



# NanoFabNet

international Hub for sustainable  
industrial-scale Nanofabrication

## EU 2030 Strategic Plan for Nanofabrication – a NanoFabNet Roadmap



**Cover Picture:**

Pixabay

**Rights of Use**

© NanoFabNet, August 2022

All rights reserved. The copyright for this website is owned fully by the NanoFabNet project coordinator AcumenIST SPRL ([www.AcumenIST.com](http://www.AcumenIST.com)).

**Disclaimer**

The information in this document is as provided and no guarantee or warranty is given that the information is fit for any particular purpose.

This document reflects only the authors' view and EASME/the European Commission is not responsible for any use that may be made of the information it contains. The NanoFabNet Project and AcumenIST SPRL shall not be liable for the content of external links. The operators of the linked pages and sites bear sole responsibility for their content.

We strive to ensure that our web content is always up-to-date and is correct and complete in terms of content. Nevertheless, we cannot completely exclude the occurrence of errors. The NanoFabNet Project and AcumenIST SPRL assume no liability for the updates, accuracy of content, or for the completeness of the information provided on this report.



## Table of Contents

|                                                                                                    |    |
|----------------------------------------------------------------------------------------------------|----|
| 1. Executive Summary .....                                                                         | 6  |
| 2. The Landscape of Sustainable Nanofabrication .....                                              | 6  |
| 2.1 Landscape Mapping .....                                                                        | 7  |
| 2.2 The NanoFabNet Concept of Sustainability in Nanotechnology & Nanofabrication .....             | 9  |
| 2.2.1 Development of the Concept .....                                                             | 9  |
| 2.2.2 Content of the NanoFabNet Concept of Sustainability in Nanotechnology & Nanofabrication..... | 9  |
| 3. Challenges & Opportunities in Sustainable Nanotechnology & Nanofabrication.....                 | 10 |
| 2.1 Nanofabrication Competence Map & Proposal for a new Nanofabrication Taxonomy .....             | 13 |
| 2.2 Challenges in Validation, Harmonisation & Standardisation .....                                | 15 |
| 4. Roadmap Implementation and Actions in Support of Sustainable Nanofabrication .....              | 17 |
| 3.1 Strategy & Implementation Roadmap for Sustainable Nanofabrication .....                        | 18 |
| 3.2 Validation, Harmonisation and Standardisation Action Plan .....                                | 22 |
| 3.3 Strategy and Implementation Roadmap on Infrastructures, Knowledge and Skills .....             | 26 |
| 3.4 NanoFabNet Visibility, Communication and Dissemination Strategy .....                          | 28 |
| 3.5 Implementation Roadmap for EU-Project Collaboration.....                                       | 29 |
| 3.6 Implementation Roadmap for International Cooperation.....                                      | 32 |
| 5. The NanoFabNet Hub - Towards a stronger European Ecosystem of Sustainable Nanofabrication       | 33 |
| 6. Conclusions.....                                                                                | 36 |
| Bibliography.....                                                                                  | 37 |

## Table of Tables

|                                                                                                                                                                                                                        |    |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| <b>Table 1:</b> Summary table, illustrating the H2020 funding scheme that are supporting the 316 projects concerned with both nanotechnology and sustainability.....                                                   | 8  |
| <b>Table 2:</b> Challenges at Scientific and Societal Level that shall be approached to transform them into opportunities for the field of sustainable nanofabrication.....                                            | 12 |
| <b>Table 3:</b> Brief overview of the C&O in validation, harmonisation & standardisation of industrial-scale nanofabrication. (C abbreviation stands for Challenge and O abbreviation stands for Opportunity/ies. .... | 15 |
| <b>Table 4:</b> The four dimensions of the NanoFabNet implementation roadmap for sustainability in nanofabrication and its recommendations for the corresponding Short-to-Mid and Mid-to-Long Term Actions.....        | 20 |
| <b>Table 5:</b> The three axes of the NanoFabNet Validation, Harmonisation & Standardisation Action Plan and the corresponding Short-to-Mid and Mid-to-Long Term Actions. ....                                         | 23 |



|                                                                                                                                                                                                                                     |    |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| <b>Table 6:</b> The three-step strategy for implementation of the NanoFabNet taxonomy for nanofabrication across all levels of nanofabrication research infrastructures in Europe and worldwide.....                                | 26 |
| <b>Table 7:</b> The three core phases of activities – Activation, Engagement & Sustain – of the NanoFabNet Visibility, Communication and Dissemination Strategy .....                                                               | 28 |
| <b>Table 8:</b> Actions that will be implemented by the NanoFabNet to reach the goals for a higher and efficient EU-funded project collaboration among projects that deals with sustainable nanofabrication and related issues..... | 30 |
| <b>Table 9:</b> Actions that will be implemented by the NanoFabNet to reach the needed international cooperation within the sustainable nanofabrication field.....                                                                  | 32 |

## Table of Figures

|                                                                                                                                                                                                                                                                                                                                      |    |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| <b>Figure 1:</b> 2D overlay map of the Top 50 keywords occurring in the combined document titles of ‘nanoscience & nanotechnology’ and ‘sustainability’ in 1980 – 2019. [NOTE: The Top 50 keywords are dominated by those used most often in recent years, due to the strong increase of publications in the past 15-20 years] ..... | 7  |
| <b>Figure 2:</b> Annotated 2D network map of the Top 50 keywords occurring in the combined document titles of ‘nanoscience & nanotechnology’ and ‘sustainability’ in 1980 – 2019; the coloured overlays illustrate the journals, from which the keywords predominantly originate.....                                                | 8  |
| <b>Figure 3:</b> The NanoFabNet concept of sustainability in nanotechnology and nanofabrication, based on three pillars .....                                                                                                                                                                                                        | 9  |
| <b>Figure 4:</b> Word cloud of NanoFabNet stakeholder answers attending the 1 <sup>st</sup> NanoFabNet DW (March 2020) to the question “What are the criteria to describe “sustainable nanofabrication?” .....                                                                                                                       | 11 |
| <b>Figure 5:</b> Word cloud of NanoFabNet stakeholder answers attending the 2nd NanoFabNet DW breakout session on ethics (January 2021) to the question "How to improve the development of nanotechnology /nanofabrication and ensure that they can serve a better future?". .....                                                   | 11 |
| <b>Figure 6:</b> Stakeholder’s answers attending the 1 <sup>st</sup> NanoFabNet DW (March 2020) to the consultation about “Ranking from 1 to 5 according to their importance to you/your organisation for sustainable nanofabrication/technology” .....                                                                              | 13 |
| <b>Figure 7:</b> The Six Implementation Action Plans of the NanoFabNet Hub. ....                                                                                                                                                                                                                                                     | 17 |
| <b>Figure 8:</b> Illustration of the different timescales considered for the actions discussed in this strategic plan.....                                                                                                                                                                                                           | 18 |
| <b>Figure 9:</b> Diagram summarising the actions and recommendations of the NanoFabNet strategy and implementation roadmap for sustainability in nanofabrication.....                                                                                                                                                                | 19 |
| <b>Figure 10:</b> Listing of the NanoFabNet actions to address challenges dealing with standardisation, harmonisation and validation topics, in the field of nanofabrication.....                                                                                                                                                    | 23 |

| Acronyms Listed in Document |                                                       |
|-----------------------------|-------------------------------------------------------|
| EC                          | European Commission                                   |
| C&O                         | Challenges & Opportunities                            |
| DW                          | Development Workshop                                  |
| EG                          | Ethics & Governance                                   |
| EHS                         | Environmental, Health and Safety                      |
| FAIR data                   | Findable, Accessible, Interoperable and Reusable Data |
| ILC                         | Interlaboratory Comparison Study                      |
| LCA                         | Life Cycle Assessment                                 |
| LCC                         | Life Cycle Costing                                    |
| LCSA                        | Life Cycle Sustainability Assessment                  |
| R&I                         | Research & Innovation                                 |
| RTO                         | Research & Technology Organisation                    |
| TRL                         | Technology Readiness Level                            |
| WP                          | Work Package                                          |

## 1. Executive Summary

Despite the quick increase over the last three decades of the production and applications of nanotechnology and nanomaterials in almost any field (e.g. medical applications, chemicals, food and consumer care, automotive and aerospace, semiconductor chips, solar cells, batteries, fuel cells) a lot of challenges are still to be met in the field of sustainable nanofabrication.

The complexity and multidisciplinary themes that need to be covered and considered to approach the topic of sustainable nanofabrication necessitate the understanding of a wide range of expertise from toxicology and ecotoxicology to risk assessment of nanomaterials and/or ethics in nanotechnology. Moreover, professionals working in sustainable nanofabrication need adequate infrastructures, skills, equipment, characterisation and metrology that permit them to perform their activities to develop their technologies or develop their products. Thus, the broad and diverse knowledge that needs to be gained to deal with sustainable nanofabrication, the difficulty on getting the right information about a related specific theme, or the availability to access the adequate infrastructure, sometimes hinders or delays the commercialisation of products enabled by nanotechnology or nanofabrication.

The *'EU2030 Strategic Plan for Sustainable Nanofabrication'* aims to present a set of actions and activities to support the field of sustainable nanofabrication in Europe to overcome the challenges that the field currently faces. This strategic plan has been created and worked out by the NanoFabNet, together with its stakeholders, through an active and continued exchange of information. The NanoFabNet involved and engaged nearly 200 core stakeholders. The expert communities consulted, formed by people with a diverse background, both technological and non-technological, interacted actively, together with the NanoFabNet Project partners during the two Development Workshops (DWs) organised by the project in March 2020 and January 2021, respectively. The outcomes of those DWs, together with some surveys sent to the stakeholders tackling specific themes, have provided insights into concerns of the stakeholders about different topics and possible actions to solve these, providing valuable information to take future steps.

The *'EU2030 Strategic Plan for Sustainable Nanofabrication'* follows a comprehensive path, introducing the reader first to a brief overview of the current landscape of sustainable nanofabrication, to pass in a second step to the identification of the different types of challenges that the field faces, together with the description of a set of actions and activities that shall help to overcome them. The document is based on a set of previous reports, released by the NanoFabNet Project during its past two years of Project duration; these can be accessed by the reader to enter into more detail if needed.

The NanoFabNet Project's current effort is devoted to the organisation of the two official launches of the NanoFabNet Hub, in the United States<sup>1</sup> and Europe<sup>2</sup>, in June and July 2022, respectively. The NanoFabNet Hub will be a self-sustained, virtual once-stop-shop for all matters and concerns pertaining to sustainable nanofabrication, that will from August 2022 onwards (i.e. when the NanoFabNet Project will end) follow up on the work of the Project and implement the different actions defined in this *'EU2030 Strategy for Sustainable Nanofabrication'*.

