SUSNANOFAB
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Roadmap draft for an EU wide strategy on nanofabrication

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1.0	30/08/2021	Submission of the final version of "Roadmap draft for an EU wide strategy on nanofabrication"

Abbreviations and Acronyms

Acronym	Description
AM	Additive Manufacturing
BIPV	Building Integrated Photo-Voltaic applications
CCM	Catalyst Coated Membrane
CCS	Catalyst Coated Substrate
CG	Coordination Group
CIGS	Copper Indium Gallium Selenide solar cells
CL	Catalyst Layer
CNT	Carbon Nano-Tube
CPS	Cyber-Physical Systems
CSA	Coordination and Support Action
EPPN	European Network for Pilot Production Facilities and Innovation Hubs
ERC-ADG	European Research Council Advanced Grant
ERC-STG	European Research Council Starting Grant
ETP	European Technology Platforms
GCP	Good Clinical Practice
GMP	Good Manufacturing Practice
GO	Governmental Organization
HE	High Education Institution
IA	Innovation Action
ICT	Information and Communication Technology
IPCEI	Important Projects of Common European Interest
KET	Key Enabling Technology
KIT	Karlsruhe Institute of Technology
KPI	Key Performance Indicators
MCFC	Molten Carbonate Fuel Cells
MEMS	Micro-Electronic-Mechanical Systems
MOEMS	Micro-Opto-Electro-Mechanical Systems
MPW	Multi-Project Wafer
MRAM	Magnetic Random-Access Memory
MSCA-RISE	Marie Skłodowska-Curie Actions - Research and Innovation Staff Exchange
NCH	Nylon 6-Clay Hybrid
NEMs	Nano-Electronic-Mechanical Systems
PE	Printed Electronics
PEMFC	Proton Exchange Membrane Fuel Cell
PVC	Poly-Vinyl Chloride
RIA	Research Innovation Action

RTO	Research Technology Organization
SDK	Showa Denko's carbon nanofibers
SME	Small-Medium Enterprise
TPO	Thermoplastic Poly-Olefins
US	United States
USA	United States of America

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Executive summary

This present document is the deliverable 3.2 "Roadmap draft for an EU wide strategy on nanofabrication" of the SUSNANOFAB project. It is one out of the two roadmap deliverables present in the project agreement.

Nanofabrication has the potential to address major socio-economic challenges, from better and affordable health care to cleaner energy and transports, improved consumer goods and higher living standards. The SUSNANOFAB project proposes an integrated strategy at a European Level that articulates the whole value-chain, aiming at the promotion of a competitive and sustainable nanofabrication industry.

This document aims at delivering a comprehensive overview and analysis of the nanofabrication landscape up to the current developments of the project. The scope of the document is to give an overall view of the current state of the roadmap and to contextualise the following steps of its development.

The document proposes at first an overall introduction to the whole project concept and aims. This is followed by a chapter on the methodology used to build the roadmap, the role of the external experts in the road-mapping process, the target sectors and products, the identified gaps and actions, and related content. Then, the vision of the roadmap for the nanofabrication sector is presented, altogether with drivers and challenges that are foreseen to play a key role for a successful market uptake of nanofabrication. Subsequently, the current nanofabrication ecosystem and a general overview of the current state of the nanofabrication sector are shown at large and discussed in detail in the following chapter, which describes the target sectors addressed by the roadmap, target product groups, and the regional capabilities, including also maps of regional and national nanofabrication projects and initiatives. In the next chapter, the identified actions for future research and innovation activities are listed, and the identified actions are divided between technical and non-technical actions. In the concluding chapter, all results achieved are summarised and the key conclusions attained by this draft version of the roadmap are drawn.

Road-mapping activities involved about 105 experts so far, which interacted in groups of people with diverse backgrounds. To yield a more accurate analysis, further experts will be involved. This will be achieved by increasing the network visibility; hence, attracting further experts and making our action well known in the European nanofabrication sector.

Our current achievements derived from two meetings, which moulded SUSNANOFAB project vision, key drivers, and challenges. The challenges were identified by an in-depth analysis of the nanofabrication landscape of the key initiatives, projects, services, infrastructures, and stakeholders. We have collected several feedbacks on the causes of such challenges and on possible actions to overcome them. In the following months, we will deliver an action plan of such actions, framed by

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priority of action and the appropriate timescale. Our current project's efforts are devoted at the collection of the industrial needs, which are the foundations for developing training and brokerage activities apt to mitigate them.

This revision and validation of our former results and the future roadmap developments will allow us to develop and validate a final roadmap. To have a coherent contribution, we will align SUSNANOFAB to the strategies of recent and former implementation adopted by the European Commission (*i.e.*, Horizon Europe strategic plan[1], the 2030 Agenda for Sustainable Development[2], A European Green Deal[3], An economy that works for people[4], A Europe fit for the digital age[5], Recovery plan for Europe[6], and Next Generation EU[7], *etc…*).

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[1] Horizon Europe, Strategic plan 2021-2024 (doi: 10.2777/083753)
[2] United Nations, 2015 (https://sustainabledevelopment.un.org/post2015/transformingourworld/publication)
[3] COM(2019) 640 final, 11.12.2019 (CELEX: 52019DC0640)
[4] An economy that works for people (https://ec.europa.eu/info/strategy/priorities-2019-2024/economy-works-people_en)
[5] A Europe fit for the digital age (https://ec.europa.eu/info/strategy/priorities-2019-2024/europe-fit-digital-age_en)
[6] Recovery plan for Europe (https://ec.europa.eu/info/strategy/recovery-plan-europe_en/)
[7] NextGenerationEU (https://europa.eu/next-generation-eu/)

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1 Introduction

The global target of SUSNANOFAB project is to put in place an **integrated concerted action on nanofabrication**, sustainable in the long term. The project establishes and promotes a robust network of European and international stakeholders and geographically distributed centres. These activities aim to provide current **missing links between policy, infrastructure, expertise, and industry requirements**, and contribute towards the **improvement of the current EU positioning and performance in the global nanofabrication market**.

SUSNANOFAB will tackle the needs of the nanofabrication sector by addressing them on three different levels:

- At a **general level,** SUSNANOFAB will establish and **promote a robust network** of EU and international stakeholders, connecting geographically distributed centres.
- At a **strategic level**, SUSNANOFAB will find a common strategy to **enable all pre-competitive conditions for a successful market uptake** of nanofabricated products and solutions. This will be reached using a structured road-mapping methodology and involving external experts in Coordination Groups.
- At an **operational and end-user level**, the project will provide **an easy access point to affordable services**, **infrastructures, and knowledge** to EU stakeholders, and especially to SMEs. This will be reached using different integrated methodologies, such as the organisation of a set **of training and brokerage workshops and services**, and via the development of a Digital Platform, which will perform in an interoperable manner with ongoing initiatives (*e.g.,* the European Network for Pilot Production Facilities and Innovation Hubs, the European Material Modelling Council etc.).

To promote international cooperation, SUSNANOFAB Consortium includes **3 US partners** not requesting EU funding. To involve a high number of key actors, the project has already gained the support of several companies, research and education establishments, European Technology Platforms, clusters and industrial associations, national, regional, and international nanofabrication related entities.

The present document constitutes Deliverable D3.2 "Roadmap for an EU wide strategy on nanofabrication – Draft version", published in the framework of the SUSNANOFAB Coordination and Support Action, entitled "Integrated EU strategy, services and international coordination activities for the promotion of competitive and SUStainable NANOFABrication industry" and funded by the Horizon 2020 Programme, under Grant Agreement nº 882506. This deliverable aims to establish a common medium-short term agenda with the identified and prioritised actions needed to fill the existing gaps and to introduce nanofabrication in the European industrial ecosystem in an effective way, solve nanofabrication issues from design to manufacturing upscaling, integrate inputs from ongoing initiatives on common research and standards in modelling, characterisation and processes, promote sustainability of nanofabrication in terms of human health, ethics, environment and life-cycle analysis, and develop the necessary skills for the nanofabrication industries. In brief, the roadmap will show the strategy to overcome the current barriers to upscaling nano-enabled functional systems. In addition to the desktop research, this deliverable draws on the opinions of experts throughout the entire nanofabrication value chain.

Nanofabrication is defined as: the **design and manufacture of structures with dimensions measured in nanometres** (*i.e.,* nanostructures). In the words of (Ding, Yu, & Wang, 2019) "*nanofabrication is the*

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future of technology and will soon be at the forefront of all manufacturing technologies by providing the design and fabrication of functional nanomaterials, which are potentially capable of responding to all major global challenges of the present and the future".

As such, nanofabrication has the potential to make a significant contribute to the top European Commission priorities, including the ones stated within "A European Green Deal", "An economy that works for people", "A Europe fit for the digital age", "Recovery plan for Europe", and "Next Generation EU". This may result in improvements in a multitude of diverse areas and in the ability to tackle major socio-economic challenges for an ever improving yet affordable health care, higher standards of living and quality consumer goods, cleaner energy, and transport. Given the above-mentioned potential of nanofabrication, the **SUSNANOFAB project tackles all nanofabrication technological and non-technological issues** of the nanofabrication value chain, facilitating interactions among stakeholders.

Chapter 2 presents **the methodology** used to build the roadmap. The roadmap is developed, with the help of **external experts** (in technical and non-technical aspects), in terms of sectors, products, identified gaps and actions, and related content.

Chapter 3 presents the **vision of the roadmap**, including drivers and challenges that are foreseen to play a key role for a successful market uptake of nanofabrication.

Chapter 4 introduces the current nanofabrication ecosystem and offers a general overview of the current state of the nanofabrication sector at wide.

Chapter 5 describes the **target sectors** addressed by the roadmap. After a general description of each sector, **target product groups** (and examples of specific products) and the **regional capabilities** are presented by sector, including also maps of regional and national nanofabrication projects and initiatives. Details of the international and European, national, and regional projects are reported in Annex A and B.

Chapter 6 reports the **identified actions for future research and innovation activities**, dividing them between technical and non-technical actions. In turn, technical actions are segmented in cross-cutting (*i.e.*, relevant for more/all sectors) and sectorial ones. In the final issue of the roadmap (D3.5), **details of each action** in terms of identified gap with the description of the current context, description of proposed activities, timespan of the action, *etc...* will be reported in Annex D.

Chapter 7 summarises the results and it draws the key conclusions attained by this draft version of the roadmap.

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2 Road-mapping methodology

The **road-mapping activity** aims at the **development of a strategic plan for** the field of **nanofabrication and its path for industrial implementation**. This plan will be able to bring forward the field of nanofabrication by identifying the **key drivers** to exploit **and key challenges** to be addressed to **enable a successful development** of a nanofabrication environment able to deliver high quality products. The main sectors, which are the focus of this roadmap, where nanofabrication can be relevant are:

- Health
- Digital and industry
- Climate change and energy
- Mobility
- Food and natural resources
- Inclusive and secure societies

Figure 1. Main fields where nanofabrication is relevant.

Details on the applied methodology are reported hereafter. The roadmap builds on other recent Roadmap, activities (Table 1) extensively revised and further developed in terms of sectors, products, identified gaps and actions, and any other related content with the help of **external experts** (in technical and non-technical aspects). It focuses specifically on the fabrication of nanomaterials.

Table 1. SUSNANOFAB road-mapping contribution with respect to other EU roadmaps.

ROADMAP	Main Outputs of Existing Roadmaps	Relation to SUSNANOFAB Roadmap
EMMC Roadmap[8]:	• EMMC has the goal to network all EU- and international stakeholders in the field and undertake coordination action to support the industrial uptake of materials modelling and digitalisation • Facilitation of Translational Workflow efforts to match identified needs with materials modelling capabilities • Creation of Marketplaces and Data repositories as part of the Open Innovation Platform • Develop an Elementary Multiperspective Material Ontology (EMMO) as a top-level ontology for applied sciences • Ensuring appropriate Infrastructural Facilities and Interoperability of materials models • Attract, educate, and train people for the use of materials modelling	The focus of the EMMC roadmap is much wider since it deals with all materials. However, all the inputs related to nano-components fabrication and the related ontologies will be duly considered in SUSNANOFAB for harmonisation and coherence with this work.

[8] EMMC – "The EMMC RoadMap 2018 for Materials Modelling and Informatics" – 2018.

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AM- Motion Roadmap[9]	The main output of the roadmap is the identified list of technological and non-technological challenges in Additive Manufacturing (AM) to reach the 2030 vision, the description of possible future research and innovation actions, and the high-impact product groups on which research efforts should be focused.	The outputs of will be considered for all the aspects related to AM fabrication of nanostructured components.
A vision for European Industry 2030[10]	This vision is set by the industry 2030 high level industrial roundtable, which was established by the European Commission in December 2017 to provide independent advice on future EU industrial policy action. The vision foresees that we will invest heavily in cutting-edge and breakthrough technologies, respect planetary boundaries and biodiversity, take leadership in smart European and global alliances, reinforce our global competitiveness and, finally, invest in current and future generations by addressing key societal challenges.	SUSNANOFAB roadmap will align with such strategy and identify how nanofabrication may contribute to such a vision.
EPPN strategic documents[11]	• Mapping of pilot production facilities: analysis & cluster • Other initiatives and services mapping: a report describing the existing capabilities/infrastructures existing around the pilot production facilities concerning modelling, characterisation, and safety related services • Pilot lines best practices and benchmark • Innovation hubs: best practices	Contributions from EPPN will be considered for in terms of pilot profiles active in the nanofabrication domain and their capabilities and infrastructures.
Sector-specific Roadmaps	• NEREID NanoElectronics Roadmap for Europe (2018)[12] • ETP Nanomedicine Strategic Research Agenda (2016)[13] • Bio-Based Industry Strategic Innovation and Research Agenda (2017)[14] • Plastics Strategic Research and Innovation Agenda in a Circular Economy (2018)[15] • IEEE International Roadmap for Devices and Systems (2018)[16] • Others to be analysed during the project	The outputs of sector-specific roadmaps will be considered mainly for the identification of target products of industrial relevance and of the sectorial research and innovation needs.

[9] AM-Motion CSA – "A strategic approach to increasing Europe's value proposition for additive manufacturing technologies and capabilities" – Grant Agreement N° 723560 – 2016-2018.
[10] https://ec.europa.eu/docsroom/documents/36468
[11] https://www.eppnetwork.com
[12] https://www.nereid-h2020.eu/roadmap
[13] https://etp-nanomedicine.eu/wp-content/uploads/2018/09/Nanomedicine-SRIA-2016-2030.pdf
[14] https://www.bbi-europe.eu/sites/default/files/sira-2017.pdf
[15] https://docs.wixstatic.com/ugd/81f3b1_57e4cd776e40404badaeff9738e7d48c.pdf
[16] https://irds.ieee.org/

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Moreover, coordination with the sister project "NanoFabNet" was included to integrate their expertise and facilitate coordination among the currently developed roadmaps on nanotechnologies.[17]

SUSNANOFAB focuses on the **6 target sectors** showed above considering sectorial and cross-cutting actions to solve current gaps, both technical and non-technical ones. The roadmap starts from a **vision for the European nanofabrication sector in 2030, which identifies key challenges and opportunities for a successful market uptake of nano-enabled materials and technologies.** In this framework, for each sector, **target products and cross-sectorial challenges** have been identified in the nano-fabrication landscape and linked with specific future actions aimed at solving current issues. The roadmap includes a semi-quantitative **impact assessment** of the identified actions, considering economic, social, and environmental key performance indicators (KPIs). It integrates SUSNANOFAB findings in terms of current **regional and national capabilities in nanofabrication** (maps of regional and national projects and initiatives by sector), potential international synergies in the **nanofabrication** sector, and suggestions on **possible business collaboration models**.

SUSNANOFAB was developed and expanded by a combination of expert workgroups and desk research, which integrated the results of key initiatives developed within the SUSNANOFAB network. Nanofabrication was considered by three different perspectives, which are represented in the three SUSNANOFAB coordination groups (CG), namely:

- Coordination group 1 (CG1): "Nanofabrication aspects from design to manufacturing upscaling", chaired by IDONIAL (Dr. Paula Queipo) and co-chaired by BROWN (Dean Prof. Kimani Toussaint, Jr.).
- Coordination group 2 (CG2): "Environmental Sustainability, Health and Ethics in a life cycle perspective", chaired by CEA (Dr. Marina Urbina) and co-chaired by BAYLOR (Prof. Christie M. Sayes).
- Coordination group 3 (CG3): "Future skills and capabilities", chaired by INL (LLM Monike Rocha) and co-chaired by GTRC (Dr. Quinn Spadola).

These working groups were established to gather experts from both Europe and USA to discuss their perspective on the future developments of nanofabrication and define how to satisfy the current and future needs of this sector with a comprehensive approach. Each working group includes at least 10 high-level experts from research, industry, policy, finance and end-users' representatives and it is foreseen to widen the participation up to at least 20 people. Each working group has a chair and a co-chair, respectively appointed from EU and US. Amongst the experts, a good background diversity is sought (*e.g.*, large companies, SMEs, RTOs, pilot's owners, policy makers, and associations).

The work that is being carried out by these coordination groups is summarised in the table below (Table 2), which collects all the available material and the foreseen outcomes of the coordination groups.

[17] https://nanofabnet.eu/

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Table 2. SUSNANOFAB road-mapping - coordination groups input and output.

<table>
<tr><th colspan="2">Input provided to the coordination groups</th></tr>
<tr><td colspan="2">Nanofabrication landscape analysis developed in SUSNANOFAB:
• market analysis, including key drivers and challenges by sector and exemplary target products;
• EU and International initiatives and projects relevant to nanofabrication;
• existing ontologies and databases (materials, design modelling, safety etc.) linked to nanofabrication;
• existing roadmaps (sectorial or cross-cutting);
• existing standards and ongoing standardisation activities and common approaches;
• educational needs identified by SUSNANOFAB end-users through surveys and interviews.</td></tr>
<tr><th colspan="2">Common output from the coordination groups</th></tr>
<tr><td colspan="2">• Development of a “2030 Vision” for nanofabrication.
• Validation and prioritisation of. SUSNANOFAB target products.
• Appraisal of the current position at EU and international level with respect with the target sectors and products.
• Promotion of best practices in the CG domains.
• Delivering a comprehensive “Roadmap for an EU wide strategy on nanofabrication” including an implementation plan for short-medium term actions.</td></tr>
<tr><th colspan="2">Additional output from each coordination group</th></tr>
<tr><td>CG1- Nanofabrication Aspects from Design to Manufacturing Upscaling</td><td>• Research and innovation agenda focusing on innovative nanofabrication technologies <u>for SUSNANOFAB target products</u> covering all relevant steps of the value chain.
• Identification of actions which require an international dimension to address existing gaps in the development and uptake of common approaches in design, modelling, characterisation, and testing focusing on nanofabrication.
• Recommendations for new standards on nanofabrication technologies.</td></tr>
<tr><td>CG2 - Environmental and Sustainability issues, Health and Ethics in a Life Cycle Perspective</td><td>• Identification of EU research and innovation actions on the economic, environmental, and health-related sustainability assessment of <u>target SUSNANOFAB products</u>.
• Identification of actions that require an international dimension to address the existing gaps in the nano-safety research and knowledge uptake by all the stakeholders, as well as in the development and diffusion of combined environmental, social, and economic life cycle assessments.
• Identification of actions where nanofabricated products and approaches will address current ethical issues and promote social inclusiveness within EU and international countries.
• Recommendations for new standards in the coordination group area.</td></tr>
<tr><td>CG3 – Future Skills and Capabilities</td><td>• Identification of EU research and coordination actions targeting different level of education, from high school to university degrees, masters PhDs up to workforce training courses, focusing on the identified nanofabrication educational needs.
• Identification of actions that require an international dimension to address the existing gaps in nanofabrication skills and education. Such actions may take the form of novel student and workforce exchange programmes, common nanofabrication curricula for masters and degrees etc.</td></tr>
</table>

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Participation from the experts is expected in different key points throughout the roadmap, specifically a minimum of 3 meetings are expected (Figure 2):

- Initial meeting (December 2020): Brainstorm session on the roadmap vision, and high-level challenges and drivers.
- Second meeting (April 2021): To check on the challenges defined and needed actions to overcome them.
- Third meeting (September 2021): Roadmap validation and impact assessment.

Up to now, the core SUSNANOFAB road-mapping and networking activities were performed by the whole consortium throughout the interaction between expert groups formed by people from different technological and non-technological areas, chaired by project partners and involving overall about 105 experts.

Figure 2. SUSNANOFAB road-mapping steps. It summarises the main SUSNANOFAB road-mapping steps, from the definition of the scope of the work to the final release of SUSNANOFAB roadmap in December 2022.

The information collected in the road-mapping process was then analysed to facilitate the nanofabrication sector by the development of clustering activities (*e.g.,* training, brokerage services).

3 Vision to 2030 in nanofabrication

Global warming crisis, pandemics, ageing population, and natural resources scarcity are impending upon us all. We need brand new approaches and a clear strategy to address them. Since the dawn of time, technological advancements are the key to any societal progress.

In this framework, **nanofabrication** may have a **critical role in addressing current societal challenges** by raising fabrication accuracy at a nano scale. By shifting manufacturing perspective to a nano scale, you challenge the approach presently held on fabrication practices. This results in astounding materials, otherwise unattainable, with a high structural definition.

A such high definition can interfere with many classical physical properties, such as reflection, adhesion, tensile strength, nucleation, and many more. A wide variety of functionalised products arises from the modification of such fine properties, ranging from hydrophobic coatings up to lightweight but robust and resistant material composites. However, currently Europe is not in the lead of this technologic field.

SUSNANOFAB vision for 2030 foresees that Europe will **bridge the technological gap in nanofabrication and raise the competitiveness of European nanofabrication sector** to an international level, **raising Europe among the key players** in the nanofabrication field. **By leveraging the potential of nanofabrication** technologies, Europe aims at the **development of key technologies for a green transition** whilst fostering the inclusion of **responsible innovation, sustainability, and safety by design** in the current production methodologies. Nanofabrication is set to **improve the quality of life** of European citizens in terms of **retention of high-quality jobs in Europe**, availability of **customised, cleaner, safer, and affordable products, cleaner energy and mobility, and an effective and personalised medicine**. By collaborating **with leading international institutions** in the field of nanofabrication, we will establish a **cooperative exchange of ideas**, which will allow us altogether **to address current and future obstacles to unleashing the disruptive potential of nanofabrication**.

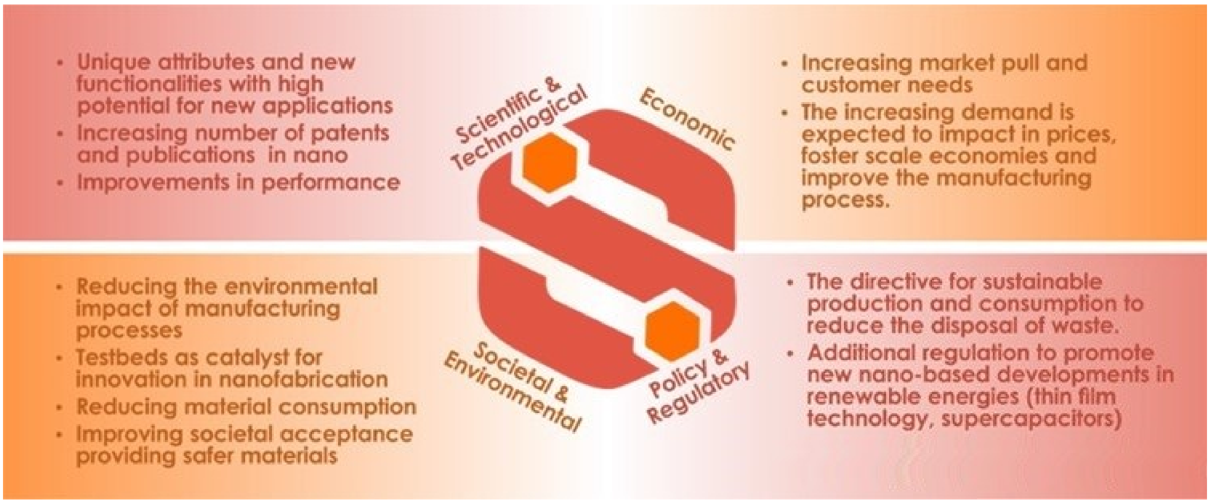

Figure 3. Summarises SUSNANOFAB cross-sectorial drivers, covered in the roadmap, divided per category (*i.e.*, scientific and technological, economic, societal and environmental, and policy and regulatory).

