NanoFabNet
international Hub for sustainable industrial-scale Nanofabrication

SUSNANOFAB

SUSNANOFAB-NanoFabNet White Paper - EU 2030 Strategic Plan for sustainable Nanofabrication

Joint White Paper

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Acronyms	
AM	Additive Manufacturing
AI	Artificial Intelligence
AR	Augmented Reality
CSA	Coordination and Support Action
EHS	Environmental Health and Safety
IA	Innovation Action
IoT	Internet of Things
KPI	Key Performance Indicators
LCA	Life Cycle Assessment
NEMs	Nano-Electronic-Mechanical Systems
RIA	Research Innovation Action
RTO	Research Technology Organization
SME	Small-Medium Enterprise
SSbD	Safe- and Sustainable-by-Design
TRL	Technology Readiness Level
VR	Virtual Reality

Executive Summary

The purpose of this document is the definition of a Strategic Plan for sustainable Nanofabrication toward 2030, by sharing the achievements and results of two projects that have received funding from the European Union's Horizon 2020 research and innovation programme, i.e.:

- NanoFabNet[1], G.A. No. 886171
- SUSNANOFAB[2], G.A. No. 882506

The two sister projects, in accordance with the EC requirements, established cross-collaborations and synergies between themselves with the aim of outlining a common and aligned vision for a more sustainable future in nanofabrication and setting the tone for future research and development efforts in this area.

Together, they are present this White Paper in support of the following objectives:

- Providing recommendations for policy makers and government agencies to help advance sustainable nanofabrication and promote its adoption on a European scale and beyond;
- Educating stakeholders in the field, such as researchers and industry professionals, regarding the opportunities and the challenges to be faced and tackled to secure a sustainable nanofabrication;
- Improving the awareness of the importance of sustainable nanofabrication in the public opinion;
- Identifying best practices and strategies for achieving a more sustainable nanofabrication industry, including – amongst other aspects - reducing waste and emissions, increasing energy efficiency, and promoting the use of sustainable material; and
- Highlighting the benefits of sustainable nanofabrication, including improved environmental sustainability, increased economic competitiveness, and better health outcomes for workers and communities.

This White Paper serves as a joint roadmap for industry, public authorities, academia, research institutes and the wider expert community by outlining the steps that need to be taken to create a more sustainable future for nanofabrication and thus secure benefits that will be achieved through these efforts.

[1] NanoFabNet Hub: https://nanofabnet.net/

[2] SUSNANOFAB Project: https://susnanofab.eu/

1. Introduction

The production of nanomaterials in general, and the pursuit of so-called 'nanofabrication' (i.e. the design and manufacture of structures with dimensions measured in nanometres (i.e. nanostructures)) in particular, and the wide spectrum of applications of nanotechnology have quickly increased over the past 30 years, yielding a wide field that encompasses most of the scientific domains (chemistry, physics, etc.). Nanofabrication is the essential bridge between the discoveries of the nanosciences and real-world nanotechnology products. It encompasses many processes from the design, manipulation and control of matter at the nanoscale to the manufacture of nanoscale materials, nanostructures, components, devices and complex systems that exploit the unique physical and chemical phenomena that occur at these smaller scales, such as quantum and surface effects (Cooper & Wachter, 2013). The EU expects that the integration of nanoscale building blocks into complex and larger scale systems will become a basis for a new European high-value industry; however, there are challenges, some of them identified and described in this report that need to be addressed. Moreover, the synergy between all type of EU stakeholders (research laboratories, industry, SMEs, etc) is a must in order to address and overcome properly these challenges. [3]

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 (cf. Box 1).[4]

Box 1: Summary of the SUSNANOFAB-NanoFabNet joint Vision for sustainable Nanofabrication in the EU by 2030 (source: SUSNANOFAB report 'Roadmap Draft for an EU wide Strategy on Nanofabrication'[4])

> The SUSNANOFAB - NanoFabNet joint **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.

The SUSNANOFAB and NanoFabNet projects elaborated approaches and roadmaps to tackling these challenges; the results to the projects' analyses and subsequent recommendations are summarise in this White Paper.

[3] NanoFabNet report on *'EU 2030 Strategic Plan for Nanofabrication – a NanoFabNet Roadmap'* (August 2022) (accessed: 30th December 2022).

[4] SUSNANOFAB report *'Roadmap Draft for an EU wide Strategy on Nanofabrication'* (August 2021) (accessed: 30th December 2022).

2. Challenges & Opportunities of sustainable Nanofabrication in the EU

The innovation that the overarching discipline of nanotechnology brought initiated, at first, questions on safety as the community was worried about the impact of the nanomaterials on the health and safety of both, the environment and humans; later on, a more general reflection on 'sustainability' entered the considerations as a more holistic, global point of view (environmental and human health). Consequently, the field of nanoscience and nanotechnology little by little became an even wider domain, involving toxicology and ecotoxicology, risk assessment and management experts each needing specific infrastructures, skills, equipment, characterisation, and metrology. In addition, a number of societal challenges need to be addressed to establish a reliable ecosystem for sustainable nanofabrication in Europe by 2030 (cf. Table 1).

Table 1: Listing of challenges at scientific and societal level that shall be approached to transform them into opportunities for the field of sustainable nanofabrication (source: NanoFabNet report 'EU 2030 Strategic Plan for Nanofabrication – a NanoFabNet Roadmap'[3]).

Challenges of sustainable Nanofabrication at the scientific Level
International collaboration networks: Need for international collaboration, in the same field of expertise as well as interdisciplinary (e.g. datasets from risk assessment would be needed to model LCSA).
Technical developments: Development of new methods for synthesis, characterisation and manufacturing of nanomaterials and nanoproducts; experimental and predictive tools for sustainability assessment (e.g. nanosafety / risk assessment, LCSA, exposure and toxicity) to obtain accurate materials and measurements; development of new methods, tools or alternatives in terms of products or energy to reach more sustainable nanomaterials and nanofabrication processes.
Guidelines and standards: Standardisation on specific nanofabrication vocabulary, methods, processes and equipment needs to be prepared and implemented to increase awareness; support for development of harmonised standard operating procedures (SOPs) for nanoscale metrology techniques and toxicology assessments.
Infrastructure: Development of a comprehensive world-class infrastructure for both industry and academia.
Sustainability assessment (Nanosafety / Risk assessment): Support for the transition from current case-by-case study approach for risk assessment towards novel concepts via grouping/ranking or via developing predictive tools by improving knowledge for nanomaterials, risk assessment and expanding datasets in existing nano-databases.
Sustainability assessment (LCSA): Enhancement of databases for LCSA with nanomaterial specific information to improve and speed up the sustainability evaluation (e.g. constitution of a nanomaterial's life cycle inventory or eco-profile database); research necessary for adapting current / new impact calculation methods to nano-specific environmental effects including characterisation factors for nanomaterial emissions.
Sustainability assessment (Ethics): (Further) development of ethical assessment methodologies, by adapting the existing methods or requirements.
Challenges of sustainable Nanofabrication at the societal Level
International collaboration networks: Need for international and interdisciplinary collaboration, inclusive networking as well as a multi-actors collaboration involving civil society organisations, industry and R&D organisations as equal partners.
***Education & Training*:** Interdisciplinary education across the different scientific fields involved in nanotechnologies including trainings on sustainability, safety, risk assessment, LCSA, best practices and standard operating procedures is needed to ease technology and knowledge transfer.