## 2. The Landscape of Sustainable Nanofabrication

The central objective of the NanoFabNet Project is the establishment of a strong international hub for sustainable micro- and nanofabrication that stands for (a) a well-implemented, guided approach to high levels of safety and sustainability, (b) trusted technical reliability and quality, and (c) compliance

---

<sup>1</sup> *NanoFabNet* US Launch Event, held during the TechConnect Conference, on the 14<sup>th</sup> June 2022 (Washington D.C, U.S.).

<sup>2</sup> *NanoFabNet* EU Launch Event, held during the SUSNANOFAB-NanoFabNet joint Networking Event on 'Project Workshop 'Sustainable Nanofabrication'', on the 6<sup>th</sup> of July 2022 (Braga, Portugal).



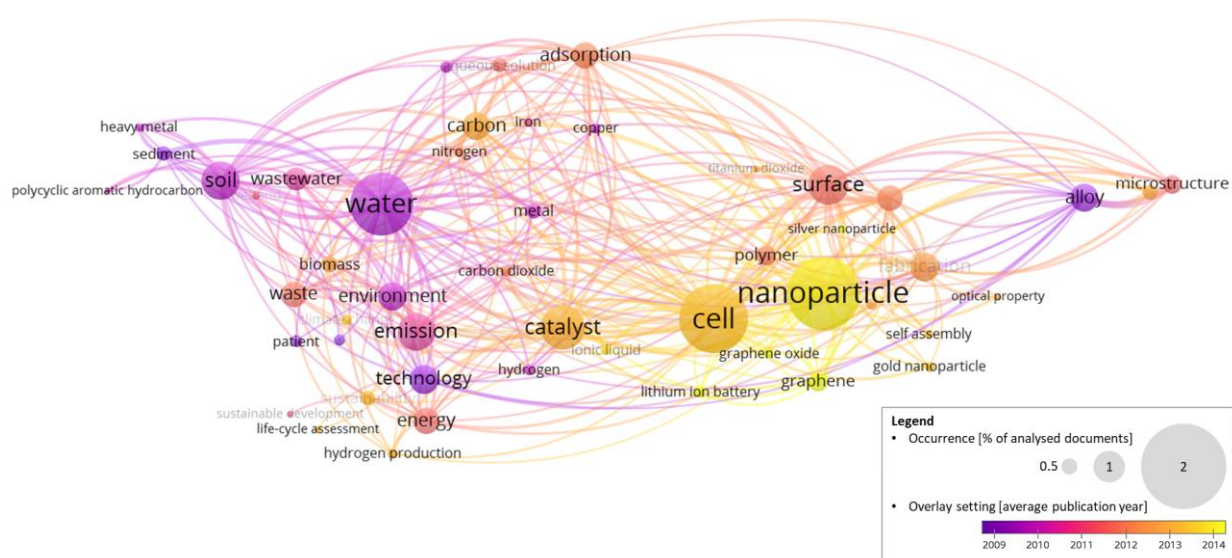
with and drive of harmonisation, standardisation, and regulation requirements, amongst all of its members and along their high-tech fabrication value chains: the **NanoFabNet Hub**. To achieve this, however, the fragmentation of the field through discipline origins and schools-of-thought barriers must first be overcome and the geopolitical clustering of its expert communities counteracted. The identified stakeholders of all involved disciplines and (geopolitical) communities will subsequently receive proactive notification of the formation of a **new bespoke network for ‘sustainable micro- and nanofabrication’**, and invitations to join the NanoFabNet Hub.

## 2.1 Landscape Mapping

The fields of ‘nanofabrication’ (by proxy of the predefined category of ‘nanoscience & nanotechnology’) and ‘sustainability’ were mapped to identify the contributing scientific disciplines, as well as their research foci, the geographical spread of the centres of excellence and their individual experts, as the NanoFabNet’s target stakeholder community. The field boundaries were delineated and overlaps identified through the use of Big Data text-mining tools and (co-)occurrence analyses combined with modern scientometrics on a body of over 1.6 million scientific publications of the past 40 years. The analysis revealed a (forced) habit for nanotechnology and sustainability experts to publish in entirely different journal categories: No single journal was listed in both the category of (a) ‘nanoscience & nanotechnology’ and (b) ‘sustainability’, indicating that there was currently no journal that offered a specific focus on both sustainability and nanotechnology; **experts working in these fields have to choose to publish their results either in designated science- and technology-focussed journals or in those offering topics of ‘sustainability’**, as identified in the journal’s title.

This strict separation of knowledge infrastructures strongly supports the need for a community space, such as the planned NanoFabNet Hub, which encourages the **establishment of new individual connections and collaborative research** in the area of ‘sustainable high-tech innovation’. As a consequence, the overlap between the fields of ‘nanoscience & nanotechnology’ and ‘sustainability’ was determined by overlaying the keyword maps of the two fields.

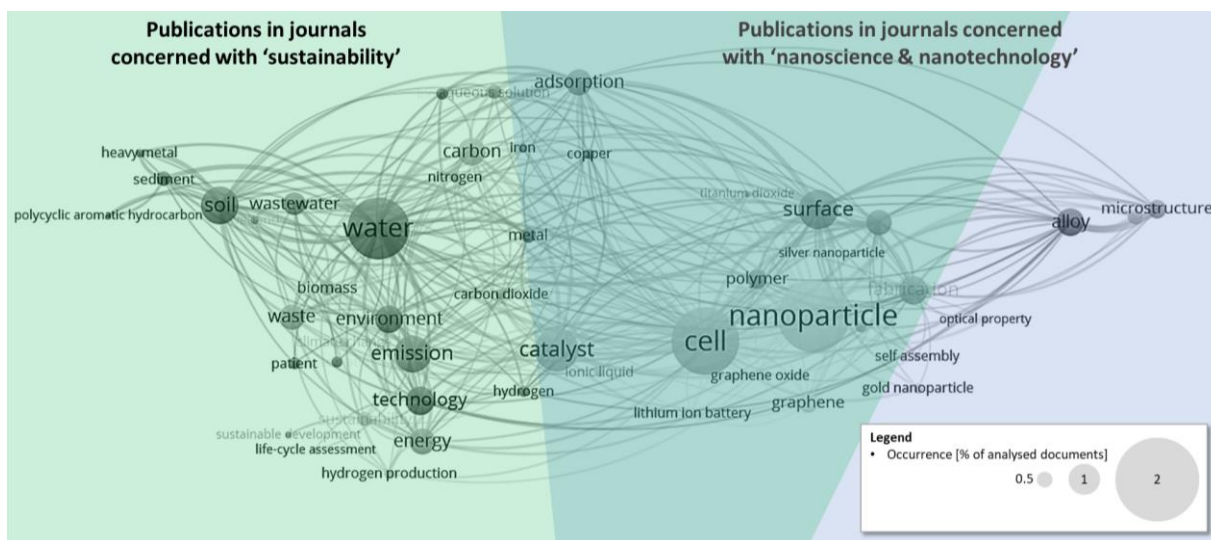
Figure 1 provides a 2D overlay map of Top 50 keywords generated through the combination of all scientific articles published in the fields of (a) ‘nanoscience & nanotechnology’ and (b) ‘sustainability’ between 1980 and 2019 (i.e. 1.653.658 publications). The journal group of origin, as well as the significant overlap in research between the fields of (a) ‘nanoscience & nanotechnology’ and (b) ‘sustainability’ are illustrated in the annotated illustration of Figure 2.



**Figure 1:** 2D overlay map of the Top 50 keywords occurring in the combined document titles of ‘nanoscience & nanotechnology’ and ‘sustainability’ in 1980 – 2019. [NOTE: The Top 50 keywords are dominated by those used most often in recent years, due to the strong increase of publications in the past 15-20 years]

In addition to the keyword mapping in scientific publications, the individual projects of the Horizon 2020 programme were analysed to identify their research activities pertaining to nanofabrication and/or sustainability.

The findings highlight that a large share of projects concerned with both ‘nanotechnology’ and ‘sustainability’ are supported by schemes that foster collaborative research and mobility of researchers, and by schemes reserved for research & innovation (R&I) activities in small- and medium-sized companies (SMEs) (see Table 1); this demonstrates that the NanoFabNet Hub provides a niche opportunity for the establishment of new connections and collaborations in both academia and industry.



**Figure 2:** Annotated 2D network map of the Top 50 keywords occurring in the combined document titles of ‘nanoscience & nanotechnology’ and ‘sustainability’ in 1980 – 2019; the coloured overlays illustrate the journals, from which the keywords predominantly originate.

**Table 1:** Summary table, illustrating the H2020 funding scheme that are supporting the 316 projects concerned with both nanotechnology and sustainability.

| Funding Schemes                                                                                      | Projects | Funding Schemes                                                               | Projects |
|------------------------------------------------------------------------------------------------------|----------|-------------------------------------------------------------------------------|----------|
| Bio-Based Industries (BBI JU)                                                                        | 7        | Leadership in enabling and industrial technologies (LEIT)                     | 2        |
| SME-Instrument (SMEInst)                                                                             | 36       | Low Carbon, Green Deal (LC-GD)                                                | 2        |
| European Research Council (ERC)                                                                      | 53       | Sustainable Food Security (SFS)                                               | 2        |
| Energy efficient Buildings (EeB) PPP                                                                 | 2        | Blue Growth (BG)                                                              | 1        |
| Future & Emerging technologies (FET)                                                                 | 18       | Spreading Excellence and Widening Participation (WIDESPREAD)                  | 8        |
| Marie Skłodowska-Curie Actions (MSCA)                                                                | 115      | FETProactive                                                                  | 6        |
| Nanotechnologies, Advanced Materials, Biotechnology and Advanced Manufacturing and Processing (NMBP) | 40       | EIC Fats-Track to Innovation (FTI) PILOT                                      | 2        |
| Nanotechnologies, Advanced Materials and Production (NMP) PILOTS                                     | 5        | Green Vehicles (GV)                                                           | 1        |
| Twinning Network (TWINN)                                                                             | 1        | Electronic Components and Systems for European Leadership (ECSEL) JU          | 1        |
| Secure, clean and efficient energy (LC-SC3)                                                          | 4        | Innovation in SMEs (INNOSUP)                                                  | 1        |
| European Innovation Council Fast-Track to Innovation (EIC-FTI)                                       | 1        | Factories of the Future (FOF)                                                 | 1        |
| Food & Natural Resources (FNR)                                                                       | 1        | Connecting economic and environmental gains - the circular economy (SC5)      | 1        |
| European research infrastructures (including eInfrastructures) (INFRA)                               | 6        | Governance for the Advancement of Responsible Research and Innovation (GARRI) | 1        |



More results of the mapping study can be found in the original report entitled '[Initial Database & Map of the Fields of Nanofabrication & Technology Sustainability](#)'<sup>3</sup>

## 2.2 The NanoFabNet Concept of Sustainability in Nanotechnology & Nanofabrication

### 2.2.1 Development of the Concept

The NanoFabNet concept of sustainability in nanotechnology and nanofabrication, as well as the associated NanoFabNet concept of sustainable nanofabrication, have been built and defined during the NanoFabNet Projects'<sup>4</sup> lifetime, not only by the engagement of the partners of the project and their work along the different activities of the project, but also by the feedback of the stakeholders of the NanoFabNet Hub. During the NanoFabNet Projects' lifetime, two Development Workshops (DWs) were conducted in March 2020 and January 2021, respectively. During those DWs preliminary work of the NanoFabNet Project was presented to the stakeholders. Their feedback was collected and included in the diverse working rounds that have taken place in later stages of the project. During the 1<sup>st</sup> DW, an initial sketch of the NanoFabNet concept of sustainable nanofabrication was presented and discussed, and during the 2<sup>nd</sup> DW the refined version of the concept was illustrated and discussed.

