NanoFabNet

international Hub for sustainable industrial-scale Nanofabrication

Common Challenges & Opportunities in sustainable Nanofabrication

NanoFabNet Report

NanoFabNet

Cover Picture Source: Pixabay

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Acronyms Listed in Document	
ACC	American Chemistry Council
ANFF	Australian National Fabrication Facility
CSO	Civil Society Organisation
DW	Development Workshop
EC	European Commission
EHS	Environment Health & Safety
EU	European Union
EUON	European Union Observatory for Nanomaterials
FDA	Food and Drug Administration
ISO	International Organization for Standardization
LCSA	Life Cycle Sustainability Assessment
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
s-LCA	Social Life Cycle Analysis
NIMS	National Institute for Materials Science
NNCI	National Nanotechnology Coordinated Infrastructure
NNI	National Nanotechnology Initiative
NSC	NanoSafety Cluster
OECD	Organisation for Economic Cooperation and Development
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
R&D	Research and Development
SCCS	Scientific Committee on Consumer Safety
SDG	Sustainable Development Goals
SOP	Standard Operating Procedure
SSbD	Safe and Sustainable by Design
TS	Technical Specification
UN	United Nations
UNEP	United Nations Environment Program
VAMAS	Versailles Project on Advanced Materials and Standards
WP	Work-Package

1. Executive Summary

This deliverable aims to present an overview of the concept of an actual sustainable nanofabrication to achieve an initial identification of the common challenges and opportunities facing this field. The relevant contribution of the nanofabrication and sustainability stakeholders during the two NanoFabNet Development Workshops (held in March 2020 and January 2021, respectively) have been added where appropriate. The definitions are first presented to highlight the underlying challenges of sustainability in nanofabrication; then a state of the art is proposed to present the different issues involved in sustainable nanofabrication (standardisation, life cycle sustainability and risk assessment, education/skills and infrastructures). During this investigation, the NanoFabNet Team found that - even if a lot of work had been done at an international level during these last 30 years in the nanofabrication field - a lot of challenges are still to be met; these can be divided in two main levels:

- 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 international collaboration network to take up these challenges (e.g. dissemination of information, results, standards, case studies).

All these topics are incorporated in the NanoFabNet Project and the NanoFabNet Hub in the form of numerous studies and their resulting reports.

2. Introduction

Production and applications of nanomaterials have quickly increased over the past 30 past years, yielding a wide field that encompasses most of the scientific domains (i.e. chemistry, physics). The innovation that it brought, at first, initiated questions on safety as the community was worried about the impact of nanomaterials on the health and safety of both the environment and humans; then 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 -technology 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.

3. Definitions of Sustainable Nanofabrication

In this first section, the definitions related to the areas of nanofabrication and sustainability will be presented to facilitate the reading of this report and to better understand related problems.

3.1 Nanofabrication

3.1.1 Existing Definitions and their Developments

Norio Taniguchi was the first to use the term "nanotechnology" to define ultra-precision machining in 1971. With the evolvement of this novel technology field over time, it has become obvious that the single term "nanotechnology" cannot cover all aspects to define this new technology field. Thus, step by step, new developments enlarged the wording by adding for example: nanomaterial, nanofabrication, nanodevice, nano-object, nanoparticles.

The term "nanofabrication" used in the context of the NanoFabNet Project describes a high-tech, high-value process that uses or creates nanoscale elements/components/devices/building blocks with nanoscale materials or devices at the heart of the unofficial definition. Therefore, the following paragraphs will focus on the existing definitions for the building blocks of nanofabrication as conducted by the different institutions.

In April 2009, the European Parliament called for the introduction of a comprehensive science-based definition of nanomaterials in its Union legislation. The recommendation for a definition was published in October 2011, and is still valid to-date and officially mentioned on the European Commission (EC) website[1]: '*Nanomaterial means a natural, incidental, or manufactured material containing particles, in an unbound state or as an aggregate or as an agglomerate and where, for 50 % or more of the particles in the number size distribution, one or more external dimensions is in the size range 1 nm-100 nm. In specific cases and were warranted by concerns for the environment, health, safety, or competitiveness the number size distribution threshold of 50 % may be replaced by a threshold between 1 and 50 %. A material should be considered as falling under this definition if its specific surface area by volume is greater than 60 m^2/cm^3.*'

Even if the size range is unanimously approved by all, some parts of the definitions' recommendation (e.g. solubility, aggregates, distribution threshold) were still diverging from one sector/country/standard to another, when the definition was reviewed by Rauscher *et al.* in 2014 (Rauscher *et al.*, 2014); the review confronted different definitions of nanomaterials and presented the feedbacks of the survey made during the implementation of the EC recommendation for nanomaterials definition, showing that there was still improvement to made on the definition and its implementation. As of May 2021, the revised version of the current recommendation is undergoing a targeted stakeholder revision launched by the European commission.[2]

To go further, beside this very general definition, the International Organization for Standardization (ISO) technical specification (TS) ISO TS 80004[3] is one of the broadest definitions on nano-wording, allowing subsequent, detailed definitions to become more and more specific and exhaustive. Initially based on the definition of nanotechnologies ISO/TS 27687:2008[4], it was first published in 2010, and then subsequently (at least partially) updated almost every five years. It defines nanomaterials as: '[*a*] *material with any external dimension in the nanoscale […] or having internal structure or surface structure in the nanoscale*' and contains 13 parts related to various nano subjects:

- *Part 1: Core terms;*
- *Part 2: Nano-objects;*
- *Part 3: Carbon nano-object;*
- *Part 4: Nanostructured materials;*
- *Part 5: Nano/bio interface;*
- *Part 6: Nano-object characterization;*
- *Part 7: Diagnostics and therapeutics for healthcare;*
- *Part 8: Nanomanufacturing processes;*
- *Part 9: Nano-enabled electrotechnical products and systems;*

[1] EU Definition of a nanomaterial (website; accessed: July 2021).
[2] EU Survey, Targeted stakeholder consultation relating to the Review of the EU recommendation on the definition of the term "nanomaterial".
[3] ISO TS 80004-2010, ISO TS 80004-2015, ISO TS 80004-2020 and ISO TS 80004-2021, Nanotechnologies – vocabulary.
[4] ISO - ISO/TS 27687:2008 - Nanotechnologies — Terminology and definitions for nano-objects — Nanoparticle, nanofibre and nanoplate.

- *Part 10: Nano-enabled photonic components and systems;*
- *Part 11: Nanolayer, nanocoating, nanofilm, and related terms;*
- *Part 12: Quantum phenomena in nanotechnology;*
- *Part 13: Graphene and other two-dimensional materials.*

The number of terms and definitions in 'Part 1: Core Terms' have increased from 14 detailed definitions in 2010 to 16 in 2015, and for 'Part 3: Carbon Nano-Objects' from 12 in 2010 to 23 in 2020, highlighting the importance of the terminology in this field. At the same time, the explanations already available have been fine-tuned in the updated version to give increasingly detailed definitions.

Even if more terms are defined, there is still a lack of harmonisation across the disciplines, as nowadays nanotechnology is becoming more and more multidisciplinary (i.e. incl. physics, chemistry, electronics, electrical, and biotechnology), and is often focused on the interfaces of these classic disciplines; this leads to an important and confusing panel of terminologies to define it, as every research area has its own definition. To complicate the situation further, each application sector (e.g. cosmetics, food, medicine) has its own terminologies to describe the use and application of nanotechnologies within it, as each international organisation and committee (e.g. ISO, ACC) and even countries defined them in the early 2010s.

3.1.2 The underlying Technologies and Processes of Nanofabrication

To produce nanoscale structures *via* nanofabrication approaches, two main routes can be taken (see Figure 1). A "top-down" approach, which starts from micro-systems and miniaturises them to a nanoscale (as a carver would go from a block of stone to its final sculpture), whereas a "bottom-up" approach starts from atoms or molecular blocks to build nano-scale structures (as a mason would build a wall). The bottom-up approach is, for the moment, less common but allows more control over the nanoparticles production.

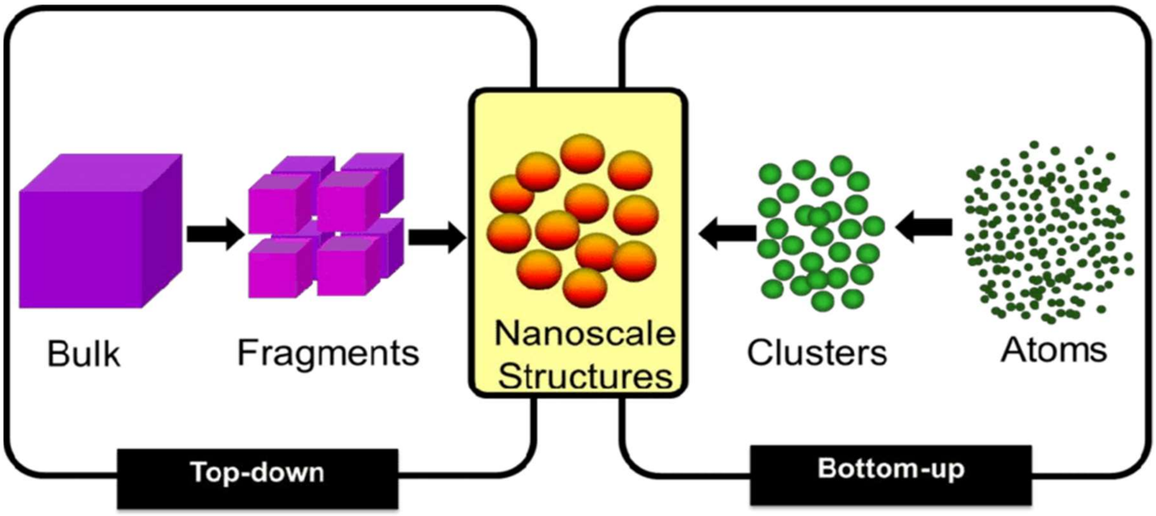

Figure 1. Representation of the nanofabrication approaches: "top-down" versus "bottom-up" (source: Rawat, 2015).

The top-down approach encompasses lithography, as well as dry- and wet-etching processes and is to be considered more like an assembly, whereas the bottom-up approach is similar to syntheses using gas, liquid, or solid phase processes (Figure 2). To go further into detail, the reviews by Rauscher (Rauscher *et al.*, 2014), and Sengul (Sengul *et al.*, 2008) present and explain an overview of the most common manufacturing techniques to produce nanostructured materials.

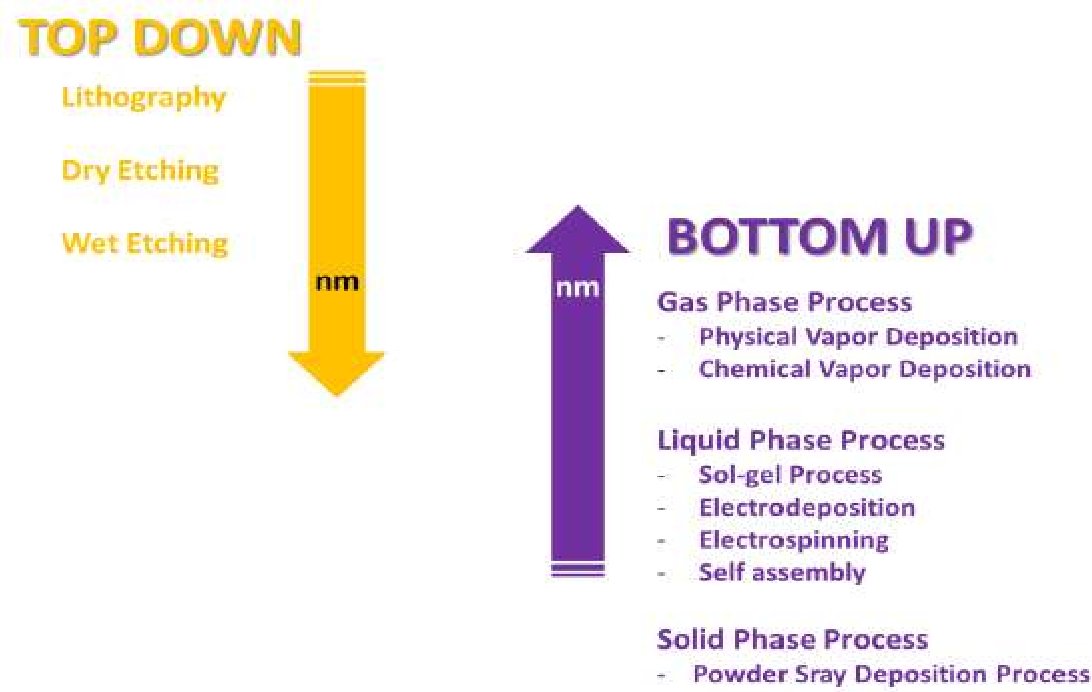

Figure 2. Most common manufacturing processes to produce nanostructured materials (source: Rauscher et al., 2014).