Ethics & Governance: Promote better integration of ethical and societal considerations under the general RRI framework and extending the public debate on nanofabrication topics.
Information dissemination: Sharing of current / new developments related to environmental impacts, environmental and human health risk assessment, social implications and economic and technical performance to foster responsible governance and public awareness.
Funding: Need to increase investments and funding to address the identified technical and societal challenges in order to achieve an economic safe and sustainable nano-revolution with focus on upstream concepts, fundamental research, as well as new methods.

2.1 Nanofabrication in industrial Applications

The use of nanofabrication processes and products can be divided into six industrial sectors, as illustrated in Figure 1:

- Health
- Digital & Industry
- Climate Change & Energy
- Mobility
- Food & Natural Resources
- Inclusive & Secure Societies

Figure 1: Illustration of the six main industrial sectors, in which nanofabrication products and processes are applied (source: SUSNANOFAB report ['Roadmap Draft for an EU wide Strategy on Nanofabrication'][4]).

In particular, in the ***Health*** sector, 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.

There are several examples, where nanofabrication plays a crucial role in the ***Digital & Industry*** sector: nanostructured semiconductor's fabrication, 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.

Regarding ***Climate Change & Energy***, 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.

In the ***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, to name but a few.

In ***Food & Natural Resources***, some of the main target products are 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.

Finally, examples of target products of high social and industrial impact where nanofabrication could lead to major technological advancements and commercial competitiveness related to ***Inclusive & Secure Societies*** sector are the following: wearable electronics for critical environments, monitoring systems for cyber security and disaster resilience approaches, nano-enabled imaging systems for security applications, smart devices for impair or elderly population.

2.2 The impact of Industry 5.0 Key Technologies applied to Nanofabrication

Industry 5.0, also known as the fifth industrial revolution, is characterised by the integration of advanced technologies, such as artificial intelligence, the Internet of Things (IoT), and advanced robotics into manufacturing processes.

The impact of these technologies on nanofabrication has already been large, enabling significant advancements in a wide range of fields and leading to increased efficiency, precision, and scalability of nanofabrication processes. In particular, the following Industry 5.0 key technologies have to be mentioned:

- ***Artificial Intelligence***: AI has been integrated into the design, simulation, and control of nanofabrication processes, leading to the optimisation of process parameters and improved manufacturing efficiency. AI-powered predictive maintenance and fault detection systems have also been developed to improve the reliability of nanofabrication systems.
- ***Internet of Things (IoT)***: IoT technologies have been used to monitor and control the various stages of nanofabrication processes in real-time, leading to improved process control and increased efficiency. IoT-powered sensors and smart devices have also been used to gather real-time data on nanofabrication processes, enabling real-time process optimisation and continuous improvement.
- ***Robotics***: Robotics technologies have been used to automate various stages of nanofabrication processes, leading to increased efficiency, repeatability, and scalability of nanofabrication processes. Robotics technologies have also been used to develop new techniques for nanofabrication, such as robot-assisted nanoscale assembly and robot-controlled nanoscale fabrication processes.
- ***Additive Manufacturing***: Additive manufacturing technologies, such as 3D printing, have been used to create complex nanoscale structures and devices with precise control over their geometry, composition, and arrangement. This has enabled the creation of new classes of nanoscale materials and devices with tailored properties and functions.
- ***Augmented Reality (AR) and Virtual Reality (VR)***: AR and VR technologies have been used to visualise and simulate nanofabrication processes in real-time, leading to improved process design and optimisation. AR and VR technologies have also been used to train and educate nanofabrication technicians, leading to improved workforce development and training.

These Industry 5.0 technologies have the potential to transform the field of nanofabrication, leading to the development of new materials and devices with unprecedented properties and capabilities.

2.3 Opportunities for and through sustainable, industrial Nanofabrication in the EU

The effects of a global warming crisis, pandemics, ageing population, and natural resources scarcity are continuously impending upon us all. We need new, agile approaches and a clear strategy to address them. Since the dawn of time, technological advancements have been the key to societal progress. In this framework, nanofabrication will have a critical role in addressing current societal challenges by raising fabrication accuracy at a nano scale. By shifting manufacturing perspective to the nanoscale, one challenges the approach presently held on fabrication practices. This results in astounding materials, otherwise unattainable, with a high structural definition.[4]

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.[4] Several cross-sectoral drivers has been identified to support the wider adoption of nanofabrication into industrial manufacturing practices (see Figure 2); these include, but are not limited to:

- **Scientific and Technologic:**
  - Unique attributes and new functionalities with high potential for new applications;
  - Increasing number of patents and publications in the discipline of nanotechnology (as well as its sub-disciplines); and
  - Improvements in performance of both products and processes.
- **Economical, policy, and regulatory:**
  - Increasing demand of components (through cost reduction and performance- and sustainability-improvement, to name but a few); and
  - Improved compliance with safety- and sustainability regulations.
- **Societal and Environmental:**
  - Improved sustainability (through aspects, such as improved resource efficiency, reduced water- and energy-requirements, improved circularity (i.e. traceability and recyclability) (to name but a few); and
  - Improved societal acceptance (through the provision of safer products and processes).

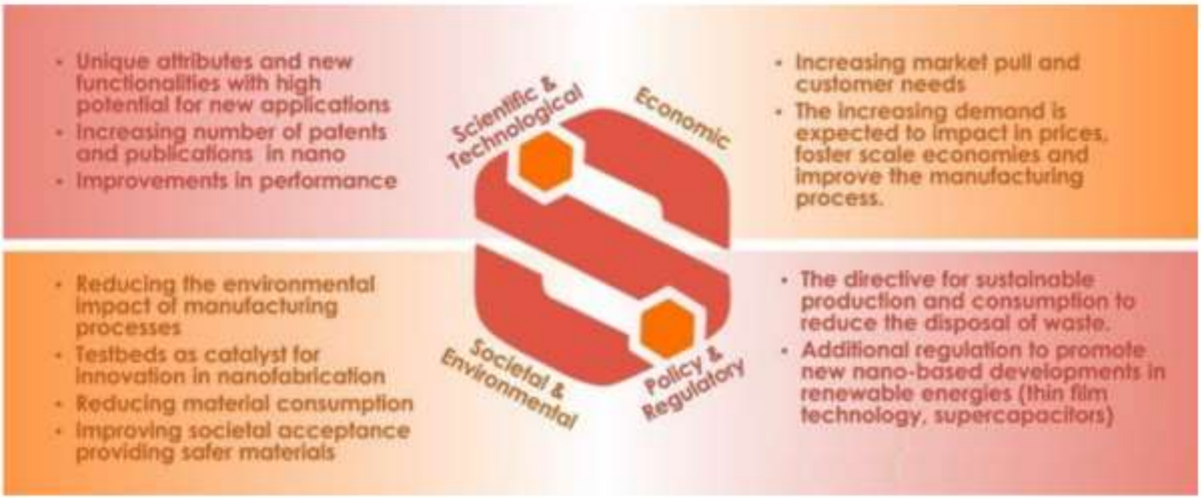

Figure 2: Schematic summary of cross-sectoral drivers for the uptake of nanofabrication by the manufacturing environment (source: SUSNANOFAB report 'Roadmap Draft for an EU wide Strategy on Nanofabrication'[4]).

2.4 Challenges for and through sustainable, industrial Nanofabrication in the EU

To make the best of the opportunities described in the previous section, Europe must address several **technical and non-technical challenges**, which may hinder nanofabrication development and market uptake (see Figure 3).