### 2.2.2 Content of the NanoFabNet Concept of Sustainability in Nanotechnology & Nanofabrication

There is to-date no universal definition of the words 'sustainable' or 'sustainability'. In 'Our Common Future', the report of the Brundtland Commission (WCED, 1987), sustainable development was defined as a "development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Thus, sustainability implies a certain long-term balance between human civilisation and the biosphere capacity. Moreover, sustainability concerns certainly the process of technology development, since development of novel technology



**Figure 3:** The NanoFabNet concept of sustainability in nanotechnology and nanofabrication, based on three pillars

plays an important role both in creating the environmental and social problems of our times, but at the same time in solving those same problems. It is not sufficient to flag a design, a product or a technology as 'sustainable' by referring to simple categories such as 'pollution free', 'creating local employment', 'being renewable', etc. (Mulder et al, 2011), since technology and society co-evolve, and the possible impacts of technology must be addressed comprehensively.

Looking at existing definitions and creating a common understanding of the meaning of the terms 'sustainability' and 'nanofabrication' was one of the first challenges addressed by the NanoFabNet Project. Even if a lot of work has been done in the last several years to clearly describe and define terms associated with 'nanotechnologies' (e.g. in ISO/TS 27687:2008), there is still a lack of harmonisation across the different scientific disciplines, application sectors and usage by international organisation and committees such as the ISO or ACC. For the term 'sustainability' the picture is even

<sup>3</sup> NanoFabNet report on the '[Initial Database & Map of the Fields of Nanofabrication & Technology Sustainability](#)' (May 2022) (accessed: 31<sup>st</sup> July 2022).

<sup>4</sup> NanoFabNet Project. (GA No. 886171). Website: [www.nanofabnet.net](http://www.nanofabnet.net) (accessed: 31<sup>st</sup> July 2022).

more blurry as there exists to date no universal definition and a multitude of concepts such as life cycle sustainability assessment (LCSA), ethics, circular economy and green chemistry are associated with the topic of sustainability.

Within the NanoFabNet Project, the topic of sustainability in nanotechnology and nanofabrication is thus considered a global concept (Figure 3), addressing issues related to the three following working areas:

- (a) Environmental, Health and Safety (EHS)
- (b) Life Cycle Sustainability (LCS)
- (c) Ethics and Governance (EG)

In the context of the many uncertainties related to the diverse risks associated, the goal of the Environmental, Health and Safety (EHS) area is to ensure the safety for human health and for the environment of the impact of nanotechnology, nanomaterials and nanofabrication. The Life Cycle Sustainability (LCS) area appreciates the potential impact of nanotechnology and nanofabrication throughout their entire life cycle on the environmental, the economic and the social level.

The goal of the third working area, Ethics and Governance (EG) is to address the array of ethical and societal issues raised by nanotechnology and nanofabrication in the diversity of their applications, helping to build public acceptability, public trust and public engagement which are considered as key elements for the development of those in the future.

The reader is encouraged to consult the NanoFabNet [‘Report on the Concepts & Disciplines of Sustainability in Nanotechnology & Nanofabrication’](#)<sup>5</sup> to gain a list-based delineation of the different disciplines involved in these three working areas, and a presentation of their constituting terms and concepts.

### **3. Challenges & Opportunities in Sustainable Nanotechnology & Nanofabrication**

The production of nanomaterials 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.). The innovation that it 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.

Consultations of stakeholders from the communities of nanotechnology / nanofabrication and sustainability, via the two interactive DWs and online surveys, allowed the NanoFabNet Project partners to create a clearer picture to the common understanding of these topics within the communities and to identify existing opportunities and challenges to be addressed.

Figure 4 and Figure 5 illustrate how stakeholders answered the questions (a) *‘What are the criteria to describe sustainable nanofabrication?’* and (b) *‘How to improve the development of nanotech/nanofabrication and ensure that they can serve a better future?’*, respectively.

---

<sup>5</sup> NanoFabNet report on the [‘Concepts & Disciplines of Sustainability in Nanotechnology & Nanofabrication’](#) (October 2020) (accessed: 25<sup>th</sup> February 2022).



**Figure 4:** Word cloud of NanoFabNet stakeholder answers attending the 1<sup>st</sup> NanoFabNet DW (March 2020) to the question “What are the criteria to describe “sustainable nanofabrication?”



**Figure 5:** Word cloud of NanoFabNet stakeholder answers attending the 2nd NanoFabNet DW breakout session on ethics (January 2021) to the question "How to improve the development of nanotechnology /nanofabrication and ensure that they can serve a better future?".

The internal research performed by the NanoFabNet Project team, based on a broad bibliographic analysis of the current state-of-the-art, the understanding of existing definitions of the field of nanofabrication and sustainability, together with the contributions of the NanoFabNet stakeholders gathered during the two DWs and several on-line surveys, permitted to identify several challenges and opportunities (C&O) in the sustainable nanofabrication field. These C&O are summed up comprehensively in the NanoFabNet report '[\*Common Challenges & Opportunities in Sustainable\*](#)



[Nanofabrication](#)<sup>6</sup>. The authors of the report identified that there are still a lot of issues that need to be addressed and solved in various domains (see Table 2) and that these issues can be classified into two main categories:

- the implementation of new developments **at the scientific level** whether it be in processes, infrastructure platforms and standardisation (first of all on the taxonomy and in nano-specific characterisation and material/processes), and
- the implementation of a broader approach **at the society level**, including needs on skills/education for this new field, involvement of decision-makers to increase funding in the sustainable nanofabrication and an international collaboration network to take up these challenges (e.g. dissemination of information, results, standards, case studies).

**Table 2:** Challenges at Scientific and Societal Level that shall be approached to transform them into opportunities for the field of sustainable nanofabrication

| Challenges at Scientific Level                                                                                                                                                                                                                                                                                                                                                                                                                                                         |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>International collaboration networks:</b> 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).                                                                                                                                                                                                                                                                     |
| <b>Technical developments:</b> 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. |
| <b>Guidelines and standards:</b> Standardization 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.                                                                                                                                                        |
| <b>Infrastructure:</b> Development of a comprehensive world-class infrastructure for both industry and academia.                                                                                                                                                                                                                                                                                                                                                                       |
| <b>Sustainability assessment (Nanosafety / Risk assessment):</b> 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.                                                                                                                                   |
| <b>Sustainability assessment (LCSA):</b> 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.                                           |
| <b>Sustainability assessment (Ethics):</b> (Further) development of ethical assessment methodologies, by adapting the existing methods or requirements.                                                                                                                                                                                                                                                                                                                                |
| Challenges at Societal Level                                                                                                                                                                                                                                                                                                                                                                                                                                                           |
| <b>International collaboration networks:</b> 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.                                                                                                                                                                                                                         |

<sup>6</sup> NanoFabNet report on the '[Common Challenges & Opportunities in Sustainable Nanofabrication](#)' (August 2021) (accessed: 20<sup>th</sup> March 2022).

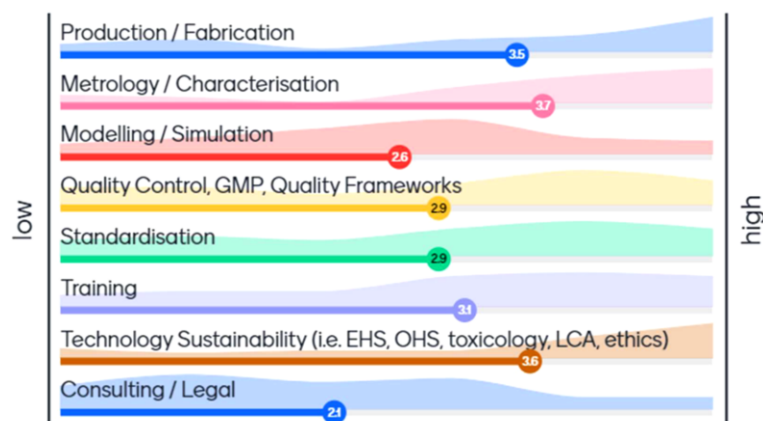
**Education & Training:** Interdisciplinary education across the different scientific fields involved in nanotechnologies including trainings on sustainability, safety, risk assessment, LCSA, best practices and standard operating procedures is needed to ease technology and knowledge transfer.

**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.

During the 1<sup>st</sup> DW, the NanoFabNet stakeholders also ranked categories according to importance to sustainable nanofabrication. The ones considered to be of high importance were metrology/characterisation followed by the production processes, sustainability, training and standardisation (Figure 6).



*Figure 6: Stakeholder's answers attending the 1<sup>st</sup> NanoFabNet DW (March 2020) to the consultation about "Ranking from 1 to 5 according to their importance to you/your organisation for sustainable nanofabrication/technology".*

Therefore, in the following subsections of this chapter about the C&O of the sustainable nanotechnology and nanofabrication field, describe a specific analysis of the landscape of the cleanroom nanofabrication facilities in Europe and the United States ([Section 2.1](#)

*Nanofabrication Competence Map & Proposal for a new Nanofabrication Taxonomy*) and provide deeper and more detailed information about which are the C&O in Validation, Harmonisation & Standardisation of industrial-scale nanofabrication ([Section 2.2](#) *Challenges in Validation, Harmonisation & Standardisation are described*).

## 2.1 Nanofabrication Competence Map & Proposal for a new Nanofabrication Taxonomy

Nanofabrication knowledge, initially developed by information and communication technology related disciplines, has spread to many other fields like, life sciences, astronomy, space exploration, environmental monitoring, etc. Nanofabrication can be done via two main routes:

- a *top-down approach* which uses lithography to define structure dimensions: this requires complex equipment for lithography, etching, deposition and other processes co-located together with characterisation in cleanrooms, and
- a *bottom-up approach* which uses chemical synthesis to connect individual molecules into larger, functional building blocks: this does not require such complex and expensive equipment and it can be performed in standard chemical laboratories.