As an example, the production of carbon-based nanoscale materials by each of these approaches is presented in Figure 3 below (Habiba *et al.*, 2014).

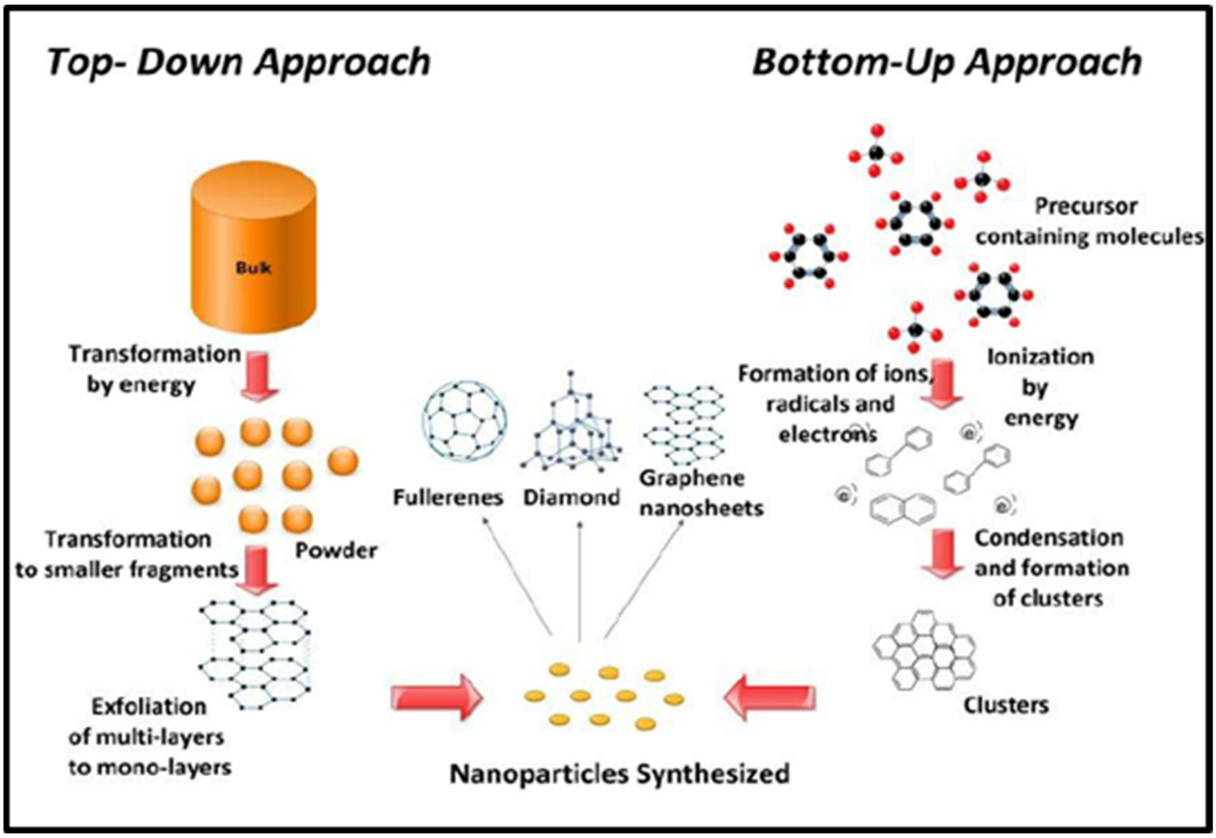

Figure 3. Bottom-up and the top-down approaches in synthesis of carbon-based nanomaterials (source: Habiba et al., 2014).

3.2 Sustainability

Unlike nanotechnology, there is no universal definition of the words "sustainable" or "sustainability". In the Cambridge dictionary, the term "sustainable" describes something that is able to continue without harming the environment or able to continue for a long period of time. On the EC website, the concept of "sustainable development" is described as 'a form of development policy which seeks to satisfy society's economic, social, and environmental needs in terms of well-being in the short, medium and - above all - long term. It is founded on the assumption that development must meet today's needs without jeopardising the welfare of future generations. In practical terms, this means creating the conditions for long-term economic development whilst ensuring due respect for the environment.'

The main problem in defining sustainability is that a lot of concepts are related to it, making it confusing: e.g. life cycle sustainability assessment (LCSA), life cycle thinking, risk assessment, ethics, circular economy, green chemistry, to name but a few.

Even LCSA itself is encompassing different disciplines, with all of them related to an assessment along the whole life cycle of a product or service (from the extraction of raw materials to end of life, Figure 4): life cycle assessment (LCA) which is a way to calculate the environmental impacts, life cycle costing (LCC) considering all the costs that will be incurred during the lifetime of the product, as well as the cost of externalities (such as greenhouse gas emissions) under specific conditions and social LCA (s-LCA), which assesses the social and sociological impacts.

Figure 4. Life cycle steps - figure adapted from Avnir-life cycle assessment platform[5] (source: Avenir platform).

[5] Avnir-life cycle assessment platform (website: access: July 2021)

The complexity of the concept of sustainability and its components is reflected by the common three pillars of sustainability: people, profit, and planet. According to Mata and al. (Mata *et al.,* 2015) sustainability can only be achieved when the three dimensions of LCSA are met (Figure 5).

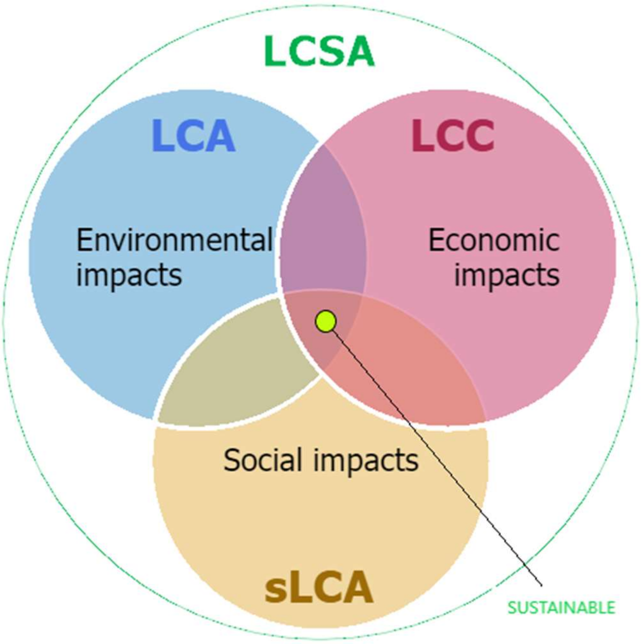

Figure 5. Definition of the sustainable state according to Mata (source: Mata et al., 2015).

3.3 Sustainable Nanofabrication

As nanofabrication and sustainability are quite young fields, the cross-over between them is even more recent. By searching both combined terms with an online search engine, the first results found are for European projects such as SusNanoFab and NanoFabNet showing that this subject is particularly on the rise.

To go further, this project task looks at a recommendation edited and published by the EC in 2008, titled “A code of conduct for responsible nanosciences and nanotechnologies research” (European Commission 2008). Even if the word sustainable is not expressively written in the document, it was implicit through the concept of its definition, whose purpose is to preserve human health and the environment while continuing to use and promote nanotechnology and the economy it represents.

During the 1st workshop of the NanoFabNet Project, to the question “what are the criteria for sustainable nanofabrication?” (Figure 6) the most important answers (by the >60 invited experts) in the word cloud were: nanowaste, safety, human health, recycling and then, resource efficiency, energy consumption, waste management, end of life and carbon footprint. This means that the term “sustainable” is defined in its globality, to be dealing with environmental and human impacts at the same time.

Figure 6. Word cloud of Stakeholders' answers attending the 1st NanoFabNet Development Workshop (March 2020) to the question "What are the criteria for "sustainable nanofabrication?".

Within the NanoFabNet, the topic of sustainability is considered as a global concept addressing the following categories:

- Environmental, Health and Safety issues
- Life Cycle Sustainability issues
- Ethics and Governance issues

To go further into detail for a definition of sustainable nanofabrication, this work package has generated a compilation on the existing concepts and disciplines of sustainability in nanotechnology and nanofabrication (*'Report on the Concepts & Disciplines of Sustainability in Nanotechnology & Nanofabrication*').

4. The State-of-the-Art of sustainable Nanofabrication and Evolutions in the past Decades

This part of the report focusses on the evolutions of sustainable and/or nanofabrication in the past forty years in all related fields: processing and characterisation, standardisation, sustainability and risk assessment, infrastructures, education and skills.

4.1 General Overview

To assess the international interest in the fields of nanofabrication and sustainability over time, a basic bibliographic search has been conducted. The results presented below are non-exhaustive data based only on keywords searches in different online databases made in April 2021. Given the quantities mentioned, it has not been verified that there are no duplicates or inconsistent results; nevertheless, this approach remains a good tool to visualise the trends of the international community's interest for these subjects.

By searching directly in the "google scholar.com"-database, the words "nano" and "sustainable" are significantly present from the 1980s and exhibit a quick expansion, reaching close to 2.000.000 contents in the 2000s (Figure 7). On the other hand, the development of keywords linked to sustainable nanofabrication or nanosafety only started to emerge from the 2000s showing that after the expansion of uses of "nano"-terms, due to its ability to produce better performing materials, the international thinking has begun to focus on safety (for human, nature, and the environment). Similar trends can be observed when conducting the same search in the "ScienceDirect"-database[6] but with less matches as these results are linked only to scientific journals available in the ScienceDirect portfolio.

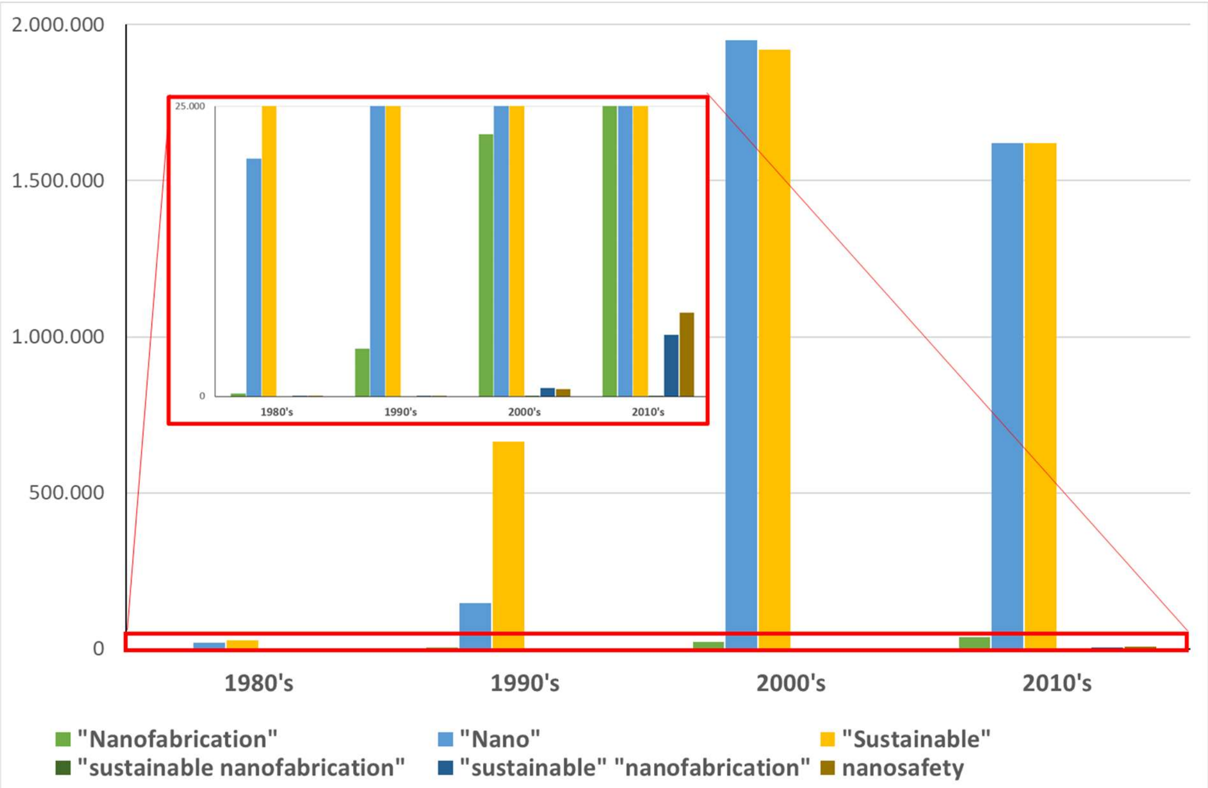

Figure 7. Evolution of keywords linked to sustainable nanofabrication in the "google scholar.com"-database (accessed: April 2021).