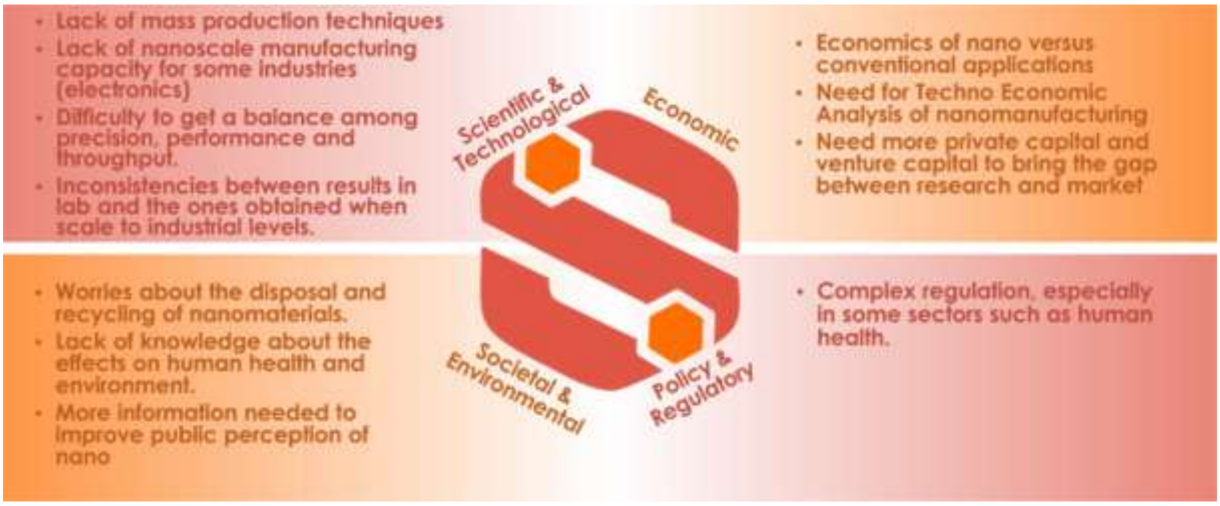

Figure 3: cross-sectorial challenges (source: SUSNANOFAB report 'Roadmap Draft for an EU wide Strategy on Nanofabrication'[4]).

- **Scientific and Technologic:**
    - Lack of mass production techniques;
    - Lack of nanoscale manufacturing capacity for some industries;
    - Difficulty to get a balance among precision, performance, and throughput; and
    - 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;
    - Need more private capital and Venture Capital (VC) to bridge the gap between research and market;
    - Bridge the gap between nanotech research and markets; and
    - Complex regulation.
- **Societal and Environmental**
    - Worries about the disposal and recycling of nanomaterials;
    - Lack of knowledge about the effects on human health and environment; and
    - More information needed to improve public perception of nano.

3. Recommendations

3.1 Necessary Steps & Actions to establish an Ecosystem for sustainable Nanofabrication in Europe

A multitude of different challenge- and sector-specific action plans and roadmaps have been developed by the two projects, in order to provide detailed guidance on how the challenges and opportunities faced could and should be addressed by the different stakeholders to foster the establishment of a flourishing ecosystem of sustainable nanofabrication.[5,6,7,8,9] The challenge-specific recommendations are detailed in the following documents (a detailed listing of the relevant goals and short-, medium- and long-term actions can be found in ANNEX – A1):

- ***Validation, Harmonisation & Standardisation Action Plan***,[6] outlining the **cross-cutting needs** and corresponding **opportunities** regarding validation, harmonisation and standardisation issues, as identified on the basis of the information and views gathered from the main stakeholders. Its actions aim at moving a step forward regarding harmonisation issues whether it be for questions of terminology, taxonomy, data formats, criteria and tools to be deployed in the framework of sustainability assessment or characterisation & testing methods.
- ***Strategy and Implementation Roadmap on Infrastructures, Knowledge and Skills***,[7] which addresses the challenge of selecting the right strategy to implement a newly proposed, harmonised taxonomy cross the community, and create a coherent and understandable picture of the nanofabrication infrastructures map.[10]
- ***Implementation Roadmap for EU-Project Collaboration***,[8] describing the necessary steps for a successful implementation of research and innovation collaborations among EU-funded projects, in order to achieve better alignments, complementarities and synergies, without disclosing sensitive information detrimental to further exploitation of results.
- ***Implementation Roadmap for International Cooperation***,[9] illustrating the way towards an important part of building stakeholder awareness in the field of sustainable nanofabrication and creating a global community of entities within a flourishing ecosystem. It furthermore aims to foster the development of the industry, promote good practices in research and the industry, and facilitate international contacts among the community of the sustainable nanofabrication field.

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[5] NanoFabNet report '*NanoFabNet Strategy & Implementation Roadmap for Sustainable Nanofabrication*' (January 2022) (accessed: 1st August 2022).

[6] NanoFabNet report '*NanoFabNet Validation, Harmonisation & Standardisation Action Plan*'(December 2021) (accessed: 1st August 2022).

[7] NanoFabNet report '*NanoFabNet Strategy & Implementation Roadmap on Infrastructures, Knowledge & Skills Development*' (August 2022) (accessed: 1st August 2022).

[8] NanoFabNet report *'NanoFabNet Implementation Roadmap for EU-Project Collaboration'* (October 2021) (accessed: 1st August 2022).

[9] NanoFabNet report '*NanoFabNet Implementation Roadmap for International Cooperation'* (February 2022) (accessed: 1st August 2022).

[10] NanoFabNet report *'Nanofabrication Competence Map for the Infrastructures, Knowledge and Skills – Proposal for a New Taxonomy'* (August 2021) (accessed: 30th December 2022).

A central aspect of all action plans and roadmaps pertaining to the establishment of an ecosystem for sustainable nanofabrication is the development and integration of the concept of 'sustainability' within any advanced high-tech manufacturing or fabrication process or product, in order to render existing practices and products more sustainable and ensure the integration of the concept into all newly designed ones, such as recommended and prescribed in the EU's new 'Safe and Sustainable by Design' framework (European Commission (2022)). Figure 4 illustrates the recommended four central activities that are regarded essential steps towards this goal. These activities are to be implemented at different timescales and by different bodies; one of the implementing bodies is the NanoFabNet Hub – a newly established international community one-stop-shop for all matters and concerns pertaining to sustainable high-tech innovation and its successful incorporation into the complex, large-scale high-value industries by bringing together governmental and academic laboratories with large industries and SMEs.