To build the nanofabrication competence map, the NanoFabNet focused its work on a) an initial in-depth mapping and listing of the different and most important cleanroom nanofabrication facilities located across Europe and the United States. This soon made visible that the current situation in presenting the offer of nanofabrication research infrastructures is very inconsistent and confusing, and does not help to yield collaborative and innovation activities; thus, a second action has been set up within the NanoFabNet which is b) the proposal of a new nanofabrication taxonomy:

**(a) Listing of the cleanroom nanofabrication facilities:** they represent the core of the nanofabrication research infrastructures and provides thus provide the landscape of the existing nanofabrication competences. These nanofabrication facilities can be classified into three categories:

- *Academic research centres:* These centres are multidisciplinary and provide open access to their equipment and knowledge, especially to academic researchers. The users might operate the equipment by themselves. Funding of these type of facilities is mainly from public resources with only a small part (typically up to 20%) financed from the industry. Research conducted at these centres is generally focused on low technological readiness level (TRLs) (i.e. TRL 1 to 3).
- *Research and technology organisations (RTOs):* these types of facilities are specialised (e.g. on semiconductors, photonics). Access to them and to their knowledge (i.e. intellectual property) is much more regulated and the majority of the funding (up to 80%) comes from the industry. The research conducted in these types of facilities may be of an applied research nature, of higher TRL (i.e. TRL 4 to 6) like building pilot production lines where a product is tested before entering into full production line or even where a new factory is built.
- *Nanofabrication foundries (fabrication plants):* These represent the final step in the research & innovation (R&I) value chain where the full system development, integration and testing is done, and mass production of the product starts. Typically, these facilities are 100% privately funded and intellectual property is heavily protected.

The NanoFabNet identified 66 nanofabrication facilities located in 15 different European countries and in the United States. The facilities selected are organised under EuroNanoLab<sup>7</sup> (in the case of Europe), and under the NNCI<sup>8</sup> (in the United States) networks. Both organisations are important NanoFabNet partners and will play an important role in the implementation of the taxonomy that has been created. For more information including a description and location of each facility the reader is encouraged to consult the NanoFabNet report '[Nanofabrication Competence Map for the Infrastructures, Knowledge and Skills – Proposal for a New Taxonomy](#)'.<sup>9</sup>

**(b) Creation of a new nanofabrication taxonomy of available tools and instruments** (including only those analytical instruments that offer some nanofabrication capabilities (e.g. lithographic scanning probe microscope or FIB/SEM systems). To start this activity the ISO standard ISO/TS 800004-8:2020 was used. It describes nanomanufacturing processes<sup>10</sup>. To expand and better cover all the needs, the NNCI terminology<sup>11</sup> has also been used and consulted. This terminology has already been adopted already by 15 US nanofabrication centres. The final competence map consists of 5 categories, 21 subcategories and 55 generic instrument names. It covers about 80-90% of nanofabrication tools available in studied

<sup>7</sup> Website: <http://euronanolab.eu/> (accessed: 31<sup>st</sup> July 2022).

<sup>8</sup> Website: <https://nnci.net/> (accessed: 31<sup>st</sup> July 2022).

<sup>9</sup> NanoFabNet report on the '[Nanofabrication Competence Map for the Infrastructures, Knowledge and Skills – Proposal for a new Taxonomy](#)' (August 2021) (accessed: 5<sup>th</sup> March 2022).

<sup>10</sup> International Organisation for Standardisation, Nanotechnologies – Vocabulary – Part 8 – Nanomanufacturing Processes, 2020 (website: <https://www.iso.org/standard/74666.html> (accessed: 31<sup>st</sup> July 2021)).

<sup>11</sup> US NNCI Tool Search (website: <https://nnci.net/> (accessed: 31<sup>st</sup> July 2021)).



nanofabrication facilities, and the map is constructed in a way that other categories can be easily added if needed.

## 2.2 Challenges in Validation, Harmonisation & Standardisation

As much as nanoscience research can free itself from certain constraints linked to validation and harmonisation issues, the deployment of real scalable sustainable nanofabrication cannot do without them. Moreover, harmonisation and validation are central to building the conditions of trust among economic actors, but also between economic actors and public authorities/society. Whatever the issue under consideration, it is necessary:

- i) first to validate, via recognised references and on the basis of accepted criteria, the tools or methods that can be developed or adapted with a view to harmonisation,
- ii) second, to make them known in order to increase their use, and
- iii) finally, to offer a framework that enables the actors concerned to demonstrate and validate their mastery of these tools and methods.

The development of increasingly complex nano-enabled systems that integrate various nanoscale components, developed by a network of complementary players, makes the interoperability between the different components and also between nanofabrication equipment and platforms, critical. This complexity can only be addressed by harmonising and validating several key points, in order to ultimately provide trust between economic actors in the value chains. The different C&O can be organised depending on two different points of view: from a technical or a sustainability perspective. For a detailed description the reader is encouraged to consult the NanoFabNet report on the '[Challenges & Opportunities in Validating, Harmonising & Standardising industrial-scale Nanofabrication](#)'<sup>12</sup>, published in July 2021; a summary of the C&O is presented in Table 3.

**Table 3:** Brief overview of the C&O in validation, harmonisation & standardisation of industrial-scale nanofabrication. (C abbreviation stands for Challenge and O abbreviation stands for Opportunity/ies.

| C&O from a technical point of view                                                                                                                                                                                                                                                                                                                              |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Implementation of a common language in the different cleanrooms:</b> This would permit the optimal interaction and interoperability levels needed between nanofabrication platforms and equipment to reach the development of complex systems. Moreover, it would facilitate the interactions between academic cleanrooms and industry.                      |
| <b>Development of a taxonomy of tools and their related processes:</b> This would support the building of a database to map the equipment and processes available and make it more visible to users.                                                                                                                                                            |
| <b>Development of harmonised process descriptions and harmonisation of data exchange formats and associated harmonised metadata:</b> This would offer to the users more flexibility and reactivity according to the load plans of the cleanrooms and also would ensure an equivalent level of performance of the systems developed in the different cleanrooms. |
| <b>Raising awareness in the various communities</b>                                                                                                                                                                                                                                                                                                             |
| <b>Creation of digital databases of materials data and extracting properties from them:</b> This would allow one to validate and feed simulation tools, critical and highly significant for industry, due to the ever-increasing complexity of materials and systems in development.                                                                            |

<sup>12</sup> NanoFabNet report on the '[Common Challenges & Opportunities in Sustainable Nanofabrication](#)' (August 2021) (accessed: 20<sup>th</sup> March 2022).



**Validation of metrological performances of new and rapid characterisation techniques and while harmonised measurement procedures should be sought to accelerate innovation in European industries**

**Pre-standardisation activities including the organisation of inter-laboratory comparisons exercises in a coordinated way and on topics identified as a priority with all relevant stakeholders:** This action shall be done through the involvement of the Materials community (i.e. through EMCC and EMMC), National Metrology Institutes, Joint Research Centre and standardisation bodies (in particular VAMAS).

**Validation services such as easier access to fully characterised reference materials and organisation of proficiency testing programme to help laboratories demonstrate their mastery of specific SOPs and support accreditation according to ISO/IEC 17025 standards.** This action can be based on the creation of databases of new materials, properties, reference materials, and calibration standards.

## **C&O from a sustainability point of view**

**Harmonisation and validation of the tools and methodologies needed for the safe generation and handling of nanostructures:** Taking into account and considering nano-specific regulatory requirements, the impact of the life cycle of nanosystems and the ethical concerns would allow the establishment of the trust necessary for the acceptability of these new technologies and processes. Harmonisation of the way in which these different subjects are approached must be sought at the international level, in particular through the establishment of collaborations and exchanges of points of view.

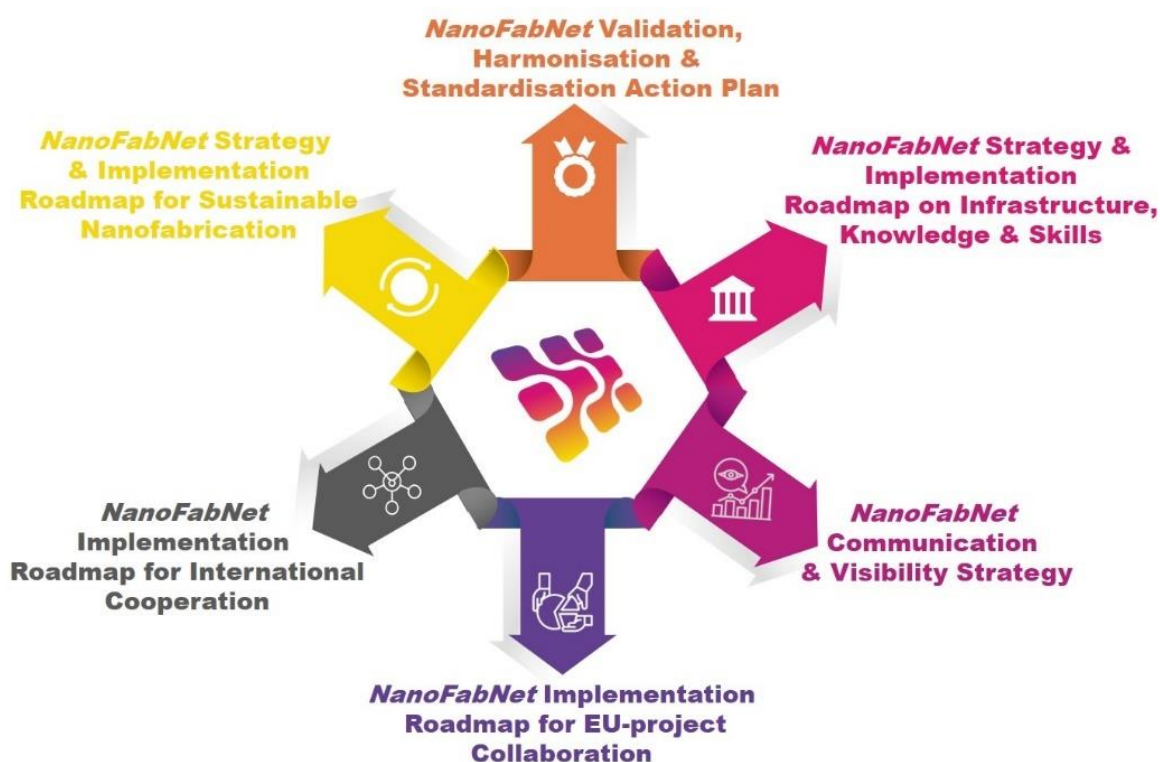
**To promote a harmonised concept of Safe-by-Design (SbD), alongside the concepts of Sustainability-by-Design (Sus-b-D) and Quality-by-Design (QbD). Harmonised guidelines for sustainability assessment of nanoscale products and processes, relevant key criteria on which these designs should be based still need to be developed and consolidated:** Although several European initiatives and projects have been implemented in recent years to pave the way in this direction, more effort is needed. These approaches could contribute to the establishment of a label based on one or more standards to disseminate these sustainability concepts in the field of nanotechnology.