The following lists describes some of the **drivers** for the uptake of nanofabrication by the manufacturing environment:

- **Scientific and Technologic**

- **Unique attributes and new functionalities with high potential for new applications.** More concretely, the small mass and size of Nano Electro-Mechanical Systems (NEMs) gives them many unique attributes offering immense potential for new applications and fundamental measurements. Also, NEMs offers a solution to obtain electronic devices with higher functionality (closely linked with semiconductor market), which constitutes an important demand driver. On the other side, Printed Electronics (PE) is set to revolutionise the electronics industry. Nano enabled materials fit with printed electronics to enable a simpler, more cost-effective, high performance and high-volume processing in comparison to traditional printed circuit board and semiconductor manufacturing techniques. Finally, in health sector, there are several technological and scientific drivers to foster nanofabrication: the development of new nanoparticles and encapsulation techniques for drug formulation, controlled release and targeted delivery, recyclable or incinerable materials for high-performance batteries and power sources, biodegradable and dissolvable materials for epidermal and implantable electronics, and ultraminiature and highly integrated sensors, substrates and systems for the future health and well-being technology integration.
- **Increasing number of patents and publications in nano.** For example, since 2000 to 2017 the increasing number of patents in nanofibers shows a raising interest in the development of this nanomaterial closely linked to electronics, sensors, and transport sector in general. Also, there is an increasing number of publications concerning nanotechnology for fuel cells between 2000 and 2016, which reveals a growing interest, specially led by Asian countries.[18]
- **Improvements in performance**. A representative example can be found in the use of nanomaterials for batteries: rechargeable lithium batteries are currently the main battery technology for mobility applications, while Gen4 (generation 4a, solid state Li-ion, and generation 4b, solid state Li metal) are considered to be the future technology. Lithium batteries are the major subject of industry investment, but performances such as energy density, power density and cycle life should be improved while cost should be reduced. Design and development of nanostructures materials-based electrodes and nano-enabled battery packaging are an interesting approach to overcome the current limitations of li-ion batteries. In this sense, the develop of new nanomaterials with better performances is a critical part of an emerging fuel cell market. In another vein, the use of nano-additives may ensure the requested functionalities maintaining the high level of performance in automotive sector. Besides, in energy sector, nanofabrication can impact on photovoltaics improving the glass thin film technology and can foster both the upscaling of heterogeneous catalytic reactions and the upscaling of supercapacitors technology.

- **Economical, policy, and regulatory**
  - **Increasing demand** of some components (*e.g.,* NEMs and electronic products) is expected to impact in prices (**cost reduction**), foster scale economies and improve the manufacturing process. The technology progress plays a crucial role by driving nanomaterials development for specific purposes thanks to the advances in computing power, modelling and design and characterization methodologies, to bring nanomaterials and nano enabled solutions into commercial products. For instance, in mobility sector,

[18] Zhu, H., Jiang, S., Chen, H. et al. International perspective on nanotechnology papers, patents, and NSF awards (2000–2016). J Nanopart Res 19, 370 (2017). https://doi.org/10.1007/s11051-017-4056-7

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the processes needed to coat the parts in an automobile with skins (*e.g.*, PVC, TPO, *etc…*) or to paint them are expensive. Replacing these coatings by nano-patterned surfaces guarantees a significant weight reduction, improved recyclability, and an important cost reduction that would have a positive effect in the final price of the part. In energy, thin film PV are ideal for large scale solar farms, as well as Building Integrated Photovoltaic applications (BIPV) due to lower production costs of certain technologies (*e.g.*, kesterites, perovskites …). Nanofabrication also offers economic advantages in health sector: for instance, the reduction on current hospital infrastructure and moving health from a reactive service system to a preventative proactive informing system. Also, substantial savings in national health budgets through better adherence, leading to remote healthcare delivery tools, reduced drug wastage, stable dosage regimes, fewer hospital visits and decreased incidences of secondary complications. There is also increased economic activity in fields of P4 patient care, artificial intelligence, personalised medicine, and high-value, low dose drug formulations.

  - **Environmental regulation** (*e.g.*, the recycling of Metalworking Fluids used in automotive sectors) to foster nanofiltration techniques. In addition, environmental regulation related to the recyclability of products can be supported by the used of nanotextured surfaces, which offers an alternative to the currently used coatings. These have proven to have harmful consequences on the environment, not only as they involved the use of ecotoxic compounds, but also as they are difficult to remove at the product's end-of-life, resulting in a reduced recyclability.
  - The directive for **sustainable production and consumption** for the prevention of Waste Electrical Electronic Equipment is an opportunity to reduce the disposal of waste and to contribute to the efficient use of resources and the retrieval of valuable secondary raw materials.
  - **Additional regulation** to promote new nano-based developments in different fields. For example, public financial support for the PV sector and incentives for consumers, additional government regulation and policy support to incentivize an adequate market development for green/clean hydrogen production policies and regulation to foster supercapacitors in energy sector, and policies to foster remote medicine and smart MedTech among others.

- **Societal and Environmental**
  - **Reducing the environmental impact** of manufacturing processes of nano-enabled products for automotive and aeronautic industries, due to the reduction of raw material use, materials waste, and energy consumption; for example, nano-materials can be used in integrated heating systems to reduce the energy consumption of a process. Also, in food and natural resources, promoting a reduction of hunger and a more sustainable use of marine and terrestrial ecosystems. On the other side, novel and better performance catalysts will support the hydrogen development and deployment which can greatly help on climate mitigation and other environmental goals, energy supply diversification, and technological leadership.
  - **Testbeds** as catalyst for innovation in nanofabrication since the success of innovation in deep-tech innovation businesses like the ones involving nanotechnologies, requires the confluence of three dimensions (3Ms): technology expertise (minds), management and smart capital from investors (money).

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- **Reducing material consumption**, especially in energy sector using, for example, thin film PV technologies.
- **Improving societal acceptance** providing safer materials (*e.g.*, supercapacitors) and demonstrators (*e.g.*, personalised medicine to empower patients to be in more control of their health and wellbeing).

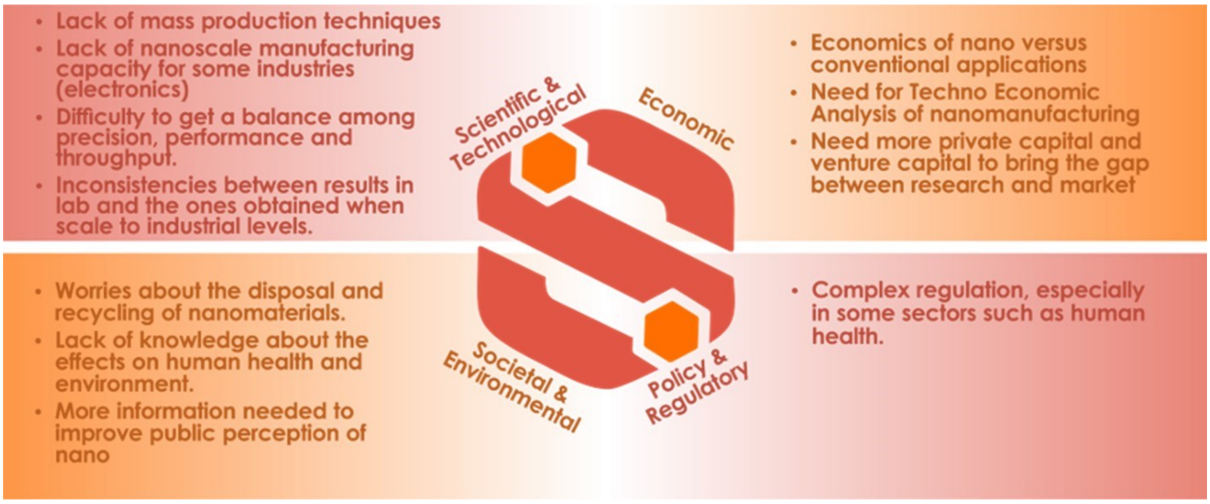

Figure 4. Summarises SUSNANOFAB cross-sectorial challenges, covered in the roadmap, divided per category (*i.e.*, scientific and technological, economic, societal and environmental, and policy and regulatory).

However, Europe must also address several **technical and non-technical challenges**, which may hinder nanofabrication development and market uptake. The following challenges were identified via a collaborative approach involving of SUSNANOFAB experts as described in the methodology section (see above):

- **Scientific and Technologic**
  - Lack of **mass production** techniques, for example, in NEMs. In fact, there are still some technological challenges to optimise NEMs production. This market is still a niche market and relatively new. The same problem, lack of mass production techniques, affects to nanofibers: production speeds need improvements and there are still high initial manufacturing costs. Also, it happens with technologies in fuel cells that have still important progress to be made (*i.e.*, durability, cost, or reduction of critical raw material content such as Platinum Group Metal).
  - Lack of **nanoscale manufacturing capacity** for some industries (*e.g.*, micro and nano-electronics). There is a big challenge for nanomaterials companies to provide the materials in volume to meet market demands, with the desired quality, economically and safely. Also, the lack of scalability of available fabrication methods such as lithography and the high cost of equipment is a major hurdle for the true commercial exploitation of advanced nano-patterned surfaces for automotive sector. In the same way, in health sector, the main technological challenges to introduce nanofabrication into the industrial ecosystem are in the scaling of volume production (MedTech requires small to medium volume manufacturing), and testing, packaging and deployment from research-grade to mass market levels. Also, one of the main barriers to be overcome for food and natural resources, and in general, for all nanofabrication sectors, is the development of large-scale production methods of products to mitigate the initial investment and to produce materials with nano-features in volume commercially at viable prices. The main challenge is to develop integration of materials and processing

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technologies for using nanomaterials in industrial production with an evaluation of the supply chain and the business model. Another major issue is that the production site needs to be equipped with in situ monitoring (*i.e.*, tolerances, characterization, etc..) of the whole process in order to deliver high quality products with consequential higher costs in production.

  - Difficulty to get a **balance among precision, performance, and throughput**, for instance in the nano-enabled chemical and processing industry. Also, NEMs must be designed to perform in short durations. On the other side, the surface-area-to-volume ratio in NEMS is large, and surface forces and viscous forces become very large compared with inertial and electromagnetic forces. There is a need for fundamental understanding of adhesion, friction, stiction, lubrication and surface contamination and environment on the nanoscale level. In energy sector, Perovskites still face some significant challenges before achieving market maturity. One of the main ones is durability. Because the crystals dissolve easily in water, they are not able to handle humid conditions and need to be protected by moisture through encapsulation, for instance through an aluminium oxide layer or sealed glass plates. The use of less expensive raw materials is another challenge for the upscaling of PV thin film systems that will enable reduced production cost to thrive their suitability for market applications requiring flexible and/or light substrates. In this sense, and related to cell catalyst, there are three main technological barriers: first, the use of non-precious metal at the cathode for the Catalyst Development and Electrode Structure design is foreseen to provide the requisite activity and minimise losses, second: impurity, pollutants (*e.g.*, SO_2, and NOx) in the flue gas that deactivates the catalyst, and a third barrier related to the stability and durability of the catalyst.
  - **Inconsistencies** between results in lab and the ones obtained when scale to industrial levels. For example, in automotive sector regarding the nano additives because of their poor dispersion in the thermoplastic matrix.

- **Economical, policy, and regulatory**
  - Investment decisions based on **cost reductions.** For instance, the profit margins of MEMS sensor are declining due to increasing market competition and increasing applications. The declining cost has led to the consumer choosing the suppliers based on costs rather than quality. Create partnerships with leading equipment manufacturers. In energy sector, manufacturing CIGS cells can be difficult due to the scarcity of indium, as well as to the complex stoichiometry and multiple phases to produce them, hampering their large-scale production in the near future. Also, for full-scale introduction of a commercial hydrogen supply chain in the future, a feasibility study and assessment should be conducted around 2025 with respect to the initial plan to reduce the cost of a hydrogen supply chain to a level comparable with the cost of fossil fuels. In relation to cost reductions biomass waste could play a key role. According to Andrew Burke's investigation, in carbon/carbon SCs, the carbon is responsible for about 60% of the total materials cost, with the total electrode material cost around 0.1 cent/F, whereas biochar-derived electrode material costs only around 0.001 cent/F. Therefore, the use of biochar has the potential to create large profits as carbon materials cost reductions will increase SC applications.[19] Using waste materials to fabricate

[19] Raza, Waseem & Ali, Faizan & Raza, Nadeem & Luo, Yiwei & Yang, Jianhua & Kumar, Sandeep & Mehmood, Andleeb & Kim, Ki-Hyun. (2018). Recent Advancements in Supercapacitor Technology. Nano Energy. 52. 10.1016/j.nanoen.2018.08.013.

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electrodes is attractive because it does not only offer a solution for waste disposal, but it also provides a way to increase the economic viability of SC technology.

- Need more **private capital** and Venture Capital (VC) to bridge the gap between research and market. Venture capitalist investment in nanotechnology companies has declined in recent years. Some of the main reasons could be the generally low level of interest among VC in material companies, the highly technical nature of nano business that make it difficult for some VC to understand it, or the unfavourable market realities of some of the sectors that nano business are targeting (*e.g.,* memory). With the decreasing involvement of VC, it is not only funding that were missing, but also feedback from the entrepreneurial vision and the market insights.
- Bridge the gap between **nanotech research and markets**. It is necessary to develop seamless integration of technologies and processing for using nanomaterials in production, to improve the control and monitoring of the conditions required for the use of nanomaterials in industrial processes, to increase the level of robustness and repeatability of such industrial processes; to optimise and evaluate the increased performance and functionality of the product as well as that of the production line in terms of productivity in actual operational environment. SMEs are particularly affected and are invited to participate, in order to develop and make use of the needed economic and knowledge and infrastructure capacity to carry out the required developments of process control, metrology and lifecycle analysis in-house, which represent critical steps before committing to pilot production.
- **Complex regulation**. For example, functional safety standards for electronic market, and for automobile industry. Also, since nanomaterials are regulated by the same health and safety regulations as macroscale products, it is important to maintain special care in design and manufacturing of products with nanoparticles that could be released into the human body. In same concrete cases, such as nanofibers, they are prohibited by safety regulations for certain uses. Specifically, in energy sector, current political-legal barriers are preventing investment in most of European PV markets namely: lack of political commitment and effective incentive schemes; insufficient and disparate monitoring systems and lack of co-operation between key actors in the definition of political action, especially on the trans-national level. Regulatory and legal barriers are especially intense in health sector: extensive clinical safety testing is required, particularly where nanoparticle-based drug formulations, both liquid and aerosol-based, are used. Besides, smart delivery systems will be viewed as combination devices and will require the full regulatory approval process before being approved for market. On the other hand, European regulatory bodies are gaining a reputation for becoming over burdensome with regulation.

- **Societal and Environmental**
  - Worries about the **disposal and recycling** of nanomaterials. In energy, and more specifically in thin film PV, one of the main challenges is mitigating environmental effects by reducing waste: in this sense, projects as the SPIRE EU project CABRISS aims to develop a circular economy strategy mainly for the photovoltaic, but also for electronic and glass industry.
  - Lack of knowledge about the **effects on human health and environment**. Some nanomaterials such as nanofibers may pose health risks similar to asbestos ones. Such effects are not yet understood, since the quantum mechanics regulating nanomaterials interactions with other substances also makes their toxicological behaviour difficult to predict. From the aspect of the food industry, the inhalation and skin penetration are almost exclusively related to workers in the nanomaterials producing factories, but the main exposure of concern for final consumers

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occurs by ingestion. The presence of nanoparticles in food mainly occurs from direct contact of nano packaging and food and migration of nanoparticles from nano packaging materials.

- More information needed to improve **public perception** of nano. Although food nanotechnology has immense benefits and potential, public perceptions are generally negative signifying that there is much to be done to change mindsets.
- Despite the large number of ISO and ASTM standards on nanotechnologies[20] and the ongoing work of standardisation technical committees for the development of new standards, there is still need for **further standardisation activities**, increasing the cooperation with industrial researchers, in order to promote the market uptake of emerging nanotechnologies and nano-enabled solutions.

The introduction of nanofabrication into the European industrial ecosystems depends on both technological improvements and non-technological issues, such as concerns about safety, regulation, education and skills, cost reductions, market acceptance, and others.

The main driver for the introduction of nanofabrication in the European industrial ecosystem lies in the advantages derived from the use of the technology itself to improve functionalities, properties, and general performance. Also, the introduction of nanofabrication can help to achieve the sustainability targets defined by the European industrial strategy, since nanofabrication can reduce not only material and energy consumption but also promote a rational use of resources and its recyclability.

And not only in terms of environmental sustainability, but also in economic aspects can nanofabrication improve the actual situation; the introduction of nanofabrication has the potential to reduce the cost of industrial processes, to improve sales figures and to open new market opportunities.

Furthermore, nanofabrication must face important challenges to realise its full potential, as the lack of scale capacity in certain areas, the lack of private investors and the reluctancy that comes both from industry and from society. This lack of knowledge about the advantages of nanofabrication and the misappreciation of the balance benefits/risks is perceived by the experts as one the biggest barriers to introduce nanofabrication in the industrial ecosystem. For its part, there is a certain duality in positions on regulation: regulation is a barrier to the fully implantation of nanofabrication, but, on the other side, it is recognised that there are aspects that need to be regulated for the industry and society to fully accept nanotechnology. The same kind of duality also applies with standardisation of novel technologies. Standards related to cutting edge technologies are difficult to create and make the different stakeholders reluctant to tackle the issue but at the same time they are waiting to have a more standardized ecosystem to ease the market penetration.

Research and development activity is crucial to foster nanofabrication and to increase the potential of nanotechnology to replace conventional technologies offering more functionalities and solutions that are not possible with current knowledge application. However, it is also important to work to fill the gap between research and market, and between research and society: the lack of knowledge, the lack of communication education, the fear of the unknown, the lack of a standardised legal framework to give confidence and trust, and the absence of citizen involvement in nano issues are, all of them,

[20] Not-exhaustive list of nanotechnology standards available at https://www.nano.gov/you/standards

factors as important as the technology itself, and all of them necessary to guarantee a successful introduction of nanofabrication in the European industrial ecosystem.

SUSNANOFAB Roadmap aims to catch the foreseen opportunities and address the described challenges by suggesting recommendations focusing on industrial sectors of high economic, social, and environmental impact, described in the subsequent chapter.

4 Nanofabrication challenges, opportunities, and best practices

Nanofabrication is defined as the design and manufacture of structures with dimensions measured in nanometres-nanostructures. In the words of (Ding, Yu, & Wang, 2019) "nanofabrication is the future of technology and will soon be at the forefront of all manufacturing technologies by providing the design and fabrication of functional nanomaterials, which are potentially capable of responding to all major global challenges of the present and the future".

European industry makes up more than 20% of GDP, accounts 80% of goods exports and employs more than 35 million people. European industry is the engine for productivity growth, high-value exports, and quality jobs for European people.[21] The European Commission is very aware of this and of the changing environment for global markets. Environmental sustainability, pressure on natural resources, technological change, digitalisation and, unexpected event such as the crisis of the Covid-19 are some of the factors that affect worldwide and European industry.

In December 2017, European Commission established an independent advisory group, the industry 2030 High Level Industrial Roundtable, to give recommendations about the future EU industrial policy action. This highlights five key drivers for the future European industry to manage a sustainable an inclusive transformation: leadership in technology, innovation and sustainability, social fairness, and wellbeing, anticipating and developing skills, a fair competitive and agile business environment, and strategic value creation networks.

After that, in June 2019, European Commission defined its main political guidelines for the period 2019-2024 articulated around six great priorities:

- A European Green Deal[22], which main objectives are to make Europe be the first climate-neutral continent, be the world leader in circular economy and clean technologies, preserve rural areas, biodiversity and land changing the way we consume, produce, trade, and establish the necessary mechanisms to support these objectives.
- An economy that works for people[23], focused on social fairness and prosperity with a strong and resilient social market economy
- A Europe fit for the digital age[24], grasping the opportunities from the digital age within safe and ethical boundaries, fostering digital technologies (especially Artificial Intelligence) and Internet of Things, among others.
- Protecting our European way of life[25], European citizens, and values with new pacts about migration and borders.
- A stronger Europe in the world[26], as a brand of responsible global leadership guaranteeing free and fair trade and going forward a European Defence Union.

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[21] COM(2020) 102 final, 10.03.2020 (CELEX:52020DC0102)
[22] COM(2019) 640 final, 11.12.2019 (CELEX: 52019DC0640)
[23] An economy that works for people (https://ec.europa.eu/info/strategy/priorities-2019-2024/economy-works-people_en)
[24] A Europe fit for the digital age (https://ec.europa.eu/info/strategy/priorities-2019-2024/europe-fit-digital-age_en)
[25] Promoting our European way of life (https://ec.europa.eu/info/strategy/priorities-2019-2024/stronger-europe-world_en)
[26] A stronger Europe in the world (https://ec.europa.eu/info/strategy/priorities-2019-2024/promoting-our-european-way-life_en)

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- A new push for European democracy[27] at regional, national, and European level.

Also, in 2019, the Strategic Forum for Important Projects of Common European Interest – IPCEI identified (Strategic Forum IPCEI, 2019) six key strategic value chains for European industry and member states: connected, clean and autonomous vehicles, hydrogen technologies and systems, smart health, industrial internet of things, low-CO2 emission industry and cybersecurity.

More recently, in March 2020, European Commission has presented a new industrial strategy to foster European industry, built on the following pillars for European industrial transformation:

- A deeper and more digital single market: new legislation, standardisation, and certification to propel the European industry and adapt it to the digital era, new mechanisms to break actual barriers for businesses, support for SMEs and intellectual property, and a new competition framework.
- Upholding a global level playing field: secure beneficial trade inside and outside Europe and guarantee fair competition with competitors around the world with different standards and principles.
- Supporting industry towards climate neutrality: modernise and decarbonise energy-intensive industries, support clean breakthrough technologies, a more sustainable built environment, new financial mechanisms —Just Transition Fund—, low carbon technologies, capacities and infrastructures, clean hydrogen, and a comprehensive strategy for sustainable and smart mobility.
- Building a more circular economy: change the way of use, design and get rid of materials, a new sustainable product policy framework, empower consumers and foster green procurement.
- Embedding a spirit of industrial innovation: regulations and other mechanisms to incentivise SMEs to innovate with new ideas in the market, make the most of Europe's research base to accelerate commercial applications, encourage place-based innovation and experimentation, and scale solutions to European and global markets.
- Skilling and reskilling: recruit and retain qualified people, reinforce higher and vocational education to provide more scientists, engineers and technicians, and support gender equality in industry.
- Investing and financing the transition: unlock private investment and public finance with existing and new mechanisms (*e.g.*, IPCEIs), revise existing ones, such as State Aid rules, incentivise new investment towards competitive sustainability, and clear rules to guide investors to sustainable investments.

Also, the Strategy mentions its support to the development of key enabling technologies, including robotics, microelectronics, high-performance computing, data cloud infrastructure, blockchain, quantum technologies, photonics, industrial biotechnology, biomedicine, nanotechnologies, pharmaceuticals, and advanced materials and technologies. The final aim of the European Industrial Strategy is to make European industry more competitive globally and enhance Europe's strategic autonomy. In 2021 the Strategy has been updated to ensure the adaptation of European industry to the new situation following the COVID-19 crisis, including a toolbox to accelerate the green and digital transitions.

There are other interesting initiatives and mechanism related to European industry, such as Investment Plan for Europe — with the European Fund for Strategic Investments and the European

[27] A new push for European democracy (https://ec.europa.eu/info/strategy/priorities-2019-2024/new-push-european-democracy_en)

Investment Advisory Group — the Single Market Strategy to unlock the full potential of Single Market, the Capital Markets Union , to mobilise capital in Europe, the European Skills Agenda to take advantage of the green and digital transitions, and support a prompt recovery form the Covid-19 crisis, and the initiative Trade for All, a trade an investment strategy for the EU.

The development of nanofabrication can be an important incentive to foster a digital and sustainable European industry for next years and to position Europe as a leading location to produce innovative products with nanotechnologies. Also, nanofabrication can be a source of high skilled employment in Europe and the way to improve the European productive system increasing the global competitiveness in face of other competitors such as USA or some Asian countries. This is especially important now, when Europe is more aware than ever of the need to promote a digitised and sustainable industry, to make the territory more resilient against current crisis - such as that of Covid-19 - and future ones.

The introduction of nanofabrication into the European industrial ecosystems depends on both technological improvements and on non-technological issues such as the concerns about safety, regulation, education and skills, cost reductions, market acceptance and others. Besides, each considered sector has some specific barriers and drivers in the very nature of the sector, that also should be considered.

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4.1 Projects and initiatives

The present chapter provides an overview of projects and initiatives relevant to the field of nanofabrication. The analysis of the identified projects and initiatives allows an assessment of the current state of the field of nanofabrication. To have a more detailed view of the results reported hereafter, Annex A – European projects and initiatives contains detailed information about all the initiatives and projects identified at European level.

The analysis was carried out by a consortium with a broad base of contributors working on topics related to sciences. As we are inherently more aware about scientific technological advancements over other topics, this makes vulnerable to biases. However, we attempted an accurate description of the nanofabrication landscape and believe this is a truthful depiction of the current state of project and initiatives in the nanofabrication sector.