In the same way, the number of published patents[7] linked to the keyword "nano" found in either the title or in the abstract has increased exponentially in less than 20 years with about 40.000 patents in the 2000s and more than 160.000 in the 2010s (Figure 8). The word "sustainable" is also increasing but at a lower rate. The presence of both keywords "nano" and "sustainable" in patents only starts to appear in the 2000s and is still negligeable in the 2010s.

[6] Science direct (website; accessed: February 2021).
[7] Espacenet (free access to international patents) (website; accessed: February 2021).

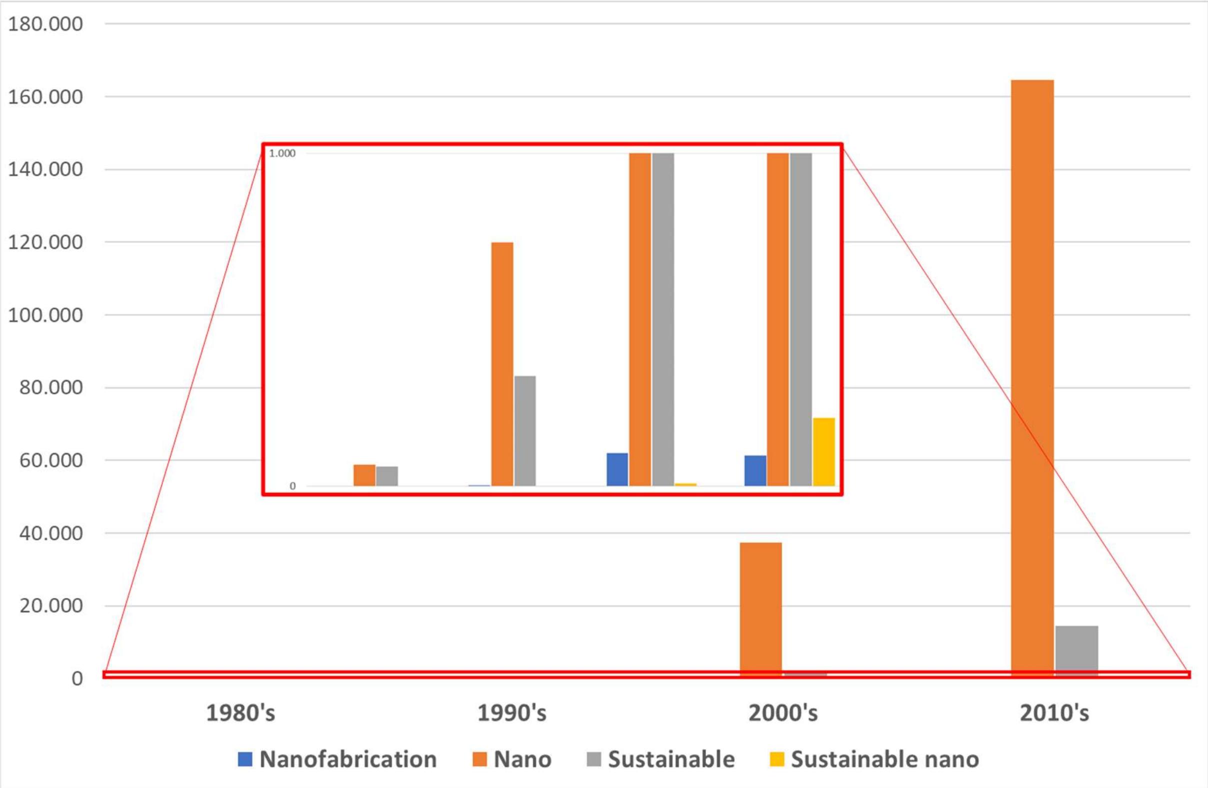

Figure 8. Evolution of keywords (present in the title or in the abstract) linked to sustainable nanofabrication in the "espacenet – worldwide" patent database (accessed: April 2021).

As described above, there is an increasing trend in the international community's interest in nanofabrication and sustainability, which supports the fact that nowadays nanotechnologies are an international subject for which every country (or group of countries) has its own initiatives. The vision of international collaboration on these topics including sustainability are further elaborated in the NanoFabNet project deliverables on EU and international collaborations (refer to the NanoFabNet publications '*NanoFabNet Strategy on EU Project Collaboration*' and '*NanoFabNet Strategy on international Cooperation*'). Some examples of relevant initiatives are listed below:

- the **National Nanotechnology Initiative** (NNI)[8]: created in 2000, this U.S. Government R&D initiative encompasses all nanotechnology-related activities of 20 departments and agencies (such as department of health and human services, as well as defence, energy, transportation, and justice). Its goal is to connect all the fields linked to nanotechnology in the same strategy: reaching a revolution in industry using nanoscience and -technology. The NNI's website (www.nano.gov) gives access to several sources of information as a map of R&D centres or possible graduation degrees in this field, as well as links to publications or educational resources.
- **The U.S.-EU Nanotechnology Communities of Research** (CORs)[9]: an international collaborative platform about environmental, health and safety (EHS – 7 CORs) and nanomedicine (1 COR). A COR on nanomanufacturing is under development.
- **The European Union Observatory for Nanomaterials** (EUON)[10]: an information website funded by the European Commission and hosted and maintained by the European Chemicals Agency (ECHA). From 2017, its website gives general information on nanomaterials (i.e. uses, safety) and lists the nanomaterials that are currently on the EU market (data collected from

8 NNI (National Nanotechnology Initiative) (website; accessed: April 2021).
9 US-EU CORs (Nanotechnology Communities of Research) (website; accessed: April 2021).
10 EUON (European Union Observatory for Nanomaterials) (website; accessed: April 2021).

REACH registrations, the Cosmetics Regulation as well as French and Belgian national inventories).

- **R-nano**[11]: Since 2013, France made it mandatory to declare every nanomaterial entering its territory (name, quantity, and use). This type of register was picked up and implemented by other EU countries (Belgium, Denmark, Sweden, and Finland) and is now regulated also by the EC using the REACH declaration extended to nanomaterials (European Commission, 2018).
- **The Thai National Nanotechnology Center** (NANOTEC)[12] is a Thai national collaborative agency involving 11 research networks on nanotechnology created in 2003 to conduct and support R&D, design, and engineering in nanotechnology, and transfer the technology to industrial and service sectors in a constructive manner to increase Thailand's competitiveness, promote social awareness and improve the quality of life and the environment. One of its missions is to identify and collaborate with strategic international partners.
- **The Australian Nanotechnology Network** (ANN)[13]: ANN was created in 2004 by four seed funding groups, to cover the broader areas and to create a larger more effective network.

As co-creation and stakeholder involvement from day one are fundamental parts of the NanoFabNet Project, the Project Team identified relevant stakeholders / stakeholder groups linked to sustainable nanofabrication and invited them to ongoing Project activities such as the workshops or surveys. These stakeholder groups encompass representatives from industry (i.e. both SMEs and large industry), academia, research organisations, regulatory bodies, national metrology institutes, standardisation bodies, and NGOs (Non-Governmental Organisation).

The main issues of sustainable nanofabrication highlighted by the stakeholders during the 1st NanoFabNet Development Workshop (DW), by ranking categories on their importance on this subject, are presented in Figure 9. The following sub-parts detail the categories considered to be of high importance: i.e. metrology/characterisation in association with the production processes, sustainability, training and standardisation. In addition, a point on infrastructures is presented.

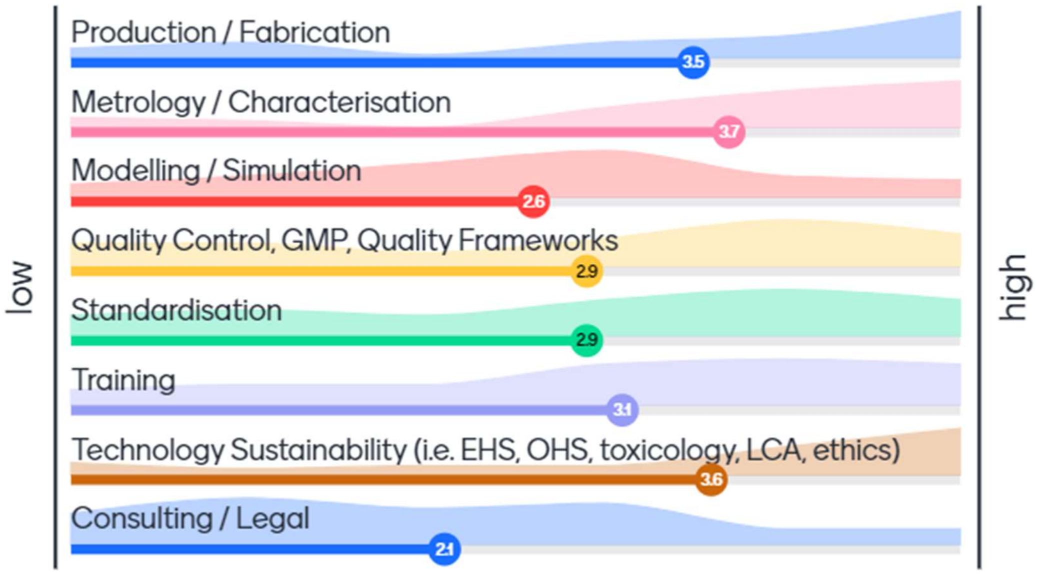

Figure 9. Stakeholders' answers attending the 1st NanoFabNet Development Workshop (March 2020) to the request "Please rank the following categories from 1 to 5 according to their importance to you / your organisation for nanofabrication/technology sustainability".

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[11] R-nano (website; accessed: April 2021).
[12] NANOTEC (Thai National Nanotechnology Center) (website; accessed: April 2021).
[13] ANN (Australian Nanotechnology Network) (website; accessed: April 2021).

4.2 Processing and Characterisation

During a breakout session on the topic of infrastructure and skills organised in the frame of the 2nd NanoFabNet DW (January 2021) most of NanoFabNet stakeholders showed an interest for characterisation (54%) before nanofabrication (42%) and synthesis of nanomaterials (4%). As presented in subsection 3.1, the term nanofabrication encompasses both top-down and bottom-up approaches to generate nanoscale structures by various manufacturing techniques (Rauscher *et al.*, 2014).

There is an important need for more reliable and comparable characterisation data to support nanofabrication development, validation, implementation, and scale-up. This requires harmonised and validated protocols (e.g. standard operating procedures (SOPs)) with validation of the protocols being realised by inter-lab comparisons, followed by proficiency testing of the labs to demonstrate the mastery of implementing these SOPs). To reach a high level of reproducibility, Eurolab[14], the European Federation of National Associations of Measurement, Testing and Analytical Laboratories, proposes to work according to the ISO 17025 general requirements for the competence of testing and calibration laboratories. Eurolab is based on scientific and technical cooperation between European laboratories sharing their experience and information, carrying out tests, calibrations, or analyses, since 1990. The main goal is to obtain reliable and comparative results by facilitating interlaboratory comparisons. Asked about participating in such interlaboratory comparisons to validate methods/SOPs, NanoFabNet stakeholders have massively, at 80%, given their agreement.