**Standardisation of life cycle costing (LCC), social life cycle assessment (S-LCA) and life cycle and life cycle sustainability assessment (LCSA) methodologies and deployment of FAIRification processes. Raise awareness among all stakeholders of the need to generate FAIR (findable, accessible, interoperable and reusable) data.** To raise the awareness among all stakeholders of the need to generate FAIR data would support more reliable and relevant risk studies associated with nanomaterials, as these concepts and associated initiatives are not well known to most stakeholders.

**Demonstrate knowledge and expertise regarding nano-specific risk assessment & risk management tools.** This can be promoted and supported by some existing nano-specific certifications. Moreover, the set-up of a mechanism (e.g. certification training programme, new certification) supported by an independent third party actor that validate the knowledge and expertise of the stakeholder would provide a big opportunity for the field and its actors.

#### 4. Roadmap Implementation and Actions in Support of Sustainable Nanofabrication

In this chapter the NanoFabNet introduces the reader to a brief overview and compilation of the six individual strategies and implementation action plans (Figure 7) designed and created by the NanoFabNet, during the last two year, with the aim to cover and give response to the challenges identified in Chapter 2. The integration and implementation of those strategic documents will allow the NanoFabNet to build a strong network and become a bridge between all the actors of the sustainable nanofabrication field and become crucial in terms of information on the new developments, trainings, facilitate access to infrastructure and characterization tools and knowledge, foster collaboration between the actors and focus on identifying remaining and future needs in the sustainable nanofabrication environment.



*Figure 7: The Six Implementation Action Plans of the NanoFabNet Hub.*

Each of the six action plans can be consulted by the reader in the following documents, if deeper and more detailed information is needed:

- the '[NanoFabNet Strategy & Implementation Roadmap for Sustainable Nanofabrication](#)'<sup>13</sup>,
- the '[NanoFabNet Validation, Harmonisation & Standardisation Action Plan](#)'<sup>14</sup>,

<sup>13</sup> NanoFabNet report '[NanoFabNet Strategy & Implementation Roadmap for Sustainable Nanofabrication](#)' (January 2022) (accessed: 1<sup>st</sup> August 2022).

<sup>14</sup> NanoFabNet report '[NanoFabNet Validation, Harmonisation & Standardisation Action Plan](#)' (December 2021) (accessed: 1<sup>st</sup> August 2022).

- the ‘[NanoFabNet Strategy & Implementation Roadmap on Infrastructures, Knowledge & Skills Development](#)’<sup>15</sup>,
- the ‘[NanoFabNet Communication and Visibility Strategy & Dissemination Plan](#)’<sup>16</sup>,
- the ‘[NanoFabNet Implementation Roadmap for EU-Project Collaboration](#)’<sup>17</sup>, and
- the ‘[NanoFabNet Implementation Roadmap for International Cooperation](#)’<sup>18</sup>.

The actions and recommendations delineated in each of the aforementioned documents are classified according to two main categories: (a) short- to medium-term actions, and (b) medium- to long-term actions. The NanoFabNet has adopted the following definition for the different timescales (Figure 8):

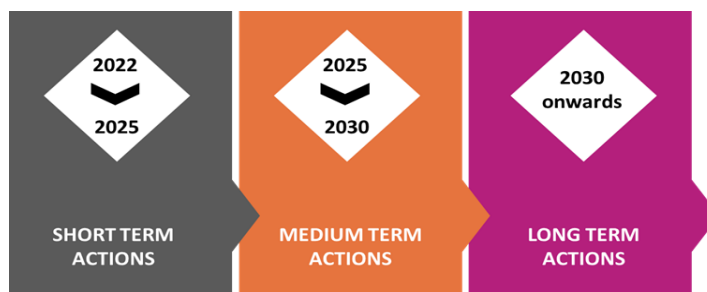


Figure 8: Illustration of the timescales considered in this strategic plan.

- ‘Short-Term’: one to three years (i.e. 2022 to 2025);
- ‘Medium-Term’: three to eight years (i.e. 2025 to 2030); and
- ‘Long-Term’: beyond eight years (i.e. 2030 onwards).

### 3.1 Strategy & Implementation Roadmap for Sustainable Nanofabrication

This first strategic document consists of a set of actions and recommendations to be implemented at different timescales and by different bodies within the next several years to achieve sustainable nanofabrication (Figure 9). The different actions are a direct output of the discoveries, advances and activities in terms of sustainability in nanofabrication performed by the NanoFabNet Project during its course; the creation of the implementation roadmap thus benefited from three different types of sources:

1. The 1<sup>st</sup> source comprises four reports developed within the NanoFabNet Project:
  - the NanoFabNet ‘[Report on the Concepts & Disciplines of Sustainability in Nanotechnology & Nanofabrication](#)’<sup>19</sup>,
  - NanoFabNet’s ‘*Detailed Database Entries & Map of the Field of Sustainability in Nanotechnology & Nanofabrication*’<sup>20</sup>,
  - the NanoFabNet report ‘*Annotated List of hard regulatory Requirements for Nanofabrication*’<sup>21</sup>, and

<sup>15</sup> NanoFabNet report ‘[NanoFabNet Strategy & Implementation Roadmap on Infrastructures, Knowledge & Skills Development](#)’ (August 2022) (accessed: 1<sup>st</sup> August 2022).

<sup>16</sup> NanoFabNet report ‘[NanoFabNet Visibility, Communication & Dissemination Strategy](#)’ (February 2022).

<sup>17</sup> NanoFabNet report ‘[NanoFabNet Implementation Roadmap for EU-Project Collaboration](#)’ (October 2021) (accessed: 1<sup>st</sup> August 2022).

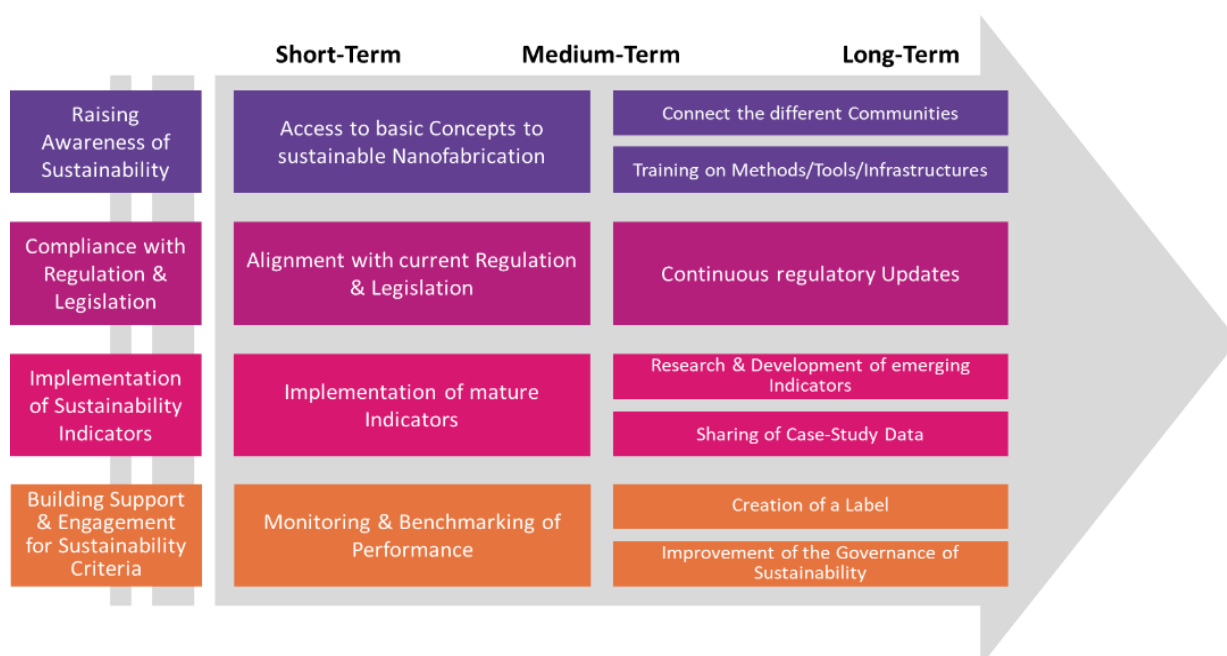
<sup>18</sup> NanoFabNet report ‘[NanoFabNet Implementation Roadmap for International Cooperation](#)’ (February 2022) (accessed: 1<sup>st</sup> August 2022).

<sup>19</sup> NanoFabNet ‘[Report on the Concepts & Disciplines of Sustainability in Nanotechnology & Nanofabrication](#)’ (October 2020) (accessed: 25<sup>th</sup> February 2022).

<sup>20</sup> NanoFabNet report (confidential): ‘*Detailed Database Entries & Map of the Field of Sustainability in Nanotechnology & Nanofabrication*’.

<sup>21</sup> NanoFabNet report (confidential): ‘*Annotated List of hard regulatory Requirements for Nanofabrication*’.

- the 'Report on recommended 'soft/exploratory' Sustainability Indicators for NanoFabNet'<sup>22</sup>
- 2. The 2<sup>nd</sup> source comprised the two NanoFabNet Development Workshops (DWs), organised and held by the NanoFabNet Project in March 2020 and January 2021, respectively.
- 3. The 3<sup>rd</sup> source was complementary literature, in particular, the following documents:
  - the report entitled 'Nanosafety in Europe 2015-2025: Towards Safe and Sustainable Nanomaterials and Nanotechnology Innovations' (Savolainen et al., 2013),
  - the report entitled 'Moving Towards a Safe(r) Innovation Approach (SIA) for More Sustainable Nanomaterials and Nano-enabled Products' (OECD, 2020),
  - the 'Mapping study for the development of Sustainable-by-Design criteria' (Amodio et al., 2021),
  - the 'First report on the CG sessions, Deliverable D3.1' (SUSNANOFAB, 2021), and
  - the concept paper entitled 'International Network Initiative on Safe and Sustainable Nanotechnologies (INISS-nano)' (Falk et al., 2021).



**Figure 9:** Diagram summarising the actions and recommendations of the NanoFabNet strategy and implementation roadmap for sustainability in nanofabrication.

The different sources described above have enabled the NanoFabNet to organise the strategy and implementation roadmap for sustainability in nanofabrication around four dimensions, which recur in a consistent manner in all the reflections devoted to the advent of sustainable nanofabrication. These four dimensions and the list of proposed actions are defined and presented in Table 4.