4.1.1 Initiatives

In this analysis, it was considered as "initiative" any entity, exception made for single organizations or companies, developing activities related to nanofabrication (*e.g.,* platforms, EU funded projects, associations, clusters, and networks). Initiatives were found both in public and private sector. Few parameters were considered during the collection of the initiatives, such as: initiative type, country, initiative character, target sectors, and, when available, target solutions (Table 3).

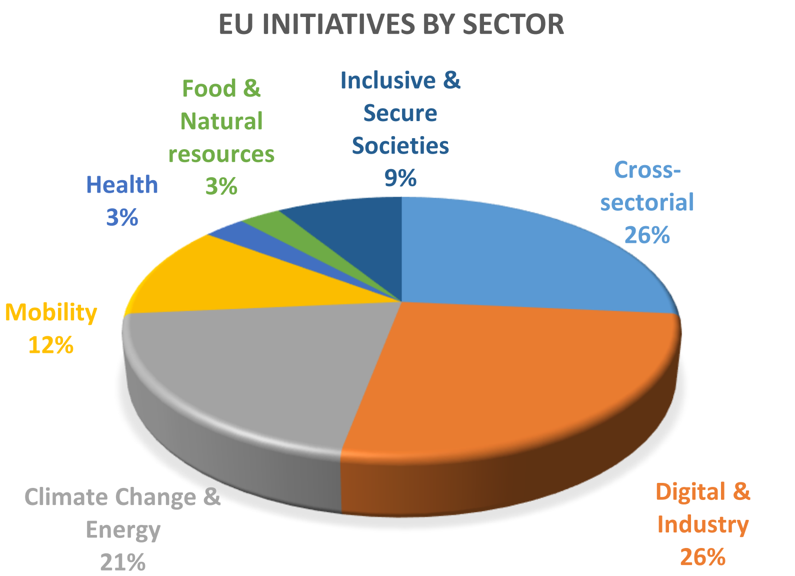

Figure 5. Pie chart of the European nanofabrication initiatives, subdivided by sector.

An analysis by sector of the initiatives (Figure 5) shows a co-dominance of actions directed to cross-sectorial and digital and industry sectors, followed by the *climate change and energy* ones. The least number of actions were targeted at *health* and *food and natural resources*. This bias in the distribution of the actions is possibly influenced by the target topic in analysis (*i.e.*, nanofabrication) and it may be also indicative of the relative acceptance of nanofabrication in the respective fields. As several concerns and misconceptions are still present around nanotechnologies, it appears straightforward to assume an influence in the penetration of nanotechnologies for fields such as *health* and *food and natural resources*. This is clearly contrasted to the larger adoption of nanofabrication in industrial environments, which is shown also in the identified initiatives.

Table 3. Table listing the nanofabrication initiatives identified in this analysis.

Initiative	Type	Character	Country	Sector
EPPN-Platform	Platform	Public	EU	Cross-sectorial
EMMC	Association	Public	EU	Cross-sectorial
EMCC	Council	Private	EU	Cross-sectorial
AM-Platform	ETP Platform	Public	EU	Cross-sectorial: Mobility, Digital and Industry, health
Nanosafety Cluster	Cluster	Public	EU	Cross-sectorial: health, environment, food, Energy, water
DIH Catalogue	Other	Public	EU	Cross-sectorial
Nanofutures Platform	ETP Platform	Public	EU	Cross-sectorial
KETs Centers	Other	Public	EU	Cross-sectorial
EIT-Raw Materials	Association	Public/Private	EU	Cross-sectorial: Mobility, Climate Change and Energy
MANUFUTURE	ETP	Public	EU	Digital and Industry
SPIRE	Association	Private/Public	EU	Digital and Industry
OE-A	Association	Private	WW	Digital and Industry
Afelim	Association	Private	FR	Digital and Industry
EPC4	Platform/Association	Private	EU	Digital and Industry
EPMA	Association	Private	EU	Digital and Industry
4M	Association	Public	EU	Cross-sectorial: Digital and Industry
ECTP	ETP	Private	EU	Digital and Industry
EIT-Manufacturing	Association	Public/Private	EU	Digital and Industry
ECERA	Network	Public	EU	Climate Change and Energy
Hydrogen Europe Research	IPCEI	Public	EU	Climate Change and Energy
EMIRI	Association	Private	EU	Mobility, Climate Change and Energy
EERA	Association	Public	EU	Climate Change and Energy
EIT InnoEnergy	Network	Private	EU	Climate Change and Energy, Mobility
EIT Climate	Network	Private	EU	Climate Change
ETC-CME		Private	EU	Climate Change and Energy
EIT Manufacturing	Association	Private	EU	Cross-sectorial: Digital and Industry
EGVIA	Association	Private	EU	Mobility
EARPA	Association	Private	EU	Mobility
ERTRAC	Council	Private	EU	Mobility
CMUA	-	-	ES	Mobility
ETPN	Platform	Public/Private	EU	Health
BBI	Network	Public/Private	EU	Food and natural resources
EARTO	Association	Public	EU	Inclusive and Secure Society

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ECSO	Association	Private	EU	Inclusive and Secure Society
EOS	Association	Private	EU	Inclusive and Secure Society
NIA	Association	Private	EU	Digital and Industry

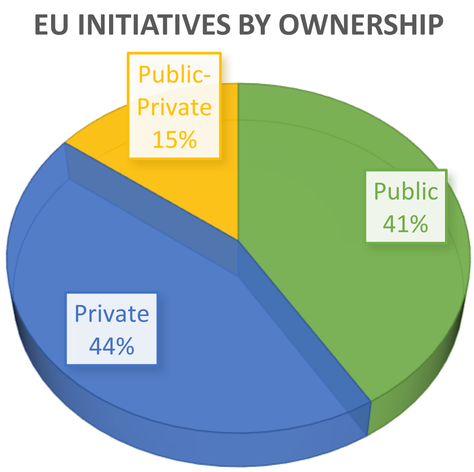

Figure 6. Pie chart of the European nanofabrication initiatives, subdivided by ownership (public or private).

The ownership of the initiatives was also considered in the evaluation process (Figure 6). A balanced subdivision of the initiatives between the private and the public sector was observed with a minor co-participation in joint public-private initiatives (15%). All the co-participation initiatives were sponsored by the European union for the public part in partnership with private entities of a specific productive sector. The largest share of private initiatives was primarily directed at *digital and industry* and secondly to *mobility* topics.

Only two of the identified actions had a national scope, all the other actions had a broader scope, with a European or worldwide focus.

Another variable considered in our analysis was the type of initiative (Figure 7). From a breakdown of the initiative types, associations are the most relevant type of initiative, followed by European technology platforms (ETP). Associations are generally more private in ownership (63%), whereas ETP instead are generally public driven (75%). Remaining initiatives are evenly distributed in ownership nature.

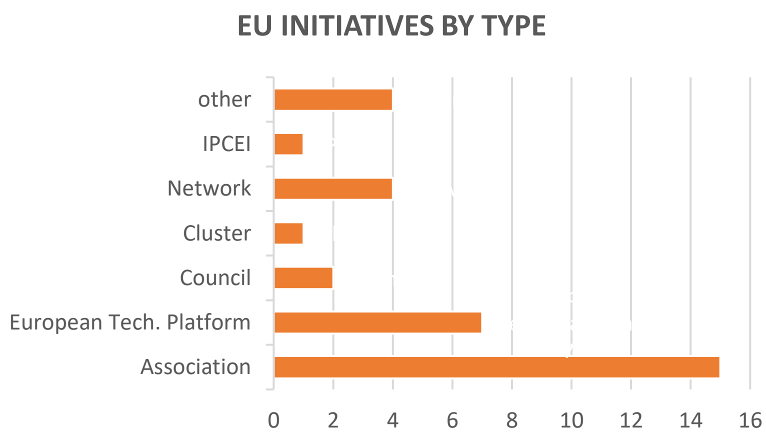

Figure 7. Bar chart of the European nanofabrication initiatives, subdivided by type.

4.1.2 Projects

In this analysis, we focused on the information sourced within the European database on funded projects (Table 4). To focus on the current state of the field of nanofabrication other than an historical view of the sector, we restricted our search to the actions of the latest decades (*i.e.*, H2020 actions). This may not be an exhaustive list of the current running projects but is representative of the current project panorama.

Few parameters were considered during the collection of the projects, such as: funding scheme, coordinator institution, coordinator activity, coordinator country, project sector.

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Table 4. Table listing the nanofabrication projects identified in this analysis.

Id	acronym	Project URL	Funding scheme	Coord. country	Project sector	Coord. activity
654384	ASCENT	http://www.ascent.network	RIA	IE	Digital and Industry	HE
862444	ASINA	https://www.asina-project.eu/	RIA	IT	Cross-sectorial	RTO
948225	B3YOND		ERC-STG	IT	Cross-sectorial	HE
642242	CARISMA	http://carisma-project.eu/	CSA	NL	Climate Change and Energy	HE
723630	CLUSTERNANOROAD	https://clusternanoroad.wordpress.com/	CSA	PT	Cross-sectorial	RTO
645993	CO-PILOT	http://www.h2020copilot.eu	RIA	NL	Digital and Industry	RTO
723623	EC4SafeNano	http://www.ec4safenano.eu/	CSA	FR	Cross-sectorial	RTO
723868	EENSULATE	http://www.eensulate.eu	IA	IT	Climate Change and Energy	Industry /SME
723867	EMMC-CSA	https://emmc.info/	CSA	AT	Cross-sectorial	HE
730957	EnABLES	http://www.enables-project.eu	RIA	IE	Inclusive and Secure Societies; Climate Change and Energy; Mobility; Health	HE
760639	EnDurCrete	http://www.endurcrete.eu/	RIA	DE	Digital and Industry	Industry /SME
768681	EPPN	https://www.eppnetwork.com/	CSA	PT	Cross-sectorial	RTO
766871	Himalaia	https://himalaia-project.eu/	RIA	FR	Digital and Industry	RTO
662155	InForMed	http://www.informed-project.eu/	ECSEL-IA	NL	Health	Industry /SME
833088	InfraStress		IA	IT	Inclusive and Secure Societies	Industry /SME
760876	INNPAPER	http://innpaper.eu/	RIA	ES	Food and Natural Resources	RTO
646155	INSPIRED	http://www.nano-inspired.eu	IA	AT	Digital and Industry	RTO
720878	INTEGRAL	http://www.integral-h2020.eu/	IA	FR	Climate Change and Energy; Mobility; Digital and Industry	RTO
686165	IZADI-NANO2INDUSTRY	http://www.izadinano2industry.eu	IA	ES	Climate Change and Energy; Mobility	RTO
653851	JOSPEL	http://jospel-project.eu/	RIA	ES	Mobility	RTO
777441	KET4CleanProduction	http://www.ket4sme.eu	CSA	DE	Digital and Industry	RTO
814485	LEE-BED	http://www.lee-bed.eu	IA	DK	Climate Change and Energy; Digital and Industry	RTO
814552	LightMe	http://lightme-ecosystem.eu/	IA	IT	Cross-sectorial; Digital and Industry	HE
760173	MarketPlace	https://the-marketplace-project.eu	IA	DE	Cross-sectorial	RTO
680263	NanoFab2D	http://www.2dmaterials.hu	ERC-STG	HU	Cross-sectorial	RTO
695206	NANOFACTORY	http://www.nanophotonics.ch	ERC-ADG	CH	Cross-sectorial	HE
646397	NANOLEAP	http://www.nanoleap.eu	RIA	ES	Digital and Industry	HE
688329	Nanonets2Sense	http://www.nanonets2sense.eu/	RIA	FR	Health	RTO
760601	NanoTextSurf	http://www.nanotextsurf.eu/	IA	FI	Digital and Industry	RTO
685559	NEREID	https://www.nereid-h2020.eu/	CSA	FR	Digital and Industry	HE
814581	OASIS	https://project-oasis.eu/	IA	ES	Climate Change and Energy; Mobility	RTO
646307	PLATFORM		RIA	ES	Mobility	RTO
644852	PROTEUS	http://www.proteus-sensor.eu/	RIA	FR	Food and Natural Resources	RTO

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872494	RADON		MSCA-RISE	DE	Digital and Industry	RTO
760941	ReSiSTant	http://www.resistant-project.eu	IA	AT	Mobility	RTO
862419	SAbyNA	https://www.sabyna.eu/	RIA	ES	Cross-sectorial	RTO
814607	SAFE-N-MEDTECH		IA	ES	Health	GO
833017	SecureGas		IA	IT	Inclusive and Secure Societies	Industry /SME
760915	SUN-PILOT		IA	IE	Digital and Industry	HE

From the analysis of the coordinator countries (Figure 8), Spain (19%), France (16%), Italy (14%), and Germany (14%) are the most frequent coordinators of the actions. Also remarkable is the 7% share of financing via EU schemes dedicated to projects with Israel as coordinator. This is indicative of a marked collaboration on the topics of nanofabrication between EU and Israel. Therefore, Israel appears to be an associated country with a particularly active research and innovation cluster in the field of nanofabrication.

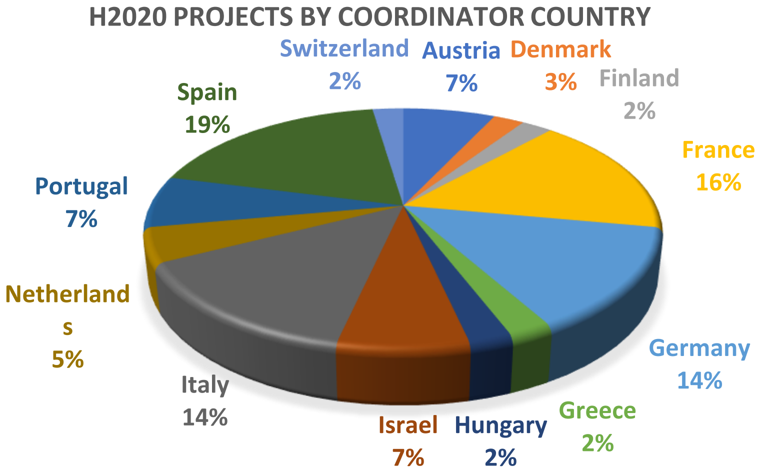

Figure 8. Pie chart of the European nanofabrication projects, subdivided by coordinator country.

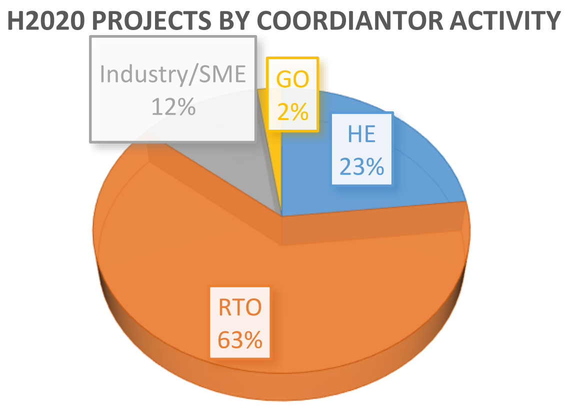

Figure 9. Pie chart of the European nanofabrication projects, subdivided by coordinator country.

A breakdown of the projects was also done by the coordinator activity. Under this figure, it is evident that both research technology centres (RTO) and high education organizations (HE) coordinate the largest share of European projects.

Another aspect taken in consideration by our analysis was the distribution of the European projects among the coordinator institutes (Figure 10). This analysis evidences an even distribution of projects among the various institutes. The only outlier under this figure is *Fundaction Tecnalia*, which coordinated 3 projects (with an average of 1.3 projects per partner).

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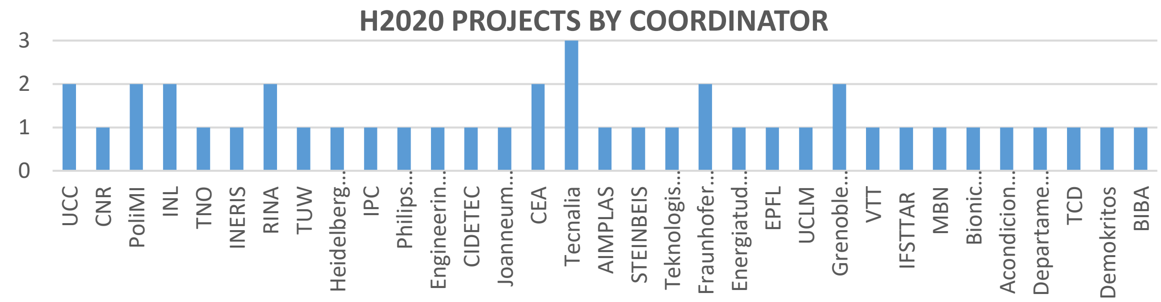

Figure 10. Bar chart of the European nanofabrication projects, subdivided by coordinator institute.

An analysis of the projects by sector was also carried out (Figure 11).

Similarly to initiatives, projects were also chiefly focused on *cross-sectorial*, *digital and industry*, *climate change and energy*, and *mobility* actions. Differently from initiatives, more projects were related to the health sector (about twice as much in percentage share).

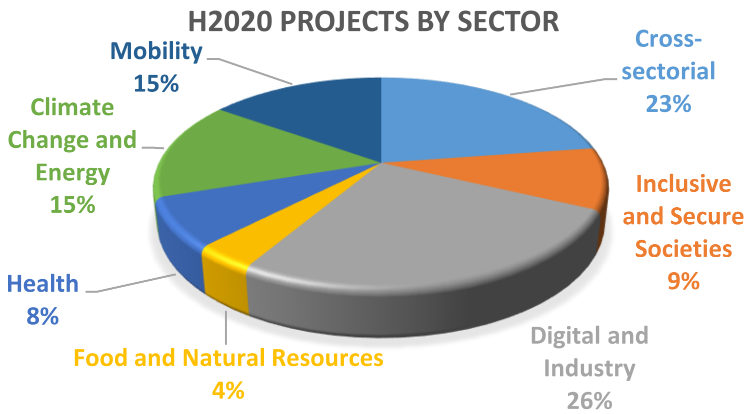

Figure 11. Pie chart of the European nanofabrication projects, subdivided by sector of interest.

Another interesting parameter to consider is the type of funding scheme within which the projects are framed (Figure 12). The largest share of the projects were innovation actions (32), research innovation actions (13) were the second most frequent type of funded actions.

As higher TRL are generally correlated to innovation actions, the high amount of innovation actions is indicative of an advanced development stage of the nanofabrication field. However, the high in numbers of research innovation actions in combination with to the presence of few European research council starting grants (ERC-STG) is indicative of an overall still developing sector with some technologies at an advanced stage of development.

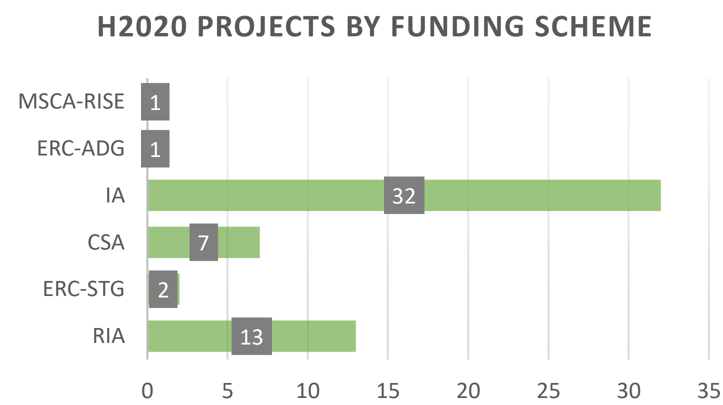

Figure 12. Bar chart of the European nanofabrication projects, subdivided by funding scheme.

4.2 Stakeholders

To ensure an efficient reach-out of the SUSNANOFAB Roadmap, as well as to guarantee the contribution and active participation in its development, an integrated map of EU and international stakeholders in the nanofabrication ecosystem was built.

The stakeholders were identified by landscaping the main actors involved in the EU and international programmes, projects, and initiatives, as well as those involved in the supply and demand of nano-enabled products, services, and access to nanofabrication infrastructures.

Additionally, the SUSNANOFAB consortium identified the relevant stakeholders from the entire nanofabrication value chain from different existing databases, such as the European Network for Pilot Production Facilities and Innovation Hubs (EPPN)[28], the Nanodata Nanotechnology Knowledge Base[29], the US National Nanotechnology Initiative[30], and the Internano Directory of Experts and Organisations[31].

The value-chain goes across regional, national, European, and international levels, and is composed of a broad community with expertise in the nanofabrication field, namely:

- Businesses, such as Small and Medium Enterprises (SMEs), Large Enterprises (LEs), and industrial associations focused on bringing to the market nano enabled products, processes and services;
- Research centres and infrastructures, such as Research and Technology Organisations (RTOs), Universities and Educational Establishments dedicated to or interested in nanofabrication;
- Pilot facilities and projects related to pilot lines;
- Cross-cutting and sectorial initiatives, such as platforms, projects and networks;
- Standardisation bodies, working groups and certification entities and laboratories;
- Policy makers, such as the European Parliament, public-private partnerships, funding agencies, regional and local authorities involved in regional cluster strategies.

[28] https://www.eppnetwork.com
[29] https://nanodata.echa.europa.eu/
[30] https://www.nano.gov/
[31] https://www.internano.org/directory

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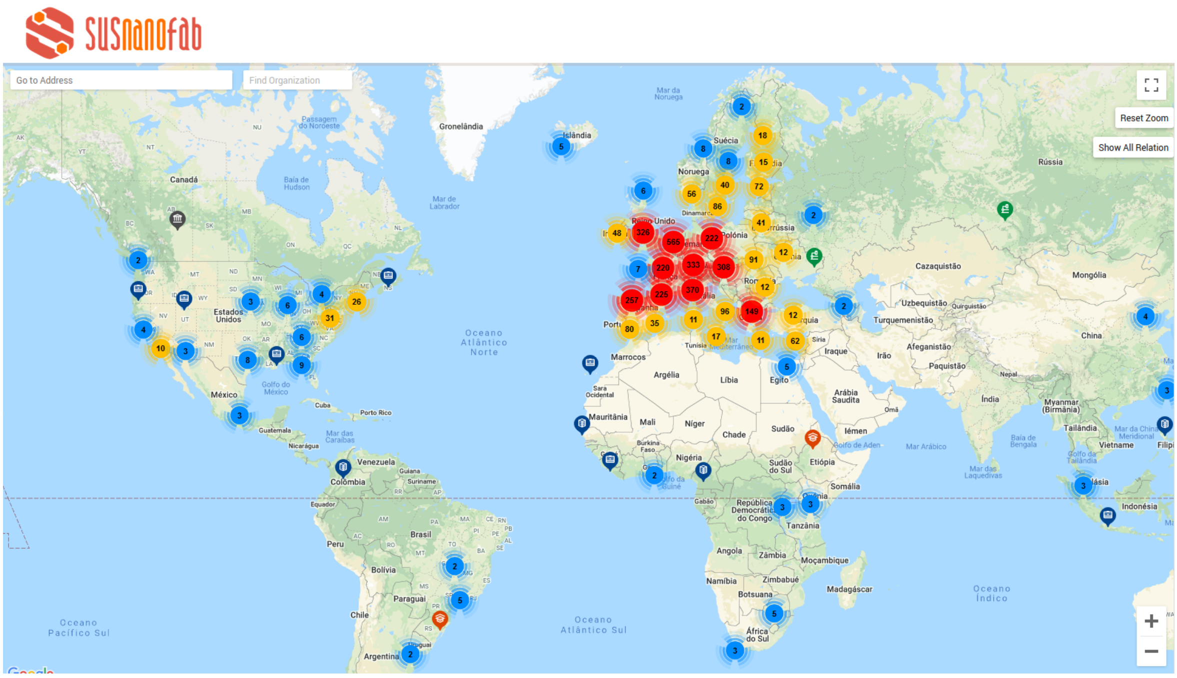

Figure 13. SUSNANOFAB Open Digital Platform - Map Feature

Currently, the integrated map of EU and international stakeholders in the nanofabrication ecosystem is available under the SUSNANOFAB Open Digital Platform[32], as a searchable geographical location-based map, as illustrated in Figure 13; as well as organised in a list of organisations, as per Figure 14.