4.3 Standardisation

Standardisation and research & innovation (R&I) are always working in a closed loop; new materials, processes, characterisations methods are always invented and then need to be standardised to become international references. Since 1990, the field of nanoscience and nanotechnology is becoming a revolutionary technology, bringing new applications, new developments, and new standards.

Standardisation is the process of making something conform to a standard or a norm, by first, agreeing on a common vocabulary, then creating and following specific guidelines (accepted standard or a way of behaving or doing things) agreed by all. Using standards is important to make production/characterisation reproducible and to enable results comparisons. In nanofabrication and in sustainability, which are young fields, it is particularly important to implement relevant standard/norms to facilitate international communication and to have a better understanding of results.

Figure 10 presents the evolution of the available and updated guidance and standards produced by main standardisation bodies and governmental agencies (ASTM, CEN, EFSA, EC, IEC, ISO, JRC and OECD), related to sustainable nanofabrication for the past 15 years. This is not to be considered as an exhaustive search, but can be used to highlight a trend, where there is a constant increase in the number of "active" norms (more than 250 new norms on these subjects from 2006 to 2020). The trends for risk assessment and characterisations measurements are visualised more clearly in Figure 11.

[14] Eurolab (website; accessed: March 2021).

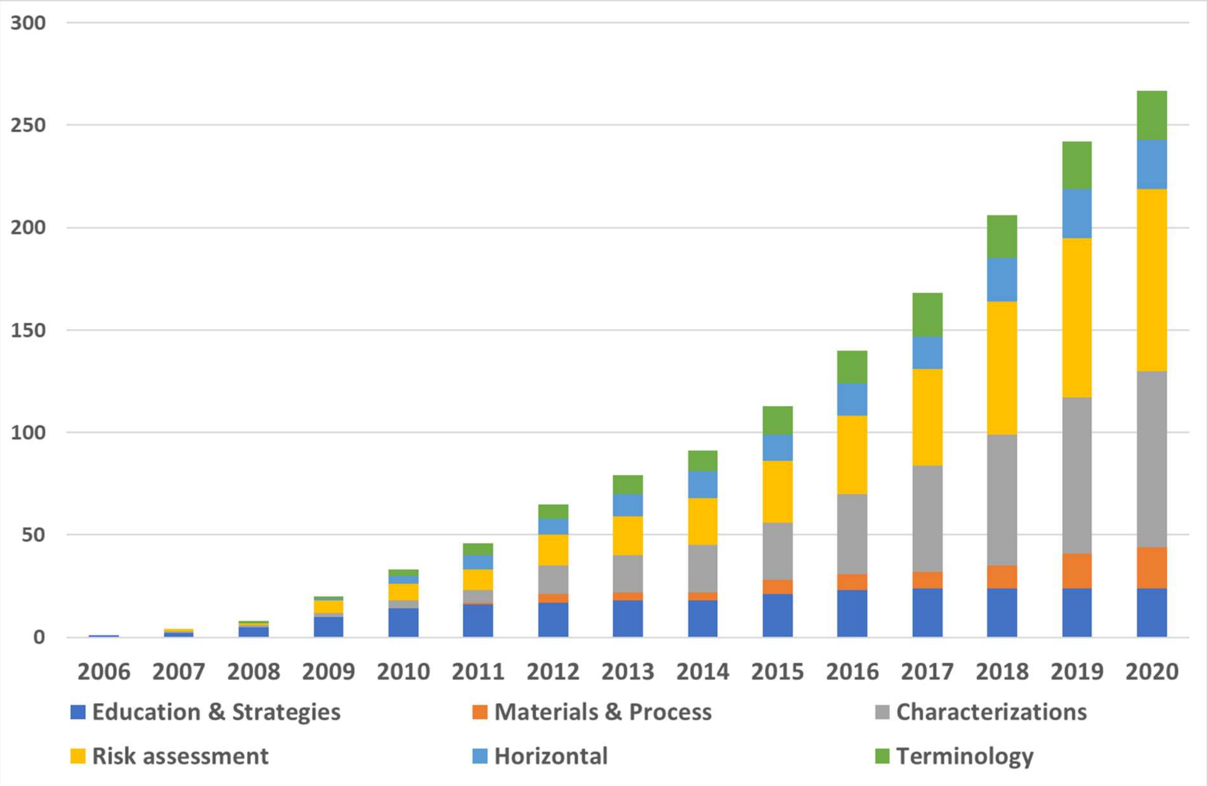

Figure 10. Evolution of the number of norms available linked to sustainable nanofabrication (sources: ASTM, CEN, EFSA, EC, IEC, ISO, JRC and OECD).

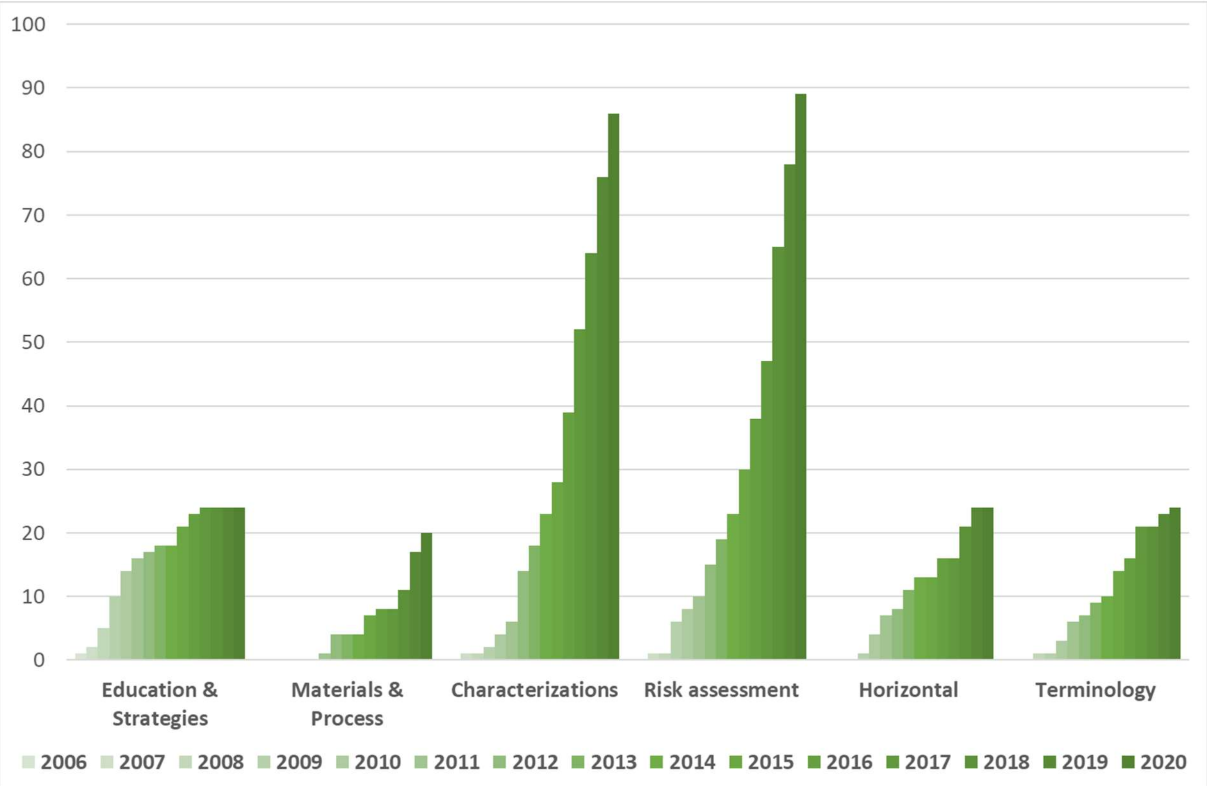

Figure 11. Evolution of the active norms in the past 15 years on different subjects linked to sustainable nanofabrication (sources: ASTM, CEN, EFSA, EC, IEC, ISO, JRC and OECD).

During the 1st NanoFabNet Development Workshop (March 2020), the stakeholders ranked the main issues for nanofabrication regarding their needs: validation, harmonisation, and standardisation aspects; below is the ranking order for the remaining aspects under consideration:

- reliability and quality: 7.1/10;
- safety (7/10);
- product design in terms of sustainability (6.9/10);
- regulatory requirements (6/10); and
- process design and control (5.9/10).

Stakeholders who responded to the NanoFabNet WP4 standardisation survey, overwhelmingly support an idea of developing additional standards and/or a labelling system on sustainability in nanotechnologies. They were also largely in favour of setting up a mechanism to demonstrate their knowledge and expertise on issues related to nanotechnologies, particularly in characterisation/metrology to improve the trust in the given results.

To go further on the topics of validation, harmonisation and standardisation, one can read the NanoFabNet *'Report on the Challenges & Opportunities in the Validation, Harmonisation & Standardisation of industrial-scale nanofabrication'.*

4.4 Sustainability

In the context of the European Green Deal[15], the plan to make the EU's economy sustainable, the EU aims to be climate neutral in 2050; to reach that goal, a European climate law was proposed in 2020 to set milestones to turn its political commitment into a legal obligation. This requires a joint action from all sectors of our economy, including investing in environmentally friendly technologies, buildings, energy, and transport, helping industry to innovate, and working with international partners to improve global environmental standards. Moreover, in 2015, the United Nations (UN) adopted 17 goals to be reached by 2030: the Sustainable Development Goals (Figure 12) in which sustainability is directly (e.g. 7, 11, 12, 13) or indirectly (e.g. 4, 6, 9) addressed. With less than 10 years to go, an ambitious global effort is underway to achieve these goals. The 2020s is now the "decade of action".

Figure 12. Sustainable Development Goals of the United Nations (source: https://sdgs.un.org/goals; accessed: July 2021).

15 EU – A European Green Deal (website; accessed: April 2021).

The United Nations Environment Program (UNEP) promotes resource efficiency and sustainable consumption and production (SCP) with the focus to achieve increased understanding and implementation of policies and actions, by decision makers and civil society. This includes the promotion of sustainable resource management in a life-cycle perspective for goods and services. In 2019, UNEP launched an online tool[16], known as the SCP Hotspots Analysis Tool, analysing the environmental and socio-economic performance of 171 countries since 1990. A link between UN SDG and LCSA was recently under investigation by the Life Cycle Initiative (hosted by UNEP) with the goal to achieve quantitative indicators (Weidema *et al.,* 2018 and Weidema *et al.,* 2020) to ease the vision of decision-makers and rationalise improvements in companies.

During the 2nd NanoFabNet DW held in January 2021, most of the stakeholders considered themselves as "learners" in the area of sustainability (22 learners, 7 experts and 4 with advanced knowledge) and the majority answered that life cycle assessment was, in their opinion, the most important topic in sustainability at present. This was followed by climate change, SDG, circular economy, health issues, as seen in the word cloud (Figure 13).

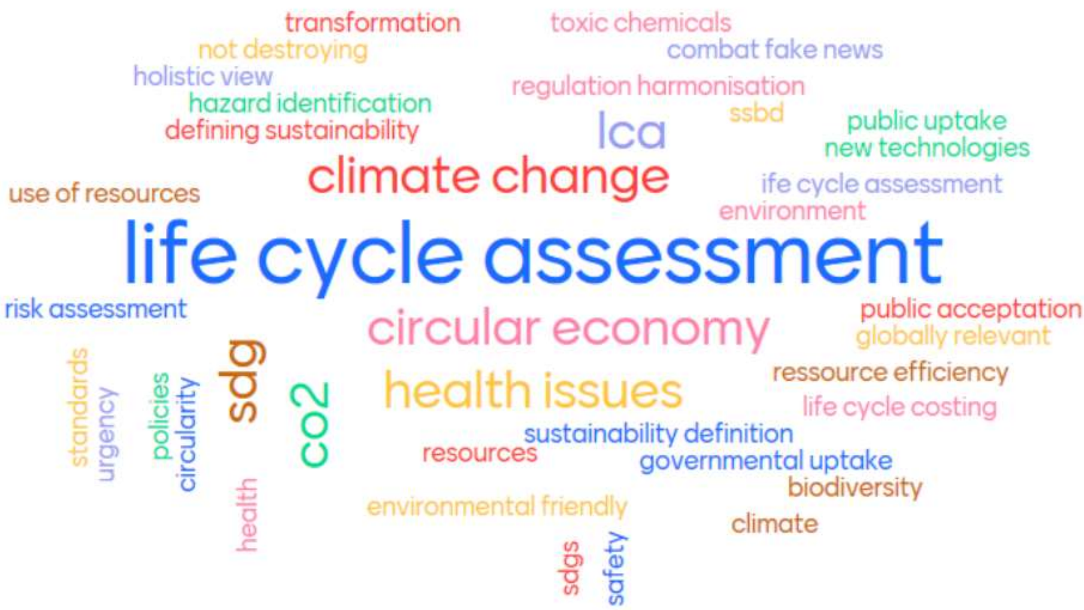

Figure 13. Word cloud of Stakeholders' answers attending the 2nd NanoFabNet Development Workshop breakout session on sustainability (January 2021) to the question "What are -to your opinion- the most important topics & issues in sustainability at present?".