<sup>22</sup> NanoFabNet report (confidential): 'Report on recommended 'soft/exploratory' Sustainability Indicators for NanoFabNet'.





**Table 4:** The four dimensions of the NanoFabNet implementation roadmap for sustainability in nanofabrication and its recommendations for the corresponding Short-to-Mid and Mid-to-Long Term Actions.

## **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*'<sup>19</sup> (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<sup>20</sup>* (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.

## **Short-to-Med Term Action:**

**Implementation of mature indicators (i.e. those with a higher level of standardisation and harmonisation).** Some actions can be performed that focus on how to make use of sustainability indicators to integrate sustainability in the development of a new technology, in particular at low TRL. They can be qualitative, and concern mainly technology developers in industry and research.

Besides the support to the development of a new technology, sustainability indicators can also be useful to a wider range of stakeholders from industry, regulatory bodies or policy, be it to improve their current practices, to support their strategies and decisions, or for communication purposes.

## **Mid-to-Long Term Actions:**

**The research and development of emerging indicators.** Research gaps and limitations still need to be tackled to improve the reliability and credibility of the indicators. These developments should be performed by researchers in the sustainability and nanotechnology fields, and should lead to a higher standardisation and harmonisation of the methods.

**Sharing of case-study data.** In order to expand and improve the use of sustainability indicators, the data generated for the assessment of nanotechnology should in particular be shared systematically and following FAIR guiding principles (Wilkinson et al., 2016). All actors (including researchers, industry or policy makers) can contribute to data collection and should contribute to increase the acceptance of sustainability criteria. In the three areas of sustainability mentioned above, the sharing of case-study data can also benefit from the advances on the 'Knowledge and Communication Platform' concept such as summarised in OECD (2020, pp.62-64).

## **Dimension 4: Support & Engagement for Sustainability Criteria**

Having shared indicators allowing the most relevant stakeholders (researchers, industrialists, regulators) to assess the sustainability of their nanotechnology-enabled products, processes and uses is essential, but not sufficient. It is also necessary to derive from them shared and accepted criteria, targets and benchmarks related to sustainability, benefiting from a social consensus, and able to give rise to concrete, achievable and incentive objectives. These could, for example, be embodied in a sustainable nanofabrication label, certain characteristics of which can be anticipated. Access to sustainable nanofabrication furthermore requires the establishment over the long term of a real collective governance of sustainability.



## **Short-to-Mid Term Action:**

**Monitoring and benchmarking of performance.** In terms of sustainability, performance monitoring is a comprehensive task that should be developed at all levels. Monitoring must then be able to lead to benchmarking. Very generally, a benchmark is a certain target, for which different actors decide that it should be reached. In terms of sustainable nanofabrication, it would be interesting to move towards the definition of benchmarks for all the indicators mentioned above, or at least for a carefully selected number of them. Such benchmarking can first be developed in a comparative manner, by comparing the risks, benefits and additional issues of nanotechnology-enabled products, processes and services to those related to more conventional alternatives. Ultimately, benchmarking should also become more general, and it could be interesting to define benchmarks and targets to reach in order to be considered 'absolutely' sustainable. The definition of such benchmarks should nevertheless benefit from a social consensus, and from a participatory process aimed at establishing it.

## **Mid-to Long Term Action:**

**The creation of a Label for 'Sustainable Nanofabrication'.** Such a label could fulfil a dual role: act as an incentive and as a reward for the players accessing this label, and guarantee the validation of their approach and of their implementation strategy in terms of sustainability. It could be based on the compliance with certain benchmarks related to some of the sustainability indicators mentioned above, and on the certification against a number of already existing standards, to be precisely defined. Several already existing frameworks can be useful as sources of inspiration (even if not as first bricks) for such a label.

**Improvement of the governance of sustainability.** The main characteristics of 'anticipatory governance' have to be promoted, including an authentic 'governance of sustainability' going beyond the simple governance of risk. Practical innovation and flexibility in its implementation must also be promoted, at the different levels of anticipation techniques, interaction techniques, and public engagement techniques.

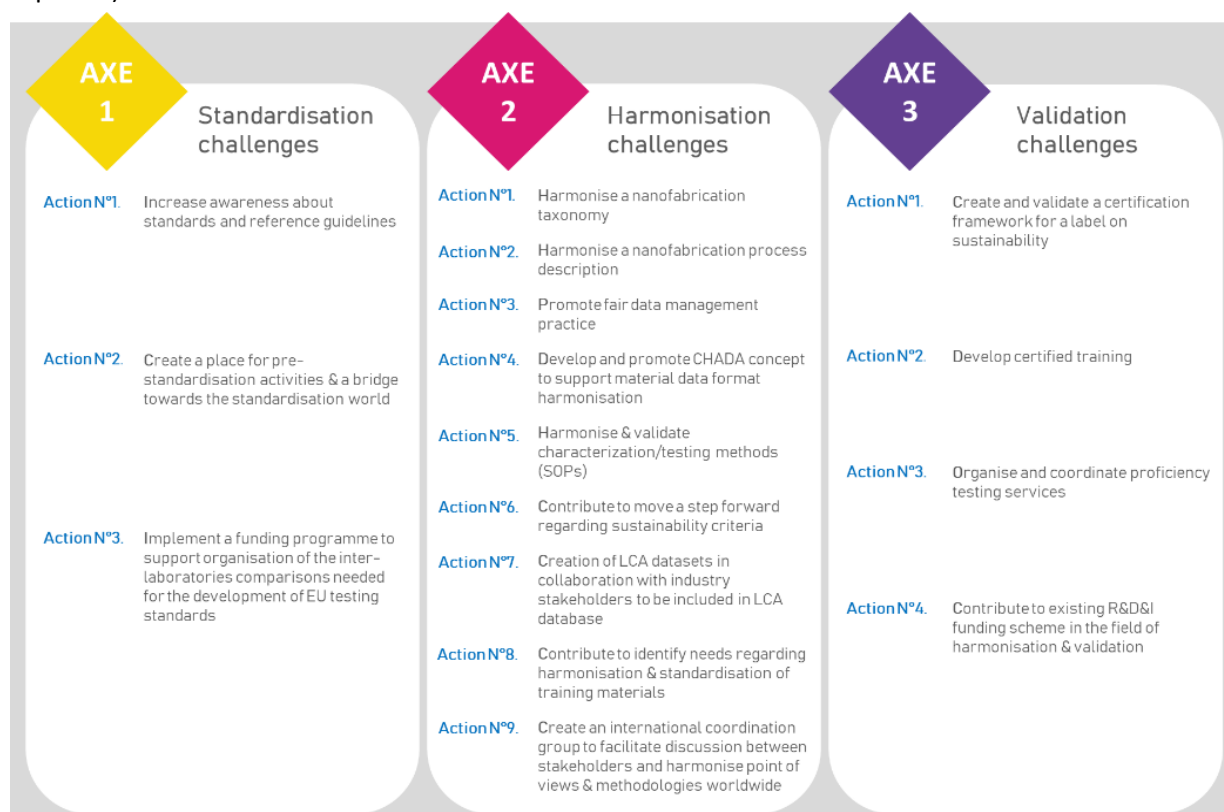
## **3.2 Validation, Harmonisation and Standardisation Action Plan**

This Action Plan responds to 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 consulted (see [Section 2.2 Challenges in Validation, Harmonisation & Standardisation](#)). It occupies an important place in this 'EU 2030 strategic roadmap for Nanofabrication', as the lack of harmonisation and standardisation was identified by the stakeholders as the most important obstacle to the introduction of sustainable nanofabrication in the industrial ecosystem.

The action plan introduces the reader to sixteen actions that have been proposed (see Figure 10 **Error! Reference source not found.**) along three main axes. These actions, briefly defined and explained in Table 5 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. Three actions focus on strengthening the impact and relevance of standardisation work, while four actions are specifically aimed at putting in place the necessary frameworks and tools to validate the mastery of various key topics by the stakeholders concerned and to enable them to have the objective elements to reassure and convince their partners.

The NanoFabNet Stakeholders expect the Hub to focus on pre-standardisation activities, in order to have a Single-Entry Point to discuss standardisation requests, to provide a framework for validating methods and tools prior to standardisation as well as, regular dissemination of state-of-the-art information on ongoing activities in this field and on available reference documents and guides (more

details given in the [NanoFabNet Validation, Harmonisation & Standardisation Action Plan](#) public report <sup>14</sup>).



**Figure 10:** Listing of the NanoFabNet actions to address challenges dealing with standardisation, harmonisation and validation topics, in the field of nanofabrication.

**Table 5:** The three axes of the NanoFabNet Validation, Harmonisation & Standardisation Action Plan and the corresponding Short-to-Mid and Mid-to-Long Term Actions.

| AXIS 1: Standardisation                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p><b><u>Short-to-Mid Term Action:</u></b></p> <p><b>Raise the awareness about standards and reference guidelines.</b> 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.</p> <p><b>Establishment of a document repository on the NanoFabNet website with information on available reference documents and standards.</b> 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&amp;D&amp;I outcomes in standardisation.</p> <p><b><u>Mid-to-Long Term Action:</u></b></p> <p><b>Implementation of a funding programme to support the organisation of inter-laboratories comparisons.</b> 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 Material (ASTM).</p> |



## 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 harmonized 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.





## 3.3 Strategy and Implementation Roadmap on Infrastructures, Knowledge and Skills

Following the extensive activity of mapping and the creation of the competence map for nanofabrication infrastructures described in the NanoFabNet report '[Nanofabrication Competence Map for the Infrastructures, Knowledge and Skills – Proposal for a New Taxonomy](#)', the next challenge lies in selecting the right strategy to implement the new proposed taxonomy and further extension of the activities in order to create a coherent and understandable picture of the nanofabrication infrastructures map. As starting point, a limited number of nanofabrication infrastructures organised under the umbrella of a pan-European academic research infrastructure – EuroNanoLab<sup>23</sup> - will be in charge to prove and finetune the concept. Once this will be achieved, it will be offered also to other partners and collaborators. These partners include other worldwide academic infrastructures, research and technology organisations and the industrial sector. The successful implementation will help all NanoFabNet stakeholders and wider nanofabrication community to find solutions for their needs as well as to offer easily their own technological capabilities. The main incentives to ensure a wide acceptance and adoption of the concept will be the initial EuroNanoLab-based seed of high-quality data and the concept of open (FAIR) linked data.

The specific actions that have been designed to implement the proposed taxonomy for nanofabrication across all type of nanofabrication research infrastructures in Europe and worldwide are categorised under three steps, defined in Table 6.