[32] https://susnanofab.oppornet.com/

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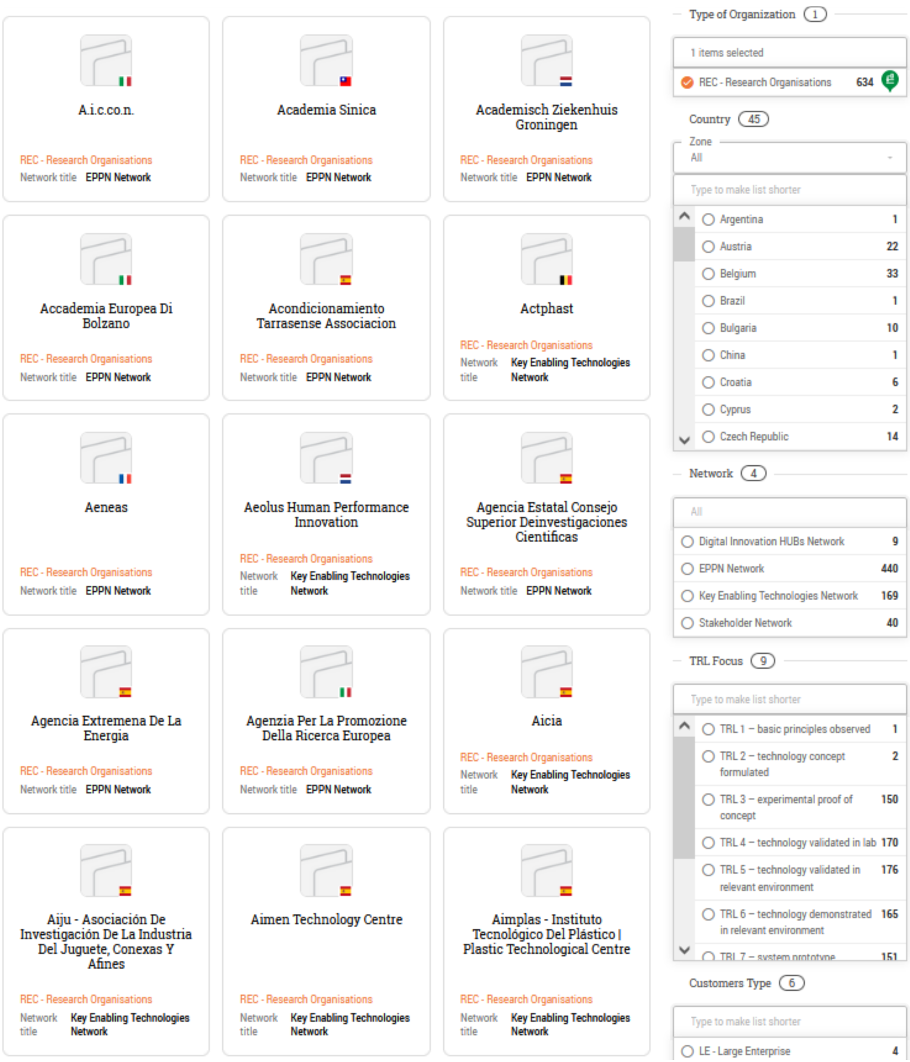

Figure 14. SUSNANOFAB Open Digital Platform - List of Organisations

Stakeholders are classified in different categories, as follows:

- Country
- TRL Focus
- Type of organisation
  - GOV – Government Sector;
  - PUB – Public Bodies;
  - HES – Higher Education and Universities;
  - REC – Research Organisations;
  - PRC – Private Profit Sector;
  - PNP – Private Non-Profit Sector;
  - SME – Small and Medium Enterprises;
  - LE – Large Enterprise; and
  - OTH – Other.
- Relevant market
  - Aeronautics & Space;
  - Automotive transportation;

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- Chemical industry;
- Construction & building sector;
- Consumer goods/products;
- Energy;
- Environment;
- Food;
- ICT industry (including electronics, computer and communication related products);
- Measurements;
- Medical & Healthcare
- Production technology (machinery/equipment/automation)
- Textile;
- Multisectorial; and
- Others.

The preliminary list, presented in the Deliverable 2.4 ("*D2.4 - Integrated Map of EU and international stakeholders in nanofabrication*", vide Annex C), is composed of 448 members from Australia, Austria, Belgium, Brazil, Canada, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Ireland, Israel, Italy, Japan, Latvia, Luxembourg, Mexico, Netherlands, Norway, Poland, Portugal, Romania, Russia, Singapore, Slovenia, South Korea, Spain, Sweden, Switzerland, Turkey, United Kingdom and United States of America. The distribution can be seen in Figure 15 **(see** below). 73% of the organisations listed are in Europe, and 22% in North America (US, Canada, and Mexico).

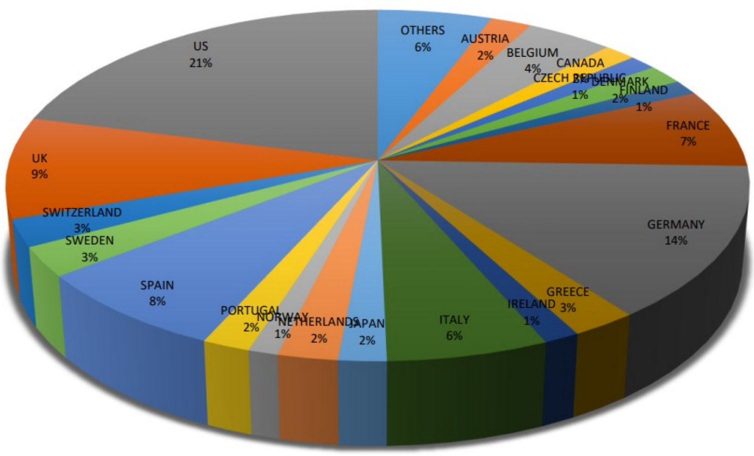

Figure 15. Distribution of stakeholder by country of origin

Considering the type of organisation, the sample presented is composed of 0.6% members of Government Sector, 17% members from Higher Education and Universities, 3% private non-profit sector, 59% private profit sector, 7% public bodies and 10% research organisations.

- The private for-profit organisations are in the highest TRL focus (7, 8 and 9). Of these, 18% have energy, environment, and food as the most relevant market; 13% have medical and healthcare, 11% ICT, and 9% transport and aeronautics market. It is also interesting to note that almost 30% of private profit organisations that work close to the market target multiple sectors.

- The stakeholders map developed is a non-exhaustive preliminary list of the most relevant players in the nanofabrication ecosystem at European and international levels. It aims at serving as a starting point and will comprehend other stakeholders in the future actions of the project.
- Hence, after describing the general stakeholders of the project, their categorisation, their inputs to the project actions and in the road mapping activities, it is of greatest importance to emphasize the stakeholders actively participating in the Cooperation Groups, which are contributing the most in the co-creation of the SUSNANOFAB Roadmap, aiming to stablish a common medium-short term agenda with prioritised actions needed to fill the existing gaps and to introduce nanofabrication in the European industrial ecosystem in an effective way, finding innovative nanofabrication solutions from design to upscaling, promoting the sustainability of nanofabrication in the scope of ethics, health, environment and life-cycle analysis, as well as further developing the necessary skills for the nanofabrication industries.
    - The effective collaboration of these selected stakeholders in the three different Cooperation Groups (CGs) is of absolute importance. Their dynamic participation in building up the roadmap was coordinated through consultations via surveys, interviews, and different group meetings aiming at collecting their views throughout the entire nanofabrication value chain.

4.3 Cross cutting/Cross sectorial best practices

This chapter includes the best practises identified by the project, covering cross-cutting and cross-sectorial topics. The best practises (or lack of thereof) and the industrial needs were identified for the fields of modelling, training, safe-by-design (SbD), and life cycle assessment (LCA) cannot be assigned to a single sector as they are relevant and applicable across all sectors. Therefore, this chapter gives an overview of the importance of developing standardized approaches for modelling, training, SbD, and LCA for industries and research institutions and offers an overview of the actual state of the art and adoption of unified approaches.

Modelling cross-sectorial best practises. Modelling is a central part of the nanofabrication process. Numerical simulations are increasingly used by small and large private companies as well as research institutes to design and engineer new products in a more effective and efficient way. Simulations are also used for the optimisation of existing processes; this allows to minimise the need for expensive and time-consuming prototyping and testing. In this context, manufacturing companies across Europe (from small SMEs to large corporations) recognise the potential of materials modelling as driver for a radical increase in speed of product designing and the concomitant decrease in production costs. As stated in the EMMC roadmap for material modelling and digitalization of material sciences[33]: materials modelling-led product innovation can be a key differentiator for success in such competitive markets.

[33] The EMMC Roadmap for Materials Modelling and Digitalisation of the Materials Sciences (doi: 10.5281/zenodo.4272033)

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However, modelling tools do not yet constitute an integral part of commercial or business development. The main reasons are related to the perceived difficulty of use, limited accuracy, and limited ability of providing answers to very specific questions in a timely manner. Another barrier towards the wide integration of modelling tools, especially relevant for small companies, is the necessary investment in expertise (people) and infrastructure, which might be overcome the long-term benefits in terms of productivity and cost. Specifically, the integration of materials models and databases into businesses decision support systems is widely hampered by the low accuracy and robustness levels, the uncertainty (both technical and financial) associated to specific designs, as well as by time constrains.

As result, while the application of modelling tools has been successfully demonstrated for several materials and manufacturing processes, their integration as essential component in commercial or business developments has not occurred yet. This integration requires the establishment of a trusted process incorporating more **unified** models. The successful addressing of the challenges and barriers above will allow substantial reduction of the time-to-market and the substantial broadening of products offering, leading to enhanced competitiveness for the European industry in key development sectors.

An excellent example of unification is provided by the Modelling Data Generalisation (MODA). The MODA initiative is an example of best practice in the field of modelling. The MODA model is comprised of a **text template** and a **graphical workflow template** which have been developed to overcome the complexity of interactions between materials modelling stakeholders often related to the use of not unified terminology and approaches. Through development of the templates mentioned above, MODA aims at establishing a common terminology in materials modelling, which will lead to simplified and more efficient communication, especially in multi-scale materials modelling requiring of a multidisciplinary approach and the evaluation of interactions between different models. Such approach has been used to document materials modelling workflows for several European projects. The aim of MODA is to establish a unified modelling language for materials modelling, leading to the development of a shared language capable attain a well organised descriptive scheme comprising the key assets and capabilities of a modelling procedure. This will allow for the creation of a share-point of several pre-made toolbox applicable to specific modelling problems, allowing for the development of a community of contributors that will slowly converge on the selection of sectorial best practices for the study of specific modelling problems.[34]

A summary of relevant EU projects whereby the MODA approach was followed to develop materials and processes across different sectors is herein reported (see below, Table 5).

[34] https://emmc.eu/wp-content/uploads/2021/05/EMMC_IntWorkshop_Vienna2017_MODA_Talk.pdf

Table 5. Exemplary list of project best practices in the field of modelling and simulations relevant for nanofabrication

Health
N2B-patch, Nose to Brain Delivery of Antibodies via the Olfactory Region for the Treatment of Multiple Sclerosis **u**sing Novel Multi-functional Biomaterials Combined with a Medical Device, ID: 721098 **INSIST**, IN-Silico trials for treatment of acute Ischemic STroke, ID: 777072 **EU-STANDS4PM**, A European standardization framework for data integration and data-driven in silico models for personalized medicine, ID: 825843
Food and Natural Resources
Oyster, Open characterisation and modelling environment to drive innovation in advanced nano-architecture and bio-inspired hard/soft interfaces, ID: 760827
Mobility
MASTRO, Intelligent bulk MAterials for Smart TRanspOrt industries, ID: 760940
Digital industry
NanoInformaTIX, Development and Implementation of a Sustainable Modelling Platform for NanoInformatics, ID: 814426 **MUSICODE** An experimentally validated multi-scale materials, process and device modelling & design platform enabling non-expert access to open innovation in the organic and large area electronics industry, ID: 953187
Secure society
SMARTFAN, Smart by Design and Intelligent by Architecture for turbine blade fan and structural components systems, ID: 760779
Climate / Energy
CORNET, Multiscale modelling and characterization to optimize the manufacturing processes of Organic Electronics materials and devices, ID: 760949 **DACOMAT**, Damage Controlled Composite Materials, ID: 761072 **EnDurCrete**, New Environmental friendly and Durable conCrete, integrating industrial by-products and hybrid systems, for civil, industrial and offshore applications, ID: 760639 **FotoH2**, Innovative Photoelectrochemical Cells for Solar Hydrogen Production, ID: 760930 **GENESIS**, High performance MOF and IPOSS enhanced membrane systems as next generation CO2 capture technologies, ID: 760899 **IN-POWER**, Advanced Materials technologies to QUADRUPLE the Concentrated Solar Thermal current power generation, ID: 720749

Training sectorial best practises. An analysis of industrial training needs as well as an identification of skills gaps and trainings shortages has been carried out within SUSNANOFAB, based on the collation of data from different external sources and stakeholders including: a map of educational projects and initiatives providing trainings; engagement of selected stakeholder organizations and individual experts and feedbacks from dedicated workshops and an online questionnaire on key enabling skills & learning needs send to several partners' network.

As outcome of these concerted actions, it was possible to build a detailed list of available professional trainings, identify a list of industrial challenges related to nanofabrication, and to identify skill gaps and trainings shortages.

More than 60 trainings were identified focusing on post-graduated and active professionals. Those trainings covered a large span of needs concerning nanofabrication challenges. They were offered either by research centres or private companies. Most of the training content covered aspects of safety, control and management of activities mainly carried out in **clean room ecosystems,** where nanofabrication processes are widely used. However, also topics such as **metrology, standardization, marketing, ethics, and modelling** were included in offered trainings.

The industrial challenges identified were very different. Safety was the focus of many industrial entities when customers' acceptance and cost were described as the main bottlenecks by others. Sustainability and environmental issues were underlining many challenges.

In addition, the integration of novel nanotechnologies in running businesses was described as a stress in the production line and in the customers that are difficult to handle.

The lack of standards and regulation are seen as roadblocks by many industries.

From this detailed analysis, the project identified major missing trainings and competencies such as:

- Clear and oriented communication skills to handle benefits/risks argumentation when it comes to nano-enabled products.
- Trainings on the creation of specific standards to answer the need for standardization of novel technologies.
- Global vision and competencies on how to handle nano in a recycling loop and how to make nano-based products recyclable.
- Training on how to deploy a proper governance structure that will allow to quickly adapt to regulation changes. Competencies on how to think ahead safety and regulation as governance.
- Very specific trainings on how to use and discover modelling tools capacity as an answer to performance prediction and safety.
- Competencies on modelling to be able to grasp the potential given by nanofabrication technologies when it comes to the safety and performances of novel products.
- Competencies on entrepreneurship and innovation soft skills. Trainings on how to pitch, how to construct a business model for a specific domain of nanotechnology and nanofabrication. Competencies in fundraising, especially in emerging technology
- Competences and trainings mixing LCA approach together with risk management.

Overall, standards were found to be lacking but, above all, the capacity to create adapted standards was lacking. Especially SMEs expect proper standards to unify best practices along the value chain and ease public acceptance. Hence, **trainings on the creation of standards**, going further than understanding the standardisation process were found missing. For example, a commonly observed issue was the lack of confidence in nano-based products by end-users. This is a problem that sits at the heart of nanofabrication development, heavily hampering it. Currently, there are some trainings addressing few of the aspects contributing to this mistrust towards nanotechnologies. The trainings on the management of the risks associated to nanomaterials and nanoparticles contribute altogether with the ones on the standards compliance to a more positive perception of nanotechnologies. However, due to the continuous evolution of the nanofabrication field, it is important to be able to correctly determine and implement own fabrication standards. **Training on how to develop own standards** was deemed crucial to aid the process of standardization and improve the public perception towards the safety of products. Due to the continuous expansion of the nanofabrication field and the complexity of many of the manufacturing techniques, it is important for companies, especially SMEs to be aware of the standards that exist, such as ISO and CEN. There are several standards already

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approved specifically around nanotechnology, including measurement, characterisation and nomenclature (see below, Table 6) set by leading standards organisations and their relevant nanotechnology committees such as: International Standardization Organisation (ISO) Technical Committee (TC) 229 on Nanotechnologies; ASTM International's Committee E56 (Nanotechnology); International Electrotechnical Commission Technical Committee 113 (Nanotechnology Standardization for Electrical and Electronics Products and Systems); Institute of Electrical and Electronics Engineers' Nanotechnology Council. Furthermore, there are sector specific standards used in many of the market application fields being targeted by nanofabrication. Training on the use of standards would help, as would a greater understanding of the process of adopting new standards. Training in this area could help SMEs become more knowledgeable and engaged with the standards process and help them participate in the standards adoption process.

Table 6. List of approved standards on nanotechnology.

Topic	Unique Identifier	Title
Terminology	**ASTM E2909-13**	Standard Guide for Investigation/Study/Assay Tab-Delimited Format for Nanotechnologies (ISA-TAB-Nano): Standard File Format for the Submission and Exchange of Data on Nanomaterials and Characterizations
	ISO/TS 80004-1:2010	Nanotechnologies -- Vocabulary -- Part 1: Core terms
Measurement	**ASTM E2490-09(2015)**	Standard Guide for Measurement of Particle Size Distribution of Nanomaterials in Suspension by Photon Correlation Spectroscopy (PCS)
	ISO/TR 13014:2012	Nanotechnologies -- Guidance on physico-chemical characterization of engineered nanoscale materials for toxicologic assessment
EHS Effects	**ASTM E2524-08(2013)**	Standard Test Method for Analysis of Haemolytic Properties of Nanoparticles
	ISO/TS 12901-1:2012	Nanotechnologies -- Occupational risk management applied to engineered nanomaterials -- Part 1: Principles and approaches
Education	**ASTM E2996-15**	Standard Guide for Workforce Education in Nanotechnology Health and Safety

Safe-by-Design sectorial best practises. "Safe-by-Design" (SbD) is a well-established concept in many fields, such as building, nuclear technology, water treatment, health facilities, and occupational health and safety. SdD is widely used in industry, and it describes safety practises for the prevention of accidents, illnesses, or environmental damages which can be adopted *a-priori* during the design stage of a facility, process, practice, material, or product. Therefore, the idea of SbD revolves around the integration of anticipated safety impacts of materials or products into design and production phases.

Still, SbD is a quite novel concept to nanofabrication. The development of functional as well as safe nanomaterials and nano-enabled products is currently associated to a substantial knowledge gap in nanomaterials and nanoproducts safety, knowledge implementation into industrial scale innovation

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processes, safety-material relationships, and function-material relationships. Overall, the objective in the implementation of SbD measures is to transfer the precautionary principle into a customary and practical use. This includes precautionary measures and tools for the timely identification of uncertainties and their respective risks at the earliest stage possible, where it is feasible to include it, in the innovation development. Uncertainties and risks are not only identified on a material basis, but also on the potential risks related to the commercialization of the product on the market related to the end-use of the process and/or product.

Therefore, a standardised approach is needed to improve both nanotechnology safety and efficacy, In a best practise scenario, the implementation of SbD practices would include the development of a template to identify the appropriate data to collect for each phase of the innovation project, in relation to the specific safety and design needs related to the process product. Such template should include sources and materials such as: standard materials references, grouping strategies, testing strategies, relevant scientific literature, exposure and toxicity models, Quantitative Structure Activity Relationships (QSARs), and any other applicable database. Moreover, it should use in the assessment process the information available at the REACH safety database, the biocidal products regulation, and/or the OECD guidelines. The list of parameters collected in the SbD process would be summarised in the form of a Safety Dossier) and could be used to support the decision making at the earliest possible time. The data collected should be then processed by the most advanced tools (Control Banding, prototyping, *etc…*), and included in a SbD library to be constantly updated, providing the most applicable and up-to-date methods for the generation and reporting of the SbD implementation plan. Once the information is collected and organized, in the form of Safety Dossier, it has to be communicated to different stakeholders (including technical operators, customers or suppliers.

Effective information sharing during nanotech innovation processes could lead to a more effective innovation process. However, effective information requires the establishment of an environment whereby both innovators and regulators feel "safe" to share information about innovations. Such an environments are referred as a "trusted environment". The trusted environment is usually an internet-based information platform, but in general is a platform in which innovators and regulators are able to exchange information rapidly and in a safe or secure way, by controlling with whom they share information and without fear of losing any competitive advantage. This trusted environment could become an internet accessible platform, available as source of collectively validated information.

<u>**Relevant projects in this area are:**</u>

NANoREG, A common European approach to the regulatory testing of nanomaterials, ID: 310584
ProSafe, Promoting the Implementation of Safe by Design, ID: 646325
NanoReg2, Development and implementation of Grouping and Safe-by-Design approaches within regulatory frameworks, ID: 646221
caLIBRAte, Performance testing, calibration, and implementation of a next generation system-of-systems Risk Governance Framework for nanomaterials, ID: 686239

Life cycle assessment (LCA) is a quantitative assessment of emissions, consumed resources, and potential impacts on human health and environment attributable to a product over its entire life cycle, from raw material extraction and conversion, up to the product manufacture, distribution, use, and end-of-life.

The International Organisation for Standardisation (ISO) has established a set of standards on LCA (ISO 14040:2006 — Principles and framework[35] and ISO 14044:2006 Requirements and guidelines[36]), which outlines the generic principles and requirements to the undertake on an LCA analysis and ensuring its quality and consistency. In principle, LCA tools are suitable for nanotechnology and nanomaterials applications, where they provide:

- an opportunity to prevent or minimise potential adverse effects to human health and the environment over the entire life cycle of a nano-based product
- a guide for researchers and business to capitalise on the benefit of a nanoproduct, compared to a traditional product.

However, the lack of an input/output data inventory; the absence of toxicological tests results; a wide process-to-process variability; the lack of understanding in certain areas (particularly end-of-life scenarios) bring uncertainties in the assessment of toxicity, large-scale impacts, and end-of-life impacts; requiring for further standards and a more in-depth knowledge.

A range of guidance documents and resources are available, providing information to support the LCA of nanotechnologies and nanoproducts. Few of the key resources and guidelines for the nanotechnology life cycle assessment are summarised below:

- ISO LCA Standards[37]
- OECD LCA Guidance Manual[38]
- European Platform on LCA[39]
- European Commission Joint Research Centre Information Hub on LCA[40]
- UNEP/ SETAC Life Cycle Initiative[41]

Professional services supporting life cycle assessment for nanomaterials are available within the SAfenano platform (SAFENANO Services[42])

Relevant projects in this area are:

CompSafeNano, NanoInformatics Approaches for Safe-by-Design NanoMaterials, ID: 101008099
AQUAlity, Interdisciplinar cross-sectoral approach to effectively address the removal of contaminants of emerging concern from water, ID: 765860

[35] https://www.iso.org/standard/37456.html
[36] https://www.iso.org/standard/38498.html
[37] https://www.safenano.org/knowledgebase/guidance/life-cycle-assessment/iso-lca-standards/
[38] https://www.safenano.org/knowledgebase/guidance/life-cycle-assessment/oecd-lca-guidance-manual/
[39] https://www.safenano.org/knowledgebase/guidance/life-cycle-assessment/european-platform-on-lca/
[40] https://www.safenano.org/knowledgebase/guidance/life-cycle-assessment/european-commission-joint-research-centre-information-hub-on-lca-(1)/
[41] https://www.safenano.org/knowledgebase/guidance/life-cycle-assessment/unep-setac-life-cycle-initiative-(1)/
[42] https://www.safenano.org/services/

5 Target sectors and products

The identification of exemplary target products of industrial relevance for each sector has the aim to contribute towards the improvement of the current European positioning and performance in nanofabrication.

5.1 Health

In health there are important target products such as medical implants, bio-printed living tissues, new formulations for transdermal drug delivery, including transdermal patches, cosmetics and topically applied medications, ultraminiature batteries for high-performance, wearable systems, new drugs for nebuliser-based drug delivery, biodegradable materials for tattoo-like 'personal electronics, and nanoscale sensors and actuators for closed-loop, wearable health devices, among others.

- BIOSENSORS: RubyNanoMed, Cellix Bio, Patsule
- SMART DRUG DELIVERY: West Pharma Onedose, BD Libertas Autoinjector
- IMPLANTABLE: Radiation/Radfet Implantable Sensor, Endotronics blood pressure, Boston Scientific Pacemaker, Medtronic GERD
- WEARABLES: PMD respiratory patch, TevaPharma Smart Inhaler, Aerogen Nebulisation Technology

5.2 Climate change and energy

In energy sector, a whole range of products only made possible by nanotechnology are already in the prototype stage or available on the market. For example, nano-porous antireflection coated solar glass, nanostructured LEDs, nano-additives for engine lubricants, nanoelectrodes for lithium-ion batteries, nanocrystalline magnetic materials for power electronics and nano-porous hydrogen storage materials, as well as nano-catalysts in fuel cells and industrial chemical production processes.

These can be high social and industrial impact products where nanofabrication can lead to major technological advancements and commercial competitiveness:

- Fuel cells: proton Exchange Membrane Fuel Cell (PEMFC) accounted for over 67.7% units shipped in 2019. PEMFC is widely used in applications, such as forklifts, automobiles, telecommunications, primary systems, and backup power systems. Versatility is a major factor slated to bolster their demand in the forecast period. Molten Carbonate Fuel Cells (MCFC).
- 3rd generation Thin-film PV: perovskites, OPV, DSSC and Quantum dots PV.
- Nano-catalyst.