At that time, the practical experience of the participants in relation to conducting a sustainability evaluation (see Figure 14) was either non-existent or limited to human or environmental risk assessment and to a lesser extent, life cycle assessment.

[16] SCP Hotspot analysis (website; accessed: March 2021).

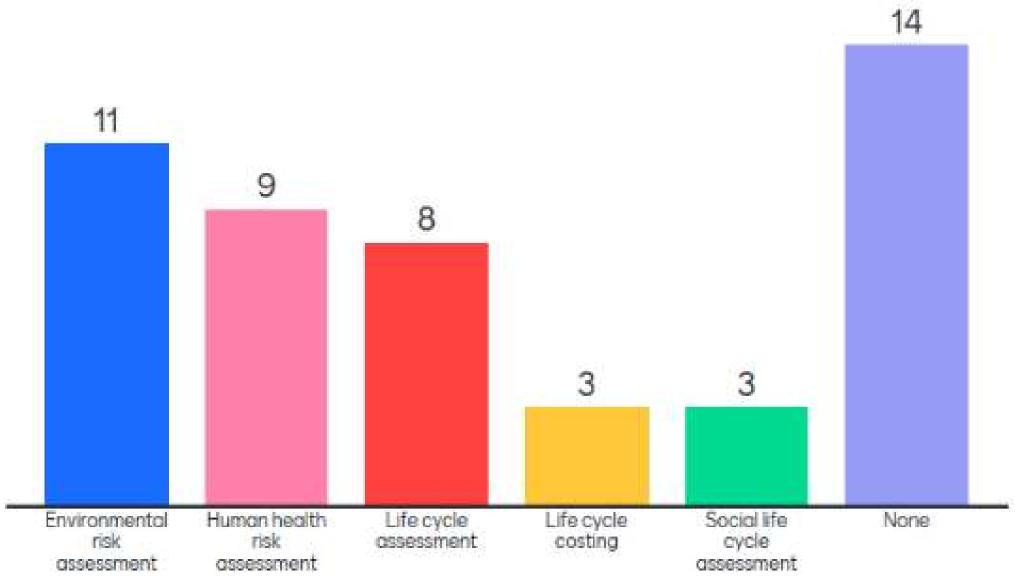

Figure 14. Stakeholders' answers attending the 2nd NanoFabNet Development Workshop breakout session on sustainability (January 2021) to the question "Have you already conducted one or more of the following evaluations?".

As outlined in section 3.3 above, sustainability is considered as a global entity dealing with three main pillars of EHS (Environment, Health and Safety), LCSA (Life Cycle Sustainability Assessment) and ethics and governance issues. An overview of these three pillars is presented in the following subsections.

4.4.1 Sustainability Area I: Environment, Health and Safety (EHS)

Nanomaterials can enter the human body through the skin, by ingestion or inhalation to reach the circulatory and lymphatic systems, and subsequently other tissues and organs. Because of their small size, nanomaterials have a larger surface area, which increases their chemical reactivity. Risk assessment frameworks follow a general process or method including the following four-step paradigm[17]:

- **hazard identification**: identification of hazards and risk factors, which can cause harm; a hazard is any source of potential damage, while risk is the probability that someone or something will suffer a dangerous effect if exposed to a hazard;
- **hazard assessment** (or dose-response assessment): identification and estimation of the effects induced by this hazard;
- **exposure assessment**: likelihood of exposure based on the measured or expected concentrations in humans and the environment; and
- **risk assessment**: conclusions on the level of risk.

The scientific basis of risk assessment for nanomaterials still suffers from substantial limitations, due to the lack of specific hazard information (depending on their chemical composition, surface and shape) and the constant new developments in this field (adding new materials to be evaluated). For a better understanding of these issues, it seemed necessary to improve the knowledge of the nanomaterials market, their uses, applications, quantities involved. Thus, the R-nano registry has been entered in force in France since 2013 (Decree no. 2012-232, 2012). The EC has then decided to include nanomaterials in the existing REACH regulation definition of a substance (European Commission, 2018) and has launched a mandatory declaration for manufacturers and importers of nanoproducts

[17] US EPA – The NRC Risk Assessment Paradigm (website; accessed: July 2021).

containing explicit legal requirements under REACH which entered into force in 2020. The documents "Working Safely with Manufactured Nanomaterials Guidance for Workers", published in 2014 by the EC (European Commission, 2014) and the employers' version in 2019 (European Commission, 2019), also highlighted the wide range of nanomaterials and the need to have a case-by-case approach in terms of safety forcing employers to undertake a specific risk assessment on each nanomaterial used.

- Some of the recent international initiatives regarding nanosafety and risk assessment of nanoproducts and nanotechnologies are presented below. With the fields of nanoscience and -technology being so wide (in terms of raw materials, processes, and applications), it is not possible to be exhaustive here.
- **A decision support system** (DSS) for risk management of engineered nanomaterials and nanoproducts called SUNDS was developed in the **SUN project** [18]. In situations where risks are not under control, the DSS proposes appropriate risk management measures (e.g. engineering controls, personal protective equipment) and provides information on the cost of implementing these measures. If the risks cannot be adequately controlled and no feasible alternatives can be found, a socio-economic analysis (SEA) can be performed to demonstrate that the benefits/risk ratio is positive.
- In 2009, the EC has mandated an expert group called "**Scientific Committee on Consumer Safety** (SCCS)" to provide opinions on health and safety risks of non-food consumer products and services. It regularly publishes scientific advice on the safety of nanomaterials in cosmetics. For example, in 2020 (SCCS, 2020), the following three substances used in cosmetics were evaluated by the committee: colloidal silver (nano), styrene/acrylates copolymer (nano) and silica, hydrated silica and silica surface modified with alkyl silylates (nano form); the results were the same across the board: *'the materials could pose a health risk to the consumer based on physicochemical, toxicological and exposure aspects considerations.'* The list of priority nanomaterials in the EC catalogue (2019) based on risk potential is accessible in Annex 1 of the document.
- The SCCS also published a guidance on the safety assessment of nanomaterials in cosmetics in 2019 (SCCS, 2019). They concluded that insoluble and persistent nanomaterials may pose a risk to the consumer as these types of nanoparticles may reach unintended sites in the body and interact with biological entities close to the molecular level.
- Another EC scientific committee, the **Scientific Committee on Emerging and Newly Identified Health Risks** (SCENIHR) published the "Opinion on the guidance on the determination of potential health effects of nanomaterials used in medical devices" (European Commission, SCENIHR, 2015). It concluded that the main risk lied in the potential release of free nanoparticles from the device during the time of exposure.
- In the same way, the FSANZ (Food Standard Australian New Zealand), a statutory authority in the Australian Government Health, also commissioned a group of experts called "**Scientific Nanotechnology Advisory Group** (SNAG)" comprising experts in the fields of nanosafety, pharmacology, nano-food technology, toxicology and nanometrology. Their work was peer-reviewed by external experts to make their conclusions the reliable. For example, in 2016 (Drew *et al.* (a) and (b), 2016), they concluded that:
    - Silicon dioxide, titanium dioxide and silver could be found in food at nanoscale;
    - There were no significant health risks for food grade materials;
    - There was no direct evidence of novel nanomaterials used in food packaging in Australia or New Zealand;

[18] SUNDS – Decision support system for risk assessment and management of nano(bio)materials used in consumer products and medical applications (website; accessed: April 2021).

  - There was no evidence from the literature of migration of nano-clay from packaging into food; and
  - The nanoscale nature of nanosilver (in packaging or food) was also not likely to be dangerous to consumers' health.

- The **NanoSafety Cluster** (NSC) is a community of the European Commission-funded projects, which was created in 2006. As of May 2021, it encompasses 23 ongoing projects including NanoFabNet. It is composed of a steering committee, a coordination group, a dissemination group and working groups working on different issues of safety in nanotechnologies: communication, training, and education; materials and standards; exposure and hazard assessment; models and tools for risk assessment; innovation and safer by design; data management.
- **The Malta initiative**[19] was launched in 2017 and involves EU members, the EC, ECHA (European Chemicals Agency), industry, and other institutions to request political and financial support to develop and modify OECD testing guidelines and guidance documents to ensure that nano-specific issues meet regulatory requirements.
- The report "**Nanosafety in Europe 2015-2025: Towards Safe and Sustainable Nanomaterials and Nanotechnology Innovations**" (Savolainen *et al.,* 2013) aimed to introduce a strategic vision for future research (2015-2025) on the safe use and safe applications of nanomaterials. It describes the current level of knowledge of nanosafety and the research needs and priorities in four main thematic areas: 1) nanomaterial identification and classification; 2) nanomaterial exposure and transformation; 3) hazard mechanisms related to effects on human health and the environment; and 4) tools for the predictive risk assessment and management including databases and ontologies.
- In the US, the **Food & Drug Administration** (FDA) aims to regulate nanotechnology products by applying a science-based, product-focused regulatory policy. The FDA has issued for example guidance documents for the use of nanomaterials in the cosmetic and animal food industry (FDA, 2014 and FDA, 2015).
- In 2006, the OECD (Organisation for Economic Co-operation and Development) created the **Working Party on the Safety of Manufactured Nanomaterials** (WPMN) to promote international cooperation in human health and environmental safety issues of nanomaterials to develop safety evaluation of nanomaterials. The OECD has published a "Series on the Safety of Manufactured Nanomaterials" which is currently at number 97. This last publication (OECD Environment, 97, 2020) presents a tour de table on the developments in various delegations (for example France, European Union, Korea, Thailand United States, depending on the discussed subject such as: national development on human health and environmental safety, good practices documents, Integrated Approaches to Testing and Assessment (IATA), Safe-by-Design and/or other anticipatory strategies. Number 96 of this series (OECD Environment, 96, 2020) dealt with "moving Towards a Safe(r) Innovation Approach (SIA) for More Sustainable Nanomaterials and Nano-enabled Product" which combines the safe(r)-by design concept and the regulatory preparedness concept.

[19] Malta Initiative (website; accessed: March 2021).

- The **Safe-by-Design (SbD) concept** is becoming more and more popular nowadays and is applied in several recent research projects (NanoReg[20], ProSafe[21], Serenade labex[22], NanoReg2[23]). It aims to identify and reduce risks and uncertainties of nanomaterials on human health and environmental safety from the design stage of a product by optimising the risk/benefit ratio, considering the entire life cycle (from the manufacturing of an industrial product to its end of life). It is thus necessary to know the characteristics that influence the toxicity of nanomaterials and their biodistribution. The modification of the size, the structure or the surface can be important parameters to limit the risks. However, given the current state of knowledge on the evolution of nanomaterials during their life cycle, it is not possible to ensure that this approach can be an absolute guarantee against the risks associated with nanomaterials. Nanomaterials differ from each other in composition, size, shape and even in the route of exposure. It is therefore complicated, if not impossible, to propose a systematic Safer-by-design method: it must be implemented.

4.4.2 Sustainability Area II: Life Cycle Sustainability

Over the years, the evolution of international economy went from a linear to a circular approach introducing life cycle thinking and a global reflexion on reducing environmental impacts. The United Nations (UN) recently proposed a novel life cycle[24] representation, introducing a link with a circular economy (Figure 15).