**Table 6:** The three-step strategy for implementation of the NanoFabNet taxonomy for nanofabrication across all levels of nanofabrication research infrastructures in Europe and worldwide.

| Step 1: EuroNanoLab equipment database as a proving ground                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p><b>Short-to-Mid Term Action:</b></p> <p><b>Implement NanoFabNet taxonomy into EuroNanoLab equipment database.</b> EuroNanoLab partners have agreed on creating a unified equipment database which will harmonize the presentation of thousands of nanofabrication tools, all of them offered by 44 EuroNanoLab associated cleanrooms. The initial technical realization allows either manual input of the entries via web-based interface or semi-automated import from a database file.</p> <p><b>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.</b> 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) and based on their feedback the taxonomy will be updated.</p> <p>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.</p> <p><b>Mid-to-Long Term Action:</b></p> <p><b>Expand the original NanoFabNet taxonomy concept to cover a broader area of nanotechnology research, including nanofabrication processes and analytical equipment.</b> 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.</p> |
| Step 2: Implementing open API and connection to other databases                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |

<sup>23</sup> EuroNanoLab website: <http://euronanolab.eu/> (accessed: 1<sup>st</sup> August 2022).

## **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 be 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 organizations 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 standardization 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.



## 3.4 NanoFabNet Visibility, Communication and Dissemination Strategy

As part of the NanoFabNet Project dissemination and communication activities, many learnings have been generated regarding optimum efforts and tools needed for the delivery of a network organisation communications strategy. The NanoFabNet Visibility, Communication and Dissemination Strategy is based on three core phases of activities Table 7. The first and the second phase have been already developed and implemented over the two years of the NanoFabNet Project and have provided already a good starting point, in terms of the NanoFabNet brand establishment. Phase three of the strategy is currently being developed, and will mainly be done during the last half year of the NanoFabNet Project and is expected to be continuously worked out in the coming months and years until reaching a more mature phase of the NanoFabNet Hub itself.

*Table 7: The three core phases of activities – Activation, Engagement & Sustain – of the NanoFabNet Visibility, Communication and Dissemination Strategy*

**ACTIVATION:** this phase was focused on raising awareness of the NanoFabNet, targeting relevant stakeholders, communities, projects and attracting new stakeholders to the international network. Key players from academia, industry and policymaking have been continuously informed and activated with targeted materials and through a variety of communication channels.

### **Actions and tools used for implementing it:**

**NanoFabNet website:** it offers users a variety of contact points and content options to provide multiple points of interest and further engagement with activities of the hub.

**NanoFabNet social media channels accounts on Twitter and LinkedIn.** Through them the stakeholder community stays tuned and informed with nearly daily updated and content.

**The NanoFabNet Newsletter,** active since July 2020 and draws together information from across the partnership and associated stakeholder networks, providing current and exciting news to the community. It is distributed regularly on a monthly basis.

**ENGAGEMENT:** this phase has been about engaging relevant stakeholders, attracting them to the community and bringing them together to build and grow the network and ecosystem around it. By the correct implementation of this phase, the set-up of the next phase and the NanoFabNet Hub itself and its membership organisation will be possible. The most important and valuable activities that have occurred until now have provided the subscription of 188 stakeholders to the NanoFabNet.

### **Actions and tools used for implementing it:**

**Internal Events:** Two Development Workshops (DWs) were programmed in March 2020 and January 2021, respectively. This allowed to build a strong connection to, and feedback process for, the stakeholders. Key learnings got from these DWs could be extrapolated, explored with the relevant community and integrated into the further developments of the NanoFabNet Hub.

**Stakeholder development and support:** the NanoFabNet has been very active in interacting with its stakeholders getting in contact to, and collecting feedback from them through specific surveys and have ensured direct contact with around 60 stakeholders from 10 different countries. Moreover, a number of social media campaigns have been undertaken to drive relevant users to the NanoFabNet activities and website.

**Outreach campaigns:** Through the activities mentioned above the NanoFabNet has already a strong foundation network of stakeholders with which to draw upon for communication delivery requirements for the hub. Alongside this, 26 related nanotechnology sector press and journal organisations have been identified, with whom NanoFabNet can connect to support the development of the network.

**External Events:** The NanoFabNet has been active in promoting its activities at a variety of international events during (e.g. NanoSafetyCluster conference, Polish nano networking event,

AFNOR Standardisation Technical Committee on Nanotech, NanoWeek 2022). Moreover, it is planned to organise two launch events for the NanoFabNet Hub: the US-NanoFabNet Launch Event held within the TechConnect 2022 Conference, in Washington D.C, US, in June 2022 and the EU-NanoFabNet Launch Event, held in July in Braga at the INL.

**Partnership Development:** it is foreseen that the NanoFabNet Hub, to be launched in August 2022, will engage in partnering activities with a number of international nanotechnology organisations. This will be essential to provide the level of connections and reputational respect the NanoFabNet Hub seeks as it moves beyond the timeframe of the project and into a self-sustaining entity level. Although at this point of time the secureness of specific strategic partnerships and cooperation with some organisations have yet to occur, a number of suggested organisations are already planned for that (e.g. EURAMET, NanoSafetyCluster, EU-US-CoR, the National Nanofabrication Platform of Japan, NNCI (US), EuroNanoLab, CEN, ISO, VAMAS, ASTM, SusNanoFab, EPPN, the Graphene Flagship, EuroLab).

**SUSTAIN:** this third phase will be implemented by the fully functional *NanoFabNet* Digital Platform.

#### **Actions and tools used for implementing it:**

**The Digital NanoFabNet Platform:** This digital platform will enable the NanoFabNet Hub to offer a sustainable hub for nanotechnology professionals, where the needs and requirements for their day to day working as well as research and development can be met and supported. The digital platform will handle members information and communication, as well as public relation issues of the NanoFabNet Hub, promoting the offer, infrastructures, trainings, and acting as a reliable singly entry point (one-stop-shop) to the overall network done within the framework of the Hub. Thus, to fulfil the requirements that all type of NanoFabNet users might have, based on their activities and level of relation with the NanoFabNet Hub, a global navigation structure has been developed to understand how each element of the digital platform will be located within the overall structure of the site. This navigation provides an overview of positioning, location of the content and user access level.

### **3.5 Implementation Roadmap for EU-Project Collaboration**

Successful collaboration implementation among EU-funded projects is often a big issue, and for many different reasons. At the same time, collaboration plays a big part in the success of any project, not only within the different project partners but also with external actors or stakeholders. The EU is searching for solutions to help increase efficient and effective communication among EU-funded projects and the projects themselves seeks ways of being aware about what is being developed in other projects, that could be complementary, synergistic or an enabler for themselves, without disclosing sensitive information detrimental to further exploitation of results. This section of the EU2030 Strategic Plan for Nanofabrication seeks to inspire as well as provide help to EU-funded projects dealing with sustainable nanofabrication to increase their collaboration and increase consequently their impact and reach their goals, minimising and avoiding unnecessary duplicities. The reader is encouraged to consult the related open access document,<sup>18</sup> released in October 2021 by the NanoFabNet Project, to get a deeper detail about the different issues described below. The roadmap was built on a number of core components designed to advance its goal in a measurable and achievable way; they comprise:

- i) to state a clear vision of what NanoFabNet aims to achieve in relation to EU-project collaboration,
- ii) to establish a mapping of the current landscape of EU-projects dealing with sustainable nanofabrication,
- iii) to establish an active dialogue with NanoFabNet's stakeholders to identify challenges, barriers, needs, when talking about EU-project collaboration, and



- iv) to identify and implement the pertinent activities and actions that shall improve the impact and unlock the identified challenges.

Alongside the components mentioned above, the NanoFabNet set key enablers that will permit the effectiveness of the process; among these, NanoFabNet highlights the importance of: a) Partnerships & Collaborations as critical to unlock the full potential of any EU-funded project, b) Data & Knowledge Generation, key enabler for any EU-project to obtain access to reliable and timely data or state-of-the-art knowledge to successfully achieve the project aim and goals, and c) Innovation capacity as, the solutions or needs related to sustainable nanofabrication may either not yet exist or is in very early stages of development.

In order to help improve the collaboration among EU-funded projects, in the field of sustainable nanofabrication, the NanoFabNet has identified a list of goals, activities and actions (Table 8) that once implemented might contribute the community to overcome identified challenges and meet the goals.

**Table 8:** Actions that will be implemented by the NanoFabNet to reach the goals for a higher and efficient EU-funded project collaboration among projects that deals with sustainable nanofabrication and related issues.

| GOAL 1 - INCREASE THE PRODUCTIVITY OF EU-FUNDED PROJECTS.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p>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 <i>NanoFabNet</i> will establish a framework that might help the projects to align certain project tasks or activities.</p> <p><b><u>Short-to-Mid Term Actions:</u></b></p> <p><i>Provide access to easy and organised information about EU-funded projects</i> (e.g. project start and ending dates, partners, main aim, expected outcomes, results), including specific capabilities and/or expertise resulting from the different projects.</p> <p><i>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.</i></p> <p><i>Provide connection to experts</i> of the sustainable nanofabrication field and related topics.</p> <p><i>Provide access to an updated repository of research infrastructures</i> related to the sustainable nanofabrication field.</p> |
| GOAL 2 - ADEQUATE FINANCING PROGRAMS.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                           |
| <p>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 utmost 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).</p> <p><b><u>Short-to-Mid Term Action:</u></b></p> <p><i>To provide easy and fast access to information about existing specific funding programmes and calls</i> related to and interesting for the sustainable nanofabrication field.</p> <p><b><u>Mid-to-Long Term Action:</u></b></p> <p><i>To include the inputs and points of view from all different stakeholders of the field</i> (i.e. academics, industry, civil society and government) during the design of the forthcoming funding schemes.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |



## 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 utmost 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.





## 3.6 Implementation Roadmap for International Cooperation

International cooperation is considered to be an important part of building stakeholder awareness in the field of sustainable nanofabrication and creating a global community of entities in this area. It can also 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.

The NanoFabNet defined an '[Implementation Roadmap for International Cooperation](#)'<sup>18</sup>, which identifies four specific goals and a list of actions (Table 9) to address the following issues:

1. to establish a strong integration of the EU community;
2. to establish a strong connection with other non-EU international stakeholders to facilitate building a global community focused on sustainable nanotechnology and nanofabrication;
3. to develop the capacity of the NanoFabNet Hub through the exchange of know-how at an international level; and
4. to monitor the mutual understanding of challenges in the field of sustainable nanofabrication and nanotechnology.