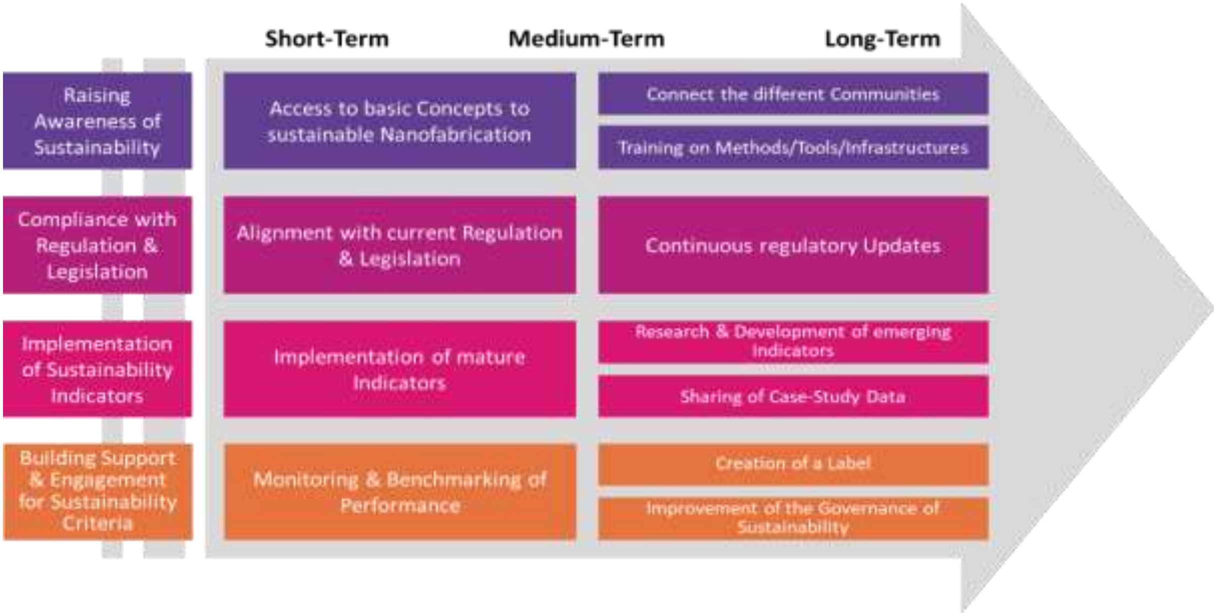

Figure 4: Diagram summarising the actions and recommendations to establish an ecosystem for sustainability in nanofabrication (source: NanoFabNet report 'NanoFabNet Strategy & Implementation Roadmap for Sustainable Nanofabrication'[5]).

3.2 Recommendations to Policy Makers

With particular reference to policy makers, the two sister projects have identified the following recommendations 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 standardisation to ease SME uptake of nanofabrication.

3.3 Implementation of sustainable Nanofabrication through collaborative Research Initiatives

In the context of the project SUSNANOFAB the following tentative action topics have been obtained:

- Action 1: Mass-production techniques for a sustainable nanofabrication: volume scaling and product testing (IA)
- Action 2: Digitalisation as enabler of optimised nanofabrication production practices (RIA)
- Action 3: A nano-regulation framework: streamlined EHS assessment for nanoparticle-based delivery systems, formulations, and additives (CSA)
- Action 4: Multi-level education strategy (upskill, reskill, and novel education curricula) for bridging the technology transfer gap from transdisciplinary nanotechnology innovation to entrepreneurialism management (CSA)
- Action 5: Metrology for reproducible and reliable product quality in high-impact nanotechnology applications (e.g., mobility, health) (RIA)
- Action 6: Reliable NEMS and MEMS for Key Enabling Technologies: future-oriented and energy efficient nano-sensors and systems for high-impact applications (e.g., mobility, health, and environment) (IA)
- Action 7: Establishing a structured Safe- and Sustainable-by-Design (SSbD) approach for the European nanomaterial ecosystem (CSA)
- Action 8: Living materials for multi-function devices (RIA)

3.4 Other Recommendations in Support of sustainable Nanofabrication

A. Environmental, Health, and Safety Priorities

As the industries connected to nanofabrication continue to grow and evolve towards 2050, it is expected that the following priorities will play a crucial role in shaping the future of nanofabrication and environmental, health, and safety (EHS) practices:

- **Improved toxicity and safety assessments**: As the use of nanomaterials becomes more widespread, there is a growing need for better methods to assess the potential toxicity and safety of these materials. This includes developing more sensitive and specific methods for detecting nanomaterials in the environment and in the body, as well as evaluating their potential to cause harm to human health and the environment.
- **Development of sustainable processes**: There is a growing emphasis on the need to develop nanofabrication processes that are sustainable and environmentally friendly. This includes reducing the use of hazardous chemicals and developing alternative processes that use non-toxic materials and minimise waste.
- **Improved waste management practices**: The management of waste generated by nanofabrication processes is a critical aspect of EHS. It is important to ensure that waste is properly handled, stored, and disposed of to minimise the risk of harm to the environment and to human health.

Overall, the priorities for EHS in nanofabrication towards 2050 will be driven by the need to balance the benefits of this technology with the potential risks to human health and the environment.

B. Standardisation & Harmonisation of Data and Techniques

The standardisation and harmonisation of data and techniques in nanofabrication is important for advancing the field, ensuring the safety and reliability of nanofabrication processes, and facilitating the development of new and innovative applications. Moreover, standardisation and harmonisation are specifically important to sustainable nanofabrication, because they secure the following important foundations:

- **Facilitation of inter-laboratory comparisons**: Standardisation and harmonisation of data and techniques enables researchers and practitioners to compare results and findings across different laboratories and institutions, leading to greater consistency and reliability in research outcomes.
- **Enhancement of reproducibility**: By establishing clear and consistent standards for data collection and analysis, researchers can more easily reproduce results, validate findings, and build upon previous work.
- **Support of collaboration and knowledge sharing**: Standardisation and harmonisation of data and techniques facilitates collaboration and knowledge sharing between researchers and practitioners in different fields, leading to new and innovative developments in the field.
- **Improvement of safety and environmental protection**: Standardisation and harmonisation of data and techniques related to the safety and environmental impact of nanofabrication processes can help to ensure the responsible use of nanomaterials and minimise any potential risks to human health and the environment.
- **Support of commercialisation and regulation**: Standardisation and harmonisation of data and techniques can provide a common basis for the development and commercialisation of nanofabrication technologies, as well as for the development of regulations and standards to ensure their safe and responsible use.

C. Process- & Product Innovations throughout the Value-Chains

In order to reduce the environmental impact and negative consequences associated with the production, use, and disposal of nanoscale materials and devices also coming from a nanofabrication process there are some general best practices:

- **Green synthesis**: This involves using environmentally friendly and sustainable methods for the synthesis of nanomaterials, such as the use of water-based solvents, reducing the use of toxic precursors, and minimizing the generation of waste.
- **Sustainable materials**: Choosing materials that are renewable, biodegradable, and non-toxic can reduce the environmental impact of nanofabrication. This includes the use of biodegradable polymers and biominerals, as well as the development of new, sustainable nanomaterials.
- **Energy efficiency**: Optimising the energy consumption of nanofabrication processes can reduce greenhouse gas emissions and save resources. This can be achieved by using energy-efficient equipment, improving process control, and reducing process times.
- **Recycling and reuse**: Encouraging the recycling and reuse of nanoscale materials and devices can reduce waste and conserve resources. This can include the development of nanoscale recycling technologies, as well as the implementation of programs for the collection and disposal of used nanoscale materials.
- **Life cycle assessment**: Conducting Life Cycle Assessments (LCAs) can help to identify and quantify the environmental impacts of nanofabrication processes and products. This can help to prioritise sustainability efforts and inform the development of sustainable nanofabrication practices.

It is furthermore important to remember that sustainability is an ongoing process that requires the continuous improvement of processes and practices.

4. Conclusions

The work jointly carried out by SUSNANOFAB and NANOFABNET contributes to the framing of European nanofabrication sector within an international outlook addressing comprehensively the nanofabrication sector and provide precise insights on the actions of upmost importance to undertake in the close and near future.

The Action Plans described above (and in more detail in *ANNEX – A1* and *ANNEX – A2*) have a cross-cutting impact throughout sectors and challenges of nanofabrication; their itemised goals and recommendations pertain to lay out a roadmap for the achievement of the 2030 vision for sustainable nanofabrication, by providing a blueprint for the work of both public and private bodies to successively build the foundations, and then firmly establish sustainable nanofabrication in Europe and beyond.

