R. (2016). Small and medium enterprises collaborations with knowledge intensive services: An explorative analysis of the impact of innovation vouchers. R&d Management, 46(S1), 291-302.

[75] European Commission (2021a). Trade Policy Review - An Open, Sustainable and Assertive Trade Policy. Communication to the European Parliament, the Council, the European Economic and Social Committee, the Committee of the Regions and the European Investment Bank. COM/2021/66 final.

technical trade-offs between sustainability goals. However, for Europe to translate this advantage into industrial value added and secure jobs, a coordinated effort by all relevant stakeholders is required. Knowledge silos must be broken down and the potential of digital technologies, especially AI, must be fully exploited to optimize the flow of specialized knowledge within the EU.

Efficient knowledge networks require cooperation in several dimensions, as our exemplary analysis for nanotechnologies underlines. This concerns the exchange of knowledge between regional clusters, research disciplines, economic sectors and different types of institutions. At the same time, the need for exchange concerns not only research and development, but information along the entire supply chain, including user phase and final utilization. The establishment of a common digital and analog support infrastructure is an important step towards removing barriers to the commercialization and upscaling of production lines of innovative materials. It should serve as a complement to measures of more general importance, e.g. upskilling of workers and promotion of venture capital markets.

A key challenge of a future-oriented development strategy is to establish the right balance between cooperation and competition. From an EU perspective, this holds both internally and externally. Internally, the strategy of pooling resources and prioritizing research areas essential to the twin transition must be weighed against the desire to maintain adaptability to changing market conditions. A two-tier strategy makes sense under these circumstances. It restricts central governance structures to the top level of defining broad strategic fields. Within these fields, decentral steering is achieved through competitive public funding schemes and openness in access to research infrastructure. At the same time, care must be taken that the establishment and strengthening of large research conglomerates does not inhibit the competition of ideas for future-oriented material solutions. The system must remain open to disruptive visions from actors outside established market positions. To this end, incentive-conform instruments are required to integrate start-ups and specialized SMEs into established knowledge networks. An awarding of vouchers to research-strong companies, which can be redeemed by entering into an R&D cooperation with small companies, could be a suitable option.

Externally, the EU must clarify its strategy in the area of international technology cooperation. In a highly specialized and integrated global research landscape, technological leadership cannot be achieved through a decoupling from global cooperation networks. Security interests and the fear of unwanted knowledge outflows must not lead EU research into splendid isolation. Instead, the EU should adopt a self-confident strategy and use its strength in the field of materials research as an asset for forging new technology alliances. These can become a further building block for the overarching goal of creating diversified international supply chains, and thus a true open strategic autonomy.

7 Appendix

Table A 1: Determinants of regional nanotech innovation – Regression results Heckman model

	Dependent variable: fam_count					
	Selection equation			Outcome equation		
	Estimate	*Std. Error*	*p-Value*	*Estimate*	*Std. Error*	*p-Value*
Regressors						
intercept	-1.424	0.153	< 2e-4***	-2.127	0.986	0.031**
inv_count (lag)	0.104	0.018	< 2e-4***	0.464	0.028	< 2e-4***
HRST (lag)	0.396	0.043	< 2e-4***	0.919	0.124	< 2e-4***
tert_ed (lag)	0.257	0.122	0.035**	-	-	-
GDP_pc (lag)	0.180	0.098	0.065*	0.573	0.337	0.089*
reg_coopins (lag)	0.170	0.084	0.043**	0.746	0.275	0.007***
inst_coopins (lag)	0.299	0.146	0.040**	0.281	0.423	0.507
Year 2010	0.385	0.156	0.014**	1.878	0.522	< 2e-4***
Year 2011	0.507	0.156	0.001***	1.720	0.523	0.001***
Year 2012	0.282	0.157	0.072*	0.908	0.512	0.076*
Year 2013	0.417	0.157	0.008***	1.178	0.511	0.021**
Year 2014	-0.059	0.157	0.709	-0.905	0.517	0.080*
Year 2015	-0.236	0.160	0.139	0.093	0.547	0.865
Year 2016	-0.104	0.159	0.514	-0.198	0.530	0.709
Year 2017	-0.016	0.158	0.917	-0.039	0.518	0.940
Year 2018	-0.059	0.157	0.709	-0.578	0.515	0.262
Year 2019	-0.344	0.162	0.034**	-0.914	0.554	0.099*
Year 2020	-0.437	0.165	0.008***	-1.098	0.564	0.052*
Inverse mills ratio	-	-	-	2.133	0.545	< 2e-4***
Adj. R^2	0.544					
No. observations	1,933					

Sources: EPO (2024); OECD (2024); Eurostat (2024); own calculations. Significance codes: 0.01 '***' 0.05 '**' 0.1 '*'

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