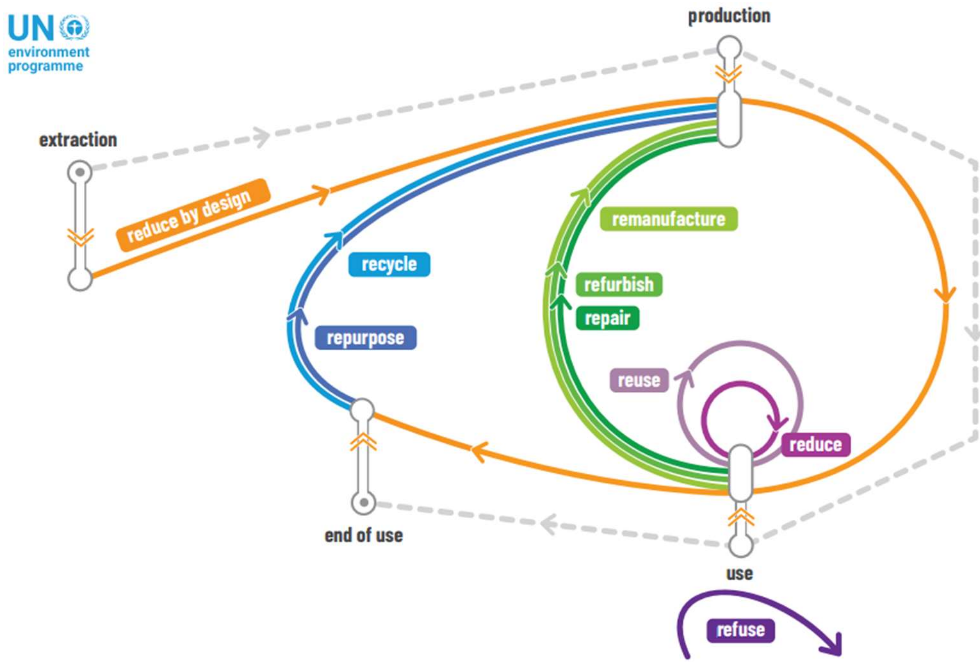

Figure 15. Representation of the possible link between life cycle approach (in grey) and circular economy proposed by the UNEP circularity platform (source: UNEP/SETAC 2009).

[20] NANoREG: Gottardo *et al.*, NANoREG framework for the safety assessment of nanomaterials, EUR 28550 EN, doi 10.2760/245972.
[21] PROSAFE – H2020 project: Promoting the implementation of Safe-by-Design (website; accessed: March 2021).
[22] Serenade Labex: Towards safer and eco-designed innovative nano-materials (website; accessed: March 2021).
[23] NanoReg II – H2020 project: Development and implementation of Grouping and Safe-by-Design approaches within regulatory frameworks (website; accessed: March 2021).
[24] UNEO Circularity Platform (website; accessed: February 2021).

When it comes to evaluating the sustainability of products and processes, Life Cycle Sustainability Assessment (LCSA) is a holistic, multistep and multicriteria method that enables the evaluation of impacts of the production, use and disposal of a system in a global perspective. LCSA encompasses three disciplines Life Cycle Assessment (LCA), social LCA (s-LCA) and Life Cycle Costing (LCC) evaluating respectively environmental, social and economic impacts, all following the subsequent steps: 1) Definition of the goal and scope; 2) Inventory analysis; 3) Impact assessment; 4) Interpretation.

The **LCA (Life Cycle Assessment)** methodology is science-based and framed by the ISO standards 14040[25] and 14044[26]. The methodology has the specificity to evaluate the environmental impact of a system by including the upstream and downstream impacts in the boundaries of the assessment. By doing so, the methodology allows the analyst to: (a) compare the environmental impact of different steps of a studied process, (b) identify the steps which could be improved, and (c) avoid environmental impact shifting from one step to another.

Accidental or deliberate release of nanomaterials into the environment can occur from point sources such as production facilities, landfills and wastewater treatment plants or from wear and tear of materials containing nanoparticles. Whether the particles are released or not, they all eventually end up in soil or water, either directly or indirectly (considered as emissions in an LCA analysis).

There are still challenges in the way LCA addresses nanomaterials. The first challenge is to implement relevant datasets in the LCA databases describing the production of nanomaterials that can be used as inputs in models for systems using them. At this time, there are not enough references in the most complete and used LCA databases such as Ecoinvent[27] or GaBi[28]. A growing corpus of LCA literature offers some description of nanomaterials production, but in most cases the life cycle inventories are not detailed enough to make them reproducible (and therefore usable) by other researchers or LCA practitioners, and the results provided in terms of calculated impacts are also poorly reusable for other purposes. There are still studies providing detailed inventory data but they are often based on lab-scale production. Basically, LCA practitioners cannot use readily available datasets for the production of nanomaterials, and therefore need to rely on literature data, where the relevance and reliability of the available data should be carefully evaluated. And yet, when studies include the integration of nanomaterials in products, it often appears that the contribution of those nanomaterials to the cradle-to-gate or life cycle environmental impacts of the latter products would be high compared to the mass proportion. This clearly shows that providing sound and realistic life cycle inventories to produce commercial nanomaterials to LCA databases would be a very relevant objective.

The second challenge is linked to the evaluation of the impacts that can be associated with the release of nanomaterials into the environment. It is suspected that human health and ecotoxicity effects could be linked to release of and exposure to some – if not all – nanomaterials. However, characterisation factors are still missing to link nanomaterials emissions to potential health or ecotoxicity impacts in LCA indicators. There are several reasons for that. The first reason is obviously that in some cases these effects are not known, or not perfectly known, yet. Research is of course needed in that field and strongly depends on the progress in the field of nanoparticles characterisation, fate, exposure, human toxicity and ecotoxicity modelling. Another reason is that the way LCA relates emissions of substances to environmental or health indicators relies on very simple arithmetic: the effect of (A+B) equals the sum of the separate effects of A and B, and the effect of 2 kg of carbon emitted is twice the effect of 1 kg of carbon emitted. This effect is a linear relationship, but it may not apply in most cases for nanomaterials, in which surface area and shape are more likely to determine the effect than mass. In recent years, attempts have been made by several authors (Walser *et al.,* 2011; Hischier *et al.,* 2015; Pini *et al.,* 2016; Tsang et al., 2017; Buist *et al.,* 2017; Ettrup *et al.,* 2017; Salieri *et al.,* 2018) to provide

[25] ISO - ISO 14040:2006 - Environmental management — Life cycle assessment — Principles and framework.

[26] ISO - ISO 14044:2006 - Environmental management — Life cycle assessment — Requirements and guidelines.

[27] Ecoinvent database (website; accessed: February 2021).

[28] Gabi database (website; accessed: February 2021).

characterisation factors for nanomaterials emissions that can be used with the consensus method for toxicity/ecotoxicity impact calculation in LCA (USEtoxTM). However, it seems that the determination of characterisation factors would have to be very case-specific, and those provided so far have not yet been implemented in the calculation methods provided with LCA software and will hence rarely be used by LCA practitioners. There is therefore a large opportunity for research to provide appropriate characterisation factors.

Social LCA (s-LCA) assesses social and sociological impacts found along the life cycle chain through information on social conditions during production, use and disposal of a product, but it does not answer the question of whether a product should be produced or not (UNEP/SETAC, 2009).

Life Cycle Costing (LCC) is a method for evaluating all relevant costs over time of a project, product or service. It takes into account the initial costs, including capital investment, purchase and installation costs; future costs (e.g., energy, financing, maintenance); and any resale, salvage, or disposal cost, over the lifetime of the product. The basis for this assessment is to collect the data throughout all life cycle stages and sum them up regarding the entire system cost at total and annual levels, in accordance, for example, with a methodology developed by the SMART SPP[29] European project and then recommended by the European Commission (European Commission, 2017). This project has created and tested a tool to help decision-makers by calculating the life cycle costs (LCC) and CO_2 emissions of different products and services.

The recent developments of sustainable nanofabrication encompass a global reflexion including safety and risk assessment for both the environment and for humans. In 2018, Windsor *et al.* (Windsor *et al.,* 2018) reviewed the tools for the sustainability assessment of nanomaterials and concluded that multi-criteria decision analysis was the best way to cover all aspects of sustainability including environmental impacts, environmental risk assessment, human health risk assessment, social implications, economic performance as well as technical performance because it was easier to understand by all.

In the 2021 report "Mapping study for the development of sustainable-by-design criteria" (Amodio *et al.,* 2021), the EC presents an overview of the existing sustainability criteria initiatives, in particular the sustainable-by-design concept including a focus of its development in the field of nanomaterials. The "sustainable-by-design" concept is a global model integrating safety, circularity, energy efficiency and functionality of chemicals, materials, products, and processes issues along life cycle to reduce the environmental footprint.

To go further in the sustainability aspect, a new approach is emerging amongst the European policies[30, 31] and projects (e.g. the H2020 project SUNSHINE - Safe and sUstainable by desigN Strategies for HIgh performance multi-component NanomatErials): to combine the safe-by-design concept (cf. subsection 0) and the sustainable-by-design concept into the Safe and Sustainable by Design (SSbD) approach to develop technologies that are safe and sustainable both to human and environmental health, whilst also retaining the desired functionality for their intended uses. The European Chemical Industry Council (CEFIC) has proposed numerous criteria which should be incorporated in a SSbD approach (Figure 16). The plan of the EC is to further develop these criteria by 2022 supported by different stakeholder interaction formats, e.g. like the recently organised first stakeholder workshop 2021[32].

[29] SMART SPP project (website; accessed: April 2021).
[30] CEFIC (European Chemical Industry Council), Safe And Sustainable-By-Design (website; accessed: April 2021).
[31] EEA (European Environment Agency), Designing safe and sustainable products requires a new approach for chemicals, 2021 (website; accessed: April 2021).
[32] Safe and Sustainable-by-Design criteria for chemicals, materials and products - First Stakeholders workshop, March 2021, European Commission (website; accessed: March 2021).

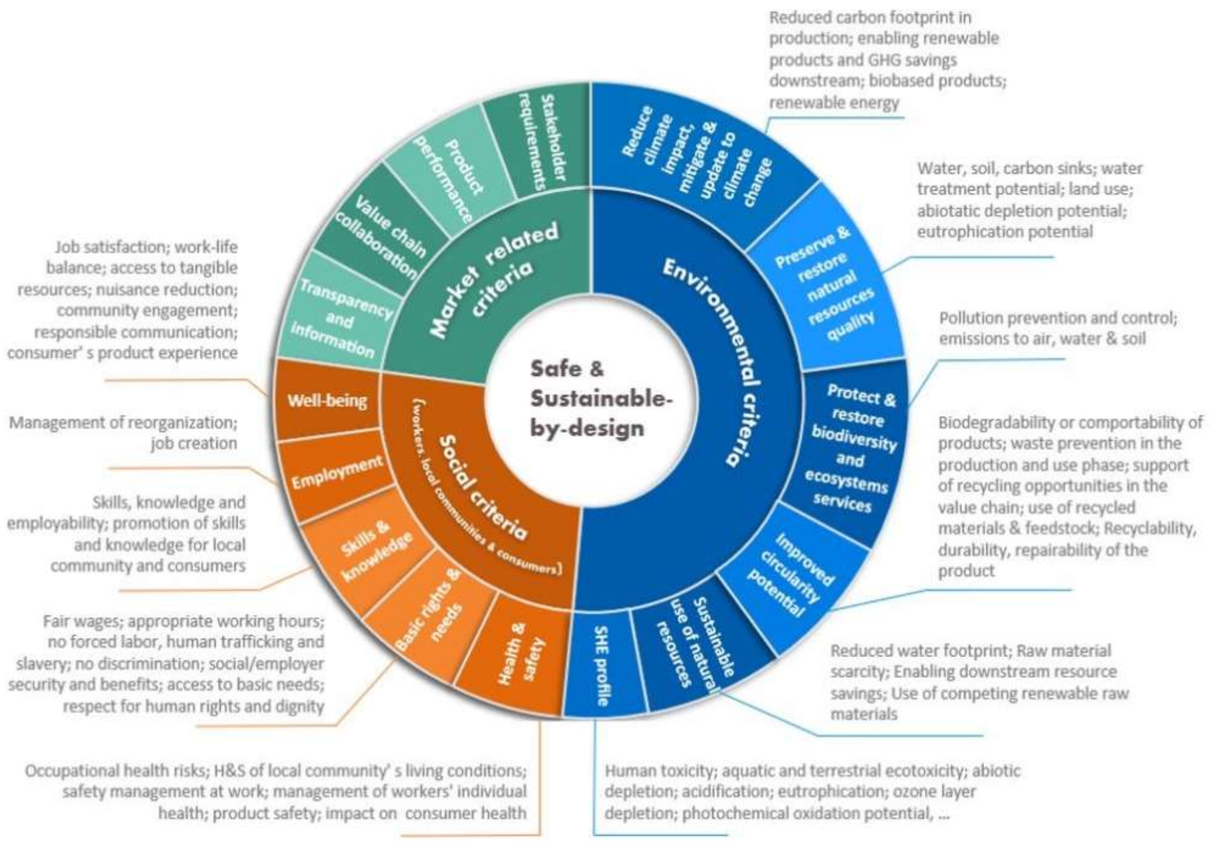

Figure 16. Representation of the ongoing development of SSbD criteria by CEFIC (source: https://cefic.org/a-solution-provider-for-sustainability/safe-and-sustainable-by-design/).