There are some interesting examples of nanofabrication in energy sector. The manufacturing process of thin film PV starts by depositing the thin photoactive film on the substrate, which could be either glass or a transparent film. Afterwards, the film is structured into cells similarly to the crystalline module. Unlike crystalline modules, the manufacturing process of thin-film modules is a single process that cannot be split up.

- The company Oxford PV presents the first manufacturing line for perovskite-on-silicon tandem solar cells.
- Together with leading photovoltaic equipment supplier - Meyer Burger, Oxford PV has installed a silicon heterojunction solar cell line, enhanced with production equipment for the

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement Nº 882506.

perovskite top cell. The fully integrated line will be built at their industrial site in Germany and will commence production at the end of 2020.

In Catalyst, a MEA can be manufactured by the following three main methods: (1) catalyst coated membrane (CCM) in which catalyst layer (CL) are deposited onto a membrane directly; (2) decal transfer CCM in which coating CL is deposited on a substrate and then transferred onto a membrane; and (3) catalyst coated substrate (CCS) which deposits CL on a GDL. Depending on the type CCM or CCS, the deposition of the catalyst layer can be done by screen printing, doctor blade, inkjet, ultrasonic spraying, sputtering, dual ion beam assisted deposition. When dealing with ink-based technique, the first step is to prepare the catalyst ink. It consists of mixing a carbon-supported Pt catalyst, isopropyl alcohol, and an ionomer solution in H+ form, and thereafter the catalyst ink is deposited. One of the objectives is to obtain a MEA with a low Pt content without sacrificing the cell performance. Therefore, it is very important to decrease the Pt catalyst loading to reduce the cost of the anode and cathode electrodes. The objective is hence to reach a microstructure: a nanocomposite material consisting of carbon nanoparticles (30-50 nm) supporting Pt or Pt alloy nanoparticles (2-10 nm) and covered by a thin layer (5-15 nm) of ionomer binder, but it is also a porous material with some pores larger than a hundred nano-meters

Another example from Thalès in the frame of OASIS project aims to develop a smart, lightweight, and robust nano-enabled composite casing for an avionic battery module. The objectives are to increase gravimetric energy density of the battery module by 10-20%, improve resistance to thermal runaway of one cell in the battery module reducing the risk of fire propagation and to reduce of thermal runaway risk by anticipated detection.

Finally, to decrease ionic impedance of supercapacitors the use of nano-structuring is promoted, with for example arrays of pores. Production of naturally porous graphene with high surface area from silicon carbide thin films for energy storage at the wafer-level is used by several organisations. Griffith and Queensland in Australia, South Florida University (US) and The Plasma-Therm LLC and Air Force Research Laboratory in the US demonstrated an approach for producing naturally porous graphene in 'the first attempt to produce graphene with high surface area from silicon carbide thin films for energy storage at the wafer-level. Thus, the method may open numerous opportunities for on-chip integrated energy storage applications.

Other nanostructures besides pores and arrays have also been exploited as nanowire structures to maximise the surface area. Surface-area tends to be directly related to an increased capacitance or energy density, and in graphene all atoms are surface atoms. Researchers at the Beijing Institute of Technology in China and the Helmholtz-Zentrum Dresden-Rossendorf in Germany review some of the advantages posed by what they describe as a 'fascinating material'—graphene fibres. The benefits they list include a 'unique and tuneable nanostructure, high electrical conductivity, excellent mechanical flexibility, light weight, and ease of functionalization.

The environmental motivation for supercapacitor research has also encouraged an impressive resourcefulness for sustainable synthesis of supercapacitor materials. Promising supercapacitor properties are freeze drying nitrogen-doped porous carbon cryogel, as well as the production of activated carbon—the most common material for electrochemical double layer capacitors—from bark and coffee grounds.

5.3 Mobility

In **mobility** sector there are numerous examples of products that contains nanotechnology: nano-manufactured engine components and batteries, embedded electronics and micro-sensors, carbon fibre moulds, chassis or hull components, composites for aircraft fuselage and wings, turbine parts, etc. Some of the most representative and concrete examples are:

- Nylon/Montmorillonite nanocomposite (Nylon 6-Clay Hybrid (NCH)), developed by Toyota in 1980, it is considered to be the first commercial nanocomposite (in the form of a timing belt cover for Toyota Camry in 1993). Now it has applications to reduce the rolling resistance of tyres, to provide ultra-hard protective coatings for paintwork, windscreen glass and headlamps.
- ENVE composites, uses Zyvex Inc's Arovex carbon nanotube prepreg system to make high-strength wheels for its mountain bikes.
- Showa Denko's carbon nanofibers (SDK), used in the fabrication of lithium-ion batteries, manufacturing of supercapacitors and fuel cells, electrically conductive paints and adhesives, and thermally conductive resin pastes.
- A123 Systems (USA) has introduced a line of lithium-ion batteries whose electrodes are fabricated from iron phosphate nanoparticles, using technology developed at, and exclusively licensed from the MIT.
- Kuraray and Ube have developed a multilayer tubing system for fuel lines with the commercial name Ecobesta-9T, that combines PA12 with polyamide PA 9T which is a fuel barrier material. Some of the features of the product include excellent cold impact and chemical resistance, superior adhesive strength with PA9T which has low permeability to gasoline and low monomer and oligomer elution.
- Bombardier C Series, Airbus A380 and Boeing B767 are equipped with carbon nanotubes composites to increase adhesive bonding.
- Structural nano-reinforced Al castings by HPDC process (Ford).
- Energy storage in prefabricated walls (Airbus).

5.4 Digital and Industry

There are interesting examples of nanofabrication in Digital and Industry sector:

- Tyndall FlexiFab. Tyndall National Institute is home to a high-tech national research infrastructure unique in Ireland and is a national research asset. Hosting the only full CMOS, Micro-Electronic-Mechanical Systems (MEMS) and III-V Wafer Semiconductor fabrication facilities and services in Ireland.
- NanoMat Nano-Enabled Printed Electronics Pilot Line. Nano-Enabled Printed Electronics offer a wide range of functionalities (smart tags and sensors, transistor, etc.) on flexible surfaces. NanoMat (KIT, Germany) is equipped with an advanced Nano-Enabled Printed Electronics Pilot Line.
- Avantama nanofabrication of quantum dots through nanoparticle engineering
- INL Micro and Nanofabrication Facilities. The INL cleanroom facility offers micro- and nanofabrication solutions on substrates from 200-mm-diameter wafers down to samples below 10 mm in size, some of which are performed in multi-project wafer (MPW) formats. This facility provides support throughout all the development chain in cleanroom processes: device modelling and design, process integration and device fabrication, packaging, and

testing. Technologies available include: Advanced Si micromachining, MEMS and NEMS, processes for spintronics, sensors, and hybrid devices, microfluidics; thin-film silicon electronics, nano-structuring methods for solar cells and other devices, fabrication of flexible substrate systems, laser micro-structuring, interconnects and packaging.

- TECNALIA buckypapers continuous manufacturing line. The first European buckypapers continuous manufacturing plant, sheets made up of carbon, based on a safe-by-design concept. A buckypaper is a randomly oriented self-supporting film of carbon nanotubes (CNTs), resembling flexible black paper. It is an assembly that represents the nanoscale material properties of the CNTs at a macroscopic scale, whilst avoiding all the inherent handling and processing issues of a nanomaterial. Buckypapers are exceptionally lightweight (10-50 gsm), flexible free-standing films with nanoscale porous structures, that typically range in thickness from 20-100 microns. The development of these sheets leads to the creation of strong, lightweight, foldable, and highly conductive materials. The CNT bucky-paper material provides a wide range of benefits including large specific surface areas, high electrical conductivity, flexibility, biocompatibility, nanometric scale porosity, scalable production, and the ability for efficient electron transfer with enzymes. Buckypapers are ideal self-supporting frameworks for both enzymes and guest molecules such as metals, polymers, and redox molecules, permitting the development of a wide range of catalytic bioelectrode interfaces.
- Bucky-papers are also essential for the introduction of high localised loadings of CNTs into composite structures. Whilst individual carbon nanotubes exhibit electrical conductivity values similar to those of metals (such as copper) and thermal conductivity values greater than diamond, the main issue has always been how to transfer these properties into composites.
- IPC pilot line for multi-nano layering. The multi-nano layering process produces films with specific properties (optical, barrier properties, etc.)
- Development and manufacturing of a smart and lightweight composite panel complying with fire regulations based on carbon nanotubes doped veils, nano-structured fire retardant, aerogel foam, and buckypapers (VDL)
- Plastic interior components with anti-scratch and anti-squeak properties offered by micro-/nanotexturing (CRF)

The Digital and Industry market sees, for example, the fabrication of nanostructured semiconductors, flexible electronics, flat panel displays, MEMS, Micro-Opto-Electro-Mechanical Systems (MOEMS), inkjet print heads, smart manufacturing machines and advanced sensing units, nanocomputing (*i.e.*), internet of things devices for manufacturing environment and consumer applications, lightweight and multi-functional components for space industries and other high demanding manufacturing sectors among others.

5.5 Food and Natural Resources

In food and natural resources, these could be some of the main target products:

- Food packaging with added functionalities
- Monitoring of food and natural resources by smart sensors
- Water decontamination
- Precision agriculture and breeding
- Plant and animal health
- Bio-based materials and bio-fuel production
- Food processing to improve nutritional values

In the food industry some of the nano-enabled applications are in smart packaging to improve quality and safety and prolong shelf-life of products; nano-filters for beverage and drink filtrations, wastewater management and cleaning processes; novel ingredients with specific functionalities and properties aiming an improved nutrition. Recently, food packages produced with nanoparticles, "nano-food packaging," have become more available in the current market; for this reason, several industries are working on the development of products that -thanks to the addition of nanoparticles- can supply improved performances.

For example, Durethan® polymers (available from Lanxess Deutschland GmbH), a combination of engineered plastic polyamide 6 (nylon 6) and nano-clay, are transparent composites for the barrier film and coating in packaging (Bumbudsanpharoke, 2015). They can be applied in various areas of packaging, from ordinary foodstuff to the medical field since the clay nanoparticles are dispersed throughout in a polymer matrix, providing excellent properties of gas and moisture barrier, strength, toughness, and abrasion and chemical resistance.

The nanotechnologies application shows a potential in the development of smart sensors that can be directly integrated in the item that it is necessary to monitor, it is the case of the chemical sensors based on carbon nanotube. An example of this application comes from PROTEUS, a project started in 2015 and funded under the H2020 framework program for research of the European Commission. The project delivered an autonomous, highly multifunctional MEMS- and nano-enabled sensor node for adaptive and cognitive drink and water quality monitoring.

5.6 Inclusive and Secure Societies

Examples of target products of high social and industrial impact where nanofabrication could lead to major technological advancements and commercial competitiveness related to **Inclusive and Secure Societies** sector includes the following:

- Nanostructured integrated circuits for sensors (*e.g.*, health monitoring systems; miniaturized, portable, and affordable biosensors for food safety authenticity and traceability of molecular biology; integration of sensors in the food value-chain with AI and blockchain technologies; sensors for air quality control; lab-on-chip devices).
- Wearable electronics for critical environments; (*e.g.*, sensors embedded in clothes able to detect movements of the body in disaster events, such as earthquakes, floods, or fire).
- Unmanned vehicles.
- Monitoring systems for cyber security and disaster resilience approaches.
- Nano-enabled imaging systems for security applications (*e.g.*, advanced X ray).
- Nanoscale 3D printing (*e.g.*, to build materials for atomically precise sensors to the semiconductor and consumer electronic sectors).
- Nano-coatings to create and/or improve the material´s functionalities (*e.g.*, antibacterial nano-coatings, anti-corrosion applications nanocoating with superconducting properties).
- Smart devices for impair or elderly population (*e.g.*, sensors for smart home devices, motion sensors, wearable devices to control heart rate, respiration, restlessness).

The information and communication technology industry is one of the most relevant sectors applying nano-enabled systems and technologies nowadays. Their applications could have a huge impact in the inclusive and secure societies sector, leading to faster, smaller, and more portable systems that can manage and store larger and larger amounts of information. Transistors, magnetic random-access memory (MRAM), ultra-high-definition displays using quantum dots and flexible electronics illustrate some of the nano-applications in the ICT industries.

5.7 Sectorial best practices

Sectorial best practises were captured by an iterative process whereby exemplary products and processes within each targeted sector were considered and analysed in terms of standardisation, upscaling, and sustainability. The topics chosen were in line with the recommendations of the coordination groups. The topic of sustainability was analysed in terms of availability of "green" technologies, fabrication routes, component materials and in terms of barriers to implementation, adoption, and upscaling of such novel approaches. In addition, cross-sectorial topics such as modelling, training, safe-by-design approaches, and analysis of end of life were taken in consideration (see section 4.2). Several partners contributed to the compilation of the Sectorial best practices, by iteratively adding information to a model template document per each sector. The technologies taken in consideration per each sector are listed in Table 7.

Table 7. Nanofabricated products by sector.

Sector	Targeted products
Health	Nano-biosensors, smart drug delivery systems, implantable materials, and wearable
Food and Natural Resources	Food processing, food packaging, functional food development, nutraceuticals, detection of foodborne pathogens, and shelf-life extension of food products, food packaging
Mobility	Nano-sensors, nano-coatings, nano-filtration, nano-additive/reinforcers
Digital industry	Nanostructured semiconductors, flexible electronics, and MEMS Nano-texturing (*i.e.*, 3D nano-printing, injection moulding, nanofillers
Secure society	Nanomaterials in electrodes for water electrolysis, novel magnetic nanoparticles for biomedical area, more efficient thermoelectric for cooling, effective water treatment and monitoring technologies and inexpensive photovoltaic (PV) modules for clean energy Nano-coatings and thin films applied to surfaces to create or improve the material´s functionalities Wearable and flexible electronics Electronic devices for high energy efficiency and optical and thermal properties in carbon nanotubes and graphene to establish a new class of electronic materials Nanostructured integrated circuits for sensors (*e.g.*, health monitoring systems; miniaturized, portable and affordable biosensors for food safety authenticity and traceability of molecular biology; integration of sensors in the food value-chain with AI and blockchain technologies; sensors for air quality control; lab-on-chip devices); Monitoring systems for cyber security and disaster resilience approaches; Nano-enabled imaging systems for security applications
Climate/Energy	Solar PV; catalysis, batteries & supercapacitors; hydrogen fuel cells

The summary of best practises collated from partners' inputs and divided per sector are presented below:

5.7.1 Health

The industry of medical devices is responsible for the design and manufacturing of a wide range of products used to diagnose, treat illnesses, and improve health in patients. Because medical devices are essential tools for healthcare, and because these devices have direct impacts on public health and quality of life, their safety is imperative.

The two new Regulations on medical devices and in vitro diagnostic medical devices were issued by the European Commission in 2017

- Regulation (EU) 2017/745 of the European Parliament and of the Council of 5 April 2017 on medical devices, amending Directive 2001/83/EC, Regulation (EC) No 178/2002 and Regulation (EC) No 1223/2009 and repealing Council Directives 90/385/EEC and 93/42/EEC
- Regulation (EU) 2017/746 of the European Parliament and of the Council of 5 April 2017 on in vitro diagnostic medical devices and repealing Directive 98/79/EC and Commission Decision 2010/227/EU

The New Directives lay down essential requirements on safety and performance of the devices they cover, but do not prescribe any specific mandatory technical solutions for the manufacturing and design of the devices. Therefore, the manufacturer can choose which technical solution to use to meet these essential requirements. The Directives offer the possibility for manufacturers to rely on specific technical solutions, which are detailed in harmonised European standards or parts thereof, published in the Official Journal of the European Union. Most European standards for medical devices have their origin in international ISO or IEC standards, as reported in the annex 2 of the Health Best Practises document, which contains a table that indicates the recognition of international standards under the legal systems of the member jurisdictions of the International Medical Device Regulators Forum (IMDRF).[43]

Good manufacturing practice (GMP) describes the minimum standard that a medicines manufacturer must meet in their production processes. Any manufacturer of medicines intended for the EU market, no matter where in the world it is located, must comply with GMP. Three legal instruments lay down the principles and guidelines of GMP in the EU:

- Regulation No. 1252/2014 and Directive 2003/94/EC, applying to active substances and medicines for human use
- Directive 91/412/EEC applying to medicines for veterinary use.

Requirements for the conduct of clinical trials in the European Union (EU), including GCP and good manufacturing practice (GMP) and GCP or GMP inspections, are implemented in:

- the 'Clinical Trial Directive' (Directive 2001/20/EC)
- the 'GCP Directive' (Directive 2005/28/EC)

<u>**Relevant projects include:**</u>

GEOENVI Tackling the environmental concerns for deploying geothermal energy in Europe (ID: 818242)

BEYOND 4.0 Inclusive Futures for Europe BEYOND the impacts of Industry 4.0 and Digital Disruption (ID: 822296)

EU-STANDS4PM A European standardization framework for data integration and data-driven in silico models for personalized medicine (ID: 825843)

One Health EJP Promoting One Health in Europe through joint actions on foodborne zoonoses, antimicrobial resistance and emerging microbiological hazards. (ID: 773830)

TRANSVAC2 European Vaccine Research and Development Infrastructure (ID: 730964)

HCA Organoid: Pilot action to establish a multi-tissue human organoid platform within the Human Cell Atlas as a booster of future disease-centric, mechanistic, and translational research (ID: 874769)

43 https://ec.europa.eu/docsroom/documents/40606

INKplant INK-BASED HYBRID MULTI-MATERIAL FABRICATION OF NEXT GENERATION IMPLANTS (ID: 953134)
iReceptor Plus ARCHITECTURE AND TOOLS FOR THE QUERY OF ANTIBODY AND T-CELL RECEPTOR SEQUENCING DATA REPOSITORIES FOR ENABLING IMPROVED PERSONALIZED MEDICINE AND IMMUNOTHERAPY (ID: 825821)
EBiSC2 – A sustainable European Bank for induced pluripotent Stem Cells (ID: 821362)

Projects related to use of green materials and manufacturing processes:
GREEN-MAP Novel Green Polymeric Materials For Medical Packaging And Disposables To Improve Hospital Sustainability (ID: 872152)
One-Flow Catalyst Cascade Reactions in 'One-Flow' within a Compartmentalized, Green-Solvent 'Digital Synthesis Machinery' – End-to-End Green Process Design for Pharmaceuticals (ID: 737266)
HyPhOE Hybrid Electronics based on Photosynthetic Organisms (ID: 800926)
REFINE Regulatory Science Framework for Nano(bio)material-based Medical Products and Devices (ID: 761104)
Powerfuse S 4 AM POWERFUSE S: Fusing the gap between 3D-printing and Additive Manufacturing – the revolutionary manufacturing method for better products and a more sustainable future (ID: 101009685)
PEGASUS Plasma Enabled and Graphene Allowed Synthesis of Unique nano Structures (ID: 766894)
PhytoAPP INNOVATIVE WATER-SOLUBLE PHYTOMATERIAL INHIBITORs FOR ALZHEIMERs AND PARKINSONs DISEASES PREVENTION (ID: 101007642)
martLi Smart Technologies for the Conversion of Industrial Lignins into Sustainable Materials (ID: 668467)
GREENSENSE Sustainable, Wireless, Autonomous Nanocellulose-based Quantitative DoA Biosensing Platform (ID: 761000)
SHIFT Shaping Innovative Designs for Sustainable Tissue Engineering Products (ID: 101008041)
SUNSHINE Safe and sUstainable by desigN Strategies for HIgh performance multi-component NanomatErials (ID: 952924)

5.7.2 Food and Natural Resources

In food production, most nanotechnology applications involve food additives which improve the stability of foods during processing and storage, enhance product characteristics, or increase the potency and/or bioavailability of nutrients in the food product. Four major classes of nanomaterials in food applications have been identified:

- Natural food structures including naturally occurring biopolymers (carbohydrates, proteins, or lipids) that have at least one dimension in the nanometre range or nanostructures introduced by processing or cooking (*e.g.*, emulsions such as mayonnaise.
- Engineered particulate nanomaterials whose components are completely metabolised within the body or excreted such as nano emulsions or nano encapsulations of nutrients (*e.g.*, vitamins).
- Persistent or slowly soluble engineered particulate nanomaterials such as synthetic amorphous silicon (SAS; E551; anticaking agent), nano-silver (antimicrobial agent), and titanium dioxide (food additive).
- Food packaging whereby nano polymer composites offer new lightweight properties and at the same time stronger materials that can keep food products secure during transportation, fresh during long storage and safe from microbial pathogens.

The safe use of all these applications is ensured by specific legislation and/or dedicated guidance as follows. The use of nanotechnology in food production is currently covered by EC Regulation No 258/97 concerning "novel foods" and "novel food ingredients" (European Parliament and Council, 1997). Substances added to food for a technological purpose or to improve solubility, flavour, or

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bioavailability, are covered by the "Food Improvement Agent Package". It includes Regulation (EC) 1332/2008 on food enzymes (European Parliament and Council, 2008b), Regulation (EC) 1333/2008 on food additives (European Parliament and Council, 2008c) and Regulation (EC) 1334/2008 on flavourings and certain food ingredients with flavouring properties. Minerals or vitamins are regulated by Directive 2002/46/EC on food supplements. Food additives, enzymes and flavourings must undergo a common (EU-wide) assessment and authorisation prior marketing, for which Regulation (EC) 1331/2008 lays down the common procedure.

Nanomaterials are either implicitly or explicitly covered by different pieces of legislation. Currently, EU legislation explicitly addressing nanomaterials includes the Regulation on the Provision of Food Information to Consumers (1169/20119), the Regulation on Plastic Food Contact Materials and Articles (10/2011), the Regulation on Active and Intelligent Materials and Articles (450/2009), the Biocidal Products Regulation (528/2012) and the Cosmetic Products Regulation (1223/2009). Other pieces of legislation are currently under revision to better address nanomaterials, for example, the Novel Food Regulation (258/97) (European Commission, 2013), or the Annexes to the REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) Regulation (1907/2006) (European Commission, 2012).

As well as the existence and use of best practises also other trends relative to the production of greener materials and adoption of greener manufacturing processes has emerged. This was particularly pronounced for the Food & Natural Resources sector but could be also extended to other sectors. For example, biodegradable packaging materials produced from biopolymers such as proteins, polysaccharides, lipids, and their combination are gaining attention due to their eco-friendly nature; Polysaccharides like starch, chitosan and galactomannans are used in edible food packaging due to their low cost and abundant supply. Guar gum can also be used in food packaging purposes owing to its high molecular weight and easy availability. Nanoparticles embedded polymeric matrix can enhance the tensile strength and desired properties of the matrix. Titanium dioxide nanoparticles are Food and Drug Administration (FDA) approved, which can be used in food and food contact material for extending its shelf life due to their known antimicrobial activity. The main barriers to the wider adoption of such materials are associated to not unified safety and toxicity effects which in turn prevent consumer trust and confidence. Across this sector and the others, a need for unified safe-by-design approaches was highlighted as well as the need for unified life-cycle analysis and green-by-design approaches. These were identified as barriers to upscaling and sustainability

<u>**Relevant projects include:**</u>

SafeConsumE, Safer food through changed consumer behavior: Effective tools and products, communication strategies, education and a food safety policy reducing health burden from foodborne illnesses (ID: 727580)

MOLOKO, multiplex phOtonic sensor for pLasmonic-based Online detection of contaminants in milK (ID: 780839)

BioMonitor, Monitoring the Bioeconomy (ID: 773297)

VALUEWASTE, Unlocking new VALUE from urban bioWASTE (ID: 818312)

NextGen, Towards a next generation of water systems and services for the circular economy. (ID: 776541)

SEALIVE, Strategies of circular Economy and Advanced bio-based solutions to keep our Lands and seas alIVE from plastics contamination (ID: 862910)

ATLAS, Agricultural Interoperability and Analysis System (ID: 857125)

HealthyLivestock, Tackling Antimicrobial Resistance through improved livestock Health and Welfare (ID: 773436)

MEISTER, Mobility Environmentally friendly, Integrated and economically Sustainable Through innovative Electromobility Recharging infrastructure and new business models (ID: 769052)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement № 882506.