The successive implementations of the steps outlined in this White Paper will ultimately help to provide a **stronger European ecosystem for sustainable nanofabrication**. Some of the recommendations listed above must be implemented by policy makers, some by the industrial sectors and individual companies active in the field of nanofabrication, and some by the wider group of stakeholders, who are to benefit from a well-established European ecosystem for sustainable nanofabrication. To create accountability of all groups addressed by the recommendations, and to foster an ongoing exchange between them, while they are pursuing their responsibilities, the NanoFabNet project, supported by the SUSNANOFAB project, has established a permanent community space: the NanoFabNet Hub, which provides a virtual collaboration space for experts of both the sustainability and the high-tech micro- and nanofabrication communities. Building on the NanoFabNet Hub's detailed analysis of the topical overlap between the two communities of sustainability and nanotechnology, as well as the opportunities and challenges outlined in this White Paper, the NanoFabNet Hub will offer the following short term (2022-2025), medium-term (2025-2030) and long-term (2030 onwards) services and activities in six strategic area (see Figure 5):

Figure 5: The Six Implementation Action Plans of the NanoFabNet Hub. (source: NanoFabNet report 'EU 2030 Strategic Plan for Nanofabrication – a NanoFabNet Roadmap'[3]).

- Raising Awareness of Sustainability,
- Compliance with Regulation & Legislation,
- Implementation of Sustainability Indicators,
- Support & Engagement for Sustainability Criteria,
- Coordinating support in Standardisation, Harmonisation & Validation,
- Development and Implementation of harmonising Taxonomies for Nanofabrication Tools & Processes,
- Activation – Engagement – Sustaining of a high visibility of sustainable Nanofabrication in general and the NanoFabNet Hub in particular, and
- Promotion and Support of EU-Project Collaborations and international Cooperations.

5. References

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ANNEX – A1: detailed Listing of Actions & Recommendations to establish an Ecosystem for suatainable Nanofabrication

Recommendations pertaining to Validation, Harmonisation and Standardisation

Table 2: Detailed recommendations of the NanoFabNet Validation, Harmonisation & Standardisation Action Plan and the corresponding Short-to-Mid and Mid-to-Long Term Actions (source: NanoFabNet report '[NanoFabNet Validation, Harmonisation & Standardisation Action Plan](#)'[6]).

AXIS 1: Standardisation
Short-to-Mid Term Action: ***Raise the awareness about standards and reference guidelines.*** A periodic report providing an overview of all the ongoing activities in the standardisation bodies and advisory services will help to identify relevant available guidance/documents and at the same time will help to increase the awareness of relevant standards and reference guidelines. ***Establishment of a document repository on the NanoFabNet website with information on available reference documents and standards.*** This will provide information and guidance (i.e. through a dedicated Focus Group and/or e-learning and webinars) about the standardisation process to stakeholders not necessarily familiar to standardisation activities. The goal is to firmly establish the NanoFabNet Hub as standard project leader in the medium term to facilitate the development of new standards and improve the transfer of R&D&I outcomes in standardisation. ***Mid-to-Long Term Action:*** ***Implementation of a funding programme to support the organisation of inter-laboratories comparisons.*** This would support the development of high-quality standards regarding characterisation and testing methods relevant for the EU priorities. The implemented programme might be similar to the Inter-laboratory Study Program from the American Society for Testing Materia (ASTM).
AXIS 2: Harmonisation
Short-to-Mid Term Action: ***Harmonisation of a nanofabrication taxonomy***. The *NanoFabNet* Hub will disseminate the *NanoFabNet* proposed taxonomy of nanofabrication equipment that with repeated reviews and updates will help to future harmonisation in this field. This work will be done in conjunction with existing initiatives in the field (i.e. with the EuroNanoLab and the NNCI) in order to provide the necessary conditions for better interactions between academic nanofabrication platforms and more efficient collaborations between academic clean-rooms and industry. ***The harmonisation of the description of nanofabrication processes, the promotion of FAIR data management practices and the promotion of the CHADA concept to support material data format harmonisation.*** These issues are central and crucial to facilitate interactions between different nanofabrication equipment or different clean rooms facilities, to accompany the use of simulation tools or also in the framework of risk assessment. The action will involve not only the dissemination of various information (e.g. projects, events) but the inclusion of these principles in internal data management and in connection and coordination with specific communities. ***Harmonisation and validation of characterisation/testing methods (SOPs).*** Information on ongoing Interlaboratory Comparison Studies (ILCs) will be gathered and shared to facilitate the identification of participating expert laboratories and complementary ILCs might be organised as appropriate, with privileged links with VAMAS and EMN (European Metrology Network) Advanced Manufacturing. ***Contribution of moving a step forward regarding sustainability criteria*** by organising discussions within a dedicated focus group with members interested in the harmonisation of sustainability criteria, taking into account the different sustainability areas (Environment, Health & Safety, Life Cycle Sustainability, Ethics &

Governance) and searching for co-development of activities with international initiatives (e.g. INISS-Nano) and standardisation bodies (CEN & ISO).

Identification of the needs regarding harmonisation and standardisation of training materials. A need for training materials reflecting new developments of equipment taxonomy and harmonised process description will be evaluated. The evaluation will be done within EuroNanoLab expert groups. Update of training materials will be then prioritised based on the output of this evaluation. Interactions with others relevant initiatives (e.g. CEN/TC 352 Nanotechnologies, NSC WG-A "Training and Education", ASTM/E56 Nanotechnologies) will be sought to coordinate activities in this field.

To support the setting up of international initiatives, such as the INISS-Nano or the International Network4Sustainable Nanotechnology, in order to propose harmonised approaches to the issues surrounding sustainable nanofabrication.

Mid-to-Long Term Action:

Enable the creation of transparent LCA datasets in collaboration with industry stakeholders to be included in LCA database by harmonising inventory flows characterisation for nanofabrication (e.g. nanoparticles emission).

AXIS 3: Validation

Short-to-Mid Term Actions:

Organisation and coordination of proficiency testing services. Laboratories proposing characterisation activities must be able to demonstrate their ability to master different characterisation methodologies in order to produce reliable and comparable data. This concerns both laboratories housed within nanofabrication facilities, as well as characterisation platforms or measurement service providers, with in the latter cases the potential desire to be accredited according to the ISO/IEC 17025 standard. *NanoFabNet* will propose the organisation of regular proficiency testing according to the requests received by the Hub.

Contribute to existing R&D&I funding schemes in the field of harmonisation & validation in particular by identifying relevant topics for harmonisation & validation in the field of nanofabrication within existing funding schemes (e.g. analytical methods, characterisation methods), creating topic description to address the identified needs in close collaboration with international collaborators (i.e. co-creation with INISS-Nano), incorporating the described topics into funding schemes (e.g. European Partnership on Metrology / EPM) and disseminating information regarding pre-normative calls for proposal from the EPM.

Mid-to-Long Term Action:

The creation and validation of a certification framework for a label on sustainability. This will allow the actors to validate their approach and strategy towards sustainability. This certification framework will be developed with *NanoFabNet* members according to harmonised criteria (including benchmarks and already existing standards) to enable them to validate their commitment to this path and for marketing purpose. The relevance of such an initiative is currently and will remain to be carefully discussed with the concerned stakeholders.

Development of certified trainings. This will allow seamless transfer of users between different nanofabrication facilities. The certificates will serve as a proof that the user has necessary theoretical

background and is capable to independently work with specific technology. Holders of such certificate can obtain faster/easier access to facilities which will be accepting it. A pilot action is planned within EuroNanoLab partners.

Recommendations pertaining to Infrastructures, Knowledge and Skills

Table 3: Detailed recommendations for the implementation of a taxonomy for nanofabrication across all levels of nanofabrication research infrastructures in Europe and worldwide (source: NanoFabNet report 'NanoFabNet Strategy & Implementation Roadmap on Infrastructures, Knowledge & Skills Development'[7]).