An important link between risk assessment and LCA is highlighted in number 57 of the OECD series on the Safety of Manufactured Nanomaterials (Semenzin *et al.,* 2019 and OECD, 2015). Indeed, to perform the LCA of a product, in particular a novel technology, such as nanomaterials, information on risk assessment (e.g. toxicology, ecotoxicology) is needed. This guidance manual also provides an overview of the datasets available for risk assessment and LCA of nanomaterials, showing that more work needs to be performed; based on this, an action to improve and facilitate the international scientific dialogue in the field of life-cycle aspects of manufactured nanomaterials needs to be done.

4.4.3 Sustainability Area III: Ethics and Governance

A state of the art of the various disciplines related to ethics and governance of nanotechnology and nanofabrication has been proposed in the deliverable D2.1 of the NanoFabNet Project. Here only the main features of the ethics and governance landscape are presented; the reader is encouraged to consult D2.1 for more additional details.

“Ethics” is the philosophical discipline dealing with the evaluation of human conduct. “Governance” in general relates to the collective definition of goals and political priorities (or of trajectories of technological development and innovations) by a large number of actors in contemporary societies.

Nanotechnology and nanofabrication have been concerned with some ethics and governance issues from the beginning of their story. The diversity of their applications (be it in medicine, in ICT (Information and Communication Technologies), in energy and environment, in consumer products, to name but a few) has the potential to give rise to a wide array of ethical and societal issues including questions of privacy, autonomy, social divide, dual use, environmental justice, and human enhancement, to name but a few. Due to their ability to prompt hopes and fears, their development has also met a strong social opposition in some countries, leading to consider public acceptance, public trust and public engagement as key elements of their governance.

In response to this situation, diverse experiences of public engagement related to nanotechnology have been carried out in Europe and worldwide for twenty years, including research-initiated dialogues, industry-initiated dialogues, CSO-initiated dialogues, national governmental events, European initiatives. It is common to distinguish upstream engagement initiatives at the policy level, midstream engagement related to R&D practices, and downstream strategies such as communication, outreach, education or training particularly developed in the U.S. (Porcari & Mantovani, 2015; Laurent, 2017). Some scholars plead today for the reinvention of public engagement practices in more experimental, reflexive, anticipatory, and responsible ways (Chilvers & Kearnes, 2020).

The development of nanotechnology in Europe has been addressed from a decade under the general umbrella of Responsible Research and Innovation (RRI). RRI includes the broad concepts of anticipation, reflection, inclusion, deliberation, responsiveness, precaution, vigilance, collective co-responsibility (Shelley-Egan *et al.*, 2018), and is claimed to guarantee ethical acceptability and orientation towards societal needs of Research and Innovation. The implementation of RRI can currently be appreciated at the macro-level of national policies, the meso-level of the shaping of funding programmes and of the soft regulation of industrial practices, and the micro-level of the direct integration of RRI into R&D practices of individual organisations (Shelley-Egan *et al.*, 2018). In this regard, Europe adopted, as early as 2008, a Code of Conduct intended to guide Research in Nanosciences and Nanotechnologies in a responsible manner (European Commission, 2008).

As a result of all these steps and attempts, the ethical discussion has gained in expertise over the years and has focused on applications rather than on the “nanotechnology project” as such. The general attitude of the general public towards nanotechnology is still fuelled by a great deal of ignorance (and irrational fears still sometimes arise, as evidenced by the recent controversies surrounding the nanoparticles present in mRNA vaccines against Covid 19). The world situation is marked by a great heterogeneity, owing in particular to cultural differences in the appreciation of ethical questions (Dalton-Brown, 2015).

During the 2nd NanoFabNet DW breakout session on ethics, the NanoFabNet stakeholders have answered that they were mainly (77%) personnally concerned by some ethical issues in the context of their activities related to nanotechnologies and nanofabrication. They added, by ranking the sentences, that concerning these issues, the most corresponding sentence, is that “some of them deserve to be further debated” before “most of them can be resolved with a little bit of common sense” and “the available tools are sufficient to resolve them”; this highlights that there is work that is still to be done in the field of ethics in nanofabrication.

To the question “which are your ethical issues in a few words?”, even if the word cloud (Figure 17) is tough to read at first sight, sustainability issues, in the broadest sense of the term (including environmental, human (and animal) health as well as social and societal aspects), are the main mentioned topic. Furthermore, asked about the social input weight, that should be involved in the developments of nanotechnologies and nanofabrication, 47% of the stakeholders think it should have a voice in any important decision, 33% answered they must be regularly informed and 20% believe they can help orientate them; outlining again the importance the stakeholders put into social aspects.

Figure 17. Word cloud of Stakeholders' answers attending the 2nd NanoFabNet Development Workshop breakout session on ethics (January 2021) to the question "Which are your ethical issues in a few words?".

4.5 Training, Education, and Skills

Since nanoscience and -technologies encompass a wide domain, various skills are needed: mainly scientific, but also in a large range of processes (e.g. fabrication, synthesis, production), characterisation, risk assessment, and safety management, but also, non-scientific (e.g. policies, communication) (Malsch, 201[4]) inducing trainings from an outreach to expert levels and interdisciplinary approaches. For this reason, the following part presents some recent initiatives only.

- In Europe, the **European Commission** has been integrating nanotechnology education in its policies since 2004 (European Commission, 2004) leading to an action plan for 2005-2009 (European Commission, 2009). More recently, the EC started operating a green and digital transition as mentioned in its "European skills agenda for sustainable competitiveness, social fairness and resilience" published in June 2020. In this document, the EC wants to strengthen the competitiveness of Europe by improving skills and long-time learning. The main purpose is to unite all the countries to the same goal of a climate change, circular economy, and efficient society.
- In March 2020, the **New Circular Economy Action Plan and the EU Biodiversity Strategy for 2030** (European Commission, 2020) also highlighted the key role of skills in the green economy transition. The EC proposed to develop a European competence framework for researchers and support the development of a set of core skills for researchers.
- The **U.S. Nanohub** website[33] (launched in 2002 by the NCN: Network for Computational Nanotechnology) presents an open database of nanoscale science and engineering education resources. Its purpose is to ease the teaching and learning of this field by sharing content (e.g. workshops, publications, courses on this subject).
- The **Sustainable Nanotechnology Organization** (SNO)[34] is a non-profit, worldwide professional society focusing on research, education and responsibility. Its missions are to improve the society, the environment and the human health by supporting the development of sustainable

[33] Nanohub (website; accessed: March 2021).
[34] SNO (Sustainable Nanotechnology Organization) (website; accessed: March 2021).

nanotechnology, promoting the advancement, application and implementation of its scientific research and provide a related forum.

Fortunately, over time, more and more trainings have become available, delivered by academic courses, research projects with focus on different aspects of sustainable nanofabrication or even by open online platforms such as edX[35] (course on "Micro and Nanofabrication (MEMS)" available on the 30.07.2021 for example).

Stakeholders, who attended the breakout session on Infrastructure & Skills during the 2nd NanoFabNet DW, were mainly interested in trainings and skill transfer (44%) followed by provided expert services (31%) or access to instrumentation (25%).

Two deliverables are scheduled in the NanoFabNet Project to identify competences and to propose a strategy & implementation roadmap on Infrastructures, knowledge and skills (i.e. *'Nanofabrication Competence Map for (the Sharing of) Infrastructures, Knowledge & Skills'* and *'NanoFabNet Strategy & Implementation Roadmap on Infrastructures, Knowledge & Skills Development'*).

4.6 Infrastructures

Nanofabrication requires expensive equipment and infrastructures. Therefore, there is an important need for knowledge/skills and infrastructure sharing within the nanofabrication community. As shown in subsection 4.1, some initiatives have been launched to address these aspects but were mainly limited to a national or continental scale. The current goal is to expand these activities by collaborating at an international level.

The EUROnanoLAB[36] network, launched in 2017, is one of these initiatives that had arisen to meet these needs. It is a distributed research infrastructure consisting of over 40 state-of-the-art academic nanofabrication centres across Europe who want to accelerate nano research by becoming a central hub coordinating user to equipment and expertise in nanotechnology. EUROnanoLAB was inspired by the U.S National Nanotechnology Infrastructure Network (NNIN)[37] which has now become the National Nanotechnology Coordinated Infrastructure (NNCI)[38], its core partners are cleanrooms. Its website presents an interactive map of nanofabrication centres and its collaboration with Nanotech (Japan), NNCI (US), ANFF (Australia). The main Key Performances Indicators (KPI) for this network are presented in Figure 18. The NanoFabNet aims to support the EUROnanoLAB initiative through synergies and widening international links, as found appropriate.

[35] EdX (website; accessed: July 2021).
[36] EUROnanoLAB (website; accessed: April 2021).
[37] NNIN (U.S National Nanotechnology Infrastructure Network) (website; accessed: February 2021).
[38] NNCI (National Nanotechnology Coordinated Infrastructure) (website; accessed: February 2021).

Figure 18. Main KPIs of EUROnanoLAB (source EUROnanoLAB[36])

In Europe, the "poles of Excellence" dedicated to infrastructure correspond to giving researchers an easy access to facilities and resources (e.g. equipment, instruments, or even pilots to bring R&D to an industrial scale). They can be founded at a regional, national, or European level (European Commission, 2004).

During the 2nd NanoFabNet DW breakout session on infrastructure and skills held in January 2021, most of the NanoFabNet stakeholders answered that they are either users or providers of research or industrial infrastructures and are interested in both these subjects. They also claimed to be looking for instruments database and access procedures in research infrastructure. The stakeholders informed us that they mainly follow colleagues' recommendations (50%) or professionnal networks or databases (42%) when looking for infrastructure for possible collaboration.

5. Common Challenges & Opportunities in sustainable Nanofabrication – Needs to be met and Changes in Progress or foreseen

The observation made in 2015 by Mata et al. (Mata *et al.,* 2015) that the lack of knowledge on the impacts of nanomaterials on human health and the environment is unfortunately still relevant (Savolainen *et al.,* 2013) and is still making nanotechnologies hard to understand for decision makers in an environmental, societal and economical point of view, as new nanomaterials and nanoproducts are constantly emerging.

For the NanoFabNet stakeholders, there is not only one challenge to take up but several to improve the development of nanotechnology/nanofabrication and ensure that they can serve a better future (Figure 19). Even if only single answers can be found in the word cloud associated to this question, three main challenges can be highlighted:

- **Communication at every level** (e.g. public society to policy makers through researchers, industrials) to inform the whole society on the field of nanofabrication
- Sustainability compliance
- Standardisation and clear guidelines

Figure 19. Word cloud of Stakeholders' answers attending the 2nd NanoFabNet Development Workshop breakout session on ethics (January 2021) to the question "How to improve the development of nanotech/nanofabrication and ensure that they can serve a better future?".

Comparing these inputs to the literature highlights seven main challenges to be achieved:

1. ***International collaboration network***: It combines international collaboration on scientific results in an interdisciplinary way, inclusive networking and collaboration involving civil society organisation, industry, research, governance as equal partner, responsible governance, and public acceptance by a mass dissemination to reach public awareness. In NanoFabNet, two deliverables related to collaboration on a European and international level will be elaborated: *'NanoFabNet Strategy on EU Project Collaboration'* and *'NanoFabNet Strategy on international Cooperation'*.