Projects related to use of green materials and manufacturing processes:

YPACK, High performance polyhydroxyalkanoates based packaging to minimise food waste. (ID: 773872)
ACCELERATE, ACCELERATing Europe's Leading Research Infrastructures (ID: 731112)
GLOPACK, Granting society with LOw environmental impact innovative PACKaging (ID: 773375)
3D-NANOFOOD, advancing frontiers in personalised foods for seniors through nanotechnology and 3D printing aiming enhanced nutrition and superior flavour (ID: 867472)
BoosT, BOOSTing the industrial application of green carbides by thermal spraying in protective coatings (ID: 784596)
NanoFEED, Nanostructured carriers for improved cattle feed (ID: 778098)
BIOMAC, European sustainable bio-based nanomaterials community (ID: 952941)
BIOMAT, an open innovation test bed for nano enabled PUR foams and composites (ID: 953270)
INN-PRESSME, open innovation ecosystem for sustainable plant-based nano-enabled biomaterials deployment for packaging, transport, and consumer goods (ID: 952972)
BIONANOPOLYS, Open innovation test bed for developing safe nano-enabled biobased materials and polymer bio-nanocomposites for multifunctional and new advanced applications. (ID: 953206)

5.7.3 Mobility

Applications of nanotechnology in the automotive area is vast and can be divided in i) exterior applications such as nano-coats with high scratch, wear resistance and anti-corrosion, smart windows, nano tyres; ii) interior applications such as automotive fabrics, nano-fluids, nano-lubricants, and nano-filters for air cleaning; iii) energy such as fuel cells, batteries, supercapacitors, photovoltaics.
The EU End-of-Life Vehicles Directive (ELV Directive, Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles) and the EU Type Approval Directive (DIRECTIVE 2007/46/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 5 September 2007 establishing a framework for the approval of motor vehicles and their trailers, and of systems, components and separate technical units intended for such vehicles) regulate market placement and the disposal of vehicles in the EU in general. The ELV Directive aims at reducing environmental risks from waste treatment and increasing recycling rates. It defines requirements on the vehicle design from the waste perspective. The Directive does not specifically address nanomaterials but the duty to minimise the use of hazardous chemicals does cover nanomaterials if they have hazardous properties. The EU type approval is a procedure to verify if a new vehicle type conforms to all relevant standards. It does not define self-standing (nano-specific) and material related requirements but refers, among others, to existing standards and regulations for example on safety and emission limit values. The EU chemicals legislation REACH (REGULATION (EC) No 1907/2006 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals) regulates the manufacturing, import, and use of chemicals on the European market, including nanomaterials.

Relevant projects include:

NEXT-GEN-CAT, Development of NEXT GENeration cost efficient automotive CATalysts (ID: 280890)
CitySCAPE, City-level Cyber-Secure Multimodal Transport Ecosystem (ID: 883321)
INN-BALANCE, INNovative Cost Improvements for BALANCE of Plant Components of Automotive PEMFC Systems (ID: 735969)
H2Haul, Hydrogen fuel cell trucks for heavy-duty, zero emission logistics (ID: 826236)

5.7.4 Digital and industry

The Technical Committee ISO/TC 299 Nanotechnologies, created in 2005, is currently working in the standardization in the field of nanotechnologies, which includes: i) Understanding and control of

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matter and processes at the nanoscale, typically, but not exclusively, below 100 nanometres in one or more dimensions, where the onset of size-dependent phenomena usually enables novel applications; ii) Utilizing the properties of nanoscale materials that differ from the properties of individual atoms, molecules, and bulk matter, to create improved materials, devices, and systems that exploit these new properties.
The ISO/TC 299 also includes the development of 5 categories of horizontal standards: for terminology and nomenclature standards; measurement and characterization standards; health, safety, and environment standards; materials specification standards; and products and applications performance-based standards. Also, the IEC/TC 113[44] "Nanotechnology for electrical and electronic products and systems", established in 2006, is working in the standardization of the technologies relevant to electro-technical products and systems in the field of nanotechnology in close cooperation with other committees of IEC and ISO. Specifically, the IEC/TC 113 is working with ISO/TC 299 in two joint working groups: terminology and nomenclature; and measurement and characterization.
In a more specific scenario, currently there are some protocols available for specific nanomaterials (*e.g.*, carbon nanomaterials, metal nanomaterials, oxide nanomaterials, quantum dots, self-assembled nanomaterials, semiconductor nanomaterials); as well as operational specific protocols for facilities and equipment (*e.g.*, handling dispersed nanomaterials, managing solid waste, liquid dispersion processing controls, local exhaust systems). Still, the lack of common nanofabrication standards and protocols is one of the biggest challenges in the field. The adoption of international standards and protocols would have a huge impact in health, safety, and environmental aspects, enhancing the trust and the adoption of nano-enabled products not only in the Digital Industry, but in all industry sectors.

Relevant projects, platforms, tools, and databases:
ACEnano, Method Decision Tool[45]
GRACIOUS, Grouping, Read-Across, CharacterIsation and classificatiOn framework for regUlatory risk assessment of manufactured nanomaterials and Safer design of nano-enabled products (ID: 760840)[46]
ECETOC, European Centre for Ecotoxicology and Toxicology of Chemicals[47]
OASIS, Open Access Single entry point for scale-up of Innovative Smart lightweight composite materials and components
Himalaia, Development of an Injection Moulding Platform for mass-production of 3D and/or large micro-structured, functional surfaces.

5.7.5 Inclusive and secure societies

The world is currently entering a new phase of information and communications technology (ICT) development that is expected to drive economic growth and sustainable development for the coming decades. In the future, people, systems, and objects will interact seamlessly with each other in Internet of Things (IoT) scenarios. Nanotechnology is expected to be a key enabling technology (KET) to sustain the development of future smart sensing systems and/or Cyber-Physical Systems (CPS) that will jointly integrate sensing, computation, communication, and energy management functions. In the short term, nanotechnology can enable wireless sensor nodes with multi-parameter sensing and long-term autonomy. Sensor networks that exploit nanotechnology are strategically beneficial to security because they generate a dynamic perception of the environment with very early detection of threats

[44] TC 113 – Nanotechnology for electrotechnical products and systems (https://www.iec.ch/dyn/www/f?p=103:7:10605715880519::::FSP_ORG_ID,FSP_LANG_ID:1315,25)
[45] https://nanodecision.z6.web.core.windows.net/Index.html
[46] https://www.h2020gracious.eu/
[47] https://www.ecetoc.org/

by analysing big data available in real time. For security, this technology is deployable at different levels, including from humans (body area networks) to buildings, cities, and large environments. Additionally, wearable embodiments of WSNs can provide battlefield evaluations of the medical status of soldiers by evaluating *in-situ* the severity of injuries and preparing the most effective treatment. Current security topics can be grouped as nano-forensic science (reactive smart materials, micro-chip technology, nanomanipulators, nanoimaging tools); secure/smart cities, smart healthcare, military interests (more for US landscape as EU does not fund military research, electronics; sensors; energy and power, including photovoltaics and solar cells; structural materials; coatings; multi-functional materials; devices; energetics, such as explosives and propellants; detectors; decontamination; and military medicine, including improved delivery of vaccines). Regulation of nanomaterials used in these applications falls under the EU chemicals legislation REACH.

Relevant projects:
CyberSec4Europe, Cyber Security Network of Competence Centres for Europe (ID: 830929)
CONCORDIA, Cyber security cOmpeteNce fOr Research anD Innovation (ID: 830927)
EOSC, Pillar Coordination and Harmonisation of National Inititiatives, Infrastructures and Data services in Central and Western Europe (ID: 857650)
ENTRUSTED, European Networking for satellite Telecommunication Roadmap for the governmental Users requiring Secure, inTeroperable, InnovativE and standardiseD services (ID: 870330)
CORONADX, Three Rapid Diagnostic tests (Point-of-Care) for COVID-19 CoronaThree Rapid Diagnostic tests (Point-of-Care) for Coronavirus, improving epidemic preparedness, public health, and socio-economic benefits (ID: 101003562)
IRIS, Integrated and replicable solutions for co-creation in sustainable cities (ID: 774199)
NANOREM, Nanotechnology for contaminated land Remediation (ID: 309517)
POCITYF, A positive energy city transformation framework (ID: 864400)
SUSTENANCE, Sustainable energy system for achieving novel carbon neutral energy communities (ID: 101022587)
UPSOIL, effective, Biogeochemical Remediation Approaches (ID**:** 226956)

5.7.6 Climate and energy

For the solutions targeted for the Climate Change and Energy sector the nanofabrication practices are the following: solar PV perovskite, catalysis, hydrogen fuel cells, batteries/supercapacitors, wind energy. As the use of nanomaterials is spread across many different applications it is difficult to identify specific best practices. Regulation of nanomaterials used in these applications falls under the EU chemicals legislation REACH.

Relevant projects:
SUPRAMOL, Towards artificial enzymes: bioinspired oxidations in photoactive metal-organic frameworks (ID: 647719)
RECYCALYSE, New sustainable and recyclable catalytic materials for proton exchange membrane electrolysers (ID: 861960)
Nano-Edison, Nanotechnology for advanced battery energy storage systems (ID: 101009493)
GREENPEG, New exploration tools for European pegmatite green-tech resources (ID: 869274)
NextGen, Towards a next generation of water systems and services for the circular economy. (ID: 776541)
ENGAGE, Exploring National and Global Actions to reduce Greenhouse gas Emissions (ID: 821471)
VERIFY, Observation-based system for monitoring and verification of greenhouse gases (ID: 776810)
DEESME, Developing national schemes for energy efficiency in smes (ID: 892235)
OPERANDUM, OPEn-air laboRAtories for Nature baseD solUtions to Manage environmental risks (ID: 776848)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement № 882506.

PLAST2bCLEANED, PLASTtics to be CLEANED by sorting and separation of plastics and subsequent recycling of polymers, bromine flame retardants and antimony trioxide (ID: 821087)

Safe-by-design projects:

ASINA, Anticipating Safety Issues at the Design Stage of NAno Product Development (ID: 862444)
SAbyNA, Simple, robust, and cost-effective approaches to guide industry in the development of safer nanomaterials and nano-enabled products (ID: 862419)

SBD4Nano, Safe-by-design for Nano (ID: 862195)
SABYDOMA, Safety BY Design of nanoMaterials - From Lab Manufacture to Governance and Communication: Progressing Up the TRL Ladder (ID: 862296)
HARMLESS, Advanced High Aspect Ratio and Multicomponent materials: towards comprehensive intelLigent tEsting and Safe by design Strategies (ID: 953183)
SUNSHINE, Safe and sUstainable by desigN Strategies for HIgh performance multi-component NanomatErials (ID: 952924)

The collection of information is an iterative process. It will be finalised by March 2022.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement № 882506.

6 Identified actions

The work carried out in the development of the roadmap is the essential starting point in the definition of the **key actions to drive the nanofabrication sector towards a brighter future**. Our initial analysis started by the consultation for the assessment of the current nanofabrication landscape. The initial landscape analysis allowed us to assess the current capabilities of the European nanofabrication sector. This was done by analysing the current development goals, policies, needs, trends, barriers, opportunities, projects, initiatives, and infrastructures within the European panorama and comparing it against the international panorama. The **initial landscape analysis** yielded a set of initial **recommendations for policy makers** to address to strengthen the European nanofabrication ecosystem:

1. **Increase risk failure tolerance** of the European industrial ecosystem.
2. Attract **venture capital** and endorse loans guarantees for nanofabrication projects.
3. Define an **international regulatory reference framework** to endorse **clear safety measures** and ensure nanofabrication trustworthiness.
4. Compel industry to **investigate the advantages of nanofabrication** via an effective communication and dissemination campaign.
5. **Effective dissemination is crucial for** the understanding of nanofabrication and technology by **the wider public**.
6. Facilitate **collaboration** among **all the stakeholders** along the **whole value chain** (also SMEs).
7. Outline an **educational agenda**, as part of the scientific and technologic curricula, to **bridge the widespread knowledge gap about nanotechnologies**.
8. Encourage trainings and awareness actions in the field of standardization to ease SME uptake of nanofabrication.

These initial recommendations derived from our preliminary analysis of the drivers and current challenges present within the nanofabrication sector performed by desk research and selected interviews to industrial and research stakeholders of nanofabrication value-chains. Further analysis of the nanofabrication landscape allowed for a more in-depth evaluation of the challenges currently faced by the nanofabrication sector. The external experts involved in SUSNANOFAB workshops and surveys identified the challenges herein reported as crucial to address for the current development of European nanofabrication sector. A preliminary elaboration of such challenges yielded the following initial suggestions on the identified actions, clustered around each of the thematic areas of the SUSNANOFAB Coordination Groups.

6.1 Identified actions relevant for "Nanofabrication aspects from material design to manufacturing upscaling"

The first set of identified actions concerns the ***"Lack of efficient mass production techniques"***. This challenge is related to the need of reproducibility and reliability in the production process. Currently, too many different processes are available, holding different features and exploiting different technologies. However, an industrial manufacturing process has to be reproducible, reliable, and allow for a continuous production process. Therefore, the industrial process scalability could be hampered

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by several factors, such as yield, reproducibly, and/or scalability. The determination of quality criteria applicable to scalable and standardizable production process is key and pre-requirement for an eventual implementation of software tools that may facilitate the assessment of the process scalability. In this process, artificial intelligence may aid in the process scale-up, through the reduction of uncertainties by close feedback loop on the process development steps.
From a more theoretical standpoint, collaboration between industry and academia should be promoted to bridge the shift of the process requirements from lab scale to large scale production. Connecting these two distant worlds (*i.e.*, industry and academia) may reduce the timescale needed for technology translation from lab to bench and render an important feedback to academia about the current real-world trends and needs.

The second set of identified actions concerns the use of ***"Metrology, especially for quality control"***. The adoption of metrology currently suffers from cost limitations in the application of metrology techniques. One way to fix this is by a reduction of costs related to a wider adoption of metrology related technologies and their integration into the production line (*e.g.*, automatized data analysis to support metrology and rectify the production on-the-go). An additional way of facilitating the adoption of metrology is setting the requirements for new procedures, reducing the costs of the technologies, developing metrology techniques with higher resolutions.

The third set of actions are related to the challenge about ***"NEMS and MEMS need still some performance improvements to fully work for mobility sector requirements"***. To overcome current barriers in the implementation of NEMS and MEMS, several issues have to be addressed to allow the integration and/or the operation in real conditions. A poor NEMS and MEMS production and performance reproducibility is one of the key issues. Additionally, they result difficult to integrate with the products, and have still a cost/performance gap with respect to "traditional" technologies. Another point to tackle in this challenge is how to address energy conversion and harvesting in relation to the powering of the sensor.

A fourth set of action was identified in relation to the observed ***"Lack of investments in nanotechnology companies"***. To tackle this issue, it would be helpful to develop a framework for facilitating the investment of venture capital funds interested in high-tech companies (amongst which are companies working on nanofabrication). Another action that could be undertook is the development of programs of cascade funding/voucher directed at SMEs for the financing of their research and innovation activities. Publicly funded investments could be another mean of action to finance medium scale manufacturing facilities, driven by the industry, in a complementary way to what it is now with the EIC programme. This is considered because, as there the market volume is small if compared to other fields, there is limited investment by EIC in the nanofabrication sector.

A fifth set of actions was identified in relation the issues experienced in the "***Production of 3D structures (most of the existing techniques are currently focused on 2D surface patterns)"***. In relation to 3D manufacturing technologies, the only actable identified action was the development of reliable and low-cost quality control, as this is a key issue for 3D manufacturing technologies.

A sixth set of actions was identified about the ***"Scaling of volume production, testing, packaging and deployment from research-grade to mass market levels in the health sector"***. The health sector is an important target of the European union, and it is generally lead worldwide by other countries (*i.e.*, US). Therefore, few actions are foreseen to overcome the current situation. Digitalization of the information related to the process could be expeditious for the development of nanofabrication within the health sector, hence, the development of framework allowing such digitalization would be

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a strong enabler of the digital transition. The creation of digital twins is a key facilitator for accurate modelling, capable to forecast the key parameters related to production volume, packaging, *etc*. Also, this approach may be used in the manufacturing of medical devices, such as smart delivery systems and others.

A seventh set of identified actions was developed about the concept that **"*Smart delivery systems will be viewed as combination devices and will require the full regulatory approval process before being approved for market*"**. In relation to smart delivery systems, the development of a digitalization roadmap for the industry 5.0 seemed to be a focal point for the development of smart delivery systems. This is because smart delivery systems rely on several levels onto digitalised services. For example, the development of modelling services for the precise analysis of the production process is needed to allow an efficient scale up of the processes from lab to production scale (*e.g.*, thermodynamics and kinetics). Another actable action is the development of innovative ways to improve production lines in a step-by-step fashion, allowing to introduce improvements to the production lines without causing disruptions because of getting astray from the initial production process flow. Moreover, the development of transferrable and more automatized technologies could be also expeditious by enabling a fast deployment of digital technologies.

An eighth set of recommended action towards the **"*Reduction of production costs and expensive raw materials*"** was also delivered. Overall, all the measures listed hereafter are directed at the reduction of the sourcing costs for key raw materials. To reduce the supply shortage risks, the supply chain could become more reliable by the diversification of the raw material suppliers all over the world. This approach is a clearly effective and it could be complemented by the search for effective, but cheaper and abundant, alternative raw materials. Alternative raw materials may reduce the burden twofold on the supply chain and onto the limited abundance of some raw materials, resulting also in a general reduction of costs.
Another way to abate the disruptions of the supply chain and its costs could be to facilitate the sourcing within EU of raw materials by the development of processing facilities capable to extract value from European lower grade raw materials located in close distance to the end-user. This would also contribute indirectly to the development of a flexible raw materials production chain, capable to protect EU market from raw materials market fluctuations. Another mean of dependence reduction from primary raw materials is the increase the usage of secondary raw materials when applicable (*e.g.*, closing the loop through a direct recycle of industrial scraps).

A ninth set of identified actions is linked to the **"*Development of new nanofabricated devices*"**. Nanofabricated devices are a well-developed field and further development, valorisation, and integration of such technologies is key for the traction of this field. Potential developments are foreseen for novel technologies, able to work with multiple materials, therefore resulting in enhanced properties of the finally produced devices (*e.g.*, fundamental enhancement of mechanical properties, but also combination of properties such as sensing and mechanical performance). Also, faster speed of fabrication and resolution, capable to address the classical inverse correlation of higher resolution to higher fabrication speed are developments strongly sought after (*e.g.*, recent advancements have been achieved with the use of digital mirror arrays). An additional actionable goal is the integration of several different technologies (*e.g.*, in-situ nanofabrication technology integrated into macro-scaled technologies).
An important sector of application of nanofabricated devices is the health sector and a specific digression is needed to tackle the needs of such devices. To further the potential of nanofabricated devices in the medical sector would be useful to develop smart micro/nano-objects resulting in the production of new medical devices. This could go by the development of modular devices (*e.g.*, objects

that can influence cell activity for regenerative medicine purposes, smart Lego-like biological blocks that can be assembled to create a macro-scaled tissue construct), but also clustered composite medical devices for specialistic diagnostic applications (for example, in this case nanofabrication is likely to be better suited than microfabrication). With the respects of diagnostic/screening applications, the development of screening platforms via nano-deposition of materials for the creation of nano/micro topographies used for screening different biological formulations to screen drug/pharmaceutical formulations at a much lower scale, resulting in higher throughput and lower costs (*e.g.*, biomaterials for regenerative medicine as listed in the former point, to enhance the performance of prosthetic devices, via topographies that can provide better integration with the surrounding tissues or stimulate anti-bacterial properties).

6.2 Identified actions relevant for "Environmental and sustainability issues, health and ethics in a life cycle perspective"

The tenth set of identified actions was tailored around the ***"Poor Adoption of safe-by-design approaches for safe production processes"***. The development of safe-by-design approaches is important for the nanofabrication sector. To enable this the simplification of current tools, models, and platform should be promoted. This will allow an easy implementation and an effective adoption of such frameworks by SMEs. These should be as open as possible (open platform or open cloud) and therefore needing of a "delocalisation platform" to allow their open usage and should include several processes to make it effective (this should be furthered with respect to what was targeted in other projects, such as "Guide nano"). To facilitate the adoption of safe and sustainable-by-design approaches and support the development of accessible information, exploitable in the open platform, the compilation of FAIR (Findability, Accessibility, Interoperability, and Reusability) compliant data, including all related tools, should be adopted.

The following set of recommended actions was directed at the ***"Need of standards for risk assessments, risk management and safety issues of nano fabricated materials"***. Currently, shared standards are not adequately developed within the European framework and there are neither many projects nor general agreements on safety standards. To follow up to this need, pre-normative work is needed to gather adequate knowledge on risk assessment and management. The integration of the gathered standards, derived from several authoritative bodies in the nano-safety cluster (*e.g.*, European Partnership on Metrology, EURAMET), is then required. In the current and future integrations to the risk assessment standardization process, it is advisable the involvement of standardisation agencies in the development of current and future standards. To facilitate the current and future integrations to the risk assessment standardization process the collaboration between different labs from countries in the standardisation processes should be considered. Also, an open discussion and collaboration with the different actors of the product life cycle should be considered to deliver a well-rounded assessment of the whole value chain (*e.g.*, end-users, manufacturers, academia). The adoption of strategy such as DIH, OITB could be helpful. Also, the development of Single-Entry Point to manage the standardisation requests could facilitate the adoption of the new standards.

One more set of identified actions concerns the ***"Lack of information on exposure to nanomaterials and health consequences"***. The challenge cited here is "exposure", but an analogous challenge is posed by "hazard". We can divide these into occupational, consumer, and environmental exposures/hazards. For occupational exposure, most studies do not report data that could then be used in models (*e.g.*, neither health relevant concentration, nor emission rates). We neither are able

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to differentiate between "exposure" and "internalized" dose, nor we do have models for that (not even raw empirical data on internal dose). Additionally, there are no spatial distribution models available for nanomaterials exposure (*e.g.*, multi-box model derived from fluid dynamics captures data in the room, but not in the lung). This asks for a strong intervention in promoting action capable to determine the occupational exposures focus both on airborne particles and direct exposure (as opposed to indirect exposure) and on manufactured nanomaterials (NMs) (as opposed to unintentional emissions of NOx). Additionally, extrapolation methods to determine real-world scenarios from lab-based studies are needed. Focusing on consumer exposure, very few papers on very few products addressing any exposure data are available (*i.e.*, models and data). Therefore, we need models capable to assess chronic effects, deriving from both direct and indirect exposure of the consumer. These models should be capable to assess environmental exposures, especially of mixtures and not as single material exposures. As for environmental exposure, the challenge is related to the difficulties in determining trace materials present in complex matrices. This poses a twofold challenge, from a differentiation and a detection perspective. The latter is related to the limit of detection of current technologies, which requires preparation steps for the matrix analysis.

An additional set of recommendations was outlined on the ***"Lack of information to improve public perception of nano"***. This is a serious issue for the field of nanotechnologies. Generally, the knowledge of the wider public on the nano topics is rather low, and the public is averse to deepening their topic knowledge. For example, little is known about public knowledgeability in relation to direct and indirect exposure. Defining ways to acknowledge the complexity and depth of the problem by increasing people awareness of the inherent properties and uncertainties would be important. To shift consumer perspective, it would be useful to acknowledge the widespread use of nanomaterials in common consumer applications. Moreover, determining the most and least concerning scenarios to whom people are concerned about (*e.g.*, food, drug, etc.) would be helpful in tailoring a targeted communication directed at tackling those concerns. In these regards, increasing the communication frequency about risks and absence of such would also be a helpful measure. Additionally, not only the public is reluctant in adopting nanomaterials but also the traditional companies are wary in using nanofabrication in their products. Also addressing this resistance in the established businesses could further improve the overall acceptance of nanotechnologies by the whole society.

6.3 Identified actions relevant for "Future skills and capabilities"

A set of actions was discussed for the ***"Lack of a unified strategy at different levels of education (i.e., high school, university, lifelong training)"***. In this case, encouraging partnerships between academia and industry seemed an effective way to foster the development educational standards tailored to industry needs and global standards. Also, the creation of an international coordination group to facilitate discussions between stakeholders. This will allow for the coordination of an international taskforce, consisting of educators, scientists and engineers and high school teachers, to identify what currently exists and how additions can be made to complement the current curriculum. This will pave the way for the creation of a model curriculum for all levels that shows pathways for different levels. Overall, the goal would be the development of a unified curriculum with learning outcomes defined for different ages, grades, and education levels.

A further set of endorsed actions was about the ***"Difficult to retrain and continually train skilled workers so they remain relevant to their sectors"***. To address this issue, the development of virtual learning programs for industrial workers seemed an effective way to disseminate current developments through lifelong training. In addition to trainings, visiting cutting edge research centres

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of industry seemed to be an effective way to foster acknowledgement and adoption of current and effective technological developments. In addition to these direct actions, additional more indirect actions were envisaged, such as benchmarking industrial federations and interest groups, developing an open-source database on trainings, and offering incentives to endorse various individuals to seek lifelong training (*e.g.*, credits or certifications). Identifying the institutions willing to offer training (*e.g.*, universities, companies, *etc…*) and recognizing them would be important to enable this action. An additional endorsement to this action could be also to encourage national labs to offer certified trainings as part of an international projects.