Step 1: EuroNanoLab equipment database as a proving ground
Short-to-Mid Term Action: ***Implement NanoFabNet taxonomy into EuroNanoLab equipment database.*** EuroNanoLab partners have agreed on creating a unified equipment database which will harmonise the presentation of thousands of nanofabrication tools, all of them offered by 44 EuroNanoLab associated cleanrooms.   The initial technical realisation allows either manual input of the entries via web-based interface or semi-automated import from a database file.   ***Fill in the data, collect the feedback from multiple review levels and perform curated changes in the form of update and expansion of the terms and definitions.*** During the process of the filling the equipment database, the cleanroom managers and other technical experts will be asked to provide feedback on the taxonomy (i.e. categories, generic names and definitions)mand based on their feedback the taxonomy will be updated.   A special data management group from the EuroNanoLab experts has been established. This group is in charge of discussing and approving the proposed changes and/or new additions.   ***Mid-to-Long Term Action:***   ***Expand the original NanoFabNet taxonomy concept to cover a broader area of nanotechnology research, including nanofabrication processes and analytical equipment***. The ultimate goal of EuroNanoLab is to offer the user a new 'nanofabrication system' able to fabricate more complex micro/nanodevices by integrating the contributions of several specialised cleanrooms to accelerate excellent scientific projects. As a consequence, the original taxonomy proposed by NanoFabNet needs to be substantially expanded to be able to describe the whole nanofabrication system, not only equipment, but also processes, materials and samples/products.
Step 2: Implementing open API and connection to other databases
Short-to-Mid Term Action: ***Start implementing the API for seamless connection of the EuroNanoLab equipment database to other databases.*** An automated data transfer between EuroNanoLab's core database and different databases of individual cleanrooms is an essential action to be done as there are thousands of pieces of equipment in the possession of nanofabrication research infrastructures. Therefore, an open API allowing bi-directional transfer of the data will be implemented and will be publicly available.   ***Building an online tool for managing equipment in small labs/cleanrooms.*** Although big cleanrooms typically run their own laboratory information management systems, some smaller sites do not. Thus, an easy online tool would the latter to connect to equipment database as well as to efficiently manage their equipment.   ***Mid-to-Long Term Action:***   ***Convert the data in the database into linked data format (e.g. RDF) and comply with FAIR standards.*** Providing the data together with context (i.e. linked data) is essential if the data should be used by many different entities and users. The whole concept of the NanoFabNet taxonomy is readily available to be transferred into linked data format as the categories themselves are provided with explanatory definitions which should be ideally directly linked to the data itself. If the data is stored in relational databases, assignment of the description is done via "translational tables" which structure must be known. The transfer to linked data format, with access policies based on FAIR principles will be necessary in order to comply with future standards.

Step 3: Further expansion and sustainability
Mid-to-Long Term Action:
Promotion of the NanoFabNet taxonomy in a broad nanofabrication community. Successful implementation of the taxonomy within EuroNanoLab shall serve as a seed and a best-practise example. The final goal is to disseminate this taxonomy to other partners and collaborators (i.e. other academic infrastructures worldwide, research and technology organisations and also the industrial sector). NanoFabNet will provide a methodology, tools and access to existing databases free of charge, so that interested partners can participate on building and growing the overall system. The successful implementation and growth will help all stakeholders to quickly find solutions for their needs and also easily offer their technological capabilities.
Entering into education and training process. A unified language greatly helps within the education process. Thus, preparing training materials, adapting courses and partnering universities will help to a seamless transfer of users between different nanofabrication facilities.
Stepping into the process of creation of new international standards. Promotion of the new taxonomy within various standardisation initiatives (e.g. CEN/TC 352 Nanotechnologies, NSC WG-A "Training and Education", ASTM/E56 Nanotechnologies) will be sought to ensure the acceptance and adoption of the concept worldwide.

Recommendations pertaining to EU-Project Collaboration

Table 4: Detailed recommendations to reach the goals for a higher and efficient EU-funded project collaboration among projects that deals with sustainable nanofabrication and related issues (source: NanoFabNet report 'NanoFabNet Implementation Roadmap for EU-Project Collaboration'[8]).

GOAL 1 - INCREASE THE PRODUCTIVITY OF EU-FUNDED PROJECTS.
There is currently lots of information (e.g. reports, documents, data) produced by the different EU-funded projects which is available in too many different repositories, databases and/or webpages. This makes it hard to find and digest the needed information for most players. While information is often available, the waste of time to gather all the information to know the ecosystem and activities in a certain field, is still a fact. To increase the overall productivity of the EU-funded projects related to the sustainable nanofabrication field, the *NanoFabNet* will establish a framework that might help the projects to align certain project tasks or activities.
Short-to-Mid Term Actions:
Provide access to easy and organised information about EU-funded projects (e.g. project start and ending dates, partners, main aim, expected outcomes, results), including specific capabilities and/or expertise resulting from the different projects.
Provide access to a centralised place where everyone involved in any EU-project can talk about its project, share ideas and/or update other projects on specific progress achieved within a given EU-funded project.
Provide connection to experts of the sustainable nanofabrication field and related topics.
Provide access to an updated repository of research infrastructures related to the sustainable nanofabrication field.
GOAL 2 - ADEQUATE FINANCING PROGRAMS.
The challenges tagging sustainable nanofabrication issues are complex and interconnect different type of fields. In most cases the full and complete development of the technologies that a given EU-funded project proposes cannot be covered by a single project lifetime. It is of upmost importance that the results coming out from a project can be further be developed in a later stage (e.g. covered by another complementary funding programme or with one designed to further mature an existing proof of concept).
Short-to-Mid Term Action:
To provide easy and fast access to information about existing specific funding programmes and calls related to and interesting for the sustainable nanofabrication field.
Mid-to-Long Term Action:
To include the inputs and points of view from all different stakeholders of the field (i.e. academics, industry, civil society and government) during the design of the forthcoming funding schemes.

GOAL 3 - OPTIMAL COLLABORATION AMONG THE DIFFERENT STAKEHOLDERS
Current EU-funded projects, sometimes are not aware of the results/methods/knowledge developed within other related funded-projects, granted in complementary and/or synergistic calls of the EC.
Short-to-Mid Term Action:
To bring together all the different expert communities and EU-projects, related to sustainable nanofabrication, ***regularly, in order to be able to exchange actions/results/knowledge.***
GOAL 4 - TO ENHANCE THE IMPACT OF THE OUTCOMES OF THE EU-FUNDED PROJECTS
The sustainable nanofabrication R&I community of Europe is excellent on providing scientific methods, results and knowledge. However, it often fails to reach the implementation and translation of those into the industry community. To some extent it also fails in bringing into the light already achieved challenges by science to the civil society.
Short-to-Mid Term Action:
To enhance the awareness of civil society about the results and outcomes of the different EU-funded projects.
Mid-to-Long Term Action:
To transfer the knowledge generated within a project to the right target group,
To contact the relevant industry partners to translate and exploit results of a project.
GOAL 5 - ACCESS TO TOP-QUALITY AND TRAINED PERSONNEL FOR THE DEVELOPMENT OF THE PROJECTS
EU-projects dealing with topics related to sustainable nanotechnology and nanofabrication needs to cover and tackle with a wide range of disciplines (e.g. biology, chemistry, engineering, ethics, physics.) It is of upmost importance to have access to high qualified and trained personnel, not only in one discipline but in some at the same time, in order to achieve the complex goals that this type of projects have to achieve.
Mid-to-Long Term Action:
Access to high quality training materials/webinars in topics relevant for sustainable nanofabrication and ensure well-balanced research teams by providing the opportunity to learn complementary knowledge or disciplines.