*Table 9: Actions that will be implemented by the NanoFabNet to reach the needed international cooperation within the sustainable nanofabrication field*

| GOAL 1 – To establish of an integrated EU community for sustainable nanofabrication                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p><b><u>Mid-to-Long Term Action:</u></b></p> <p><b>To create a European community in sustainable nanofabrication.</b> 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.</p> <p><b>To facilitate the creation of new partnerships and the implementation of international projects.</b> 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.</p>                                                                                                                                                                                                                                                                                                                                                                |
| 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.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
| <p><b><u>Short-to-Mid Term Action:</u></b></p> <p><b>To connect the communities working in the field of sustainable nanofabrication.</b> 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.</p> <p><b>To strengthen the EU-US collaboration.</b> 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 organized 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.</p> |



## **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**

## **5. The NanoFabNet Hub - Towards a stronger European Ecosystem of Sustainable Nanofabrication**

The European industry makes up more than 20% of GDP, accounts 80% of goods exports and employs more than 35 million people, thus is the engine for productivity growth, high-value exports and quality jobs offer in Europe<sup>24</sup>. However, this European industry, since and even before the beginning of the health crisis, is struggling to tackle unprecedented challenges that imposes to become more resilient in order to survive. At the same time the EU Commission aims to ensure coherence between industrial, environmental, climate and energy policy, to create an optimal business environment for sustainable growth, job creation and innovation. To do so, an ambitious agenda has been designed by the European Commission that aims to transform the EU economy into a circular one and to support the European industry in its move to a climate-neutral economy and energy efficiency way of producing.

Along to the transformation that the European industry is and will face in the coming years are a broad variety of society's problems that needs to be solved, going from medicine to aerospace technology, and from environmental solutions to agriculture. It is here, where nanotechnology takes the lead as one of the key enabling technologies that during the past decade has been – and continues to be – the major promise to contribute solutions to all these society's problems and become one of the most important assets and motors for the European industry. The many 2030 to 2050 roadmaps and

<sup>24</sup> A New Industrial Strategy for Europe, COM/2020/102 final; [CELEX:52020DC0102](#) (accessed: 1<sup>st</sup> August 2022).

strategies, published over recent years, all share one conclusion: the transition towards a greener and circular economy in Europe requires a fundamental transformation of all the sectors and nanotechnology can definitively help achieving this transformation, thanks to the small change in the properties of materials: size.

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.

Aware of the potential that nanofabrication can offer to the European Industry in the coming years, in 2019, the EU Commission, under the H2020 Framework Program, specifically under the ‘H2020-EU.2.1.3 – INDUSTRIAL LEADERSHIP – Leadership in enabling and industrial technologies – Advanced materials’ program, launched the ‘H2020-NMBP-TO-IND-2018-2020’ call. This call contained a specific topic - DT – NMBP-12-2019 – Sustainable Nano-Fabrication – which main objectives were the establishment and creation of a network of EU stakeholders, able to manage information and communication among its members in the technical domains, such as nanomanufacturing, nanofabrication and/or nanostructure assembly.

The network to be established is expected among others to establish: i) common approaches for nomenclature, metrology, measurements and characterisation applied for nanomaterials by design, ii) to provide access across Europe to services and infrastructures for the scale-up and production of nanomaterials, iii) cover sustainability in terms of human health and environment, ethics, LCA analysis etc., and iv) cover the development of the necessary skills for this new type of industry<sup>25</sup>. The NanoFabNet Project is one of the two projects granted under this specific call<sup>26</sup>. Since March 2020 the NanoFabNet has been engaging all different type of European stakeholders and has been working towards the growth and nurturing of an initial loose stakeholder community to transform it into a formally registered NanoFabNet Hub.

Whilst releasing this **‘EU2030 Roadmap for Sustainable Nanofabrication’** the NanoFabNet Hub is aiming to communicate with and engage these sustainable nanofabrication stakeholders, as well as the broader related community, and introduce them to a framework and a set of actions, worked out during the two last years, that shall enable the field of sustainable nanofabrication to grow, remain on track and aligned to the objectives of the European Commission and move towards the objectives defined by the European Green Deal<sup>27</sup>.

The NanoFabNet and the **‘EU2030 Roadmap for Sustainable Nanofabrication’** provides a brief overview about the landscape and the challenges of the field and provides specific actions to implement that shall contribute to approach and solve what the EU Commission described in the text of the ‘DT – NMBP-12-2019 – Sustainable Nano-Fabrication’ topic, this is:

- To cover sustainability in terms of human health, ethics, environment and life-cycle analysis; *The Landscape of Sustainable Nanofabrication* provides the most complete picture on the global landscapes of the fields of nanofabrication and technology sustainability, with focus on the

<sup>25</sup> Website: [https://cordis.europa.eu/programme/id/H2020\\_DT-NMBP-12-2019](https://cordis.europa.eu/programme/id/H2020_DT-NMBP-12-2019) (accessed: 5<sup>th</sup> May 2022).

<sup>26</sup> Projects granted under the ‘DT – NMBP-12-2019 – Sustainable Nano-Fabrication’ topic: the SUSNANOFAB project (GA N° 882506) and the NanoFabNet (GA N° 886171).

<sup>27</sup> <https://ec.europa.eu/info/publications/communication-european-green-deal.en> (accessed: 1<sup>st</sup> May 2022).

identification of the fields and sub-disciplines, overlaps and synergies between them. In its first sub-chapter *The NanoFabNet Concept of Sustainability in Nanotechnology & Nanofabrication* is described. This concept is based on three pillars: (a) Environmental, Health and Safety (b) Life Cycle Sustainability, and (c) Ethics and Governance.

- *Challenges & Opportunities in Sustainable Nanotechnology & Nanofabrication and Roadmap Implementation and Actions* provide an overview on the challenges that the NanoFabNet has identified as well as a set of actions, distributed in different time scenarios, that shall give response and solutions to these challenges. More specifically, the different sub-chapters give answer to the EU Commission identified needs, described in the call: i) Cover research and new standards for functional nanoparticles, nanomaterials, components, devices and processes. Establish common approaches for nomenclature, metrology, measurements and characterisation applied for nanomaterials by design, covered and detailed in sub-chapter 3.2 *Validation, Harmonisation and Standardisation Action Plan*, ii) to link and consolidate existing infrastructure, as well as to provide access across Europe to services and infrastructures for SMEs, and support the development of the necessary skills for this new industry, covered and detailed in sub-chapter 3.3 *Strategy and Implementation Roadmap on Infrastructures, Knowledge and Skills*, iii) to create a sustainable community of stakeholders managing information and communication within and outside the group and develop an EU wide research and innovation strategy. The NanoFabNet will implement the strategy defined under sub-chapter 3.4 *NanoFabNet Visibility, Communication and Dissemination Strategy*, iv) the sub-chapter 3.5 *Implementation Roadmap for EU-Project Collaboration* gives a detailed plan to build a network of existing EU funded projects and initiatives, which will solve common issues through cross-project collaboration, and will strengthen technology take-up across Europe, and v) sub-chapter 3.6 *Implementation Roadmap for International Cooperation* will establish an international cooperation in particular with the nanomanufacturing programme of USA-NSF and the NNI Signature initiative of Sustainable Nanomanufacturing.

## 6. Conclusions

The bibliographic analysis of over 1.6 million scientific publications in nanotechnology and sustainability revealed that the two fields are acting largely separately from each other; scientific journals, for instance, which offer a pre-defined overlap between the fields of biotechnology and nanotechnology (Friedrichs, 2018), keep publications pertaining to the wide topic of ‘sustainability’ separate from those concerned with nanotechnology. These findings strongly support the need for a community space, such as the planned NanoFabNet Hub, which encourages the **establishment of new individual connections and collaborative research** in the area of ‘**sustainable high-tech innovation**’. Moreover, a strongly international authorship of the publications in both fields of research support the need to provide a network for a truly international membership, and to engage this geographically and thematically diverse membership at an early stage of the network’s development. The mapping exercises ultimately formed the basis of the development of the NanoFabNet Database - the ‘digital twin’ to the NanoFabNet stakeholder community, whose main goal is to provide structured access to the collected and curated information that has been collected by the NanoFabNet to offer niche services and products to the new expert community of sustainable high-tech innovation.

The NanoFabNet Hub community space will provide 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, as well as the opportunities and challenges prevalent in that field of work, the NanoFabNet Hub will offer short term (2022-2025), medium-term (2025-2030) and long-term (2030 onwards) services and activities in the following areas:

- 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.

The successive implementations of the steps outlined in this roadmap will ultimately help to provide a **stronger European ecosystem for sustainable nanofabrication**.

## Bibliography

- Amodio, A., Malyska, A., Markouli, C., Salinas, S., Sanfeliix, J., Van Humbeeck, T. (2021). Mapping study for the development of Sustainable-by-Design criteria. European Commission, Directorate-General for Research and Innovation Prosperity; [doi:10.2777/109081](https://doi.org/10.2777/109081).
- Cooper, K., & Wachter, R. (2013). Nanomanufacturing: Path to implementing nanotechnology. *Int. J. Nanomanuf.*, 540–554; [doi: 10.1504/IJNM.2013.057598](https://doi.org/10.1504/IJNM.2013.057598).
- Falk, A., et al. (2021). International Network Initiative on Safe and Sustainable Nanotechnologies (INISS-nano). Zenodo. Retrieved from <https://doi.org/10.5281/zenodo.5004929>.
- Friedrichs, S. (2018), “Report on statistics and indicators of biotechnology and nanotechnology”, OECD Science, Technology and Industry Working Papers, 2018/06, OECD Publishing, Paris. <http://dx.doi.org/10.1787/3c70afa7-en>.
- Mulder, K., Ferrer, D., Van Lente, H. (eds.) (2011). What is sustainable technology? Perceptions, Paradoxes and Possibilities. Greenleaf Publishing; <https://doi.org/10.4324/9781351278485>.
- OECD (2020). Moving Towards a Safe(r) Innovation Approach (SIA) for More Sustainable Nanomaterials and Nano-enabled Products. Series on the Safety of Manufactured Nanomaterials No. 96, ENV/JM/MONO(2020)36/REV1; [https://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=env/jm/mono\(2020\)36/REV1&doclanguage=en](https://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=env/jm/mono(2020)36/REV1&doclanguage=en).
- Savolainen, K., Backman, U., Brouwer, D., Fadeel, B., Fernandes, T., Kuhlbusch, T., Landsiedel, R., Lynch, I., Pyllkkänen, L., et al. (2013). Nanosafety in Europe 2015-2025: Towards Safe and Sustainable Nanomaterials and Nanotechnology Innovations, Finnish Institute of Occupational Health; <https://www.nanosafetycluster.eu/outputs/nsc-research-roadmap-2015-2025/>.
- SUSNANOFAB (2021). First report on the CG sessions. Deliverable D3.1 of the EU-funded SUSNANOFAB Project.
- WCED (World Commission on Environment and Development) (1987). Our common future. Oxford University Press.
- Wilkinson, M. D., et al. (2016). The FAIR Guiding Principles for scientific data management and stewardship. *Sci. Data* 3, 160018 (2016); <https://doi.org/10.1038/sdata.2016.18>.





**NanoFabNet**  
international Hub for sustainable  
industrial-scale Nanofabrication