The following set of identified actions was directed at the **"*Lack of entrepreneurship and innovative management skills which is relevant on exploitation of knowledge and technology transfer*"**. Especially link with novel and advanced technologies, research centre and university shall promote translational skills to ease among other things the technology market driven development or public/private fund raising. The sole identified action in these regards was promoting the implementation and operation of programs for nano-enabled industries, analogous to the successful "translation advisory board" concept adopted in the HealthtechTAB project.

The last set of recommended actions was developed about the **"*Lack of researchers/workers soft skilled to operate effectively in diverse, transdisciplinary teams*"**. This issue could be tackled by the development of action facilitating the technological transfer by linking the demand/need to the supplier. For example, this could be tackled by the development of centres of matchmaking, acting as curators of the new services/products developed by the meeting of the demand with the supply. Another action may consist in supporting the implementation during education and training of the works of interdisciplinary trainings at various educational levels. This may inherently facilitate the development of more transdisciplinary educated researchers/workers (*e.g.*, via lab rotations, internships, and secondments). Another way to tackle this need may go by supporting the creation of a new type of professional capable to act as a mediator/translator between several disciplines.

6.4 Further work

As we are in the midterm of SUSNANOFAB project, the actions listed above are only preliminary insights on the content of this section, which will be radically updated in the final roadmap. Further insights about the nanofabrication sector will be gathered as further work is needed to analyse and re-cluster actions by priority and timescale instead of challenge. This will allow us to determine the key enabling actions with a cross-cutting impact throughout sectors and challenges of the nanofabrication segment. This approach will allow to identify priority actions to undertake for overcoming current challenges and enabling further and faster development of the nanofabrication segment. These actions will be published altogether with the current industrial best practices. All of the work carried out will allow the framing of European nanofabrication sector within an international outlook. This will allow us to address comprehensively the nanofabrication sector and provide precise insights on the actions of upmost importance to undertake in the close and near future. These actions will enable our vision for the 2030 nanofabrication sector and lay the foundations for the vision for the 2050 nanofabrication sector.

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7 Conclusions

SUSNANOFAB road-mapping and networking activities involved so far overall about 105 experts. The experts interacted in groups chaired by our project partners and formed by people with a diverse background, both technological and non-technological. To gather a more accurate analysis of the nanofabrication sector, we are going to broaden the group of experts involved in the road-mapping process. This will be achieved by increasing the network visibility through several communication channels via the implementation of good networking and dissemination practices to get our current achievements beknown. This will aid us in both attracting further experts to our meeting but also to make our action well known in the European nanofabrication sector.

Our current achievements derived from two consortium meetings, held in December 2020 and April 2021. These meetings moulded SUSNANOFAB project vision and identified the overarching key drivers and challenges to be considered in the development of the project itself. The exploitation of challenges and drivers is a central step to a successful road mapping process. The challenges currently experienced by the nanofabrication sector were identified from an in-depth analysis of the nanofabrication landscape. This analysis comprised an analysis of the currently active key initiatives, projects, services, infrastructures, and stakeholders present within the nanofabrication sector. Overall, the analysis yielded a well-rounded overview of the current capabilities and setbacks in the field of nanofabrication, altogether with the current level of integration of nanofabrication into the industrial ecosystem and some best practices exerted within the sector. From this initial analysis, we proceeded into a more in-depth analysis on specific challenges experienced by the nanofabrication sector. This additional analysis allowed us to collect a subset of some key cross-cutting challenges, which were discussed in-detail to determine the eventual course of action to undertake to alleviate the current setbacks experienced by the nanofabrication sector.

Currently, we have collected several feedbacks on the causes of such challenges and on possible actions to overcome them by enabling the nanofabrication sector. In the following months, we will further re-elaborate such feedbacks and deliver an overall picture of such actions, framing them in relation to the challenge priority and the appropriate timescale for the action development.

Our current project's efforts are devoted at the collection of the industrial needs from the industrial nanofabrication sector. This is a key step for the following developments of the action, as it will allow us both to depict a more accurate picture of the nanofabrication sector needs and to set the foundations for the training and brokerage activities apt to mitigate those needs. Training and brokerage activities highly tailored to the nanofabrication sector will allow us to become an even more central actor in the evolution of the nanofabrication sector.

Also, all the actions reported above will contribute to the development of the final version of the roadmap. The final roadmap will gather the collected actions re-clustered by priority and presented as an action plan listing the actions by short-, medium-, and long-term actions. This action plan will act as blueprint for the work of both public and private policymaking bodies.

To deliver a contribution coherent with the objectives set by the European Commission, we will further align the SUSNANOFAB to the strategies of recent implementation by the European Commission (*i.e.*, Horizon Europe strategic plan[48]) and to the ones formerly adopted (*i.e.*, the 2030 Agenda for

[48] Horizon Europe, Strategic plan 2021-2024 (DOI: 10.2777/083753)

Sustainable Development[49], A European Green Deal[50], An economy that works for people[51], A Europe fit for the digital age[52], Recovery plan for Europe[53], and Next Generation EU[54], *etc…*).

All this process of revision and validation of our former results and the future developments of the roadmap will allow us to proceed to the development of the final roadmap and to the validation of such.

[49] United Nations, 2015 (https://sustainabledevelopment.un.org/post2015/transformingourworld/publication)

[50] COM(2019) 640 final, 11.12.2019 (CELEX: 52019DC0640)

[51] An economy that works for people (https://ec.europa.eu/info/strategy/priorities-2019-2024/economy-works-people_en)

[52] A Europe fit for the digital age (https://ec.europa.eu/info/strategy/priorities-2019-2024/europe-fit-digital-age_en)

[53] Recovery plan for Europe (https://ec.europa.eu/info/strategy/recovery-plan-europe_en/)

[54] NextGenerationEU (https://europa.eu/next-generation-eu/)

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Annex A – European projects and initiatives

Table 8. List of the identified European initiatives

Initiative	Type	Character	Country/region	Sector
EPPN-Platform	Platform	Public	Europe	Cross-sectorial
EMMC	Association	Public	Europe	Cross-sectorial
EMCC	Council	Private	Europe	Cross-sectorial
AM-Platform	ETP/Platform	Public	Europe	Cross-sectorial: Mobility, Digital and Industry, health
Nanosafety Cluster	Cluster	Public	Europe	Cross-sectorial: Health, Environment, Food, Energy, Water
DIH Catalogue	other	Public	Europe	Cross-sectorial
Nanofutures Platform	ETP/Platform	Public	Europe	Cross-sectorial
KETs Centers	Other	Public	Europe	Cross-sectorial
EIT-Raw Materials	Association	Public-Private	Europe	Cross-sectorial: Energy, mobility, climate change, ….
MANUFUTURE	ETP	Public	Europe/National	Digital and Industry
SPIRE	Association	Private-Public	Europe	Digital and Industry
OE-A	Association	Private	Word wide	Digital and Industry
Afelim	Association	Private	France	Digital and Industry
EPC4	Platform/Association	Private	Europe	Digital and Industry
EPMA	Association	Private	Europe	Digital and Industry
4M	Association	Public	Europe	Cross-sectorial: Digital and Industry
ECTP	ETP	Private	Europe	Digital and Industry

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Initiative	Type	Character	Country/region	Sector
EIT-Manufacturing	Association	Public-Private	Europe	Digital and Industry
ECERA	Network	Public	Europe	Climate Change and Energy
Hydrogen Europe Research	IPCEI	Public	Europe	Climate Change and Energy
EMIRI	Association	Private	Europe	Mobility, Climate Change and Energy
EERA	Association/Council	Public	Europe	Climate Change and Energy
EIT InnoEnergy	network	private	Europe	Climate Change and Energy/ Mobility
EIT Climate	network	private	Europe	Climate Change
ETC-CME				Climate Change and Energy
EIT Manufacturing	association	private	Europe	Cross-sectorial: Digital and Industry
EGVIA	Association	Private	Europe	Mobility
EARPA	Association	Private	Europe	Mobility
ERTRAC	Council	Private	European	Mobility
CMUA	-	-	Spain/regions	Mobility
ETPN	Platform	Public/Private	Europe	Health
BBI	Network	Public-Private	Europe	Food and natural resources
EARTO	Association	Public	Europe	Inclusive and secure societies
ECSO	Association	Private	Europe	Inclusive and secure societies
EOS	Association	Private	Europe	Inclusive and secure societies

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Table 9. List of the identified European projects

id	Project Acronym	Funding scheme	Work Programme/	Coordinator	Coordinator activity type	Coordinator country	Sector	Nanofabrication technical domain	Key targeted solutions
654384	ASCENT	RIA	H2020-INFRAIA-2014-2015	UNIVERSITY COLLEGE CORK - NATIONAL UNIVERSITY OF IRELAND, CORK	HE	IE	Digital and Industry	Cleanroom nanofabrication	CMOS technologies and infrastructure
862444	ASINA	RIA	H2020-NMBP-TO-IND-2019	CONSIGLIO NAZIONALE DELLE RICERCHE	RTO	IT	Cross-sectorial	Bottom-up and Top-Dow nanomanufacturing processes	Management methodology and roadmap
948225	B3YOND	ERC-STG	ERC-2020-STG	POLITECNICO DI MILANO	HE	IT	Cross-sectorial		
642242	CARISMA	CSA	H2020-SC5-2014-one-stage	STICHTING KATHOLIEKE UNIVERSITEIT	HE	NL	Climate Change and Energy	-	On-line platform services
723630	CLUSTERNANOROAD	CSA	H2020-NMBP-CSA-2016	LABORATORIO IBERICO INTERNACIONAL DE NANOTECNOLOGIA	RTO	PT	Cross-sectorial	-	-
645993	CO-PILOT	RIA	H2020-NMP-PILOTS-2014	NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO	RTO	NL	Digital and Industry	Surface modification	nanocomposite

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id	Project Acronym	Funding scheme	Work Programme/	Coordinator	Coordinator activity type	Coordinator country	Sector	Nanofabrication technical domain	Key targeted solutions
723623	EC4SafeNano	CSA	H2020-NMBP-CSA-2016	INSTITUT NATIONAL DE L ENVIRONNEMENT ET DES RISQUES INERIS	RTO	FR	Cross-sectorial	ALL	Advanced nanosafety services
723868	EENSULATE	IA	H2020-EEB-2016	RINA CONSULTING SPA	Industry /SME	IT	Climate Change and Energy	Bottom-up: CVD, ALD	Nanocomposite materials
723867	EMMC-CSA	CSA	H2020-NMBP-CSA-2016	TECHNISCHE UNIVERSITAET WIEN	HE	AT	Cross-sectorial	-	Materials Modelling
730957	EnABLES	RIA	H2020-INFRAIA-2017-1-two-stage	UNIVERSITY COLLEGE CORK - NATIONAL UNIVERSITY OF IRELAND, CORK	HE	IE	Inclusive and Secure Societies; Climate Change and Energy; Mobility; Health		
760639	EnDurCrete	RIA	H2020-NMBP-2017-two-stage	HEIDELBERGCEMENT AG	Industry /SME	DE	Digital and Industry	Nano/micro enabled coatings and fillers for	Environmental friendly and Durable concrete

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								multifunctional concrete	
768681	EPPN	CSA	H2020-NMBP-CSA-2017	LABORATORIO IBERICO INTERNACIONAL DE NANOTECNOLOGIA	RTO	PT	Cross-sectorial	All	Advanced materials and processes
766871	Himalaia	RIA	H2020-FOF-2017	CENTRE TECHNIQUE INDUSTRIEL DE LA PLASTURGIE ET DES COMPOSITES	RTO	FR	Digital and Industry	Surfaces nano-texturation by injection moulding	Nano textured surfaces
662155	InForMed	ECSEL-IA	ECSEL-2014-2	PHILIPS ELECTRONICS NEDERLAND BV	Industry /SME	NL	Health	Bottom-up techniques	Smart medical devices
833088	InfraStress	IA	H2020-SU-INFRA-2018	ENGINEERING - INGEGNERIA INFORMATICA SPA	Industry /SME	IT	Inclusive and Secure Societies	-	Security solutions and technologies for cyber and physical threat detection;
760876	INNPAPER	RIA	H2020-NMBP-PILOTS-2017	FUNDACION CIDETEC	RTO	ES	Food and Natural Resources	Top down techniques: Nanoimprint lithography	
646155	INSPIRED	IA	H2020-NMP-PILOTS-2014	JOANNEUM RESEARCH FORSCHUNGSGESELLSCHAFT MBH	RTO	AT	Digital and Industry	-	Nanomaterials for printed electronics

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720878	INTEGRAL	IA	H2020-NMBP-PILOTS-2016	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES	RTO	FR	Climate Change and Energy; Mobility; Digital and Industry	Bottom-up approach	New generation TE materials
686165	IZADI-NANO2INDUSTRY	IA	H2020-NMP-PILOTS-2015	FUNDACION TECNALIA RESEARCH & INNOVATION	RTO	ES	Climate Change and Energy; Mobility	Injection moulding, casting and coating	
653851	JOSPEL	RIA	H2020-GV-2014	AIMPLAS - ASOCIACION DE INVESTIGACION DE MATERIALES PLASTICOS Y CONEXAS	RTO	ES	Mobility	-	Waste heat recover by TE
777441	KET4CleanProduction	CSA	H2020-INNOSUP-03-07-08-2017	STEINBEIS 2I GMBH	RTO	DE	Digital and Industry	-	-

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id	Project Acronym	Funding scheme	Work Programme/	Coordinator	Coordinator activity type	Coordinator country	Sector	Nanofabrication technical domain	Key targeted solutions
814485	LEE-BED	IA	H2020-NMBP-HUBS-2018	TEKNOLOGISK INSTITUT	RTO	DK	Climate Change and Energy; Digital and Industry	Top-down: Thin films, lithography	Nano-enabled printed electronics
814552	LightMe	IA	H2020-NMBP-HUBS-2018	POLITECNICO DI MILANO	HE	IT	Cross-sectorial; Digital and Industry	Nano-reinforcement of extruded on injected parts. Not nanoparticles development	MMnCs parts
760173	MarketPlace	IA	H2020-NMBP-2017-two-stage	FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.	RTO	DE	Cross-sectorial	-	Materials & products
680263	NanoFab2D	ERC-STG	ERC-2015-STG	ENERGIATUDOMANYI KUTATOKOZPONT	RTO	HU	Cross-sectorial		
695206	NANOFACTORY	ERC-ADG	ERC-2015-AdG	ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE	HE	CH	Cross-sectorial		

id	Project Acronym	Funding scheme	Work Programme/	Coordinator	Coordinator activity type	Coordinator country	Sector	Nanofabrication technical domain	Key targeted solutions
646397	NANOLEAP	RIA	H2020-NMP-PILOTS-2014	UNIVERSIDAD DE CASTILLA - LA MANCHA	HE	ES	Digital and Industry	Top-down: Thermal Plasma synthesis of nanoparticles; spray drying,	
688329	Nanonets2Sense	RIA	H2020-ICT-2015	INSTITUT POLYTECHNIQUE DE GRENOBLE	RTO	FR	Health	-	Biosensosrs for medical applications
760601	NanoTextSurf	IA	H2020-NMBP-PILOTS-2017	TEKNOLOGIAN TUTKIMUSKESKUS VTT OY	RTO	FI	Digital and Industry	Bottom-up: Screen-printing	Bio-based membranes
685559	NEREID	CSA	H2020-ICT-2015	INSTITUT POLYTECHNIQUE DE GRENOBLE	HE	FR	Digital and Industry	Top-down and Bottom-up: ALD, Lithography	Smart products
814581	OASIS	IA	H2020-NMBP-HUBS-2018	FUNDACION TECNALIA RESEARCH & INNOVATION	RTO	ES	Climate Change and Energy; Mobility	Bottom-up: sol-gel, PVD,	
646307	PLATFORM	RIA	H2020-NMP-PILOTS-2014	FUNDACION TECNALIA RESEARCH & INNOVATION	RTO	ES	Mobility	CTN reinforced composites	Buckypapers, CNT pre-preg and CNT doped veils

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id	Project Acronym	Funding scheme	Work Programme/	Coordinator	Coordinator activity type	Coordinator country	Sector	Nanofabrication technical domain	Key targeted solutions
644852	PROTEUS	RIA	H2020-ICT-2014-1	INSTITUT FRANCAIS DES SCIENCES ET TECHNOLOGIES DES TRANSPORTS, DE L'AMENAGEMENT ET DES RESEAUX	RTO	FR	Food and Natural Resources	-	Adaptative micro-fluidicis
872494	RADON	MSCA-RISE	H2020-MSCA-RISE-2019	MBN RESEARCH CENTER GGMBH	RTO	DE	Digital and Industry		
760941	ReSiSTant	IA	H2020-NMBP-PILOTS-2017	BIONIC SURFACE TECHNOLOGIES GMBH	RTO	AT	Mobility	Bottom-up: Chemical and/or physical deposition of nanostructured riblets	
862419	SAbyNA	RIA	H2020-NMBP-TO-IND-2019	ACONDICIONAMIENTO TARRASENSE ASSOCIACION	RTO	ES	Cross-sectorial	All Bottom-up and Top-Dow nanomanufacturing processes	Guidance Platform
814607	SAFE-N-MEDTECH	IA	H2020-NMBP-HUBS-2018	DEPARTAMENTO DE SALUD GOBIERNO VASCO	GO	ES	Health	-	Nanotechnology-based Medical and Diagnosis Devices

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id	Project Acronym	Funding scheme	Work Programme/	Coordinator	Coordinator activity type	Coordinator country	Sector	Nanofabrication technical domain	Key targeted solutions
833017	SecureGas	IA	H2020-SU-INFRA-2018	RINA CONSULTING SPA	Industry /SME	IT	Inclusive and Secure Societies	-	Solutions to mitigate cyber threats
760915	SUN-PILOT	IA	H2020-NMBP-PILOTS-2017	THE PROVOST, FELLOWS, FOUNDATION SCHOLARS & THE OTHER MEMBERS OF BOARD OF THE COLLEGE OF THE HOLY & UNDIVIDED TRINITY OF QUEEN ELIZABETH NEAR DUBLIN	HE	IE	Digital and Industry	nanotexturing	Nanostructured surfaces
814106	TEESMAT	IA	H2020-NMBP-TO-IND-2018	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES	RTO	FR	Climate Change and Energy; Mobility	-	Nanocharacterisation of electrochemical devices
787120	TRESSPASS	IA	H2020-SEC-2016-2017-2	"NATIONAL CENTER FOR SCIENTIFIC RESEARCH ""DEMOKRITOS"""	RTO	EL	Inclusive and Secure Societies	-	Biomimtric technologies, sensing technologies

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id	Project Acronym	Funding scheme	Work Programme/	Coordinator	Coordinator activity type	Coordinator country	Sector	Nanofabrication technical domain	Key targeted solutions
768634	UPTIME	IA	H2020-FOF-2017	BIBA - BREMER INSTITUT FUER PRODUKTION UND LOGISTIK GMBH	RTO	DE	Inclusive and Secure Societies	-	Predictive maintenance technologies
760907	VIMMP	IA	H2020-NMBP-2017-two-stage	FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.	RTO	DE	Cross-sectorial	-	Materials modelling

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Annex B – International projects and initiatives

Table 10. US initiatives considering their type, character, and sector

Initiative	Type	Character	Sector
Cornell NanoScale S&T Facility	Collaborative Facility	Private-Public	Digital & Industry, Health, Climate & Energy
Stanford Nanofabrication Facility	Collaborative Facility	Private-Public	Digital & Industry, Health, Climate & Energy
Columbia Nano Initiative	Collaborative Facility	Private-Public	Digital & Industry, Health, Climate & Energy
Purdue Birck Nanotechnology Center	Collaborative Facility	Private-Public	Digital & Industry, Health, Climate & Energy
UWA-OSU Northwest Nanotechnology Infrastructure	Collaborative Facility	Private-Public	Digital & Industry, Climate & Energy, Health
UMich Lurie Nanofabrication Facility	Collaborative Facility	Private-Public	Digital & Industry, Climate & Energy
UD Nanofabrication Facility	Collaborative Facility	Private-Public	Digital & Industry, Health, Climate & Energy
Minnesota Nano Center	Collaborative Facility	Private-Public	Digital & Industry, Climate & Energy
UHouston Nanofabrication Facility	Collaborative Facility	Private-Public	Digital & Industry, Climate & Energy
Albany Nanotech Complex	Collaborative Facility	Private-Public	Health, Digital & Industry, , Climate & Energy
MIT Nano	Collaborative Facility	Private-Public	Digital & Industry, Health, Climate & Energy
Harvard Center for Nanoscale Systems	Collaborative Facility	Private-Public	Digital & Industry, Health, , Climate & Energy
CIT Kavli Nanoscience Institute	Collaborative Facility	Private-Public	Digital & Industry, Climate & Energy, Health
UPenn MANTH / Singh Center for Nanotechnology	Collaborative Facility	Private-Public	Digital & Industry, Climate & Energy, Health
U Chicago Pritzker Nanofabrication Facility	Collaborative Facility	Private-Public	Digital & Industry, Climate & Energy
Princeton PRISM	Collaborative Facility	Private-Public	Digital & Industry, Climate & Energy
Penn State Nanofabrication Lab	Collaborative Facility	Private-Public	Digital & Industry
CUNY Nanofabrication Facility	Collaborative Facility	Private-Public	Health, Climate & Energy, Digital & Industry
KY MultiScale	Collaborative Facility	Private-Public	Digital & Industry

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UMN Midwest Nano Infrastructure Corridor	Collaborative Facility	Private-Public	Digital & Industry, Health
UMT Nanotechnology Facility	Collaborative Facility	Private-Public	Health, Digital & Industry
UNE Nanoscale Facility	Collaborative Facility	Private-Public	Digital & Industry, Climate & Energy
ASU Nanotechnology Collaborative Infrastructure Southwest	Collaborative Facility	Private-Public	Digital & Industry, Climate & Energy, Health
Research Triangle Nanotechnology Network	Collaborative Facility	Private-Public	Health, Climate & Energy, Digital & Industry
UT Austin Nanoelectronics Research Lab	Collaborative Facility	Private-Public	Digital & Industry
UT Arlington Shimadzu Instutute	Collaborative Facility	Private-Public	Digital & Industry, Climate & Energy, Health
VT NanoEarth	Collaborative Facility	Private-Public	Climate & Energy
Soft and Hybrid Nanotechnology Experimental Resource	Collaborative Facility	Private-Public	Digital & Industry, Food & Resources, Health
GIT Southeastern Nanotechnology Infrastructure Corridor	Collaborative Facility	Private-Public	Health, Digital & Industry
UC San Diego Nanotechnology Infrastructure	Collaborative Facility	Private-Public	Health, Climate & Energy, Digital & Industry
Berkeley Marvell NanoLab	Collaborative Facility	Private-Public	Digital & Industry
Argonne Center for Nanoscale Materials	Collaborative Facility	Public	Digital & Industry, Climate & Energy
Los Alamos Center for Integrated Nanotechnologies	Collaborative Facility	Public	Digital & Industry
ORNL CNMS Nanofabrication Research Laboratory	Collaborative Facility	Public	Digital & Industry
LLNL Center for Micro and Nano Technology	Collaborative Facility	Public	Health, Digital & Industry
BNL Nanofabrication Facility	Collaborative Facility	Public	Digital & Industry, Health, Climate & Energy
Nano-Bio Materials Consortium	Association	Private	Health
NSF National Nanotechnology Coordinated Infrastructure	Association	Public	All Sectors

Table 11. US projects related to nanofabrication activities

Project Acronym	Funding Agency	Award Number	Sponsor	Sector
NHMFLR_18-22	NSF-DMR	1644779	Florida State	Health, Mobility, Climate & Energy
NSF_CHEXS	NSF-DMR	1829070	Cornell	Digital & Industry
NIST_NSF_CHRNS	NSF-DMR	2010792	NIST	Digital & Industry, Health, Climate & Energy
CR_AN_GQL	NSF-OISE	2020174	UMN Twin Cities	Digital & Industry, Secure Societies

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CREST_CNRE_UDC	NSF-HRD	1914751	UDC	Digital & Industry
EFRI_ACQUIRE_CHEQMMSC	NSF-EFMA	1741707	UCLA	Digital & Industry, Secure Societies
EFRI_ACQUIRE_IQCTN	NSF-EFMA	1640986	U of Washington	Digital & Industry, Secure Societies
EFRI_ACQUIRE_SIQPI	NSF-EFMA	1641099	U of Rochester	Digital & Industry
EFRI_ACQUIRE_SQCECSQ	NSF-EFMA	1641064	MIT	Digital & Industry, Secure Societies
EFRI_NL_NRMAWCMS	NSF-EFMA	1641989	UC Irvine	Digital & Industry
EFRI_NL_NRWPDFEEPP	NSF-EFMA	1741694	Cornell	Digital & Industry
MRI_AEBLS_NGNE	NSF-ECCS	2018876	Ohio State	Digital & Industry
MRI_AFIBSEM_RAMEE	NSF-ECCS	2018626	SD SMT	Digital & Industry
NNCI_CNF	NSF-ECCS	2025233, 1542081	Cornell	Digital & Industry, Health, Climate & Energy
NNCI_CNS	NSF-ECCS	2025158, 1541959	Harvard	Digital & Industry, Health, Climate & Energy
NNCI_MANTH	NSF-ECCS	1542153	UPenn	Digital & Industry, Climate & Energy, Health
NNCI_MONT	NSF-ECCS	1542210	Montana State	Health, Digital & Industry
NNCI_NNI	NSF-ECCS	2025489, 1542101	U of Washington	Digital & Industry, Climate & Energy, Health
NNCI_NS	NSF-ECCS	2026822	Stanford	Digital & Industry, Health, Climate & Energy
NNCI_RTNN	NSF-ECCS	2025064, 1542015	NC State	Health, Climate & Energy, Digital & Industry
NNCI_SDNI	NSF-ECCS	1542148	UCSD	Health, Climate & Energy, Digital & Industry
NNCI_SENIC	NSF-ECCS	2025462, 1542174	Georgia Tech RC	Health, Digital & Industry
NNCI_SHYNE	NSF-ECCS	2025633, 1542205	Northwestern	Digital & Industry, Food & Resources, Health
NNCI_SNSF	NSF-ECCS	1542152	Stanford	Digital & Industry, Health, Climate & Energy
NNCI_TNF	NSF-ECCS	1542159	UT Austin	Digital & Industry
NSF_ERC_QESST	NSF-EEC	1041895	Arizona State	Climate & Energy
P2_NCCS_CFM	NSF-IIP	1624572	UNC Charlotte	Digital & Industry, Climate & Energy
PREM_FN	NSF-DMR	1827847	Fort Lewis College	Digital & Industry
RTEHQPQD	NSF-ECCS	1838976	Stanford	Digital & Industry
SNM_POMS	NSF-ECCS	1449397	UC Irvine	Digital & Industry

SSB_DBMHDISMCFRM	NSF-CCF	2027215	Arizona State	Secure Societies

Table 12. List of identified international initiatives outside US

Initiative	Country	Character	Type	Sector
Nanocluster	Singapore	Public	Cluster	Cross-sectorial
Singapore-MIT Alliance	Singapore			
US	Public-private	Alliance	Cross-sectorial	
Nano and Microfabrication				
Core	Singapore	Public	Network	Cross-sectorial
Nanotech Cluster	Japan	Private-Public	Cluster	Cross-sectorial
NBCI-Nanotechnology Business Creation Initiative	Japan	Private	Industrial association	Cross-sectorial

Annex C – List of the collected challenges

CG1 challenges

The following tables provide the feedback collected during the table discussions related to each CG1 challenge.