Recommendations pertaining to international Collaboration

Table 5: Detailed Recommendations to reach the needed international cooperation within the sustainable nanofabrication field (source: NanoFabNet report 'NanoFabNet Implementation Roadmap for International Cooperation'[9]).

GOAL 1 – To establish of an integrated EU community for sustainable nanofabrication
Mid-to-Long Term Action:
To create a European community in sustainable nanofabrication. The NanoFabNet digital platform will maintain a calendar of upcoming events in the area of nanofabrication and nanotechnology where the community can meet and exchange their views. ***To facilitate the creation of new partnerships and the implementation of international projects.*** The organisation of regular online meetings where researchers and other participants may find potential international partners for their activities will help to increase the number of international projects and partnerships in the field of sustainable nanofabrication.
GOAL 2 – To establish a strong connection with stakeholders based outside the EU to facilitate the building of a global community focused on sustainable nanotechnology and nanofabrication.
Short-to-Mid Term Action:
To connect the communities working in the field of sustainable nanofabrication. Give access to an up-to-date information on sustainable nanofabrication capabilities world-wide and reach out with initiatives, projects will

engage actors willing to participate in the further development and implementation of good practices in the sustainable nanofabrication field. ***To strengthen the EU-US collaboration.*** The organisation of and participation in webinars and/or workshops focused on sharing good practices and state-of-the-art knowledge in the field of sustainable nanofabrication, especially those organised by NNCO and NNCI, for example, within the EU-US Nanomanufacturing CoR will provide access to experts to state-of-the-art information related to the areas of expertise will enable the participants to save time when looking for experts or good practices that could support or help them to solve some of the challenges they face in their day-to-day work. ***Mid-to-Long Term Action:*** ***To create a global community in sustainable nanofabrication.*** The promotion and support of good practices in the collaboration between EU-US nanofabrication initiatives (i.e., the establishment of joint EU-US research programs, the exchange of young scientists, the mobility of researchers, and the twinning of existing projects) will be supported by the NanoFabNet.
GOAL 3 – To develop the capacity of the *NanoFabNet* Hub through the exchange of knowledge at an international level.
Short-to-Mid Term Action: ***To enable the individual stakeholder's access to easy and organised information about the international landscape of sustainable nanofabrication.*** This means, in particular, information on EU-funded projects (e.g. project start and ending dates, partners, the main aim, expected outcomes, results, etc.), including specific capabilities and/or expertise resulting from the different projects. ***To provide access to a centralised platform where everyone can share ideas and know-how on sustainable nanofabrication and nanomanufacturing.*** ***To develop and provide a repository of research infrastructures related to the field of sustainable nanofabrication.***
GOAL 4 – To monitor the mutual understanding of challenges in the field of sustainable nanofabrication and nanotechnology.
Short-to-Mid Term Action: ***To enable the knowledge transfer between the NanoFabNet and key international organisations,*** as well as the dissemination of their achievements from working in the field of sustainable nanofabrication. ***Mid-to-Long Term Action:*** ***To become an international support in setting sustainable nanofabrication standards worldwide***

Recommendations pertaining to the Establishment of Sustainability in Nanofabrication

Table 6: Detailed recommendations of the implementation roadmap for sustainability in nanofabrication and its recommendations for the corresponding Short-to-Mid and Mid-to-Long Term Actions (source: NanoFabNet report 'NanoFabNet Strategy & Implementation Roadmap for Sustainable Nanofabrication'[5]).

Dimension 1: Raising Awareness of Sustainability This dimension deals with the need to raise the awareness of sustainability within the different categories of nanofabrication stakeholders.
Short-to-Mid Term Action: **Creation of a platform providing access to basic concepts, tools and information related to sustainable nanotechnology and nanofabrication.** Currently, there are diverse sources of information related to sustainability in nanotechnology and nanofabrication in Europe and worldwide. Yet these sources are often incomplete, redundant, fragmented, or very specialised. Moreover, they tend to focus mainly on issues related to health and environmental risks. It remains thus necessary to develop and generalise information that is relevant and applicable to the wider field of sustainable nanofabrication. ***Mid-to-Long Term Action:***

Connexion of the different communities. Achieving sustainable nanofabrication is a collective challenge. Various NanoSafety communities are already existing in Europe, diversely structured according to regions and nations. In general, the different communities of stakeholders that make up sustainable nanofabrication suffer of a lack of internal connexions and mutual interactions. It seems necessary: i) to unify these communities around issues specific to nanotechnology and nanofabrication, ii) to develop links between these different communities and iii) to bring together the actors active in the field of sustainability with those active in the field of nanotechnology and nanofabrication.

Development of trainings about sustainability in nanofabrication. Such trainings should be systematically offered or integrated: i) in the framework of nanotechnology and nanofabrication training courses; ii) within R&D structures in nanotechnology and nanofabrication; ii) within companies in the nanotechnology and nanofabrication sectors and iv) as generalised trainings for politicians and decision makers, standardisation and regulatory bodies, interest groups and NGOs, and to civil society.

Dimension 2: Compliance with Regulation & Legislation

Being compliant with regulation and legislation is one of the key steps for industry to manufacture, to place on the market and to use raw materials, technologies, or final products. Being compliant with legal requirements represents an important challenge for many industries that need to be aware of multiple, constantly evolving legal instruments.

Short-to-Mid Term Actions:

Alignment with current regulation and legislation. For an industry to be compliant with the legal requirements is inherent to its activities. Thus, the first thing is to be aware of the different current legislations applicable, and to find the correct information and guidance helping it to proceed. The *NanoFabNet* report *'Annotated List of hard regulatory Requirements for Nanofabrication'*[19] (confidential) identified fifteen pieces of European legislation with specific provisions for nanomaterials, which cover only few sectors (e.g. chemicals, cosmetics, medical or food sector). Fourteen other pieces of European legislation were identified with provisions that implicitly cover nanomaterials (e.g. chemicals, plant protection products, waste or water legislations). Besides the legislation available at the European level, five Member States have taken national initiatives to request more information on nanomaterials from industry. Besides the need for information, determining exactly what are the obligations of each specific activity of industries is another step to be compliant.

Mid-to-Long Term Action:

Continuous regulatory updates. Besides the need to clearly understand and be compliant with the current legislations in place, industries also need to follow the on-going and future initiatives related to new developments and improvements of the legislations, to define the future constraints that could impact their businesses. The case of the chemicals sector is typically one sector that needs to be aware about future legal developments, in that companies need to follow the developments pertaining to substances that could be forbidden on the European market in the next years, and try to develop safer alternatives at any stage of their business. Upstream exchanges between all stakeholders, including regulators, must also be promoted, in concordance with the *'Regulatory Preparedness'* concept, such as described in OECD (2020).

Dimension 3: Implementation of Sustainability Indicators

Besides the mandatory requirements for the compliance with regulation, sustainability indicators can be implemented and monitored by nanotechnology and nanofabrication stakeholders to steer the development and the deployment of nanotechnology and nanofabrication. As highlighted in the *NanoFabNet Report on recommended 'soft/exploratory' Sustainability Indicators for NanoFabNet*[20] (confidential report), a variety of sustainability indicators already exist, covering the three areas of sustainability promoted by *NanoFabNet* (Environment, Health and Safety; Life Cycle Sustainability; Ethics & Governance). Moreover, several related methodologies and tools exist, but with a variable maturity level.