2. ***Technical developments***: The purpose here is to develop new methods (of investigation, synthesis, or manufacturing) or experimental and predictive tools (for exposure and toxicity for example) to obtain accurate materials and measurements. For R&I issues, the main challenge is to keep improving the properties of the nanomaterials and nanoproducts while adding sustainability aspects by finding alternative materials requiring less energy or less toxic substances, as well as finding new approaches to process them more sustainable. There is also a lack of in-line characterisation techniques at the nanoscale. Validated standard operating procedures (SOPs) for in-line, rapid, and inexpensive nanoscale metrology techniques need to be developed.

3. ***Guidelines and standards***: First, a standardisation regarding vocabulary related to nanofabrication equipment and processes as well as a guidance on how to classify nanofabrication equipment and processes (taxonomy issue) are needed for the stakeholders. Then, an efficient dissemination of these documents will have to be implemented to increase stakeholder awareness. Moreover, harmonisation and guidance are still needed to describe process steps (e.g. which parameters to control for each process), appropriate measurands, tools, sustainability (and in particular for nanotechnologies), nanosafety, to allow interoperability between different nanofabrication stakeholders and to obtain comparable and more reliable results. However, to face the quantity of new materials and the required testing and screening (of toxicity or ecotoxicity for example) new methods/standards and prediction methods are needed. There is also a difference of maturity of standards for lab and industry scale. Upscaling issues have to be taken into account.

4. ***Increase funding***: As nanotechnology development is still on the rise, investment and public funding are important to be able to work in the best way to reach the goal of an economic-nano-revolution which is at the same time safe and sustainable, with focus on upstream concepts, fundamental research, as well as new methods.

5. ***Infrastructure***: Even if some structures have emerged, there is still a demand for the development of a comprehensive world-class infrastructure which can fulfil the needs of both industry and academia. These high-performance facilities would be integrated centres for a more efficient and responsible transition. Nano-inspired solutions require physical infrastructure and skilled people. Nanofabrication, especially *via* top-down approaches requires expensive equipment and cleanroom facilities. The research field is historically rooted in microelectronics and electrical engineering, however, nowadays nanofabrication is becoming more and more multidisciplinary; the researchers are coming from different fields, such as physics, chemistry, life sciences, mechanical engineering, and bioengineering. Harmonisation of terminology, technology and needs together with skills training and knowledge transfer between all these research fields using nanofabrication facilities is needed do advance research and technology transfer.

6. ***Education/skills***: An interdisciplinary education would be a huge asset to ease technology and knowledge transfer. A lack of structure for training, and information on safety, risk assessment, LCSA, ethics and governance related to nanotechnology and nanofabrication can be underlined. There is also an important need for the implementation of a specific database for all the fields of sustainable nanofabrication: risk assessment and management, allowed nanomaterials, available and under development standardisation documents, dissemination of good practices, safety issues or even cost/benefits studies.

7. ***Sustainability***: Concerning sustainability issues for our stakeholders, the main issues to be considered are environmental impacts, environmental and human health risk assessment, then social implications and economic and technical performance. All these fields have important challenges to meet.

   a. ***Nanosafety/risk assessment***: As the case-by-case approach is currently the recommended standard to address nanosafety issues, a lot of work is still to be done.

Indeed, it is very important to improve the international knowledge on several fields: bio-nano-interactions, hazard assessment (e.g. needs in terms of key descriptors and of dose metrics), understanding of release and exposure, process-dependent transformation, environmental mobility, transport, effects of ageing), and biokinetics. There is also a lack of predictive tools which would allow to accelerate nanosafety, LCSA and risk assessment. That is why current projects (such as GRACIOUS[39] or PATROLS[40]) are working on more general approaches to group/rank nanomaterials for risk assessment.

b. ***LCSA***: An improvement of the LCSA databases on issues of nanomaterials would be beneficial to improve and speed up the sustainability evaluation. To do that reliable toxicology/ecotoxicology data are needed.

LCA: Accounting for nanomaterials' inclusion in products and/or exposure to released nanomaterials in LCA studies is for the moment very difficult because of 1) the lack of inventory data describing the production of nanomaterials and 2) the lack of characterisation factors that would link nanomaterial emissions to environmental indicators. There is a need for the constitution of a nanomaterials' life cycle inventory or eco-profile database, research for adaptation of the impact calculation methods to the nanospecific environmental effects and for research for feeding available or future impact calculation methods with characterisation factors for nanomaterials emissions (and therefore prior determination of toxicity parameters and exposure scenarios).

c. ***Ethics and governance***: The challenges related to ethics and governance in the context of the development of nanotechnology and nanofabrication development are:

- The need to progress in ethical assessment methodologies, and in particular the need to adapt already existing ethical assessment methods and standards to the stakes of nanotechnology and nanofabrication (e.g. SATORI project 2017).
- The need to promote a better integration of ethical and societal considerations in the development of research and innovation under the general RRI framework. This undoubtedly requires the development of more targeted and more operational ethical guidelines, and the adaptation and specialisation of the previously mentioned European Code of Conduct (European Commission, 2008).
- The need to adapt the requirements currently promoted by Europe to the specificities of nanotechnology and nanofabrication in terms of research integrity, as expressed in particular in the European Code of Conduct for Research Integrity (Allea, 2017).
- The need to organise and to extend (both locally and internationally) the public debate around nanotechnology and nanofabrication, in a continuous process in real contact with developments of research and of innovation.

During the last years, several European projects such as SATORI[41] and SIENNA[42] have partly addressed these issues related to ethics and governance. The TechEthos[43] project is currently also addressing these issues and therefore a potential interaction partner for the NanoFabNet.

[39] GRACIOUS – H2020 project (website; accessed: July 2021).
[40] PATROLS – H2020 project (website; accessed: July 2021).
[41] SATORI: Stakeholders Acting Together On the ethical impact assessment of Research and Innovation (website; accessed : July 2021).
[42] SIENNA – H2020 project (website; accessed: July 2021).
[43] TechEthos – H2020 project (website; accessed : July 2021).

d. **Safe-and-Sustainable-by-Design (SSbD) approaches**: Even if the Safe-and-Sustainable-by-Design (SSbD) concept seems to combine both safety and sustainability issues into all development stages of new nanomaterials and their applications (Figure 20), it has to overcome some challenges, such as defining additional cost for technical and human resources, the lack of knowledge and data gaps, inadequate legislation (lack of regulatory process to support SSbD for nanomaterials), cultural changes concerning the responsibility of the innovator/manufacturer and an effective collaboration throughout the life cycle of the nanomaterial.

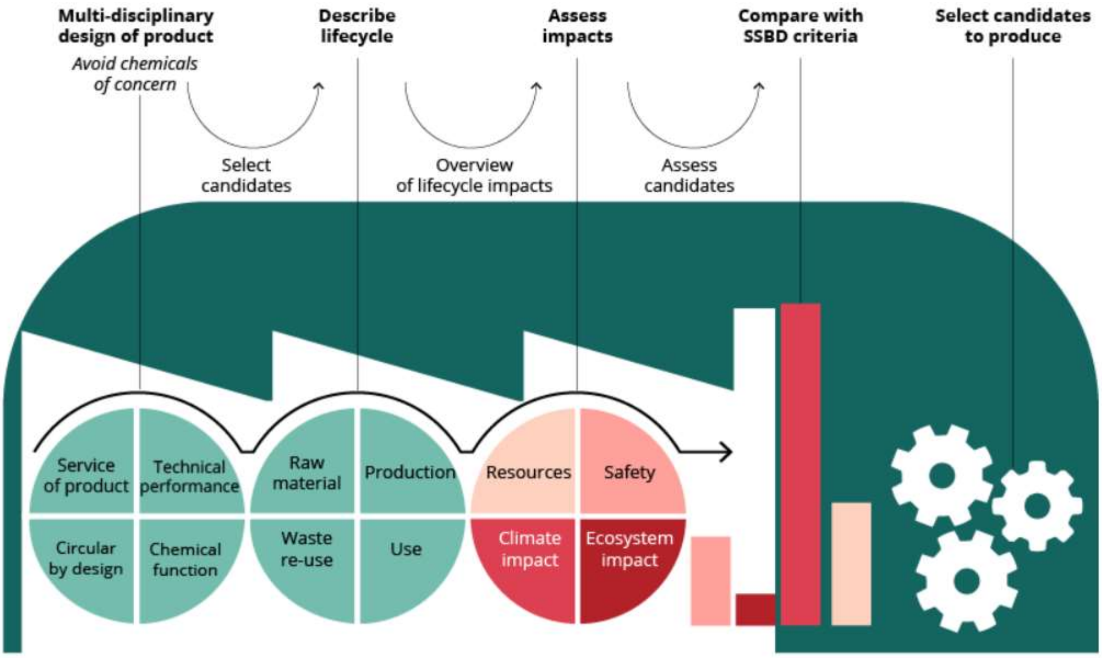

Figure 20. Implementing safe and sustainable by design approaches – figure by EEA (European Environment Agency) (source: EEA[31]).

6. Conclusions – what the NanoFabNet Hub can improve

The NanoFabNet Hub aims to build a strong international network for sustainable nanofabrication. The stakeholders have a key role in this development process as their input will contribute to identify and shape the Hub's services and products (e.g. structure, business model) and ultimately form the Hub through their interest and support. For this reason, a wide range of NanoFabNet stakeholders was asked to contribute to the shaping of the NanoFabNet Hub through detailed feedback from several angles.

During the 2nd NanoFabNet Development Workshop, it became clear that the stakeholders mainly supported a membership organisation (with or without fee) (i.e. by 74%); when asked about the services and product-offerings of such a membership organisation, they provided the following ranking:

- identification of relevant partners,
- access to infrastructure,
- training and standardisation services,
- consultancy and data services,

- proficiency testing,
- business development services, and
- calibration.

The NanoFabNet stakeholders furthermore identified the dissemination of information on sustainability as the main topic for NanoFabNet to raise awareness towards sustainability, before trainings, and workshop; stakeholders mainly added that a digestion of updated information would be appreciated.

The stakeholders asked for databases on (in priority order): characterisation facilities and infrastructure, standard and guidance documents, service providers (with feedback of customers), interlaboratory comparisons, service providers and reference materials and then experts and training.

In addition, an access to good training materials and to infrastructure network, transfer to lab-scale to test-bed or plant scale were also amongst the challenges that needed to be met.

The stakeholders agreed on the importance for the NanoFabNet Hub to participate in the standardisation field of sustainable nanofabrication. But the role they want NanoFabNet to play was not totally clear cut: 40% think NanoFabNet should only have a dissemination role, whereas 35% want NanoFabNet to be an initiator, and 25% a project leader for harmonisation activities. But they would like to be individually supported by NanoFabNet in the (pre-)standardisation/validation process (description in subsection 4.2 Standardisation of this report). The stakeholders also mentioned *(i)* sustainable funding, (*ii)* implementation of nanomaterials in the industry, *(iii)* sharing of good or best practices, *(iv)* strengthening of the network with small and medium sized industries for better technology transfer, *(v)* increasing access to and usage of nanofabrication infrastructures/facilities, (*vi)* fostering of knowledge transfer by sharing of information, and *(vii)* publications as key points for the development of sustainable nanofabrication.

Stakeholders want to be kept informed about currently running / close-to-be finished EU projects and updated on recent developments in sustainable nanofabrication by literature, conferences & workshops, social media (such as LinkedIn). Concerning ethics, they are mainly in favour of a discovery and use of the different tools available (gathered in a database) and a participation in multi-actors reflexion sessions.

In brief, NanoFabNet stakeholders want the NanoFabNet Hub to become a bridge between all actors of sustainable nanofabrication:

- **to be informed of the new development of process, characterisation and standardisation linked to sustainable nanofabrication;**
- **to facilitate access to nano-characterisation and nanofabrication infrastructure;**
- **to be trained and be supported in their evolution to reach sustainable nanofabrication;**
- **to identify the needs of industry, governmental agencies, and non-governmental organisation; and**
- **to foster and support collaborations between characterisation experts, standardisation actors and users.**

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