Challenge 1	**Lack of efficient mass production techniques**
Short description of one action to address such challenge	The challenge is to get the necessary stability in the production process. Currently, there are many different processes, having different features and exploiting different technologies. However, an industrial manufacturing process has to be stable and allow for a continuous production. Process industrial scalability could also be hampered by its yield, reproducibility, and/or scalability.
Expected outcomes	• A several quality criteria are needed to determine process stability • Software tools are needed to facilitate data sharing among nanofabrication manufacturer (*e.g.*, process parameters) to facilitate the assessment of the industrial process scalability. • Artificial intelligence may be included in the process development process to allow for a close feedback loop that could reduce process uncertainties and instabilities. • Collaboration between universities and technology centres should be further promoted to facilitate the communication between the industrial and the academic world about the different process requirements of lab scale production against large scale production. • Act as an intermediary between these 2 worlds and companies to be able to respond to real industrial needs, whilst keeping them informed about the latest developments and their applications.
Scope of future actions	
Timeline	Medium term
Most relevant destination	

Challenge 2	**Metrology, especially for quality control**
Short description of one action to address such challenge	Overcome the cost limitations in the application of metrology techniques by a wider adoption of their technologies. Integration of metrology into the production line. Additional way of facilitation in the adoption of metrology may consist in the setting requirements for new procedures, reducing the costs of the technologies, developing metrology techniques with higher resolutions. • Removing the barriers in accessing highly specialized tools, traditionally used only within the research field • Address the knowledge gap present within the industry and the academia. Facilitate the adoption of up-to-date techniques and methods via trainings dedicated to the dissemination from academia to industry. • Promoting additional investment in the sector of metrology to facilitate the development of cost-effective, advanced characterization techniques

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	• Integration of metrology into the production-line. Inclusion of an automatized analysis (*e.g.*, AI) of data to support metrology and rectify the production on-the-go. • Develop contactless characterization techniques (*e.g.*, electrical, optical) and link them to robust modelling techniques and simulations. This will allow for a synergetic development of the two fields. • Develop and implement robust standard operating procedure standard of practices
Expected outcomes	• Facile Adoption of the developed of shared metrology techniques available to all entities, including the ones that cannot afford large investments (*e.g.*, start-up, SME) • Development of nano-enabled products and materials, reliability produced with a high level of accuracy. • Development of robust standards and standard operating procedures collected within open repositories for standardized procedures, combining both experimental and theoretical approaches. This it is expected to facilitate the attainment of a consensus on harmonized methods and standard operating procedures. • Promotion of FAIR (Findability, Accessibility, Interoperability, and Reusability) data management practices, in term of quality and global data access. Generation of a digital product twin by its characterization data to enable the direct development of a virtual model to support its nano-characterisation, production, and development processes. All this corpus of developments is expected to enable improved and more reliable products, capable to gain a higher level of trust in the consumer
Scope of future actions	Development of a solid link between characterization with robust modelling and simulations, allowing for a complementary support between the data derived real and digital twin
Timeline	-
Most relevant destination	-

Challenge 3	**NEMS and MEMS need still some performance improvements to fully works for mobility sector requirements**
Short description of one action to address such challenge	Overcoming the current barriers in the implementation of NEMS and MEMS goes through several issues that have to be addressed to allow the integration and/or the operation in real conditions. Such issues are: • Poor reproducibility of production and performance • Difficulty to integrate the products • Cost/performance gap, difficulty to compete with “traditional” technologies • Safety • Energy conversion/harvesting and powering
Expected outcomes	• Improvement of energy efficiency

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	• Diversification of power/energy sources in vehicles
Scope of future actions	-
Timeline	-
Most relevant destination	• Pillar 2 – mobility

Challenge 4	**Lack of investments in nanotechnology companies**
Short description of one action to address such challenge	• Investment's framework development for venture capital funds interested in high-tech companies (inclusive of nanofabrication but not exclusive to it). • Development of cascade funding/voucher programs directed to SMEs for financing their research and innovation activities • Publicly funded investments for medium scale manufacturing facilities, driven by the industry (complementary to what it is now the EIC) • Note: in nanofabrication because there is no volume there is no investment.
Expected outcomes	-
Scope of future actions	• Political promotion of investments in nanotechnology. For example, this could be acted by tax reductions for innovative ventures. Development of coordinated actions for the dissemination of effective incentivization schemes for venture capitalists • Impact assessment of the formerly funded actions. If not properly managed, innovation funding may result in unfair competition for SMEs.
Timeline	-
Most relevant destination	-

Challenge 5	**Production of 3D structures (most of the existing techniques are currently focused on 2D surface patterns)**
Short description of one action to address such challenge	Development of reliable and low-cost quality control of 3D manufacturing technologies.
Expected outcomes	-
Scope of future actions	• Current technology in 3D/2.5D manufacturing is limited and generally relying on a bottom-up approach. However, top-down methods are much better scalable. Novel technologies enabling reliable and high-quality control are needed as well novel metrology means to achieve quality control. • The technologies shall be directed at concrete high-impact applications, this could be fostered by further developing the collaboration between academia and industry. This could be supported by the introduction of team exchange programs through the linking with existing programmes (*e.g.*, MSCA RISE).

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Timeline	-
Most relevant destination	-

Challenge 6	**Scaling of volume production, testing, packaging and deployment from research-grade to mass market levels in the Health sector**
Short description of one action to address such challenge	Build frameworks for the digitalization of the information related to the process. This allows for the creation of digital twins, aiding in the modelling of parameters related to volume production, packaging, *etc*. Such approach may be applied for the manufacturing of medical devices such as smart delivery systems and others.
Expected outcomes	Development of a standardised access to FAIR data, available in structured repositories.
Scope of future actions	-
Timeline	• Short term actions (starting in 2022-2023)
Most relevant destination	• Maintaining an Innovative, Sustainable & Globally Competitive Health Industry • Climate Neutral, Circular & Digitised Production • Digital & Emerging Technologies for Competitiveness & Fit for The Green Deal • Unlocking the Full Potential of New Tools, Technologies & Digital Solutions for A Healthy Society

Challenge 7	**Smart delivery systems will be viewed as combination devices and will require the full regulatory approval process before being approved for market**
Short description of one action to address such challenge	• Development of a digitalization roadmap for the industry 5.0 • Development of modelling services for the precise analysis of the process to allow an efficient scale up of the processes from lab to production scale (*e.g.*, thermodynamics and kinetics). • Development of innovative ways to improve production lines via a step-by-step pathway, allowing to introduce improvements to the production lines without causing disruptions because getting astray from the initial production process. • Development of transferrable more automatized technologies.
Expected outcomes	• Developing energy integration strategies • Use of AI strategies and robotics (*e.g.*, problem reduction by automatization, reduction lab costs, cost forecast, and cost reduction). • Simplification of the process, allowing for the reduction of steps, maintenance, and workers. • Improvement of maintenance scheduling by forecasting and scheduling maintenance. This inherently allows for reducing the production line maintenance downtime

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	• Increase in the exchange of good production practices amongst related industries.
Scope of future actions	• Development of continuous production lines • Development of circular strategies for the use on-site of waste materials • Introduction of renewable energy in the production lines, reducing and optimizing the energy load on the electricity network
Timeline	• Short term: Energy integration • Medium term: Robotics • Long term: Simplification of the process (you need a lot of knowledge to tackle it)
Most relevant destination	• Climate Neutral, Circular and Digitised Production • Increased Autonomy in Key Strategic Value Chains for Resilient Industry

Challenge 8	**Reduction of production costs and expensive raw materials**
Short description of one action to address such challenge	• Diversify the raw material suppliers all over the world to reduce the supply shortage risks • Look for effective, but cheaper and abundant, alternative raw materials • Use low value raw materials located in close distance to the end-user (development of processing facilities capable to extract value from European lower grade raw materials) • Increase the usage of secondary raw materials when applicable (close loop, direct recycle of industrial scraps)
Expected outcomes	• Development of a flexible raw materials production chain, protecting EU market from raw materials market fluctuations • Facilitate the sourcing within EU of raw materials • Reduction of the overall sourcing costs for key raw materials
Scope of future actions	• Definition of alternative materials, within EU availabilities, for key technologies (*e.g.*, catalysts) that are currently dependent on outsourcing them • Definition of a distributed recycling ecosystem, able to avoid the production of waste and facilitate the recovery of valuable production scraps
Timeline	• Medium/long term actions
Most relevant destination	• Climate Neutral, Circular and Digitised Production • Increased Autonomy in Key Strategic Value Chains for Resilient Industry

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New challenges proposed by experts at lower TRLs:

Challenge 9	Development of new nanofabricated devices
Short description of one action to address such challenge	• Development of new technologies, able to work with multiple materials, resulting in enhanced properties of the finally produced devices (*e.g.*, fundamental enhancement of mechanical properties, but also combination of properties such as sensing and mechanical performance). • Development of new technology with faster speed of fabrication and resolution, capable to address the classical inverse correlation of higher resolution to higher fabrication speed. (*e.g.*, recent advancements have been achieved with the use of digital mirror arrays). • Integration of different technologies (*e.g.*, in-situ nanofabrication technology integrated into macro-scaled technologies). • On the health-side: o Develop smart micro/nano-objects resulting in the production of new medical devices (*e.g.,* objects that can influence cell activity for regenerative medicine purposes, smart lego-like biological blocks that can be assembled to create a macro-scaled tissue construct), but also broader on medical devices that could be used for diagnostic applications (nanofabrication would be probably better suited than microfabrication). o Develop screening platforms via nano-deposition of materials for the creation of nano/micro topographies used for screening different biological formulations (*e.g.*, biomaterials for regenerative medicine as listed in the former point, to enhance the performance of prosthetic devices, via topographies that can provide better integration with the surrounding tissues or stimulate anti-bacterial properties), to screening of drug/pharmaceutical formulations in a much lower scale, resulting in higher throughput and lower costs.
Expected outcomes	-
Scope of future actions	Develop the theoretical groundings for the development and fabrication of new innovations and devices
Timeline	Long term (2027 - onwards)
Most relevant destination	-

CG2 challenges

The following tables provide the feedback collected during the table discussions related to each CG2 challenge.

Challenge 1	Poor Adoption of safe-by-design approaches for safe production processes

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Short description of one action to address such challenge	• Promote the simplification of current tools, models, and platform so that they could be easily implemented and effectively adopted by SMEs • Delocalisation platform to launch an open platform, or an open cloud including different processes (beyond what it was targeted in other projects: *e.g.*, Guide nano) • Compilation of FAIR (Findability, Accessibility, Interoperability, and Reusability) compliant data, including all related tools to facilitate the adoption of the challenges
Expected outcomes	• Integration of the potential impact of the nanoparticles character on the final solution. • Assessment of the risks at all stages including, also early ones, whilst keeping in mind the easiness of implementation • Definition of different effective safe by design approaches for different use cases with high performances with respect to the state of the art. • Costs must be considered in the processes. The companies should be involved at the early stages and should collaborate in the process. End-user should collaborate in the open platform as validators. • Facilitation and acceleration of the evaluation process via the use of the developed open platform • Promotion of the collaboration between academia and industry
Scope of future actions	• Improvement of the safety considerations at all process stages • Use nano enabled materials along the whole process life cycle • Improvement of safety practices already implemented in the production process • "Waste upcycling as a mean of nanomaterial waste avoidance and source for the industry • Development of a simple platform, fitted for an early adoption in the product development process by the SMEs • Adoption of business and management strategies apt to ensure long-term sustainability of such open platform (*e.g.*by considering management structure with a Single-Entry Point, like in the OITB or DIH approaches)
Timeline	• Medium term actions (2024-2027)
Most relevant destination	• Digital and Emerging Technologies for Competitiveness and Fit for the Green Deal • Others

Challenge 2	**Need of standards for risk assessments, risk management and safety issues of nano fabricated materials**
Short description of one action to address such challenge	Standards are not sufficiently developed within EU and there are not many projects nor general agreement on such topics. Therefore, the following points should be tackled: • As pre-normative work, gather adequate knowledge on risk assessment and management.

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	• Integrating standards derived from several authoritative bodies in the nano-safety cluster (*e.g.*, European Partnership on Metrology, EURAMET). Involvement of standardisation agencies in the development of current and future standards, basing their policy work on current developments of the field. • Standards are not sufficiently developed within EU and there are not many projects nor general agreement on such topics. • Collaboration of different labs in standardisation processes, maybe adopting a strategy of DIH, OITB, including different stakeholders and a Single-Entry Point to manage the standardisation requests.
Expected outcomes	• Harmonization of current approaches and improvement of their robustness to facilitate the development of standards • Standards fitting for the industry, and follow regulations that industry needs to enter the market • Standardised, market-ready safe by design approaches • Harmonisation in the data collection, considering all the actors of ecosystem
Scope of future actions	Two are the topics that may need of further development in the future: exposure containment and reduction and hazards reduction. These may be tackled by the development of updated protocols, standards procedures. Participation to such projects of industrial partners may enable a faster adoption of standards. Regulatory bodies should take part to the consortium.
Timeline	• Medium term actions (2024-2027)
Most relevant destination	-

Challenge 3	**Lack of information on exposure to nanomaterials and health consequences**
Short description of one action to address such challenge	The challenge here is "exposure", but a similar challenge may be posed by "hazards". We can divide these into occupational, consumer, and environmental exposure/hazards. For occupational exposure, most studies do not report data that could then be used in models (*e.g.*, neither health relevant concentration, nor emission rates). We do not able to differentiate between "exposure" dose and "internalized" dose; we do not have models (or raw empirical data on internal dose. There is no spatial distribution models (*e.g.*, multi-box model derived from fluid dynamics captures data in the room, but not in the lung). • Occupational exposures focus on airborne particles and direct exposure (as opposed to indirect exposure) • Occupational exposures focus on manufactured NMs (as opposed to unintentional emissions of NOAA) • More methods (and examples) of how to extrapolate from lab-based studies to real-world scenarios are needed • For consumer exposure, there are very few papers on very few products that address any exposure data (models and data) • Chronic effects do not have models; consumer market can be exposed directly as well as indirectly

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	• Specific to consumer and environmental exposures, we are more likely to be exposed to a "mixture" and not an individual material • For environmental, especially if the material is present in the matrix naturally, there is limited info on differentiating these constituents • For consumer and environmental, challenge exists to measure low dose (when trace materials are below detection limits of analytical instruments or require preparation steps)
Expected outcomes	• Development of data related to non-intentional emissions of NOAA (*e.g.,* additive manufacturing, brakes emission, *etc.*) • Development of process-specific release rates (independent of the controls implemented on site) • Development of release rates for consumer and environmental exposure • Development of models for the extrapolation and evaluation of long-term and chronic exposures • Multi-factorial analyses helping with chronic and mixed exposures • Development of systematic risk analyses approaches • Development of strategies for the metrology, allowing for a harmonized quality assurance (safety into everyday life products) • Development of analytical techniques able to measure low-dose repetitive exposures impact (*e.g.*, sampling, and local monitoring)
Scope of future actions	• Development of accurate *in-silico* modelling • Gather experimental data on mixtures, low-dose, and chronic exposure • Definition of the standard operational procedure with regards to the experimental instrumentation and measurement strategies • Jointly funded projects Integration of computational and experimental workflows to allow the cross-validation of the respective results and the widening of the scope and impact of the collected data
Timeline	• Short term: computational and experimental (separate) smaller short-term projects and larger jointly funded com-exp projects • Medium term: multi-factorial analyses of mixtures (short term) and chronic exposures (and effects). These actions will be devoted to populating the literature with the data needed to carry out exposure assessments
Most relevant destination	• Living and Working in a Health-promoting Environment • Clean Environment and Zero Pollution • Clean and Competitive Solutions for All Transport Modes

Challenge 4	**Lack of information to improve public perception of nano**
Short description of one action to address such challenge	• Information on public perception of nanomaterials has been published recently (name, year) • Knowledge of the wider public on the nano topics is rather low, and the generally the public is averse in deepening the knowledge in topic • Gender differences; product differences • Need to rebrand nanomaterials by acknowledging their widespread use in common consumer applications.

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	• Determining the most and least concerning scenarios to whom people are concerned about (*e.g.*, food, drug, *etc.*) • Determining public knowledgeability of the public in relation to direct and indirect exposure? (*e.g.*, biomagnification chain) • Acknowledging the complexity and depth of the problem by increasing people awareness of the inherent properties and uncertainties • Increasing the communication frequency about risks and absence of such
Expected outcomes	• Include education on nano-based topics, may favouring the dissemination via innovative channels (*e.g.*, internet) or embed it in the general education curriculum as well as university level • Policy enforcement of the inclusion of statements about the nanomaterial nature of ingredients contained within products and of developing a communication program devoted at demystifying the unfounded public concerns about nanomaterials
Scope of future actions	• There have been recent European funded projects dealing with the public perception on nanomaterials (*e.g.*, Go Nano)
Timeline	• Short term: develop new communication channels from scientists/engineers to public; continue to support the existing public perception projects • Medium term: include nano into the education curriculum
Most relevant destination	• Clean Environment and Zero Pollution • Circular Economy and Bioeconomy Sectors • Clean and Competitive Solutions for All Transport Modes

CG3 challenges

The following figures provide the feedback collected during the table discussions related to the four CG3 challenges discussed.

Challenge 1	**Lack of a unified strategy at different levels of education (*i.e.*, high school, university, lifelong training).**
Short description of one action to address such challenge	Encourage partnerships between academia and industry to develop educational standards tailored to industry needs and standards. Create an international coordination group to facilitate discussions between stakeholders. Create a model curriculum for all levels that shows pathways for different levels. Need to develop a taskforce consisting of educators, scientists and engineers and high school teachers to identify what currently exists and how additions can be made to complement the current curriculum. Find out if there are any obstacles to reforming the curriculum. The goal should be the development of a unified curriculum with learning outcomes defined for different ages, grades, and education levels.
Expected outcomes	• Access to educational standards for schools to use as guidelines. • Certified trainings on nanofabrication • Promote sustainable nanofabrication to young generations

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	• Educate the general population to nanotechnologies and the associated risks. • Gather the relevant stakeholders for the definition of a unified strategy to be adopted in at different levels of education Build strategy and benchmarks for pathways • Understand the limitations for each country and/or institution • Open access of a model curriculum for all levels of education • Determine an implementation strategy of the defined educational goal with European and USA Education boards
Scope of future actions	Funds to develop shared standards (like ASTM International Education Standards but at technician level) Similar initiative: SEMIWorks[55] (among the other topics, working in the identification of workforce needs) Support the cost for time/travel of stakeholders Support study exchange programmes to learn how other countries address education Survey studies to define what exists and fill in any gaps. Provide professional development for the educators, especially at the high school level, including opportunities for immersion and tours Seek support of influential individuals, particularly at a national level, able to endorse the development of the educational curriculum.
Timeline	Medium term actions (2024-2027)
Most relevant destination	

Challenge 2	**Difficult to retrain and continually train skilled workers so they remain relevant to their sectors**
Short description of one action to address such challenge	• Development of virtual learning programs for industrial workers. • Visit some research centres for industry in addition with trainings. • Benchmark the best practices and experiences in trainings performed by industrial federations and interest groups • Develop an open-source database on trainings • Offer incentives to endorse various individuals to seek lifelong training, for example, credit or certificate/certifications. Find institutions willing to offer training and recognize those institutions (for example, universities, companies, *etc…*). Encourage National Labs to support training and offer certificates of completion as part of an international project.
Expected outcomes	• Short term programs, with small steps and certificates • Visits program on specific industry topics • Broad trainings for a general audience and specialized training for a targeted audience • Awareness on occupational risks and regulatory implications (both for employees and employers)

[55] https://www.semi.org/en/workforce-development/semi-works

	• List of best practices and experiences gathered by the performed trainings by federations and interest groups • Organized database with an easy sorting system • Assessment of the courses for a continuous content improvement • Trained workers being ready to address new innovations
Scope of future actions	• Create a set of curriculums • Regular review of the content • Benchmark trainings in industrial research centres and academic research centres • Support benchmarking activities • Organize meetings between professional organization • Creation of programmes/actions to support training costs of the staff.
Timeline	• Short term actions (starting in 2022-2023) • Medium term actions (2024-2027)
Most relevant destination	-

Challenge 3	**Lack of entrepreneurship and innovative management skills which is relevant on exploitation of knowledge and technology transfer**
Short description of one action to address such challenge	• "AIRBNB/UBER" for tech transfer ("tech push") focused on linking the demand and supply. Action for the implementation of "liaisons" acting as curators of new services/products (not all scientists want to be entrepreneurs). • Support implementation and operation of programs for nano-enabled industries analogous to the successful "translation advisory board" concept adopted in the HealthtechTAB project
Expected outcomes	• Acceleration of the technology transfer of nano-enabled technologies
Scope of future actions	• Provide a process for evaluation, selection, and support for business ideas, starting from a low level of maturity. • Provide an individualized mentoring program for junior researchers.
Timeline	• While both advisory board and mentorship can be initiated in the short term, their outcomes will be expected in medium-to-long term
Most relevant destination	-

Challenge 4	**Lack of researchers/workers soft skilled to operate effectively in diverse, transdisciplinary teams**
Short description of one action to address such challenge	• Support projects that implement interdisciplinary training during education at different levels (*e.g.*, via lab rotations, internships, and secondments). • Support the creation of a new type of professional capable to act as a translator (same model as proposed in CG3 challenge #1 - HealthtechTAB)

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Expected outcomes	• Fair remuneration distribution; mitigating the risk for all stakeholders; new model for governance ecosystems. • Enhancement of transdisciplinary skills of nanofabrication researchers and workers. • New training opportunities with multidisciplinary approaches, focused on the nanotechnology ecosystem.
Scope of future actions	• Present the benefits and challenges of working in interdisciplinary environments to future workers and researchers. • Provide an incentive to employers to test interdisciplinary, rather than siloed operations • Support to the creation of Private/Public Partnerships, Venture Capital approaches and multi-stakeholders ecosystems to act as intermediaries in the exploitation of knowledge and technology transfer. Training actions in the "translation of nanotechnologies"
Timeline	• Training activities can be initiated in the short term, meaningful engagement with employers is likely to be in the medium to long-term
Most relevant destination	-