ANNEX – A2: Recommended Action Plan towards sustainable Nanofabrication

The following tables provide more details about the recommended Action Plan (for the sake of brevity in some cases some relevant keywords have been provided only).

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Action 1: Mass-production techniques for a sustainable nanofabrication: volume scaling and product testing (IA)
Expected outcomes: • Increase process reproducibility, yield, energy efficiency, • Scalability for of nanofabrication processes, • Decrease the environmental footprint of production • Mathematical models that describe the mass production process • Contactless characterisation and non-destructive tests • Cost-effective strategies and up-to-date methodologies for metrology adoption • Promote process-related safe-by-design approaches (i.e., engineering controls)There is currently lots of Scope: • Solutions covering processes and operational guidelines, aiming to increase process reproducibility, yield, and scalability in a broad range of nanofabrication production lines. • Solutions able to empower each and all the production chain steps in a holistic way, resulting in a systemic design advancement of the production processes • Exploitation of metrology and contactless characterisation techniques to support product standardisation and just-in-time product rectification.

Action 2: Digitalisation as enabler of optimised nanofabrication production practices (RIA)
Expected outcomes (keywords): • Development of an advanced process-analysis modelling services through predictive techniques for an efficient scale-up to production scale. • Development of cost-effective AI-enabled systems to facilitate just-in-time production rectification and to correlate multiple metrology techniques • Develop a standardised database of digital models • Operational guidelines directed at the standardisation in production processes characterisation. Scope: • Solutions covering processes and operational guidelines, aiming to increase process reproducibility, yield, and scalability • Exploitation of metrology and contactless characterisation techniques, with a particular attention for non-destructive ones, as key enablers of production chain digitalisation and just-in-time AI-enabled production rectification. • Successful experiences in the adoption of metrology and result in FAIR guidelines to allow transparency and transferability of industrial experiences across the nanofabrication processes • Consider the whole product life cycle as well as the safe handling of NMs along the whole production process • Clustering activities with councils (European Materials Modelling Council, EMMC, or European Society for Composite Materials, EECM) and other relevant projects

Action 3: A nano-regulation framework: streamlined EHS assessment for nanoparticle-based delivery systems, formulations and additives (CSA)
Expected outcomes: • Harmonisation of current Environmental Health and Safety (EHS) approaches • Contribute to the development of current and future standards, involving standardisation agencies. • Assessment and modelling of the occupational, user and environmental risks • Support interlaboratory studies focused on promising alternative model for nanotoxicity. • Promote the use of AI/ML in predictive toxicology • Promote the live process of collecting high-quality data that fit in an AI/ML model • Simplification/merging of existing nano-risk assessment methods • Consider synergistic/adverse effects of mixtures of NM in models and health consequences. Scope: • Promotion of a generalised tiered approach, with general guidelines and specific questionnaires addressed separately to both processes and to formulations. • Critical analysis on EHS risks related to nanoparticles manufacture • Collection of all the methods/tools available on nanotechnology risk • Collaboration with relevant authoritative bodies in the nano-safety cluster

Action 4: Multi-level education strategy (upskill, reskill, and novel education curricula) for bridging the technology transfer gap from transdisciplinary nanotechnology innovation to entrepreneurialism (CSA)
Expected outcomes: • Establishment of an international roundtable on educational standards • Creation of an open-access model curriculum to direct education on nanofabrication at all education levels • Definition of an implementation strategy, internationally shared, of the identified educational goals. • Virtual learning courses and exchange programs for the lifelong training of current workers. • Development of interdisciplinary trainings focused on fostering innovation and entrepreneurialism management. • Educate through several channels the wider public about nanoscience Scope: • Development of a unified open-access model curricula. • Development of an organised database of the trainings with a simple and effective filtering and sorting system. • Actions should be able to cross-benchmark current best practices and training experiences and provide feedback to further develop effective learning experiences for lifelong education. • Contribution to develop shared educational standards • Clustering activities with other relevant selected projects for cross-projects co-operation, consultations, and joint activities

Action 5: Metrology for reproducible and reliable product quality in high-impact nanotechnology applications (RIA)
Expected outcomes: • Developing open-source reliable, metrology techniques defining a "zero-defect strategy" • Developing modular interconnectable devices for metrology • Correlation across multiple, readily available, and cost-effective micro- and macro-scale metrology techniques, • Development of metrology techniques directed at quality control for specific applications • Contactless characterisation techniques linked to robust modelling and simulation techniques • AI-ready interfaces, able to provide the characterisation outputs in a standardised format • Development of solutions for handling missing data by means of machine learning methods and/or simulation Scope: • Development of metrology technologies easily integrable in the production line • Definition of criteria/measured quantity that best describes the quality of the production • Clustering activities with other relevant selected projects for cross-projects co-operation, consultations, and joint activities

Action 6: Reliable NEMS and MEMS for key enabling technologies: future-oriented and energy efficient nano-sensors and systems for high-impact applications (IA)
Expected outcomes: • Reducing NEMS and MEMS production costs • Development of low-cost quality-control manufacturing technologies • Improving the cost/quality ratio of reliably produced devices at a high level of precision. • Overcome product integration barriers by meeting operational requirement conditions. • Improve the energy management and efficiency of the produced devices Scope: • Development of NEMS and MEMS by overcoming the current barriers in their implementation of NEMS and MEMS • Development of novel nano-devices and -sensors applicable for several cutting-edge applications especially for health, environment, and mobility sectors, such as cell activity sensing, environmental monitoring sensors, nano-bio interaction, nano-topologies, and nano bio-blocks. • Clustering activities with other relevant selected projects for cross-projects co-operation, consultations, and joint activities

Action 7: Establishing a structured safe and sustainable-by-design (SSBD) approach for the European nanomaterial ecosystem (CSA)

Expected outcomes:

- Adoption of safe and sustainable-by-design and circular approach.
- Improvement of cross-KETs activities to provide better integration of SSBD
- Approach to implement safe- and sustainable-by-design strategies early in the innovation process, a systematic and standardised risk-analysis assessment and of market-ready approaches; fitting the industry needs and following market products regulations.
- Promotion of safe- and sustainable-by-design approaches by the verification/validation of applicability robustness and correctness of tools, models and platform;
- Monitoring of material streams to identify circular approaches for by-products as well as for products.

Scope:

- To develop open standards and standard operating procedures repositories for standardised safe-by-design development procedures. Actions should address safety aspects
- Analysis on the use nano-enabled materials along the whole process life cycle, assessment of the risks at all stages
- Adoption of such standardised procedures.
- Clustering activities with other relevant selected projects for cross-projects co-operation, consultations, and joint activities

Action 8: Living materials for multi-function devices (RIA)

Expected outcomes:

- Development of multi-scale (from nano to micro and macro scale) and multi-function devices integrating complex living materials with a positive impact on regenerative medicine strategies and in vitro models.
- Improve biomimicry of intended biological systems and increased production speed.
- Monitoring or stimulating different biological events and tissues at a time.
- Ready-to-use methods & technologies to be included in this multi-function devices

Scope:

- Development of new bio-fabrication technologies (including nanofabrication) able to work with multiple materials,
- Involvement of technologies such as, for example, volumetric bioprinting, digital light processing, extrusion-based bioprinting, allowing the fabrication of multi-scale objects with fast speed of fabrication and high resolution
- Optimisation of the afore-mentioned technologies through innovative complex multi-scale modelling and digital twin approaches

NanoFabNet
international Hub for sustainable industrial-scale Nanofabrication